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Impact of Gaussian blur on perceptual-motor behaviour in boxing: a virtual reality assessment

Annabelle Limballe

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THÈSE DE DOCTORAT DE

L'UNIVERSITÉ DE RENNES 2

ÉCOLE DOCTORALE N° 646

Éducation, Langages, Interactions, Cognition, Clinique, Expertise
Spécialité : STAPS

Par

Annabelle LIMBALLE

**Impact of Gaussian blur on perceptual-motor behaviour in boxing:
A virtual reality assessment.**

Thèse présentée et soutenue à l'Université Rennes 2, le 21 juin 2023

Unité de recherche : Univ Rennes, Inria, M2S - EA 7470, F-35000 Rennes, France

Rapporteurs avant soutenance :

Gilles Montagne Professeur d'université, Aix-Marseille Université
Kerstin Witte Professor, Otto-von-Guericke-Universität Magdeburg

Composition du Jury :

Membres du jury :	Gilles Montagne	Professeur d'université, Aix-Marseille Université
	Kerstin Witte	Professor, Otto-von-Guericke-Universität Magdeburg
	David Mann	Associate professor, Vrije Universiteit Amsterdam
	Stefanie Klatt	Professor, German Sport University Cologne
Dir. de thèse :	Richard Kulpa	Professeur d'université, Univ. Rennes 2
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GENERAL INTRODUCTION

Sports performance is multifactorial and complex to understand. Accompanied in particular by their trainer, high-level athletes seek every day to push their limits through training in order to make gains of 1% or less that make the difference to competitive success. In combat sport, where the average punch speed is said to be between 9 and 11 $\text{m}\cdot\text{s}^{-1}$, responding 200 ms earlier can make that all important difference between avoiding an attack or being hit. Traditional combat sport training tends to focus on the players' ability to be strong, to move quickly, to organise themselves collectively and individually in consideration to the opponent's action. In other words, the emphasis is on the physical, tactical and technical aspects. The ability to perceive, extract information, anticipate and choose appropriate actions are all key to competitive performance and are often overlooked in combat sports. Indeed, despite it being established that perception is a key factor in performance (Appelbaum & Erickson, 2018; D. Mann et al., 2007), there are still unanswered questions about the assessment and eventual possibility to improving these qualities in combat sports (Hodges et al., 2021).

English boxing, on which I will focus this PhD, is an Olympic and professional combat sport. According to Ottoboni et al., 2015, boxing is a combat sport that involves two athletes fighting for victory. To achieve this goal, each athlete must be able to adapt quickly to changing events, anticipating the opponent's actions and taking into account external stimuli, while at the same time attempting to disrupt the opponent's tactics. This has to be done in an extremely short time, given that boxing, like other combat sports (Savate boxe française, karate and taekwondo for example), is a so-called "open" sport characterised by very rapid and uncertain movements. In other words, while trying to defeat their opponent, boxers have to avoid blows, to protect themselves and avoid a knockout blow. In other sports with similarly high temporal and event pressure, perceptual-cognitive skills appear to be a determinant of performance (D. Mann et al., 2007; Romeas et al., 2022; A. M. Williams et al., 2011). In boxing, coaches recognise the need for anticipation but they do not have specific training tools for the development of this and other perceptual-cognitive skills. The only solution is for boxers to learn during a combat situation, whether

that be in practice or competition. However, repeated practice in a combat situation leads to an increase in osteoarticular risks, particularly in the extremities (fists, wrists), as well as an accumulation of fatigue. Perhaps even more important is the risk associated with repeated blows to the head. The accumulation of head impacts causes short and long term cerebral damage, directly deteriorating perceptual-cognitive skills (the very ones we are trying to develop) and leads to major long term health risks (M. Bianco et al., 2008; Hukkanen & Häkkinen, 2017; Lesiakowski et al., 2018; Mishra et al., 2018; J. Moriarity et al., 2004; J. M. Moriarity et al., 2012). Moreover, after a knock-out, a return to combat, even in practice, is forbidden for a long period, which could limit drastically training and subsequent competitive performance. Taken together, it is clear that more work is needed on understanding perceptual-cognitive skills in boxing, such that ultimately these can be developed and trained as means of improving the ability to avoid attacking punches. Therefore, in this thesis, I will focus on the anticipation of a boxer in a defensive situation.

In this context, the defending boxer must locate and attend to the appropriate information about the attacking boxer in order to select and then execute an efficient action (e.g., dodging the right side while keeping the distance short to counterattack). The best players/fighters (in team sports, combat sports) are recognized to make the difference in the game/combat because they capture information more quickly and make the best choices; in other words, they use their perceptual-cognitive skills rather than simply physical strength to gain an advantage over their opponents (Brault et al., 2012; Faubert, 2013; Mallek et al., 2017; D. Mann et al., 2007). They "see" the right decision before the critical moment. A large part of this ability, and thus a key determinant of expert performance, is said to be underpinned by perceptual-cognitive expertise (D. Mann et al., 2007). For example, based on their previous experience (e.g., training and competition) skilled athletes are better at anticipating an opponent's movement (A. M. Williams et al., 2011) and consequently make more appropriate decisions (Raab et al., 2019). In addition, they can achieve high levels of performance on the basis of less information, whether that be due to temporal (e.g., information determined earlier) or spatial (e.g., information determined from fewer stimuli) constraints (A. Williams & Jackson, 2019). In part based on such findings, the role of basic visual functions such as acuity and contrast sensitivity, and their potential for improvement following training, have often been overlooked. Indeed, it is generally well accepted that there is no additional advantage of supra-threshold levels of visual function (i.e., above the general population average), and thus little or no benefit

of general visual training programmes in those who already have normal visual function (N. Smeeton et al., 2013). These experts do not necessarily have better eyesight but they detect and use information better (Brault et al., 2012; Faubert, 2013; Mallek et al., 2017; D. Mann et al., 2007; Romeas & Faubert, 2015). Therefore, the goal of this work will be to identify and assess the perceptual-cognitive processes underpinning boxing performance, and in particular anticipation.

Among the methods reported in the literature for identifying anticipation and decision-making expertise, the use of blur has gained a lot of interest. This could seem counterintuitive given the amount of work and debate concerning the importance of vision to elite sports performance. However, it should be recognised that the physiology of the human retina and visual cortex is such that “normal vision” integrates partially blurred inputs from peripheral vision, which is sensitive to motion, and has been linked with specific neural processing pathways (D. L. Mann et al., 2010b). As will be discussed in more detail in the following chapters, learning to extract relevant information from blurred input or shifting attention away from high acuity regions towards blurred input, are potential explanations given in studies that have shown improvements or at least maintenance of performance in conditions with blurred stimuli (R. Jackson et al., 2009; Ryu et al., 2015; Ryu et al., 2018; Ryu et al., 2016). As has been the case in much of the work on perceptual-cognitive skills in team sports, racket sports (tennis, badminton) or combat sport, the blurred stimuli were typically presented on 2D displays and required no real physical measure of the performance response (for exceptions see D. L. Mann et al., 2010a; D. L. Mann et al., 2010b). Therefore, one could argue that the protocols used in research on the effect of blurring visual stimuli are not representative of the real-world sporting context, which would then call into question the applicability of the findings. VR offers a recognized research tool that allows the realistic simulation of real-world tasks (e.g., the presence of a virtual opponent that performs realistic combinations of punches thrown, in a full-scale virtual ring) with a high level of control and reproducibility (Bideau et al., 2010; Craig, 2013; Miles et al., 2012; Stone et al., 2018). Even more important, VR allows the immersed user to interact with this simulated environment in a first-person and adaptive viewpoint in real-time (Harris et al., 2019). This preservation of the normal perception-action coupling means VR allows each individual to develop a particular interaction with the world and to experience it according to their skills, knowledge and morphology (Fajen & Warren, 2007; Gibson, 1979). These advantages make VR an ideal

tool for perceptual assessment and training, as well as new possibilities of visual manipulation, which are difficult to realize in real settings.

The main goal of this PhD is to develop a tool to identify and assess anticipation in boxing. This task must satisfy the perception-action loop and the representativeness of the context in order to target and assess the skills involved in real context during fighting. VR will be used to fulfil these conditions, and in addition will enable a thorough and controlled means of exploring the use of blur as potential way to assess, and potentially train, anticipation in boxing. To this end, in the first chapter, a general literature review will be presented, which will consider perceptual-cognitive skills in the context of boxing, and especially anticipation, an overview of the methods to assess anticipation and discuss how VR responds to the different constraints to assess the anticipation performance in boxing. In the second chapter, a synthesis of relevant background literature will be presented, culminating in global objectives for the subsequent studies. In the fourth chapter, a detailed review on the use of blur in studies of perceptual-cognitive skills in sport will be presented. The next chapters will be dedicated to the presentation of three studies conducted during this PhD. The first study examined the effect of a gaze-contingent manipulation of stimulus properties using blur in virtual reality boxing. The second study investigated the impact of gaze-contingent blur on elite boxers' anticipation performance in virtual reality boxing. The last study examined the impact of local and global blur on anticipation performance in virtual reality boxing. A general discussion, limitations and perspectives will follow, before concluding about the main findings of this work.

LITTERATURE REVIEW

1.1 The role of perceptual-cognitive skills in sport performance

1.1.1 Comparison of experts and novices' skills

In a dynamic sports environment, the athlete is confronted with a multitude of information, which could exceed the limited processing resources (Hodges et al., 2021; D. Mann et al., 2007). This could be particularly problematic in a sport such as boxing where there is a very short amount of time available to respond (e.g., 200 ms or less). The capacity to be tuned to the most relevant cues in order to identify, select and use them efficiently are referred to as perceptual-cognitive skills. More specifically, *“perceptual-cognitive skills have been defined as the ability to identify and process environmental information, and integrate them with pre-existing knowledge and motor capabilities, to select and execute adequate actions (e.g., Marteniuk, 1976).”* (Renshaw et al., 2019). As skill level determines sport performance, the observation and comparison of experts and novices has been used as an inductive way of skills identification (Hodges et al., 2021; Zhang et al., 2022). The objective is to identify capacities of experts as the goal to reach for novices. However, as suggested by Hodges et al., 2021, the traditional definition of perceptual-cognitive skills lacks clarity and consensus. Indeed, many concepts are overlapped under this term, with a constellation of skills evoked, from attention, anticipation, visual search, to pattern recognition, working memory, and many others (Hodges et al., 2021). These authors proposed the following definition. *“Perceptual-cognitive skills describe capacities related to the perception of sensory information in the environment; including detection, discrimination, identification, recognition, and classification. These skills are also related to the evaluation and integration of sensory information with existing knowledge, resulting in appropriate interactions with the environment. In most sports, perceptual skills are centered on vision. Other senses, such as hearing and touch, can contribute to sports performance, but*

few studies exist on skill-level differences in these other senses. In the context of sport, perceptual-cognitive skills are highly embodied, such that what we see and what we think are tightly bound to how we move.” (Hodges et al., 2021).

This revised definition enables us to understand why an athlete with exceptional motor skills in field and track will not necessarily be good in an interactive sport where they have to deal with an opponent, and “see” his intentions. It is interesting to highlight, in the preceding quote, the importance of vision in perceptual-cognitive expertise. The link between perception – action and cognition, detailed in chapter 1.4.2 of this thesis, is of major importance. The salient points of perceptual-cognitive expertise are the ability to pick up early visual cues on the opponent (e.g., postural and kinematic information; D. Mann et al., 2007), which is often associated with an efficient visual search and use of vision (like the association of peripheral and central vision) (Schorer et al., 2013), leading to an appropriate choice of action (D. Mann et al., 2007). This notion of early recognition of important visual cues defines anticipation skill, which it plays a crucial role in boxing due to the strong temporal constraints.

In the classification of the perceptual subskills, general visual and cognitive skills are distinguished from sport specific skills (Hodges et al., 2021). General visual and cognitive skills are related to global visual abilities such as visual acuity, depth and contrast perception, which are not thought to be developed from sport experience. Still, these general skills could impact upon sport performance. A body of studies have tried to develop general visual and cognitive skills to improve performance but the results seem marginal (A. Williams & Jackson, 2019). The second set of subskills, the sport-specific skills, have gained more interest, being more related to sport experience and thus expertise. Several subskills have been explored for training such as pattern recognition (North et al., 2017), visual search (Roca et al., 2018) or quiet eye (Causer et al., 2017), but decision making and anticipation have been of more interest to coaches and sport scientists seeking to enhance performance. As explained by Broadbent et al., 2015, *“These perceptual-cognitive skills combine to produce two judgements, namely, anticipation and decision-making (A. M. Williams et al., 2004) [...]. Anticipation is the ability to recognise the outcome of other athlete’s actions prior to those actions being executed. Decision-making is the ability to plan, select and execute an action based on the current situation and the knowledge possessed (A. M. Williams, 2013).”* The precise identification of perceptual-cognitive skills

according to expertise is an important challenge in order to define the steps to reach the maximal performance. In the meta-analysis of D. Mann et al., 2007, experts were characterised as making more accurate judgments facing sport specific stimuli, faster responses, and more fixations of smaller duration than less-skilled and novices athletes. Altogether, these findings indicate an earlier use of the information by experts and thus improved anticipation.

Perceptual-cognitive skills are a key determinant of dual sport performance. The targeting of these skills through identification, evaluation and training is a way of improvement that needs to be developed. One statement is clear; the earlier the information is picked-up and the faster it is processed, the more performance improves. Thus, anticipation seems to be a basis and support of other perceptual-cognitive skills.

1.1.2 Anticipation in sport performance

As stated earlier, the different past works on anticipation agree on the definition of anticipation as a successful prediction of the future action before this action has ended or even started, based on kinematic and contextual information (Müller et al., 2022). In other words, experts' anticipation is characterised by earlier information pick-up, integration of different sources of information (from the opponent's body, for instance, compared to a lesser expert's focus on an isolated part of the body) and contextual information (Murphy et al., 2016; Murray et al., 2018), as well as a better sensitivity to genuine action (A. Williams & Jackson, 2019). Indeed, experts detect better, and with less information, the deceptive movements of an opponent and thus are better able to make an accurate judgement (Brault et al., 2012; R. C. Jackson et al., 2018). Experts "buy" themselves more time for action and can delay their motor action to the correct timing as their anticipation of the incoming action occurs early in the sequence (Brault et al., 2012). Generally, this is referred to as a better use of kinematic and contextual information by experts compared to less expert athletes. They are better at ignoring irrelevant cues and instead focus on the essential information that supports expert performance (Belling et al., 2015; A. Williams & Jackson, 2019).

Expert anticipation is often associated in previous work with specific gaze activity, which enabled an efficient use of the visual system to scan and extract relevant informa-

tion (see Figure 1.1, A. Williams and Jackson, 2019). For dynamic events, such as control a long flight pass in soccer, anticipation may also be linked to basic visual skills such as motion prediction and accuracy of eye movements (Hodges et al., 2021). The specificity of gaze activity is detailed in part 1.2 below. In consideration of the specific experts' pattern gaze behaviour, A. Williams and Jackson, 2019, proposed the following representation of experts' anticipation and the related skills encompassed: perceptual-cognitive performance is the produce of “*dynamic interactions between the perceptual-cognitive skills underpinning anticipation*” (A. Williams & Jackson, 2019). This dynamic interaction is driven by the state of the athlete (skills, stress, anxiety, environmental condition) and the task constraints. In that sense, anticipation and associated subskills like gaze behaviour are expressed differently regarding the sport specificity or even the type of situation (e.g. far task versus near task, Roca et al., 2013). The role of gaze behaviour and its interaction in anticipation performance is well documented in team sport like soccer or rackets sports, however there has been less consideration of the interaction between anticipation and gaze behaviour in Olympic boxing. In the work of Ripoll et al., 1995, on gaze behaviour of French boxing experts, it was suggested that the major areas of interest were around the trunk. Hausegger et al., 2019, later developed the idea of a fixation point around the chest to understand experts gaze behaviour in different combat sports.

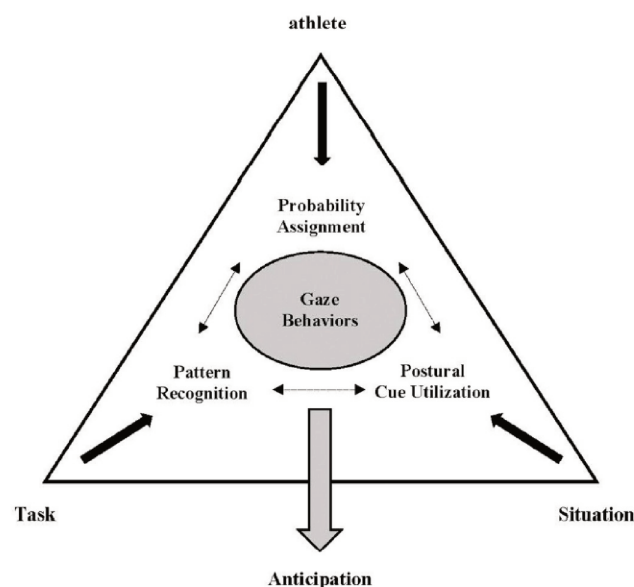


Figure 1.1 – The potential interaction between perceptual-cognitive skills and constraints (A. M. Williams, 2009)

1.1.3 Boxing context

Perceptual-cognitive skills, and anticipation in particular are fundamental in boxing (Krabben et al., 2019; Romeas et al., 2022). As described earlier, during a fight, two boxers compete within a constrained area of the ring (6.1m x 6.1m in Olympic boxing), over a limited time (3 rounds of 3 minutes with 1 min break in between). This open-skill sport is classified as an interceptive sport (Russo & Ottoboni, 2019), with the fighters judged on the quality of their blows, their technical and tactical domination over the round, as well as their combativeness (Romeas et al., 2022). The distance between the two fighters is crucial in the opposition (Krabben et al., 2019; Martínez de Quel & Bennett, 2019; Romeas et al., 2022; Zhang et al., 2022) and constantly evolving to take the advantage over the opponent. As a consequence, the temporal and spatial constraints are extremely strong, and the movement is continuous (Krabben et al., 2019; Ottoboni et al., 2015; Romeas et al., 2022). Deceptive movements are frequently used by fighters in the distance interaction, in an effort to create uncertainty regarding the onset of their attacking actions (Martínez de Quel & Bennett, 2019; Ottoboni et al., 2015; Romeas et al., 2022; Russo & Ottoboni, 2019). As a punch in boxing is about 240 ms (242 ms for karate punch, Martínez de Quel and Bennett, 2019) and the mean simple reaction time observed in boxers is between 215 ms (Badau et al., 2018) and 250 ms (Martínez de Quel & Bennett, 2019), it is clear that simply reacting will not enable an effective avoidance or counter attack. For these reasons, anticipation plays a critical role in the fight and reaction time is not a good enough indicator to explain a better performance (Martínez de Quel & Bennett, 2019; Zhang et al., 2022).

Consistent with the observation made on team sports or rackets sports, Russo and Ottoboni, 2019, suggested that superior anticipation and decision making is a characteristic of expert combat sports athletes. Indeed, experts seem to use early advance cues on the kinematics from the opponent's bodily movements, which provide subtle clues of the incoming attack (Martínez de Quel & Bennett, 2019; Romeas et al., 2022; Russo & Ottoboni, 2019; Zhang et al., 2022). This reveals a strong capacity of anticipation, based on the available visual information and possibly contextual information (like the knowledge of opponent strength/weakness or preferred pattern) (Romeas et al., 2022; Zhang et al., 2022). As markers of anticipation skill in combat sports, Zhang et al., 2022, found in their review a better accuracy of experts in the task, a faster reaction time, and a smaller number of fixations compared to non-experts. The mean fixation duration was

not significantly different across the pooled analysis of the articles included. In the sense of picking-up the information earlier, Martínez de Quel and Bennett, 2019, proposed a model of perceptual skills and anticipation during the attack progression in combat sports (see figure 1.2). To understand deeper this model of perception and how information can be picked-up earlier to make the correct choice, the analysis of the gaze behaviour could be informative.

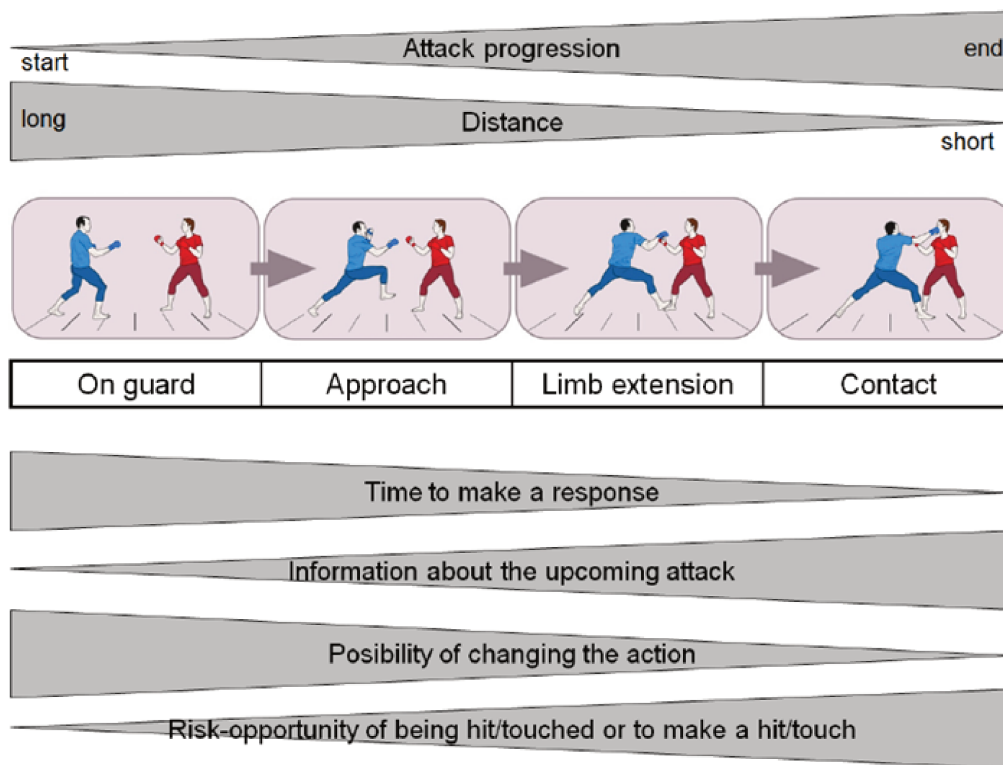


Figure 1.2 – A model for perception and action on combat sports based on distance, attack progression and opponent reaction (Martínez de Quel & Bennett, 2019).

Among the perceptual-cognitive skills, this PhD will focus on anticipation. It has been investigated in many dual sports like team sport or racket sports but there are a limited number of studies on combat sports. Given the temporal constraints of boxing, it is clear that anticipation is a key determinant of expertise. Although the importance of anticipation is recognised by athletes, coaches and sport scientists alike, the means to apprehend expert anticipation remain vague.

1.2 Gaze behaviour

1.2.1 Common parameters

When considering perceptual-cognitive skills, it is difficult not to mention the role of gaze behaviour. As stated by Hodges et al., 2021, vision is central in the process. Eye movements are identified as support of action, associated with anticipation skills (see figure 1.1). Gaze location provides insight about the information used and the distribution of attention (Blascheck et al., 2014), which can be disturbed by the presence of different stimuli. Specially, as commented by Hodges et al., 2021, *“Eye movements provide a tool to assess both overt and covert visual spatial attention. They provide unique information about how visual attention is allocated and the control of eye movements appears to be an important skill in sport.”* The different parameters of gaze behaviour and visual search reflect the underpinning cognitive strategies (Schorer et al., 2013; Zhang et al., 2022) and thus are a marker of expertise.

In perceptual-cognitive studies, the common parameters investigated are: mean number of fixations and mean fixation duration; time spent fixating in Areas Of Interests (AOI); scan path; or number, speed and amplitude of saccades (Klostermann et al., 2020; Kredel et al., 2017; D. Mann et al., 2007). A fixation is a gaze stabilisation behaviour at a specific point for a minimum of 100 ms, but generally between 200 and 400 ms (Salvucci & Goldberg, 2000). Thus, spatial dispersion and temporal duration are parameters used to determine fixations (Salvucci & Goldberg, 2000). During a fixation, central vision remains stable on a location in order to facilitate extraction of detailed information, and limit the loss of information due to the saccades cost (i.e., saccadic masking) (Klostermann et al., 2020; Salvucci & Goldberg, 2000; Vater et al., 2019). Central vision refers to a part of the retina that comprises approximately 5° of the human visual field (which is around 180°, Hausegger et al., 2019; Rooney et al., 2017), see the partition of visual field in Figure 1.3. In normal or corrected-to-normal vision, high acuity input is perceived from cone cells that are concentrated at the center of the eye in the area known as the fovea. Cone cells detect light of different wavelengths, which is the basis of color perception, operate best in bright light, and enable perception of fine details (i.e., high spatial frequency). They thus play a critical role in being able to distinguish shapes and details of objects in our surrounds. The other main photoreceptor cells, known as rods, are not attuned to the same light wavelengths as cones, and instead are better for detecting motion and low

acuity input.

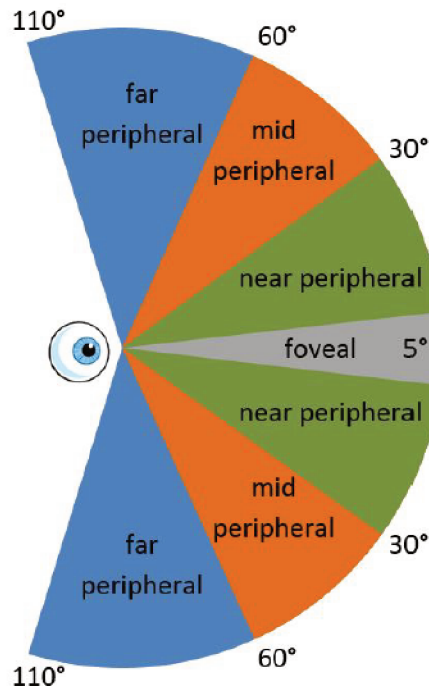


Figure 1.3 – Human field-of-view for both eyes showing the foveal, near, mid, and far peripheral regions, from Hussain et al., 2021.

Still, it is difficult to measure if the information is picked-up at a fixation location or from the surrounds. Some insight could be gained from the differentiation between ambient fixation and focal fixation. Based on their duration, fixations from 50 to 150 ms are classified as ambient, whereas fixations longer than 250 ms are focal (Negi & Mitra, 2020; Rooney et al., 2017). Focal fixations are thought to reflect the conscious perception of an object and are thus associated with central vision and ventral stream processing. Spending a long time at a particular location with a focal fixation is said to facilitate a very detailed identification. On the other hand, short fixations have been more associated with peripheral vision and the use of covert attention, based on low detailed information processed through the dorsal stream. In other words, fixation duration could reflect the underlying processing of visual information (Negi & Mitra, 2020; Rooney et al., 2017). The K coefficient is the proportion of ambient fixations over focal fixations and allows the comparison between groups/conditions (Negi & Mitra, 2020). If positive, this ratio

indicates a greater reliance on ambient processing, and if negative there is a focal processing dominance; this ratio and thus processing dominance evolves dynamically during task performance (Krejtz et al., 2016; Negi & Mitra, 2020). Importantly, these concepts were described and advanced from eye movement research in reading and learning (Negi & Mitra, 2020), scene identification (Krejtz et al., 2016; Pannasch & Velichkovsky, 2009) or architecture (Rooney et al., 2017). As yet, they have not been considered in a sport context, which could be an oversight given the potential to assess the mode of visual processing.

In this sense, the fixation duration and the number of fixations has been used in perceptual-cognitive studies to identify the location of the useful information. Specific areas where information should come from, the areas of interest (AOIs), are defined relative to the behaviour being observed (e.g., in boxing, the fists, head, and torso are of interest to read the opponent's behaviour). Scan path is the analysis of the order and hierarchy that gaze follows as it moves between the AOIs. During fixation, where central vision is located on a specific AOI, information from other areas can still be perceived from peripheral vision. However, the nature of the information is different from that perceived in central vision. Cone cells play a critical role in being able to distinguish shapes and details of objects in our surrounds. Yet, these cells are few on the retina and the neural input frequency is relatively slow. Fixations allow this detailed and relatively long processing by maintaining the position of the gaze still, giving time for neural processing. The other main photoreceptor cells, known as rods, are not attuned to the same light wavelengths as cones. They are numerous outside the central part of the retina and have a high temporal frequency. Therefore, rods cells are sensitive to movement and low contrast information but give coarse output information.

Gaze orientation and changing location are achieved thanks to saccades and smooth pursuit eye movements, as well as vergence. These eye movements allow a subject to follow an object as it moves in its surrounds and thus the detection of the stimuli appearing in the visual field. Saccades and smooth pursuit are conjugate movements, meaning the eyes move in the same direction when following an object that moves in a single depth plane, whereas vergence is a deconjugate eye movement that follows an object that changes depth. A saccade is an eye behaviour that rapidly shifts overt attention from one location to another, and thus enables a change of locus of central vision. It is a discrete movement

that quickly change the position of the eyes, thereby translating the image of the object of interest from an eccentric retinal location to the fovea, the central area of the eyes (Krauzlis, 2004). Saccades are fast movement of duration around 12 ms to 120-160 ms, depending on magnitude (Galley, 1989). Indeed, the magnitude of the saccade and the average velocity are positively linked and referred to as the saccadic main sequence (Bahill et al., 1975). Smooth pursuit is defined as "*a continuous movement that slowly rotates the eyes to compensate for motion of the visual object, minimizing blur that would otherwise compromises visual acuity*" (Krauzlis, 2004). Smooth pursuit is mainly driven by visual motion, like an object or a ball moving toward us (Krauzlis, 2004), but there is also an influence of cognitive factors such as expectation (Barnes, 2008).

Gaze analysis comparing experts and novices in interceptive sports has revealed recurrent differences when facing sport-specific stimuli (D. Mann et al., 2007; Romeas et al., 2022; A. Williams & Jackson, 2019). In general, it has been established that experts tend to have fewer fixations of longer duration compared to less-skilled participants in interceptive sports like racquets sports or baseball (D. Mann et al., 2007; Romeas et al., 2022). Additionally, consistency across task repetitions is an element of expertise, with experts tending to exhibit a very similar gaze behaviour when faced with repetitions of a situation (Kredel et al., 2017). On contrary, novices' gaze behaviour is generally inconsistent when asked to repeat the task (gaze behaviour different from one trial to another) and various strategies can be observed between novice participants. The areas of interest focussed upon are both sport and situation dependant. In boxing, for instance, the torso, head and leading fist are the mainly areas focussed, which indicated that they are possible important sources of information (Ripoll et al., 1995). Still, these gaze behaviour patterns observed in past works seem to be task and context specific (Roca et al., 2013), and longer fixation alone is not always associated with performance (and expertise) in a specific task (Lounis et al., 2021; Vater et al., 2019). For example, in their work Lounis et al., 2021, investigated pilots' gaze activity and observed that expert pilots had shorter fixation duration than novices. Yet, in interpretation with other parameters like dwell time, number of fixations, pattern of transition between AOI (in this case flight instruments), experts presented higher perceptual efficiency and a different mode of visual attention (ambient) compared to novices. Moreover, in addition to foveal information, parafoveal information can also be important (Hausegger et al., 2019; Klostermann et al., 2020; Vater et al., 2019) as information can come from different locations that can't be in foveal vision

simultaneously (like the two fists in boxing, Hausegger et al., 2019).

1.2.2 Central and peripheral vision, overt and covert attention, ambient and focal fixation

The gaze location gives the locus of central vision and overt attention. Yet, as mentioned, the size of central vision is quite small and does not cover a wide range of information in the visual field. Moreover, cones cells that serve central vision have longer processing time. That is, in dynamic and fast sport like boxing, different locations must be taken in consideration simultaneously (both fists, torso). The location of gaze could be changed by saccadic movements, but, during this movement, information pick-up is not possible. Indeed, information is masked to minimise processing of blurred information that results from rapid shifts of the fovea. This phenomenon of information loss during saccade is referred to as saccade masking. That is, constantly changing the location of central vision is not an efficient strategy as it results in periods of saccade masking and potential loss of information processing. Combat sports athletes generally gaze at a central point around torso (Hausegger et al., 2019; Ripoll et al., 1995), which indicates the location of central vision but does not necessarily coincide with the information that is critical for anticipation (Schorer et al., 2013). Indeed, gaze location gives information about the locus of overt attention but a gaze stabilisation can allow peripheral information pick-up (Hausegger et al., 2019). That is, an increased fixation time could either mean more information from the central vision, an increased peripheral processing, or a combination of both. When the point of fixation and the locus of attention are congruent, attention is overt. On contrary, in case of peripheral processing, we refer to covert attention. There are thus limitations to consider only central vision location and overt attention. The distinction between looking at a point of interest and allocating attention to this point to extract information is crucial to understand visual processing in boxing. Specifically, the distinction between central and peripheral vision, as well as overt and covert attention are important. In particular, Klostermann et al., 2020; Vater et al., 2017b, supported the idea that both central and peripheral vision are used simultaneously, and are more effectively integrated by experts. Indeed, experts could use both central and peripheral vision, and their different information, to adapt in quite demanding task like combat sports. According to A. Williams and Jackson, 2019, experts are different from novices in their capacity to extract more qualitative information from a fixation and more from their capacity to

switch the locus of their attention without moving their eyes. In other words, experts seem able to use peripheral vision in addition to central vision by exhibiting an efficient gaze strategy. Three main strategies to change the locus of attention have been identified for experts: the visual pivot, the gaze anchoring and the foveal spot (Vater et al., 2019).

Vater et al., 2017a stated “A gaze anchor would be defined as to the use of a rather long fixation on a position that is not necessarily related to an informative cue (as it would be the case in a foveal spot) but that optimizes information processing via peripheral vision and eliminates the costs associated with saccadic eye-movements.” (Vater et al., 2019). Very closely, the “visual pivot would be distinct from a gaze anchor because it would refer to a behaviour where gaze, rather than covert attention, is shifted frequently between different cues around a pivot location. Frequent fixations close to the defined pivot point might be explained by the closeness of other important cues that need to be processed via the fovea such that the pivot location should be characterized by a minimal retinal distance between peripheral objects and the fovea.” (Vater et al., 2019). The two strategies are often confused or used interchangeably (Vater et al., 2019). In opposition, “a foveal spot would characterize the functionality to primarily process information via the fovea with a narrow or broad attentional width.” (Vater et al., 2019). During a task, these different visual strategies can be used alternatively like in team sports, in one-one dual situation compared to a large field visualisation (Klostermann et al., 2020; Vater et al., 2019).

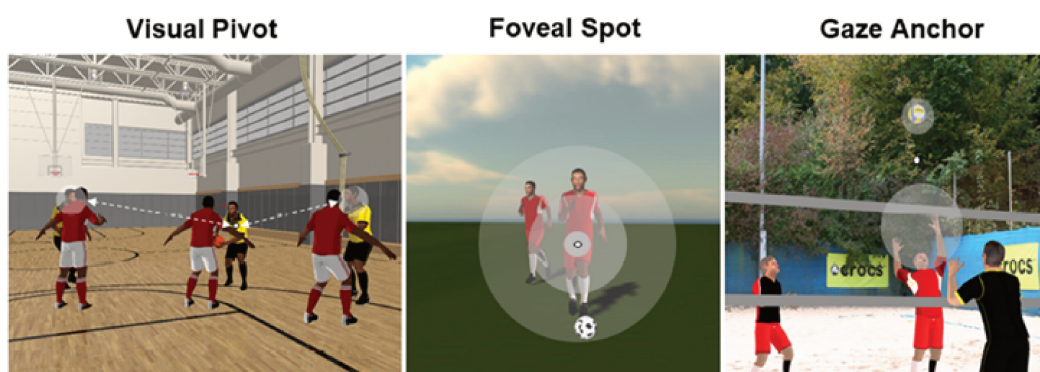


Figure 1.4 – Three types of gaze behavior for the use of foveal and peripheral vision in sports (modified from Vater et al., 2019). It should be noted that the small white spot illustrates the current gaze point and the grayish circled areas indicate potential attention locations as a function of respective relevant cues. Finally, in case of a foveal spot the breadth of attention can be modified as a function of the task demands. (Klostermann et al., 2020)

The combined use of central and peripheral vision is relevant for boxing, where experts gaze more at the head and torso compared to novices, who tend to focus more on opponent's forehead (and pelvis in French boxing) (Hausegger et al., 2019; Martínez de Quel & Bennett, 2019; Ripoll et al., 1995; Romeas et al., 2022). Experts' gaze behaviour suggests a gaze anchoring strategy, with possibly important processing in parafoveal vision, which would limit eye movements and minimise saccade cost (Hausegger et al., 2019). The head of the opponent is used by expert boxers as a central fixation point to maximize covert attention on important peripheral areas like shoulders and fists, with fewer fixations of longer duration compared to novices (Hausegger et al., 2019; Ripoll et al., 1995; Vater et al., 2019). Considering the definition of visual pivot and gaze anchoring given previously, it is not clear in related works whether one is better than the other in combat sports, as the vocabulary used in the studies could be interpreted that both gaze anchoring and visual pivot are employed. Moreover, the type of combat sports influences the processes, as for example attacks can come from the leg in karate or French boxing, whereas in Olympic boxing attacks are only made with the arms. The two arms cannot be focussed upon simultaneously in foveal vision (see figure 1.5), thus peripheral information is needed to identify and anticipate successive punches from different locations. Still, the majority of studies on boxing (French boxing) suggest a gaze anchoring strategy, using the head or the torso as stable point (Ripoll et al., 1995). Thus, covert attention seems to be involved in experts behaviour; experts privilege a switch of attention rather than a switch of gaze (Vater et al., 2019).

To understand these visual strategies, it is relevant to comment on the neural pathways of information processing, specific to central and peripheral parts of vision (Goodale, 2017; Goodale & Milner, 1992; Milner & Goodale, 2008). According to the dual-processing classification of vision, perception is dependent on the ventral stream, whereas action is dependent on the dorsal stream. Specifically, the ventral stream is dedicated to the recognition of objects and scene, whereas the dorsal stream is more involved in action recognition and regulation, and thus strongly related to movement (Goodale, 2017; Goodale

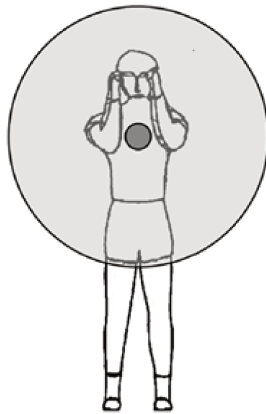


Figure 1.5 – Areas of foveal vision (2° of visual angle; dark gray) and peripheral vision (40° of visual angle; light gray) when facing an opponent standing at a 1.2-m distance. (Hausegger et al., 2019).

& Milner, 1992; Milner & Goodale, 2008). Different neural networks are dedicated to object and action perception, with different brain areas involved. The ventral stream is strongly associated with central vision, with a slower processing of high spatial frequency, and hence detailed information. On contrary, the dorsal stream is mainly associated with peripheral vision, with faster processing of the information but lower spatial frequency and detail. Importantly, these two systems were never intended by Milner and Goodale to be separate and dichotomous, but instead they work conjointly with the predominance of one or another depending on the situation. In line with the use of gaze anchoring and covert attention in combat sports, the use of the peripheral processing seems more appropriate to the time constraints. An opponent's attack has to be detected very quickly to anticipate and avoid the punch, and this is probably best served by the retinal and cortical physiology of peripheral vision, which has evolved to be faster than central vision and more sensitive to movement-related information (Milazzo et al., 2016a; Vater et al., 2019).

1.3 Method for assessing anticipation

In sum, there are three important conditions to be satisfied for expert anticipation: 1) where is the information extracted?; 2) what information is extracted?; and 3) when is the information extracted? To answer these three questions, different methods were de-

veloped to assess and understand anticipation in sport. Anticipation assessment has been investigated mainly in laboratory tasks as it is difficult to isolate and target anticipation in on-field tasks (Farrow, 2013). For reasons of feasibility, standardisation and use for training purposes, video displays have been used, often requiring a button click or verbal response (Farrow, 2013; D. Mann et al., 2007; Müller et al., 2022; A. Williams & Jackson, 2019). Participants are typically asked to predict the direction or time-to-contact of the impending opponent or attacking limb, with performance then assessed through accuracy of the response and reaction time. In such protocols, video displays have been the main media for stimuli presentation, with various methods used to identify the anticipation and nature of information associated. Among them, spatial and temporal occlusions have been most widely used (Müller et al., 2022). The occlusion paradigm is classified by Kredel et al., 2017, as an indirect investigation of information pick-up. Temporal occlusion protocols can also be used on the field thanks to rapidly-responding LCD occlusion glasses. In temporal occlusion, the visual information is occluded during the ongoing action, at different times with respect to key moments. For example Brault et al., 2012, occluded the information at four different times (separated by 100 ms, from the footfall before the first orientation step) of a rugby player during a sidestep feint. The comparison between experts and novices in this kind of task often provides a good indication of differences in anticipation skills (Hodges et al., 2021; Zhang et al., 2022). With this procedure, many studies confirmed an earlier use by experts of key information, with performance remaining stable for long occlusion times, which was not the case for novices (A. Williams & Jackson, 2019). Following a similar logic, spatial occlusion involves masking a part of the visual field that includes key information. The identification of the key information can then be determined by comparing performance between control and spatially occluded conditions, potentially as a function of different skill levels (Hodges et al., 2021; Müller et al., 2022; A. Williams & Jackson, 2019). From current work, we know that experts use specific sources of visual information when there is no spatial occlusion (control condition), and that these are sport dependent (hips in rugby, torso in boxing, racquet in tennis) (Müller et al., 2022; A. Williams & Jackson, 2019). Even when information is missing due to spatial occlusion, experts are able to adapt and maintain better performance compared to novices by using complementary cues, such as secondary areas of interest, probability of action and contextual information. Spatial and temporal occlusions can also be combined to better depict the demands on information pick-up (what information and when) and understand basis of the anticipation performance (A. Williams & Jackson, 2019).

Advancing on the use of these methods to assess anticipation and information pick-up, studies have also examined their use in training, repeating the exposure to an early loss or targeted loss of the video display in order to encourage the athlete to use advanced, specific cues (A. Williams & Jackson, 2019). That said, video displays and button-click or verbal response, have received a lot of criticism and questions on the correspondence to real-world field skills and its transferability for potential training (see details on chapter 1.4).

The use of occlusion methods, as an indirect way to assess where gaze would typically be located, is debateable as the information pick-up may be disturbed by the visual manipulation (Kredel et al., 2017). Conversely, direct methods, where the position of gaze is recorded over time, use eye tracking methods based on the displacement of the corneal reflexion and/or pupil (Kredel et al., 2017). Eye-tracking can be performed in isolation of head movement (using a chinrest and/or bitebar), and is often seen as the gold standard when one is interested in saccades because of the very high spatial and temporal resolution (0.1 deg accuracy and 2000 Hz with the EyeLink) and direct synchronisation with the video display. However, the necessity of a fixed head may limit the natural visual exploration and hence the extent of experimental design. Mobile eye-tracking devices, which are often mounted in glasses worn by the participant, can be used in the field under more natural viewing conditions involving head movement. However, they generally offer lower spatial and temporal resolution (in mean 30 Hz, Kredel et al., 2017) and require an external signal such as an illuminating LED in order to synchronise gaze recording with external stimulus events. Still, these tools have been widely used to characterise experts' gaze behaviour in sport and anticipation skills (Kredel et al., 2017; A. Williams & Jackson, 2019). In particular, as discussed earlier, experts tend to have fewer fixations of longer duration in interceptive task like rackets sports, baseball, combat sports (D. Mann et al., 2007; A. Williams & Jackson, 2019). As commented by Russo and Ottoboni, 2019, *“Eye-tracking appears to be a very important technique because it is capable of providing very interesting insight on processes of information selection and attention”*. However, to overcome limitations concerning the lack of coincidence between gaze location and overt attention, there could be an advantage to combine indirect and direct methods (Pastel et al., 2022). One such approach is known as gaze-contingency, whereby the visual display is adapted to gaze location, meaning that central or peripheral vision can be altered by occlusion. However, using a gaze-contingent manipulation to introduce an opaque mask

occlusion, Ryu et al., 2013a, does not resolve the problem of information removal.

To avoid complete removal of information, several alternative methods exist to perturb or simplify the information available. One of these involves the use of a point-light display, which presents a visual representation of the movement in which only anatomical landmarks like the joints are shown (Diaz et al., 2013; Müller et al., 2022; A. Williams & Jackson, 2019). Studies using point light displays highlighted the nature of the useful information, that is the kinematic information. In other words, in a sports context, detailed information on the opponent (like facial expression, clothes details) is not necessary to give a successful response (Müller et al., 2022; Petri et al., 2019b; A. Williams & Jackson, 2019). Methods like point-light display indicate that kinematic information is essential, and that detailed information is not necessary for motor anticipation. Following this logic, several studies investigated the effect of a blurred visual stimulus on perceptual-cognitive performance in sport (R. Jackson et al., 2009; D. L. Mann et al., 2010a; D. L. Mann et al., 2010b; Ryu et al., 2015; Ryu et al., 2018; Ryu et al., 2016; van Biemen et al., 2018). As will be discussed in more detail in chapter 3, blur removes the high spatial frequency information, such as details on facial expression, from photo or video displays. If perceptual-cognitive performance is maintained, it follows that participants are relying more on the dorsal stream and/or peripheral vision, or that the highly detailed information was in fact irrelevant. Applying this logic to learning, it has been suggested that perceptual-cognitive performance in sport could be improved under a moderate blur by directing participants to more useful and relevant information (e.g., the kinematic information on the opponent body). However, while there are some findings of improved performance during a decision making task in tennis (R. Jackson et al., 2009) or in soccer referees (van Biemen et al., 2018), a facilitatory effect is not always observed (D. L. Mann et al., 2010a) and appears to be dependent on the population (experts vs novices). Overall, current findings on the effect of blur on perceptual-cognitive performance, and learning, are somewhat equivocal and difficult to reconcile. Therefore, although a promising approach, a more in-depth consideration of the potential facilitatory effect of blur is needed, and will be presented in the following chapter.

Globally, the current methods to investigate anticipation involve the removal, impoverishment or perturbation of the normal viewing condition, which could modify information pick-up. Findings of a deterioration in performance, as well as differences between experts

and novices, led to the identification of expert anticipation characteristics. However, previous works largely used video displays or laboratory tasks, with a fixed viewpoint, which questions the potential application of the findings to sport performance. Motor action was often limited or absent, again questioning the relevance of the findings from the experiments to the sport setting. In an effort to overcome these limitations, the current thesis will use Virtual Reality (VR) to provide more realistic and controllable manipulations of the visual display, while also allowing for motor responses that match more closely those of the sport setting. Specifically, based on a review of the conceptual and practical issues involved in reported studies on blur (see chapter 3), VR methods will be developed to investigate perceptual-motor skills in boxing.

In the literature, diverse methods to assess and train anticipation in sport have been developed. They present advantages and disadvantages. Among those, and considering the visual properties of the visual system, the central and peripheral vision, this PhD will target specifically the use of blur. I will investigate the possible use of this method to assess and potentially improve visuo-motor performance in combat sports. The following literature brings in light the potential facilitator effect on performance but there is no consensus on this effect.

1.4 Virtual Reality

As discussed above, work investigating anticipation in sport has often used a 2D video display from a fixed viewpoint, with a limited or no motor response, thus creating conditions that are far from the normal sport setting. For these reasons, the results observed in those works can be difficult to extend to the global or sport context. To go beyond these limitations in perceptual-cognitive studies, virtual reality (VR) is a tool beginning to gain traction. The strengths of VR promise a new way of practising, complementary to sports training, which is safe and does not require access to a sport infrastructure or training partners (Neumann et al., 2018). Moreover, it allows to create original programs and exercises, impossible or even unreal to implement in the field conditions. However, to guarantee its development and usefulness to sport (being more than a distracting video game), scientific studies must support the generalisation of the tool by ensuring, in particular, the possibility of transferring the targeted skills to the specific sport context (Stone et al., 2018). It is also important to recognize the limitations of its use and its scope

to benefit most from the technology. In this section, the current state-of-the-art will be presented on the use of VR in sport science for the investigation of perceptual-cognitive skills in sport. First, VR will be defined, and then some of the main principles inherent to this tool will be discussed, such as perception-action coupling, the feeling of immersion and presence, and the representativeness of environments. Finally, the current work using VR in sport will be presented.

1.4.1 Definition

The term virtual reality is often used to denote different tools, which are sometimes not strictly speaking virtual reality devices (Faure et al., 2019; Neumann et al., 2018). It is necessary here to clarify exactly what is meant by virtual reality and define the term used in this PhD. According to Harris et al., 2019, "*virtual reality is a collection of technologies that allow the user to interact with a simulation of some environment, in real-time, using their own senses and motor skills (Burdea et al., 2003)*". As VR offer a visual display and a manipulation of what you see (or hear, or feel when haptic devices are included), it is said to be perfectly suited as a visual training tool for visually-guided motor skills (Harris et al., 2019). Thus, VR proposes advantages to go beyond some 2D videos limitations. Indeed, the possibility for the participant to move and interact with the virtual world allows a realistic motor behaviour (Neumann et al., 2018). VR also provides feedback to participants in response to their actions, thus preserving the perception-action loop. In addition, there are key points that distinguish virtual reality from 2D videos or 360° videos that attempt to provide a more realistic experience. First, in VR, the viewpoint is adaptative, which means it follows the user's head (and eye) movements, as in the real world. Second, the presentation of the image is stereoscopic (Faure et al., 2019; Harris et al., 2019; Miles et al., 2012; Renshaw et al., 2019). That is, two separate 2D images are presented, one for each eye, with a small offset representing the pupillary distance. This allows the user to perceive the 3D representation of the virtual world with depth information. This depth perception is an important element contributing to the realism of the situation and the feeling of immersion (Harris et al., 2019).

VR is thus a promising tool for researchers in sport science as the constructed environment can be representative of the sport context, but, first of all, can be completely reproducible, controlled and easily manipulated (Bideau et al., 2010; Craig, 2013; Faure et al., 2019; Miles et al., 2012; Renshaw et al., 2019; Stone et al., 2018; A. M. Williams

et al., 2011). The athletes can repeat again and again the same task, in front of a virtual opponent, for example, in combat sports, that is always available, with the same performance, which is not being influenced by emotional constraints or fatigue (Neumann et al., 2018). Alternatively, athletes can be confronted with a multitude of scenarios, with a lot of variability and adjustment to their own skill level (Michalski et al., 2019). Individualised training is therefore easy to implement (Michalski et al., 2019). In other words, VR devices allow flexibility and inventiveness in research protocols while preserving the need of standardisation and quantification. It is noteworthy that VR training will not substitute the traditional training on field. The aim is to enhance learning while avoiding risk of injury or repeated blows for example, to give the extra skills that makes the difference at highest level of performance, by bringing a different approach and a diversity in training (Neumann et al., 2018).

Several devices are available to present a virtual environment. The choice of system can affect the experience and lead to device-specific technological limitations (Faure et al., 2019; Neumann et al., 2018; Slater, 2009). First, the Computer Automatic Virtual Environment (CAVE) is constituted of large screen presentation. The user stands in a large cube, surrounded by display screens. Thus, the participant is physically within the virtual environment. The user wears small stroboscopic glasses, which allow a stereoscopic vision of the 3D virtual environment projected on the screens (Neumann et al., 2018; Slater, 2009). The space is equipped with motion capture system which allows the tracking of markers on the glasses (and other possible markers on different body parts) and thus the adaptation of the viewpoint depending on the user's movement. These devices have the advantage to allow the participant to see his own body inside the virtual environment and to freely move between the screens. However, these systems are very expensive and impossible to move. Second, the Head-Mountain Display (HMD) are device worn on the head like a helmet, in front of your eyes. They are lighter and transportable. The user's field of view is entirely covered by the system, thus the participant is no longer aware of his surroundings and cannot see his own real body but only perceive the virtual environment (Neumann et al., 2018; Slater, 2009). The image is projected (generally) on two separate little screens located in the HMD, one in front of both eyes. The desynchronisation between presentation of the two images allows the stroboscopic and stereoscopic vision of the environment, which produce the 3D perception. Head tracking is used to evaluate the head position and rotation, allowing viewpoint adaptation. As the user cannot see his

own body, it must be reconstructed in VR if needed. To this end, trackers are provided by the constructor to get their 3D position and rotation, and thus the body parts motion for instance when they are placed on the user's body. Full body suits like XSens can also be used to have a more complete motion capture of the participant but they are more expensive and make the apparatus heavier and more cumbersome to use. HMD are widely available, cheap compared to CAVE, offered by several manufacturers (e.g., HTC VIVE, OCULUS RIFT, PICO, FOVE) (Clay et al., 2019), and thus the most popular device.

1.4.2 Perception-Action principle

In sport psychology and visual/perceptual training, so far, 2D videos have been widely used. These studies have advanced the understanding of information processing, the nature of the information used, and the differences based on the level of expertise. However, as described earlier, there are questions regarding the correspondence of responding (with a button press) to 2D videos compared to interacting with surrounding opponents and events in a real sports situation (Klostermann & Mann, 2019). Video presentations seem more related to vision-for-perception and less about vision-for-action, as there is limited or missing motor response and no perception-action interaction. Therefore, to assess, track and train the development of perceptual-cognitive skills, it may be important to use protocols and devices that allows the *"vision for action"* context.

A great advantage of VR is that it can preserve the perception/action loop, which is a concept first advanced by the ecological theory of Gibson, 1979. Because we perceive the world, we act in response to what we see, and as a consequence our actions modify our perception of the world, in a constant loop (Gibson, 1979). This cyclical interaction is one of the key features of sport performance where vision supports action. To go further, Stone et al., 2018, added, in their model that *"cognition, perception and action are deeply intertwined in regulating athlete performance in satisfying key constraints"* (Stone et al., 2018). In this thesis, the interaction between cognition, perception and action is fundamental, and will be manipulated using a VR device to help the user/learner orient themselves to specific information in the environment (Stone et al., 2018). This assumption frameworks the use of VR in sport training. Still, this principle is not the only condition to design a suitable environment for sport experimentation. The representativeness is an important aspect.

1.4.3 Ecological validity, representative design and transfer

In their review, Pinder et al., 2011, recount the history of "*representative design*". Over time, this concept, according to the authors, had been misused, intertwined with the term of ecological validity. They stated that "*external validity came to refer to the generalisation of research findings from the study of a specific sample to either a larger population often referred to as population validity (Bracht & Glass, 1968) or to behavioural situations beyond the experimental context and population studied (Lucas, 2003).*" (Pinder et al., 2011). In contrast, ecological validity "*originally referred to the statistical correlation between proximal cues available in the environment (perceptual variables) and the extent to which they depict the distal criterion state of the environment*" (Pinder et al., 2011). These authors assumed that the term ecological validity was often evoked in sport science research, instead of the term external validity of research design. That is, in sport science, ecological validity generally refers to the correspondence between the observed behaviour in the experiment task and the global sport context (considering the performance for example). In the sense of representative design, the important elements are thus to satisfy the correct representation of the sport constraints and the interaction with the environment in the experimental task (Pinder et al., 2011). Another point, participants must reflect the population to whom the results will generalised. A small change in the interaction with the environment can modulate the participant's behaviour (Hristovski et al., 2011), meaning that to be reliable, the experimental environment must contain all the relevant constraints from the real situation. Accordingly, researchers must be cautious while extending results from their experiment to a general context and test the general transfer (Pinder et al., 2011). The term "*representative learning design*" includes a dynamic situation, where there is an interaction with the environment and a possibility of action, with adequate provision of visual information. The action fidelity is an important feature that ensures adequate motor action possibilities in the virtual task. In this sense, the preservation of the perception-action loop described in the previous paragraph is an important part of the representativeness of the design. Especially for the investigation of visual skills like anticipation, the coupling of perception-action is fundamental and was typically missing in previous works on blur and more broadly those using 2D video stimuli (Stone et al., 2018). As Gibson, 1979, said, the environment must be shaped by the movement of the user, meaning that the action fidelity is preserved. To go beyond, Gray, 2019, declined the fidelity in two types, the physical (representation of the action, action fidelity) and the psychological fidelity (matching of the perceptual-cognitive demand, and

further a corresponding gaze behaviour and attention). These authors supposed that psychological fidelity would favour more transfer than physical fidelity.

The importance of representativeness is associated with the effort to extend the progress obtained during practice in VR to the competition setting, that is, the transfer of skills to performance. Michalski et al., 2019, define transfer as the fact that *“the trained skills can transfer to the real-world setting. Transfer has been defined as the process by which skills, abilities and knowledge developed through training are applied in a real-world situation or task (Baldwin & Ford, 1988)”*. This definition is close to that of Renshaw et al., 2019, quoting Schmidt and Young, (1986, p. 2): *“Transfer of learning has been defined as “the gain (or loss) in the capability for responding in one task (termed the criterion task) as a function of practice or experience in some other task(s)” (Schmidt & Young, 1986).”* If this question is often discussed in works aiming to developed skills in VR, very few have actually tested the transfer to real world sport competition (Michalski et al., 2019). According to this review, five experiments tested transfer to sport performance (included in the review, published in 2019, Gray, 2017; Rauter et al., 2013; Tirp et al., 2015; Todorov et al., 1997). Four of them tested the real sport context but only Gray, 2017, attempt to evaluate the benefit of VR training on sport performance in a competitive context. More recently, Harris et al., 2020, observed a positive transfer of golf put learning with novices from VR to a real putting task. A distinction is also made between near transfer, which is an evaluation of skills improvement in a task close to the training situation, and far transfer, which is the evaluation of improvement in the general context, like sport competitions (Michalski et al., 2019; Renshaw et al., 2019). Although some VR works tried to evaluate near transfer, far transfer is mostly lacking, often evoked when considering future directions, but never really reached. This question of transfer is not exclusive to VR but more largely to perceptual-cognitive and visual-skills training. The question of representativeness and action fidelity is central to the integration of skills improvement in the sport general context (Renshaw et al., 2019). According to Harris et al., 2021, the *“ecological validity of VR”* promises a great possibility of skills transfer thanks to the action fidelity. The psychological fidelity, which involves attention, anticipation and prediction (Gray, 2019; Harris et al., 2021) are key to effective transfer, assuring the correspondence from virtual to real of gaze behaviour and the perception-action-cognitive coupling demands (Gray, 2019; Harris et al., 2021). A series of studies are commonly quoted to justify the effectiveness of using VR in sport training (Bideau et al., 2010; Craig, 2013; Faure et

al., 2019; Miles et al., 2012; Vignais et al., 2015), but it is good practice to confirm the representativeness and action fidelity for each sport setting examined. With current technology, achieving these conditions is more complicated for open-skills sports, where the interaction with opponents and teammates makes the environment and the performance multifactorial; the creation of realistic opponent, who will react and create a behavioural response representative of a real athlete’s behaviour in dynamic and evolving context is a major challenge.

Considering these definitions, the current thesis is more focused on developing a representative design, which will not be completely ecological since, for example, there is no haptic feedback present. A VR environment is not the real context, so the current task will not be ecological in the sense it was defined earlier. Even though haptic feedback will not be available, the visual inputs and opportunity for action will mimic a boxing practice. Bearing this in mind, the aim is to develop a tool which, in the first instance, permits the investigation of perceptual-cognitive skills under conditions that are well matched to the real context. This thesis will not investigate training or skill transfer to a real word context, even if they are very important points and clear directions for future work. For instance, in sport, athletes often practice segmented exercise (i.e., part-whole practice), which focuses on a specific skill, and not the complete competition involvement (e.g. a boxer practices shadow boxing, strength training or punching bag exercise during a training session and not only a combat fight situation). This PhD will focus on a defensive task to target the anticipation skills. To observe a realistic motor behaviour in this defensive task and make the VR experience complete and useful, the feeling of immersion and presence are necessary.

1.4.4 Immersion and presence

Michalski et al., 2019, defined “*Presence refers to the subjective experience of “being there” in a VE, while immersion refers to the technological capabilities of delivering this experience (Witmer and Singer, 1998). Presence and immersion are highly related to one another, as they are both necessary to convey a realistic experience to the user (Slater and Wilbur, 1997)*”. In other words, the immersion is related to the technological construction of VR environment, which the capacity to look all around and the adaptative viewpoint. The materials’ features like the field of view, the resolution or the latency of the system

are important to ensure an high degree of immersion (Gray, 2019; Miles et al., 2012; Slater & Sanchez-Vives, 2016). Presence is the individual subjective feeling and impression of being in the virtual world (Slater & Sanchez-Vives, 2016). These two concepts are linked and allow a realistic response of the user (Faure et al., 2019; Miles et al., 2012). Altogether, immersion, presence, cognition-perception-action loop and representative design made the VR experience a reality for the user, with proper consequences of his action in a virtual world (Slater & Sanchez-Vives, 2016).

1.4.5 Limitations and transfer limits

Despite the many advantages of VR, there are some limitations. For instance, depth perception and more generally the perception distance are a common concern in VR, with distance often being underestimated (Gray, 2019). This issue is in part associated with the accommodation-vergence conflict (Dits et al., 2013; Eadie et al., 2000; Fulvio & Rokers, 2017; Gerig et al., 2018; Klinghammer et al., 2016). Vergence is the adaptation of eye movement to objects in different depths. When fixating an object moving back and forth, the eyes rotate disconjugately, converging or diverging to adapt the focus to the object distance. When using an HMD, the two displays are actually fixed, so the focus is on the displays at a very close distance in front of the eyes (Gray, 2019; Harris et al., 2022); see illustration figure 1.6 (Clay et al., 2019). Depth perception is recreated using binocular disparity (Harris et al., 2022) but is more heavily reliant on pictorial cues and movement (expansion size for example). This is not identical to real world settings and thus make depth perception a bit inaccurate. That is, vergence is necessary for depth perception but there is no accommodation associated as it would be the case in the real world because the displays are at fixed distance (Harris et al., 2022). In this regard, the correspondence of gaze behaviour between real and virtual worlds is a challenge to ensure representativeness and psychological fidelity. Moreover, to mimic natural vision and minimized computation cost, the VR setup applies an artificial blur in the horizon background, which could affect depth perception. According to Harris et al., 2019, the normal use of ventral and dorsal streams could be changed by this virtual presentation, with a possible reinforcement of the ventral stream. To limit this effect, the reconstruction of the user's virtual body appears to be fundamental for the perception of distance (Harris et al., 2019), as Warren, 1984, demonstrated in real life situation. The knowledge of our own body scale influences our action, taking in consideration our possibilities (Warren, 1984).

However, Gray, 2019, supposed this is not a major issue for sport training in VR, which should rely more on motion in depth perception (dorsal stream) rather than perceived distance (ventral stream), and thus should not strongly affect the psychological fidelity.

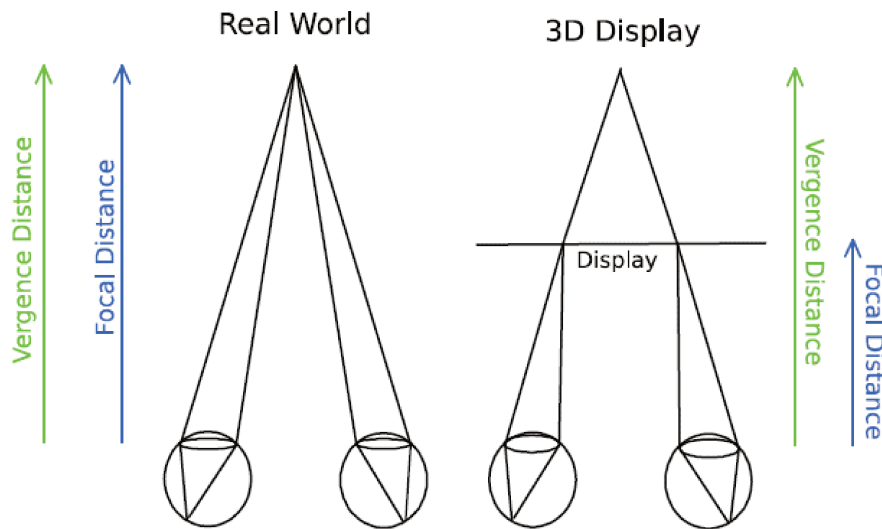


Figure 1.6 – Extract from Clay et al., 2019, (left) real world: vergence = focal distance. (right) Focal distance always stays the same in VR.

Maintaining a high level of detail to increase the ecological validity and/or representative design imposes high processing demand in VR and could increase system lag when rendering the stereoscopic images (Faure et al., 2019; Gray, 2019). However, the response time of the system and the capacity to react quickly to the user’s movement is also of great importance in the representativeness and the feeling of immersion. That is, a trade-off is necessary between high levels of detail, the complexity of the environment, and system lag.

Cybersickness occurs when the user feels unwell during a VR immersion experience, and is similar to travel sickness. The user can sometime feel dizzy and nauseous; this is very common when the display presents movement information but the participant is sitting or still, creating a conflict between vestibular and visual information (Clay et al., 2019). This issue is individual-dependant and a withdrawal from the immersive VR environment is necessary to alleviate the symptoms. Lag problem can increase this feeling, creating a delay between the user movement and their visual perception of the movement (Clay et al., 2019).

1.4.6 Eye tracking implementation

As part of the skills that underpin perceptual-cognitive expertise, gaze activity is an important element for anticipation (Harris et al., 2020; Harris et al., 2021). Gaze behaviour is strongly associated with the cognitive processes and the interaction with the environment (Harris et al., 2022; Pastel et al., 2022). For several years, HMDs integrate eyes tracking, allowing the in-situ measurement of gaze activity, as well as the use of the online position for visual manipulations (Sundstedt & Garro, 2022). This possibly brings a game-changing way to analyse in-situ gaze behaviour (Clay et al., 2019; Harris et al., 2022; Pastel et al., 2022). However, the visualization and interpretation of 3D data are quite new and challenging (Sundstedt & Garro, 2022). The actual methods and standard processing procedures were developed on video and 2D data, so the processing of 3D data brings new questions to transfer the 2D pipeline to 3D analysis (Clay et al., 2019). Still, the integration of eye tracking directly within the VR built environment, and thus the synchronisation associated with the use of ray cast (e.g. the projection of the gaze vector in 3D environment), facilitates gaze analysis related to scenario events and easy identification of areas of interests (AOIs) (Clay et al., 2019; Pastel et al., 2022).

Considering the specification of VR and the identified issues such as depth perception, the development and transfer of gaze related skills needs to be confirmed with more investigations (Gray, 2019; Harris et al., 2021; Pastel et al., 2022). To date, very few studies on transfer of gaze behaviour skills (Tirp et al., 2015; Vickers, 2007) have examined this from the perspective of perceptual-cognitive skills. Harris et al., 2020, for instance, observed a small negative impact on performance after using a VR training warm-up, suggesting the quiet eye pattern had been disrupted. Indeed, the use of VR leads to a potential disturbance of visual acuity and thus could impact visually-guided tasks requiring high levels of endpoint accuracy and precision, when switching rapidly from VR to real tasks (Harris et al., 2020). Still, Pastel et al., 2021, reported encouraging results, stating that VR eye tracking was accurate enough to analyse gaze behaviour, despite the limitations which will need further investigations. The improvement of athletes' visual performance and perceptual-cognitive training is the upcoming challenge for VR sport applications (Pastel et al., 2021).

1.4.7 Past work in combat sports using virtual reality

So far, very few attempts have been made to investigate combat sports in virtual reality, especially boxing. Although VR boxing has been used for rehabilitation of populations with diverse pathologies, it is less the case for athletic performance. In karate, Petri et al. developed a series of studies that examined the use of VR in practice (Petri et al., 2019a; Petri et al., 2019c; Petri et al., 2019d). In one such study, these authors investigated the effect of a VR training on response behaviour in karate kumite (Petri et al., 2019c). They created a virtual opponent (male or female to match the participant's gender) executing different attack sequences. Fifteen young karate athletes were trained over 6 weeks, surrounded by a pre-test and a post-test session (with a cross-over design between normal training and VR training). Response time, quality, and kind of response to the virtual attack were analysed. The authors observed an improvement in the time for response, the response quality, as well as the kind of response. In a follow-on study, Petri et al., 2019a, modified the training in order to target early cue recognition and anticipation. Using a similar design, they investigated the experts' response at different key times in relation to early movement information from the opponent. They observed an improvement of attack recognition, with an earlier use of information (like reduction of the distance prior the onset of the attack) after a VR training. Thus, it was concluded that VR training could benefit anticipation skills with experts. In another study, again with similar apparatus, Petri et al., 2019d, confirmed the improvement of response quality and time of response (so generally, anticipation) and the retention of the learning with youth karate athletes training in VR, even using passive virtual opponent (that is which could not react to user's movement).

To our knowledge, only one study, using 360° video, trained perceptual-cognitive skills in boxing (Romeas et al., 2022). As defined in the section 1.4.1, 360° video should not be considered as a strict virtual reality, as there is no interaction possible with the environment. Yet, the authors referred the apparatus as “360VR” as it allows a realistic immersive environment, but not systematically in 3D. Still, it is relevant to take into consideration this study and the reported findings. First, the authors report a good acceptance from the boxers of the 360° stimulus in addition to their usual training, displayed with an HTC Vive HMD, which provided an enjoyable, immersive, “*safe and complementary approach*” (Romeas et al., 2022). They trained the participants over 5 weeks, two to three times per week (10 min sessions). The training (and tests) was comprised of diverse offensive scenar-

ios, occluded at specific time of the action. The quality of the participant's response was evaluated by a coach and one of the authors. They compared pre-test and post-test results on the 360° VR task. The 360° VR group increased their decision-making accuracy and slightly the speed of the response. However, the authors were cautious about the results because far transfer was not tested. Moreover, 360° VR doesn't not allow an interaction and response relative to the virtual opponent, so the representativeness and extent of the results may be questionable. The potential learning effect using VR must be confirmed.

Virtual reality allows a representative design of a sporting task, with an adaptative viewpoint and a possible interaction that verifies the perception-action loop. Although some limitations have been raised from this method, the possibility of standardisation, visual manipulation and integration of eye tracking makes virtual reality a relevant option for the study of perceptual-cognitive skills in boxing.

SYNTHESIS AND OBJECTIVES

Boxing is a combat sport where the athlete must defend against the punches of an opponent and take control of the fight by punching the opponent. This sport involves a great physical strength, endurance and strategy. In particular, the boxer needs to perceive the intention of the opponent to dodge their punch and find an opening to make their own strike. The information necessary to control this interaction arrives in a very short amount of time, making the spatio-temporal and event constraints very strong. If perceptual-cognitive skills are important in boxing performance, it is true to say that they are less the focus of training, compared to physical or tactical skills. This could in part be because perceptual-cognitive skills are difficult to define, assess and train in specific boxing task. From diverse investigations in sports, we know that experts tend to pick-up relevant information earlier, which often involves a focus on basic kinematic information rather than distracting high detailed information such as facial expression. Experts also rely more on peripheral vision, which could be associated with dorsal stream processing. This is accompanied by a gaze strategy with more fixations of longer duration compared to novices. In boxing, the area around the trunk or the head is prioritised in order to facilitate the use of covert attention to perceive information from peripheral locations, such as the opponent's fists. Yet, the current methods to investigate perceptual-cognitive skills in boxing suffer from several limitations and as such the validity and scope of the findings are questionable.

The use of blur to assess and gain more insight about the perceptual-cognitive skills of experts appears to be a promising development that could be applied to boxing. The principle of using blur is to remove the high detailed information, which can be unnecessary or even disturbing, and thereby to direct participants to perceive basic kinematic information on the opponent and thus their intention (Petri et al., 2019b; A. Williams & Jackson, 2019). It has been inferred that kinematic information often involved peripheral vision, which is suited to processing low spatial/high temporal frequency information,

and largely dependent on dorsal stream processing. In addition, the literature on expert performance indicates a greater use of peripheral vision compared to novices (Hausegger et al., 2019; Vater et al., 2019). Therefore, a blurred visual stimulus could possibly improve perceptual-cognitive skill, and in particular anticipation, by encouraging (in novices) or reinforcing (in experts) the use of basic kinematic information. In this context, the gaze behaviour and manipulations of information available from peripheral and/or central vision are a window to understand the information processing underpinning anticipation skill.

While the use of blur seems promising based on current literature, the previous works were mainly designed on 2D videos, without the need for realistic motor response, and thus a weak link between perception and action. The fixed viewpoint, for instance, is another limitation that questions validity and generalisability of findings regarding perceptual-cognitive skills in these experiments. As described above, to overcome this and other limitations, it is relevant to consider the use of VR apparatus. VR allows the user's immersion in an environment with an adaptative viewpoint, which allows the link between perception and action to be maintained. High levels of control and standardisation are achievable in VR, as is the possibility to manipulate the visual stimuli. Moreover, the latest Head Mounted Display (HMD) technologies integrate eye tracking and display with high levels of spatial resolution. These strengths make virtual reality an ideal and safe solution for studying perceptual-cognitive skills in boxing.

After reviewing the literature, there is a clear need to better understand the information used in combat sports such as boxing, and the role of anticipation in dealing with the high spatio-temporal constraints. Similarly, there are several questions that remain unanswered regarding the use of blur as a means to investigate, improve, and potentially train anticipation performance. Current results are somewhat disparate, in part due to the use of different methods that each have their own limitations. Also, the experts' response to blur has not been the subject of much investigation. At this stage, several general questions emerge: What is the effect of blur in a representative task in virtual reality where a motor response is involved? Is the effect mediated by expertise? Does blur act differently on central and peripheral vision? This PhD will provide answers to these questions in the specific context of anticipation performance during a realistic boxing task.

The **first objective** is to review in detail the research that has used blur to study perceptual-cognitive skill. As well as synthesising the findings, the review will consider the methodological limitations of studies that have manipulated blur in field and laboratory settings. The findings from the review will then inform the **second objective** to develop a VR environment in which blur can be implemented to study anticipation in a boxing task. A main issue to consider will be the use of integrated eye tracking for the purpose of gaze-content manipulations of blur to central and peripheral vision. Following the review and development of an immersive and representative VR boxing environment, **the third objective** is to investigate the effect of different blur manipulations on anticipation performance in VR boxing. As a preview, the first experiment will investigate the effect of a central and peripheral blur on anticipation performance of novice and expert boxers in a chasing parry task. Based on the results of this study, the second experiment will investigate anticipation of expert boxers when performing a dodging-counterattack task. The third experiment will seek to disambiguate the contribution of central and peripheral vision when performing a dodging-counterattack task. In a final chapter, **the fourth objective** is to discuss and synthesise the main findings from the three experiments in order to explore the contribution to understanding of perceptual-cognitive skills in boxing.

PROSPECTIVE REVIEW: USING BLUR FOR PERCEPTUAL INVESTIGATION AND TRAINING IN SPORT? A CLEAR PICTURE OF THE EVIDENCE AND IMPLICATIONS FOR FUTURE RESEARCH

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3.1 Introduction

For more than two decades, sport scientists have investigated the contribution of perceptual-cognitive skills such as anticipation, attention and decision making to expertise, and thereby expert performance (D. Mann et al., 2007; A. Williams & Jackson, 2019; A. M. Williams et al., 2011). It is now well accepted that experienced/skilled athletes in dynamic and interactive sports are better at anticipating an opponent's movement (A. Williams & Jackson, 2019) and consequently make earlier and more appropriate decisions (Raab et al., 2019). In addition, they can achieve high levels of performance on the basis of less information, whether that be due to temporal (e.g., information determined earlier) or spatial (e.g., information determined from fewer stimuli) constraints (D. Mann et al., 2007; A. Williams & Jackson, 2019; A. M. Williams et al., 2011). Compared to novices, overall performance of experts is better when the environment is impoverished, thus indicating that the experts' ability to extract basic kinematic information is more resistant to visual stimuli deterioration. In part based on such findings, the role of visual

functions such as acuity and contrast sensitivity have often been overlooked. Indeed, it is found in most sports that there is no additional advantage of supra-threshold levels of visual function (i.e., above the general population average), and thus little or no benefit of general visual training programmes aimed at improving vision to above-normal levels (A. Williams & Jackson, 2019). Somewhat counterintuitively, however, several studies have shown that perceptual and perceptual-motor behaviour does not deteriorate (D. L. Mann et al., 2010b; Ryu et al., 2018; van Biemen et al., 2018), or can even be improved (R. Jackson et al., 2009; van Biemen et al., 2018), when the visual stimulus is artificially blurred by the experimenter. Early signs of an improvement of performance in the presence of blur (R. Jackson et al., 2009) has led to several studies on the use of blur to improve perception, anticipation and decision making, with the largest improvements typically found in novices and/or less skilled participants (R. Jackson et al., 2009; Ryu et al., 2015; Ryu et al., 2013a; Ryu et al., 2016). However, it seems there is less evidence for a positive impact of blur on performance of experts (van Biemen et al., 2018), and even a negative effect in some studies and particular tasks (Ryu et al., 2015; Ryu et al., 2013a; Ryu et al., 2016).

In this article, we review and synthesise the current research on the use of blur in a sporting context, with an overall aim to provide some guidance for future research on perceptual training in sport. We include published articles that have manipulated blur in a sport setting/task using lenses (i.e., refractive blur) or image filtering (i.e., Gaussian blur). Accordingly, we begin by describing the potential impact of these different methods on the visual stimulus. We then consider the effect of blur on the perceptual-cognitive skills (i.e, anticipation and decision making) of novice and expert sports performers, followed by a section that describes the findings from perceptual-motor tasks where blur has been applied to the entire visual field or areas surrounding gaze location. We next consider if training in conditions of blur can facilitate learning and transfer, and finally we provide a critical reflection and discuss some perspectives for extending the applicability and scope of manipulating blur through the use of virtual reality.

3.2 Dioptric vs Gaussian blur – conceptual aspect

Normal healthy vision typically involves a seamless integration of high acuity and low acuity (i.e., blurred) inputs from the central and peripheral retina. Indeed, one does not normally notice that objects located away from the point of fixation are in fact blurred,

even though this can provide useful information on spatial location (e.g., depth from crossed and uncrossed disparity). In normal or corrected-to-normal vision, high acuity input is perceived from cone cells that are concentrated at the centre of the eye in the area known as the fovea. Cone cells detect light of different wavelengths, which is the basis of colour perception, operate best in bright light, and enable perception of fine details (i.e., high spatial frequency). They thus play a critical role in being able to distinguish shapes and details of objects in our surrounds. The other main photoreceptor cells, known as rods, are not attuned to the same light wavelengths as cones, but they are more sensitive to light and are located mainly in the peripheral region outside the fovea. Although more numerous than cone cells, multiple rod cells converge onto single retinal ganglion cells, thus resulting in a specialisation for processing low spatial frequency visual stimuli, as well as motion. Accordingly, in those with normal healthy vision, individuals fixate gaze location in a way to best combine high acuity and low acuity input. For example, in combat sports such as French boxing (Ripoll et al., 1995) and Karate (Milazzo et al., 2016b; A. M. Williams & Elliott, 1999), experts direct their eye gaze mainly to the head and trunk of the opponent, whereas less experienced individuals tend to look at the opponent's fist and arms. Presumably, fixating gaze on a relatively static location (i.e., the center of the opponent's body) facilitates perception of information from central and peripheral vision. Indeed, minimizing the number of saccades to distal locations (i.e., opponent's fists and feet) would result in fewer periods of saccadic suppression, and thus a more continuous input of information¹.

In the presence a partial central blur (e.g., macular degeneration), and hence the removal or alteration of high spatial frequency stimulus characteristics, individuals often respond by changing gaze fixation to a location that still enables a reasonable perception of object characteristics (Shima et al., 2010; Van der Stigchel et al., 2013). Similar effects on gaze location and outcome performance have been reported when a partial central blur has been artificially introduced by the experimenter (Ryu et al., 2015; Ryu et al., 2016). Even when there is a full blur applied across central and peripheral vision, individuals can still exhibit high levels of performance in some tasks (D. L. Mann et al., 2010b) pre-

1. In addition, when gaze is fixated on an object at a particular depth, surrounding objects not located on the horopter will be perceived at different depths. Just beyond the horopter, disparity in the retinal images provides a reliable cue to depth. However, as the surrounding objects move further away from the point of gaze, blur can also provide an important contribution to depth perception (Held et al., 2012; Langer & Siciliano, 2015)

sumably from processing low spatial frequency input such as motion and spatial layout. Importantly, however, while the impact of both experimenter-imposed partial and full blur has been studied in a sporting context, this has been achieved using two different methods (i.e., dioptric blur and Gaussian blur). As we highlight below, these methods do not influence the stimulus in the same way and could thus impact upon the experimental findings.

A dioptric blur is equivalent to optical defocus caused by a visual impairment (e.g., myopia) or inaccurate accommodation. Experimentally, this is achieved using lenses (i.e., contact lenses or glasses) that alter focal length, thereby increasing focal length error and creating a so-called blur disk on the retina that is a function of defocus (in diopters) and pupil diameter. The consequence of wearing such lenses is a perturbation of high spatial frequency information, and thus a reduction in contrast sensitivity and visual acuity due to the stimulus edges being more difficult to discriminate (Kwon et al., 2016; Strasburger et al., 2018; Watson & Ahumada, 2011). The relative reduction in visual acuity (i.e., acuity with blur / best corrected acuity) can be derived as $1 / 1+D^2$, where D is the spherical error in diopters. Accordingly, as was reported by Bulson et al., 2008, it is possible to create different conditions of optical defocus, using convex and cylindrical lenses (PLANO, +0.50 D, +1.00 D, +1.50 D, +2.00 D, +1.00 D x 90, +2.00 D x 90 and +10 D) and estimate the corresponding level of visual acuity (20/20, 20/25, 20/60 20/100, 20/180, 20/25, 20/60 and 20/2000). Improving on this relative course estimation, D. L. Mann et al., 2010a, recognized the importance of taking into account best corrected visual acuity, although they did rely on the mean habitual visual acuity across participants (i.e., 6/5.3) when estimating the effect of three dioptric lenses (i.e., +1.00D, +2.00D, +3.00D) on mean visual acuity (i.e., 6/11, 6/20 and 6/49).

The other experiments described in this review applied a Gaussian blur on images viewed on a computer monitor. A Gaussian blur is the result of an image or video processing procedure, whereby the optical system of the eye is unperturbed but the displayed stimuli are altered by removing the high frequency information (Kwon et al., 2016; Ma et al., 2018; Oleskiw et al., 2018; Strasburger et al., 2018; Watson & Ahumada, 2011). A Gaussian blur is different from dioptric blur in the sense that it does not create spurious resolution (see below) and does have a simple relationship with visual acuity. In terms of computation, the method requires the calculation of the transformation that

needs to be applied to each pixel when rendering the image; it is the result of applying a Gaussian function to the pixel matrix. The Fourier transform decomposes the domains of frequencies contained in the image. Applying a Fourier transform to a Gaussian results in another Gaussian, and is thus similar to a low pass filtering to remove the high spatial frequencies (Ma et al., 2018; Strasburger et al., 2018). The new pixel coloration is the weighted average of the neighboured pixel characteristics included in the computation. Different software can be used to apply the processing, with directly implemented tool or custom processing. For example, R. Jackson et al., 2009, added 20% and 40% blur in both horizontal and vertical dimensions using the special effects module in Pinnacle editing software. Unfortunately, details on this method of applying the Gaussian were scant, thus making it difficult to compare both the experimental condition and results to other studies. van Biemen et al., 2018, also used software (Premiere Pro CC software) and the camera blur option to create their blur video, whereas Ryu et al., 2015; Ryu et al., 2016, used the Adobe Premiere CS 4 software to apply a low-pass Gaussian filter with the 20, 50 and 100 units option.

It is often assumed that the dioptric and Gaussian blur are equivalent because they both alter the spatial frequencies of an image. However, as described by Strasburger et al., 2018, dioptric blur is a consequence of naturally occurring or experimenter-imposed alterations in physiological optics and is not identical to low-pass filtering (i.e., Gaussian blur) of a computer image. This becomes particularly evident when considering the point-spread function (PSF) that results from different methods of blur, and the resulting spurious resolution that is available in conditions of dioptric blur (see figure 3.1). For example, Strasburger et al. showed that high spatial frequencies are detectable under dioptric blur, meaning that the orientation of a sine-wave grating may still be discernible but the appearance of blurred optotypes are likely too dissimilar from the original unblurred counterparts to permit identification without extended practice. No such spurious resolution is present when blur is created by low-pass Gaussian filtering (Strasburger et al., 2018). Consequently, while dioptric blur is easy to implement and is closest to the naturally-occurring blur caused by some visual impairments (e.g., myopia, presbyopia), it is debatable whether it is suitable for experimentation in a sporting context unless the study aims to investigate the effect of a visual impairment. That said, the application of Gaussian blur is not without limitations, such as the use of diverse software and computer algorithms, as well as a lack of coherence between the level of induced blur and visual

acuity. These differences between dioptric and Gaussian blur have not been explicitly recognised in most research to date on blur in a sport context.

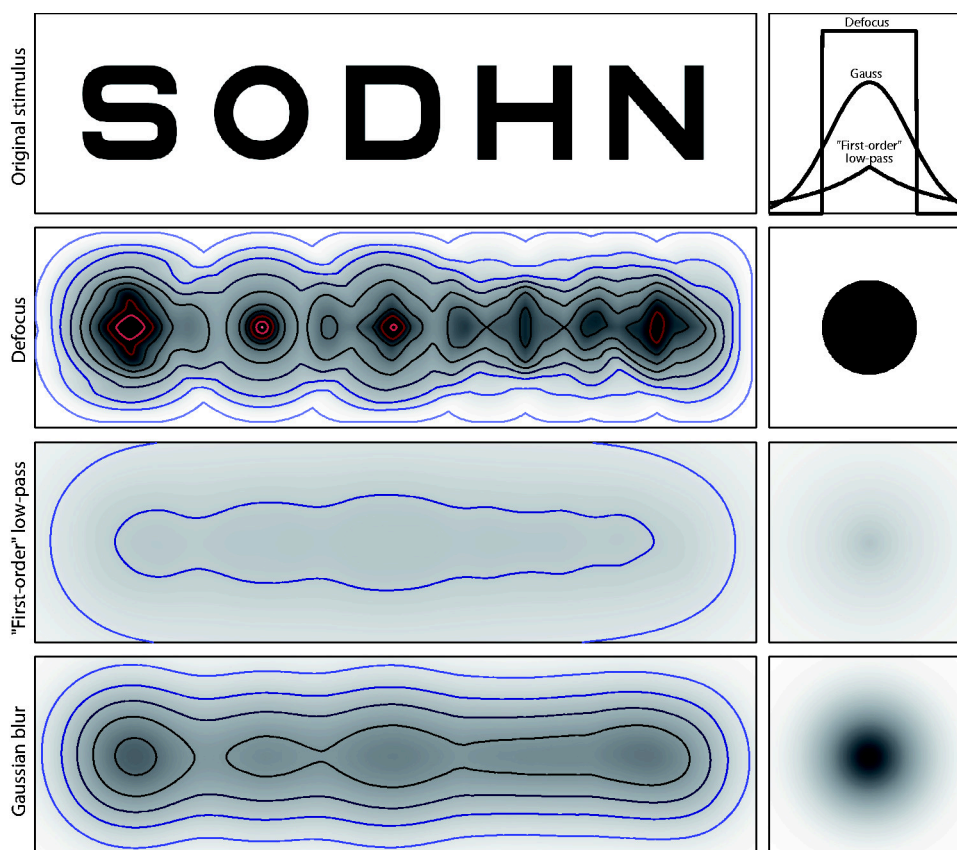


Figure 3.1 – Illustration from Strasburger et al., 2018, of the effect of blur on Sloan letters. Top row: original, unblurred letters, together with point-spreadfunction profiles (right) for the lower rows. FWHMs of the three PSFs are equal. Note that PSF amplitudes are necessarily different since their volume needs to be normalized to unity (light is neither added nor lost). Second row: letters with dioptric blur simulated by using a disk with a diameter equal to the letter height as blur kernel. The effect of spurious resolution is so strong that the blurred letters look quite unlike their original. Third row: PSF with exponential drop-off (analogous to a first-order low-pass filter). Energy is spread over a wide spatial range, such that amplitude is rather low. Bottom row: letters with simulated Gaussian blur. For display, blurred images were increased in contrast to enhance the visibility of structures. Isolumes for all three patterns represent luminance steps of 7 percentage points (white $\frac{1}{4}$ 100%). The gray scale representation of the PSF in the right column uses a different scale than the blurred images (Strasburger et al., 2018).

3.3 The effect of blur on anticipation and decision making

R. Jackson et al., 2009, examined the influence of applying a low-pass Gaussian blur on configural information and anticipation during a dynamic perception task. Anticipation performance of tennis players (N=32) with varying levels of competitive playing experience was examined using a 2-choice prediction task (i.e., judgement of direction). Video clips of a tennis serve occluded at 4 different times relative to final frame before ball contact (i.e., t1: -320 ms, t2: -160 ms, t3: 0 ms, t4: +160 ms) were presented on a computer screen, and viewed under 3 levels of blur (0% [no blur], 20% and 40% blur). Based on performance in normal vision condition (i.e., 0%), participants were assigned to two groups: “good anticipators” and “poor anticipators”.

An interaction was found between anticipation skill (“good anticipators” vs. “poor anticipators”) and the level of blur. Performance of “good anticipators” was more disturbed with a low level of blur, such that performance declined significantly from the 0% to 20% blur condition (approximately -0.2 mean transformed accuracy). In contrast, performance of “poor anticipators” was slightly better in the 20% compared to 0% blur condition (approximately +0.03 mean transformed accuracy). Despite these significant group differences between the 0% and 20% blur conditions, performance of both groups was equal in the 20% blur condition. Moreover, both groups exhibited a similarly small increase in performance from the 20% to 40% blur condition. Overall, then, participants who were better at anticipating in the normal vision condition did not maintain this advantage with the introduction of the blur, as the authors expected. Only participants who were less competent in the normal vision condition exhibited an improvement in performance following the introduction of 20% and 40% blur, thus providing some preliminary support for the suggestion that the application of blur can make participants more attuned to basic kinematic information (i.e., motion).

According to the R. Jackson et al., 2009, an explanation for the non-linear effects of blur could be a change in participant’s strategy. That is, in 20% blur condition, better anticipators could have still been looking for the high spatial frequency visual information, which was missing and thus performance declined. However, in 40% blur condition, participants may have changed strategy and thereby become more attuned to the essential

movement kinematics that was present in the low spatial frequency information. While a reasonable account for the findings, the strategies used by players, whether unconscious or conscious, cannot be determined based on the recording of performance alone. Moreover, because there was only a single testing session, it is likely that blur acted as a momentary perturbation.

Based on the above findings, Ryu et al., 2018, designed a study using videos that showed either normal or blurred (i.e., low-pass Gaussian filter) badminton shots. Participants were 46 novices in badminton, who anticipated the direction of badminton shots across a pre-intervention/post study design. The pre-test and post-test comprised 96 video clips with different occlusion times (i.e., one frame before contact between racquet and shuttle, at the moment of contact, or one frame after contact) that showed deceptive actions. For the intervention, participants were divided into three training groups: low spatial frequencies only (i.e., blurred video), high spatial frequencies only (only detailed information conserved in the video) and normal vision. The frequency manipulations were made using low-pass and high-pass filters applied to the video images. The video clips showed non-deceptive action (n=360) with different occlusion times, plus a direct performance feedback. The intervention lasted three days, with a total of four days from the pre-test to the post-test. A retention test was performed one week after the post-test. Eye movements were recorded in all sessions using an Eyelink II operating at 250 Hz.

The authors reported different effects on anticipation accuracy and reaction time when comparing the type of video training. When facing deceptive actions, the low frequency training group (i.e., blurred video), improved the most from pre-test to post-test, and then kept this advantage in the retention test one week later. This observation is consistent with the performance improvement of novices reported by R. Jackson et al., 2009. The high frequency training group also improved from pre-test to post-test, and to a greater extent than the normal vision group. However, the advantage did not persist such that in the retention test, there was no difference compared to the normal vision (i.e., control) group. In addition, both groups performed worse than the low frequency group. When facing the non-deceptive trials, all groups exhibited a similar improvement in performance after training (response accuracy and reaction time). That is, the type of video (low frequency, high frequency or normal) used in training did not influence performance while facing non deceptive trials.

In terms of gaze behaviour, no changes were noted in fixation duration and breadth of search after training. A small change in saccadic amplitude was reported ($p=0.058$), with larger saccades during retention test compared to pre-test and post-test, but this was the same for all groups. The time spent on the area of interest revealed some more notable differences between groups. The low frequency group (blurred video) spent more time with gaze located on racquet-shuttle contact in post-test and retention compared to normal group. However, they also spent less time fixating on the head compared to normal group but in the retention test only. The high frequency group spent less time fixating the head, compared to normal group but only in the post-test. There were no differences between these two groups at pre-test and retention test.

As described above, the trials used in training did not contain deceptive intent. Still, such training seemed to help participants recognise deceptive movement in post-test and retention, even though they did not face any examples of deceptive actions. According to the authors, the training intervention encouraged participants to rely more on the meaningful information, which they were then able to disambiguate from deceptive information in the post-test. This was supported by the finding that the low frequency training group decreased the time spent directing gaze toward the face of the opponent, instead locating gaze toward the racquet-shuttle contact, presumably to extract the most useful information. This pattern can be considered an improvement of visual strategy, and is consistent with the pattern of eye movement observed in experts (D. L. Mann et al., 2007). Indeed, gaze direction and facial expression can be used to fake one's intention and mislead an opponent, thus indicating that the head area could be a source of distracting information (Petri et al., 2019b). Conversely, the racquet-shuttle contact point contains important information about the direction of the shuttle and the type of shot.

The studies discussed up to this point were primarily based on novice populations (Applegate & Applegate, 1992; Bulson et al., 2008; R. Jackson et al., 2009; Ryu et al., 2018) and indicated some evidence that blur can improve anticipation performance, and potentially maintain this improvement following a relatively short, 7-day intervention (Ryu et al., 2018). These positive effects on performance and learning could have occurred because blur alters the process of visual information extraction. That is, applying a blur removes some irrelevant or even distractive information, which helps novices avoid an overload in

visual processing when confronted with a multitude of stimuli. In the blur condition, the task could in effect become easier as participants are guided to the most useful information. However, such positive effects of manipulating blur are more limited for experts, and could even be detrimental. For example, it could be that experts have already learned to extract useful kinematic information from the environment, and as such removing high frequency information conveys no advantage, or even a disadvantage if experts use some aspect of high frequency information to support their perceptual-motor behaviour. One such study of an expert population was reported by van Biemen et al., 2018, who investigated decision making of skilled football referees in a blurred condition. This represents an interesting population because although they are not skilled in performing the motor activity per se, referees are skilled in observing and detecting deceptive intent and movement of players. The 22 participants in this study were divided into two training groups: normal vision training and blurred vision training. The training took 45 minutes and was run the same day as a pre-test and post-test, which required the referees to make judgments on whether the situation shown in a video clip was a foul or not (26 clips, 13 foul and 13 no foul). The training intervention comprised 70 clips in which all situations showed a foul. In this phase, the referees had to judge the severity of the foul, choosing to award a red card, yellow card, or no card as quickly as possible. Feedback on the correct response was given after each trial.

The authors found that the blurred vision group improved their response accuracy to a greater extent than the normal vision group, although this was not associated with a change in reaction time. The blurred vision group appeared to become more sensitive to genuine fouls, which echoed the results from R. Jackson et al., 2009; Ryu et al., 2018, but this time with an expert population. However, at the individual level, some participants in the blur training group exhibited a decrease in performance. Although this was not discussed by the authors, one can suppose this could have been related to inattention or participant skill level. Therefore, although there is some evidence of a possible advantage afforded by blurring video images in training decision making of skilled participants, this requires further investigation. In addition, most of the above studies (R. Jackson et al., 2009; Ryu et al., 2018), used tasks where perception was not coupled to a motor response. This raises questions about the representativeness of the tasks compared to the actual sport setting and thus whether the findings from laboratory tasks are transferable.

3.4 Perceptual-Motor behaviour in the presence of blur

In an early investigation, Applegate and Applegate, 1992, compared basketball shooting performance under five conditions in which dioptric blur was achieved using 6/6, 6/12, 6/24, 6/48 and 6/75 diopter lenses. The 19 male participants (all with a visual acuity of 6/6) performed 25 shots from one position in each condition. The authors observed a small drop in performance as a function of dioptric blur from 6/6 to 6/12. However, the decrease was not significant, and participants were still able to shoot the basket even with strong level of blur. Moreover, performance remained constant across all other levels of blur (from 6/12 to 6/75), thus showing that a static aiming task does not depend on high acuity information.

In another static aiming task (i.e., golf putting), Bulson et al., 2008, examined the effect of dioptric blur on 16 young participants. Similar to Applegate and Applegate, 1992, participants performed the task while wearing different lenses: PLANO, +0.50 D, +1.00 D, +1.50 D, +2.00 D, +1.00 D, +2.00 D and +10 D. These corresponded to visual acuity levels of approximately 20/20, 20/25, 20/60 20/100, 20/180, 20/25, 20/60 and 20/2000. It was found that the different levels of blur had little or no effect on completion of the golf putting task. The authors suggested that an adaptation to the blur could have explained the maintenance of performance. In addition, they suggested that automaticity related to repetition of practice at a fixed distance could have minimised the effect of a low level of blur. In fact, it is notable that in both Applegate and Applegate, 1992, and Bulson et al., 2008, the target was fixed and there was no need to consider information from moving teammates and/or opponents. Thus, it is questionable whether these findings generalise to dynamic sport situations where it is important to follow moving stimuli and anticipate future events.

To this end, Mann and colleagues conducted a series of studies using a cricket batting interception task, with intermediate to skilled cricket batters (D. L. Mann et al., 2010a; D. L. Mann et al., 2010b; D. L. Mann et al., 2007). In the first study D. L. Mann et al., 2007, 11 intermediate batters faced a bowling machine under five conditions of refractive blur (PLANO, +1.00D, +2.00D, +3.00D, and normal correction lenses to control the effect of wearing lenses), with four different ball end locations. The authors confirmed

that the performance of the cricket batting task did not require normal levels of visual acuity. In fact, there was even a tendency for better performance in +1.00D and +2.00D conditions compared to the PLANO condition. The only decrement in performance was found in +3.00D blur condition, which is recognised as the point of legal blindness.

In the second study, D. L. Mann et al., 2010b, compared the performance of 10 skilled male cricket batters when receiving balls delivered by a real bowler vs. a projection machine. Participants faced 196 trials, comprised of the two ball projection conditions, four blur conditions (PLANO, +1.00D, +2.00D, +3.00D, see figure 3.2) and three different paced ball deliveries (medium-pace only for the machine, slow and fast-pace for the bowler). They found no differences in batting performance between the projection machine and real bowler, irrespective of the blur condition. Again, a significant decrease in batting performance was only found in the +3.00D blur condition. The authors suggested that the resilience of interception to refractive blur could be explained by the batting task being regulated by visual information processed in the dorsal stream, which is sensitive to motion and thus less affected by reduction in visual acuity. Moreover, they concluded that visual acuity is not a primary limiting factor in cricket batting and thus called into question whether there is benefit to improve visual acuity above an average level.

At this point, Mann and colleagues considered whether the effect of blur depended on the type of response required by the participant. To this end, D. L. Mann et al., 2010a, examined the influence of refractive blur in conditions where participants (10 skilled male cricket batters) responded to real ball deliveries by verbal response only (uncoupled) or verbal response plus batting movement (coupled). Two ball speed conditions were included (fast and slow), as well as four levels of blur (PLANO, +1.00D, +2.00D, +3.00D). In the uncoupled condition, performance (response accuracy) improved slightly from normal vision to the lowest level of blur, consistent with previous observations (R. Jackson et al., 2009; Ryu et al., 2018; van Biemen et al., 2018) and remained quite constant as the level of blur was increased. In the coupled condition, performance did not change from normal vision to the lowest level of blur and was better than the uncoupled condition. However, performance did deteriorate at the greater level of blur such that it was no better than performance in the uncoupled condition with the +2.00D blur manipulation, and somewhat worse than the uncoupled condition with the +3.00D blur manipulation.

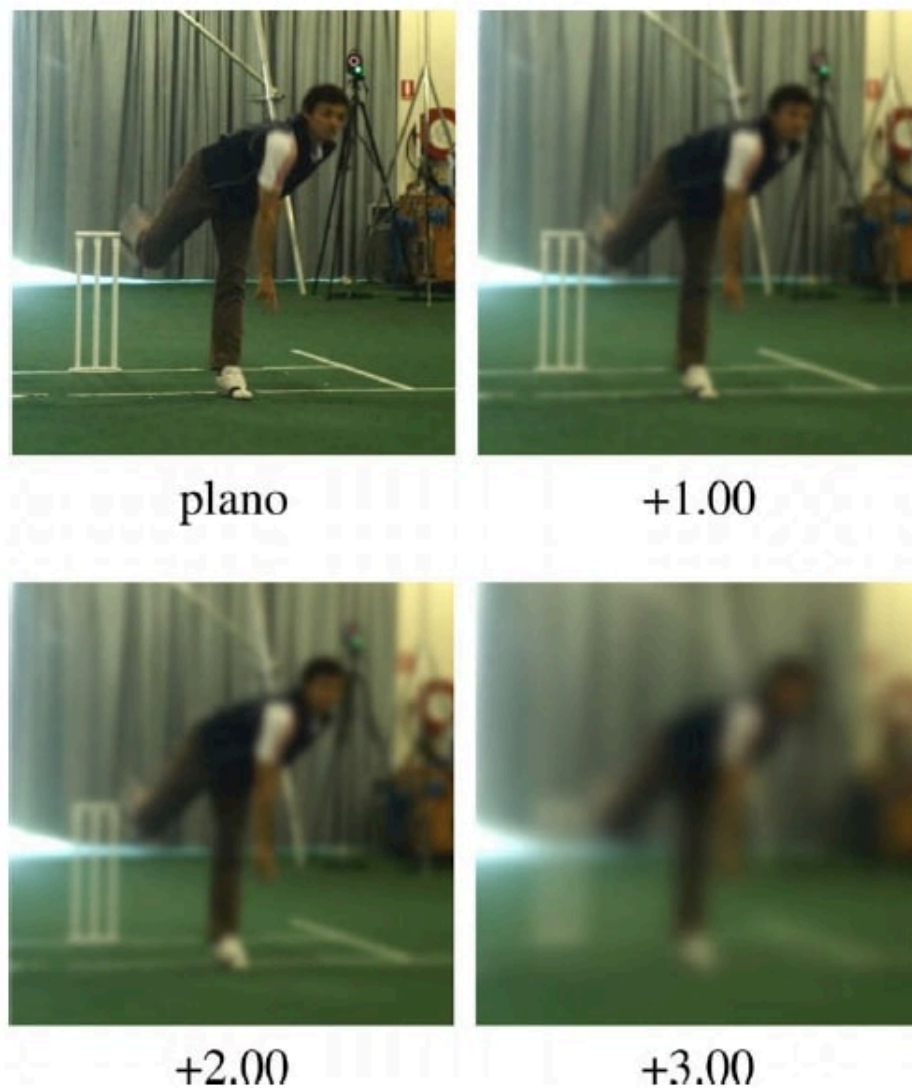


Figure 3.2 – Illustration of D. L. Mann et al., 2010b’s experiment : simulation of the four refractive blur conditions experienced by the participants.

Overall, then, the findings again indicate that anticipation performance can be improved (uncoupled condition) or maintained (coupled condition) in conditions of blur, and further that coupled anticipation is better than uncoupled anticipation (Farrow & Abernethy, 2003; Milner & Goodale, 2008; Van der Kamp et al., 2008). The authors suggested that the improvement in performance of the uncoupled task (fast-pace bowler) in some conditions of refractive blur could be explained by a shift in contribution from ventral to dorsal stream processing. A greater reliance on dorsal stream processing could also

explain the maintenance of performance in the coupled condition. This interpretation is consistent with the notion that perceptual and perceptual-motor tasks are not dependent on a single processing stream and that the contribution from ventral and dorsal stream processing depends on the task demands and nature of the visual stimuli. For example, although in D. L. Mann et al., 2010a, there was no need to regulate a complex motor response when giving a verbal response, performance was influenced by the ability to anticipate motion of a fast moving visual object. Accordingly, while blurring the visual stimuli could impact negatively upon perceptual or perceptual-motor tasks that depend on normal levels of visual acuity to identify features and characteristics, this may not be the case if low spatial, high temporal frequency information such as object motion played a major role.

3.5 Peripheral and central blur

Many dynamic sporting tasks involve motion between oneself and surrounding objects, and thus require attention to be distributed successively and/or concurrently to different locations. Defined relative to gaze location, overt attention is involved in the processing of colour and high acuity stimulus details in central vision, whereas covert attention is more involved in processing object location and motion in peripheral vision. Covert attention to information available in peripheral vision is suggested to play a major role in perceptual-cognitive expertise in dynamic sport settings (Hausegger et al., 2019; Vater et al., 2019). For example, novices tend to overtly attend to and process information in central vision, which means they often fail to perceive a large amount of information in the periphery. Experts, on the other hand, are better attuned to the relevant information, which they perceive simultaneously (overt and covert attention) in both central and peripheral vision.

As the perception of an object or limb as it moves through peripheral vision is based on processing of low spatial, high temporal frequency visual inputs, there should be minimal impact of applying a refractive blur to the entire visual field (D. L. Mann et al., 2010a; D. L. Mann et al., 2010b; D. L. Mann et al., 2007). In addition, it follows that blurring the entire visual field has limited ability to identify the contribution of specific sources and types of information that experts use to regulate perceptual-motor tasks in dynamic sport settings. This can potentially be overcome using a gaze-contingent blur

manipulation (Ryu et al., 2015; Ryu et al., 2013a; Ryu et al., 2016). The general idea is that because eye gaze does not necessarily coincide with covert attention, simply reporting spatial-temporal patterns eye gaze (i.e., visual search behaviour) does not actually indicate what information is being extracted. Indeed, without additional manipulation, it can only be assumed that relevant information is picked-up in peripheral vision. With a gaze-contingent manipulation on a video display, the content of the video is adapted relative to gaze location, with an image artefact applied to a specific area of the display. For example, this method allows the experimenter to alter (e.g., occlude or blur) central vision whilst preserving normal peripheral vision, and vice versa.

To this end, Ryu et al., 2013a, used an interesting approach to examine the role of central and peripheral visions, based on the gaze behaviour, in a basketball decision-making task. Specifically, they used a gaze contingency display-change paradigm composed of two display conditions: a moving window or moving mask. In the moving window condition, only a circle of 5° surrounding the fixation point (i.e., gaze location) was visible, whereas in the moving mask condition, only information outside of a 5° circle surrounding the fixation point was available. In effect, the two conditions provided access to information in central vision (i.e., moving window) or peripheral vision (i.e., moving mask). The authors compared expert and novice participants in a full vision condition and the two gaze-contingent conditions. Video clips were presented showing sequences of a 5x5 basketball situation, where the participants viewed from a third person perspective and had to decide (i.e., button press response) the best action given the sequence presented (i.e., pass or drive to the basket). Overall, it was found that experts exhibited better decision-making performance in all conditions, thereby indicating a better capacity to use both central and peripheral visions. However, when discussing the limitations of their study, the authors pointed out that applying an opaque mask on the manipulated area could have changed a participant's gaze behaviour. That is, by completely removing the visual information from some locations, participants may have shifted their gaze to another location in order to find sufficient information to make a correct decision.

To overcome the limitations of using an opaque mask, Ryu et al., 2015, revised their earlier 2013 protocol by applying a different level of blur to the gaze-contingent location. In total, there were 19 different viewing conditions (see figure 3.3) comprised of 5 levels of blur (no blur, low, moderate, high blur and opaque mask) and 5 configurations of visual

alteration (see figure 3.3, i. Moving window – clear/blur. ii. Moving mask -blur/clear. iii. Moving window – blur/opaque. iv. Moving mask – opaque blur. v. Central + peripheral blur, complete blur). The moving window condition will be referred as peripheral blur and the moving mask as central blur. Only one aspect of vision was altered in conditions a to i (peripheral blur or central blur). In condition j to o, two aspects of vision were altered by combining the gaze-contingent blur manipulation with an opaque mask (e.g., condition j – low level central blur and opaque peripheral vision). In condition p to r, the combination of central and peripheral blur resulted in a uniform blur across the entire visual field. In experiment 4 of the paper, the video clips were occluded at a critical moment (i.e., when the ball carrier had to make a decision to which teammate to pass the ball). The participants (18 skilled and 18 less skilled male basketball players) were required to click on a vacant court (response slide) to indicate the position of the most appropriate teammate to receive the ball. Performance was measured in terms of response accuracy and response time.

Overall, in both the peripheral blur (clear central vision, blurred peripheral vision) and the central blur condition (blurred central vision, clear peripheral vision), performance of the experts was better than the novices for all levels of blur. When only one aspect of vision was altered, the experts performed above level of chance in all conditions. Noticeably, when information from a part of the visual field was unavailable (opaque central or opaque peripheral vision), experts were still able to perform above the level of chance. The authors suggested that experts were able to adapt and use information based on what was available. Findings for the novices indicated that they were unable to perform above the level of chance when central vision was blurred. However, it was interesting to note that novices did improve their response accuracy with moderate and high blur applied in peripheral vision (NB. there was no improvement for the experts in these conditions). This positive effect is in accordance with the previous results observed on novices (R. Jackson et al., 2009; D. L. Mann et al., 2010a; Ryu et al., 2018), although one should probably exert some caution when interpreting the facilitatory effect of blur because this was not evident when blur was applied to the whole field (c.f. R. Jackson et al., 2009; D. L. Mann et al., 2010a; Ryu et al., 2018).

In terms of the conditions where a part of vision was occluded by an opaque mask and the other part was blurred (see panel j. to o.), it was found that performance accuracy of

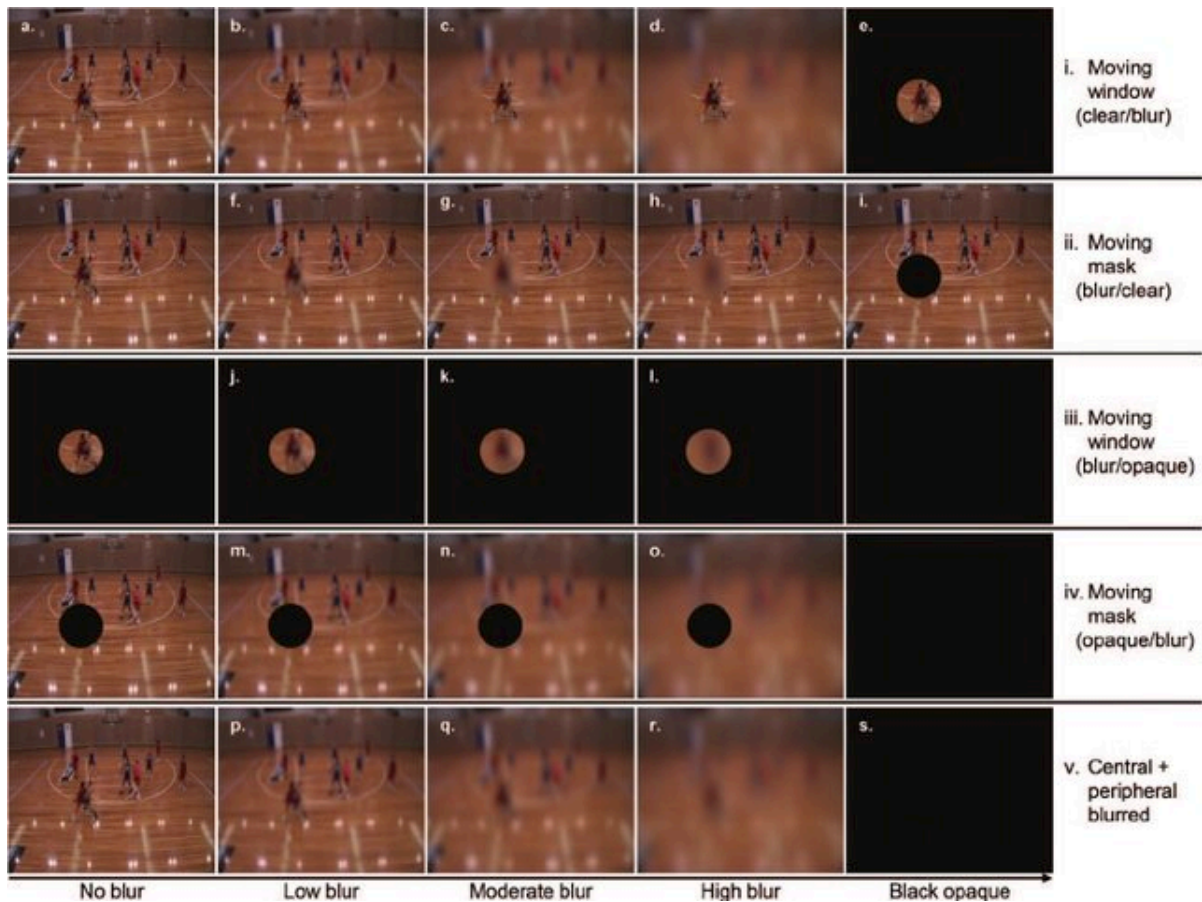


Figure 3.3 – Screenshots of the 19 different viewing condition studied by Ryu et al., 2015: (a) full-clear, (b-e) moving window (clear/blur) conditions (low, moderate, high, and opaque, respectively), (f-i) moving mask (blur/clear) conditions (low, moderate, high, and opaque, respectively), (j-l) moving window (blur/opaque) conditions (low, moderate, and high, respectively), (m-o) moving mask (opaque/blur) conditions (low, moderate, and high, respectively); (p-s) central + peripheral blurred conditions (low, moderate, high, and opaque, respectively). The information in brackets (e.g., clear/blur) refers to the respective quality of the visual information in the central and peripheral sectors of the visual field. Reprinted from “The contributions of central and peripheral vision to expertise in basketball: how blur helps to provide a clearer picture” by Ryu et al., 2015.

experts was better than novices when a central blur (low and moderate blur) was applied (i.e., peripheral vision opaque). However, experts still performed better when there was no alteration of central vision. Performance of the novices was below the level of chance with blurred central vision and no peripheral vision. Moreover, when the opaque mask was applied to central vision, performance of experts was above the level of chance (contrary to novices), although it did decrease with the introduction of a peripheral blur. For both

expert and novice participants, there was an increase in response time in the presence of blur (central or peripheral). Analysis of gaze behaviour revealed somewhat mixed findings. Overall, fixation duration was affected to the same extent by central or peripheral blur when remaining visual field was occluded by an opaque mask, although there were some subtle differences for some levels of central blur. For example, fixation duration increased for the low and moderate central blur but decreased for the high level of central blur, all of which were still longer than the no-blur level. As for saccadic amplitude, both expert and novice participants exhibited an increase when there was a high blur applied to central vision and an opaque mask in the periphery. Finally, saccadic amplitude of novice participants decreased with the levels of blur.

3.6 From performance to learning

As described above, while intermediate and expert level participants are relatively impervious to the presence of blur, it seems that there is a facilitatory effect on performance of novices when blurring the entire visual field (D. L. Mann et al., 2007) or only the periphery (Ryu et al., 2015; Ryu et al., 2013a). The next important question to be considered was whether these performance effects could enhance learning and ultimately be retained. To this end, Ryu et al., 2016, conducted a training study using the gaze contingent blur manipulation. Based on the materials and apparatus reported in Ryu et al., 2015; Ryu et al., 2013a, the previous study design was extended to include a pre-test (Day 1), intervention (Day 2-4), post-test (Day 5) and retention test (two weeks after the post-test). Fifty novice basketball players (recreational level) completed the pre, post and retention tests in three different conditions (see figure 3.4): full vision, peripheral blur and central blur. The response was recorded by clicking on a vacant court slide to indicate the position of the most appropriate teammate to receive the ball. For the intervention, the population was divided into four groups that received different types of training: full vision, peripheral blur, central blur and control group. Video clips taken from NBA game-play were viewed in the respective training condition (occlusion at a key passing time), and participants had to decide as quickly and accurately as possible the most suitable action. Feedback on their response accuracy was provided after every trial. The exception was the control group, who watched an NBA dunk contest video, which did not involve any action play or decision-making.



Figure 3.4 – Illustration of Ryu et al., 2016’s experiment: static screenshot of the (a) full-vision, (b) moving-window, and (c) moving-mask viewing scenarios.

The authors reported that in the retention test after training, the peripheral blur group (clear central vision, blurred peripheral vision) exhibited a slightly better improvement of performance (in terms of response accuracy) than the other 3 groups. They were also the only group to improve from pre-test to post-test, and then from post-test to the retention test in all viewing conditions. Conversely, performance of central blur group (blurred central vision, clear peripheral vision) decreased significantly from post-test to retention test, and almost back to the baseline, pre-test level. These results were observed across all the three viewing test conditions, that is, independently of the training modalities they received. Thus, training with the peripheral blur manipulation also led to an improvement in the full vision and central blur testing condition. Regarding eye behaviour, the specific training regimen did not influence fixation duration. However, taking part in the training intervention per se (i.e, irrespective of training group), led to an overall increase of fixation duration. The authors suggested that the enhanced learning (i.e., best retention) following training in the peripheral blur condition was in part a result of the peripheral blur enhancing participants’ use of information available in central vision. It was reasoned this occurred because the peripheral blur guided overt attention to information in central vision and away from potential distracting information in peripheral vision, thereby attenuating the overall attentional demands. Then, when transferring to the full vision condition, it was suggested that participants who had trained with a moving window were able to combine their newly learned enhanced use of central visual information with the unrestricted peripheral visual information now available, and thereby further improve decision-making performance.

More recently, Ryu et al., 2020, applied the gaze contingency manipulation to the detection of hazards in newly licenced drivers compared to experienced drivers. To better determine the mechanism involved in training using blur, the authors also measured cortical activity using EEG (i.e., alpha wave power). The logic is that an increase in alpha wave power reflects an increase in inhibitory control, whereas a decrease in alpha wave power suggests a neural activation. In this way, the high alpha wave power gives a view of basic cognitive processes, and in particular attention suppression and attention selection (Klimesch, 2012). Thus, in the situation of driving with blur, a decrease in alpha power would reflect a greater attention dedicated to visual processing (Klimesch, 2012; Ryu et al., 2020). In the first study of the experiment, performance of newly licenced drivers was compared to experienced drivers under full vision, central blur and peripheral blur conditions. Video clips were presented to participants that showed a non-adaptive first-person viewpoint. One or two hazards appeared in the visual field and participants had to identify them as quickly as possible by clicking on the video with a computer mouse. Overall, hazard discrimination and detection time were impaired in the central blur condition, while no differences were found between the other two conditions. The peripheral blur condition produced longer fixation duration and smaller saccadic amplitudes than the full vision and central blur conditions. Regarding the EEG findings, alpha wave power decreased in the peripheral blur condition and full viewing condition (e.g., more cortical activation). There was even some evidence that the peripheral blur condition offered the most benefit over some parameters like hazard processing time, with longer fixation on hazard and no difference in response time. According to the authors, the peripheral blur condition favoured an efficient fixation leading to faster information processing, reflective of a visual search strategy that was more focused on central vision. This statement was supported by evidence of an increase of neural activation in cortical areas involved in perceptual-motor decision making information processing and motor response programming.

In the second study of the experiment, the authors conducted a training intervention on unlicensed trainee drivers. Based on the findings of the first study, the central blur condition was not included, so the design involved a comparison between a peripheral blur group (i.e., clear central vision and blurred peripheral vision) and a normal vision group. The study comprised a pre-test (Day 1), the training intervention (Day 2-5), post-test (Day 6) and a retention test one month after the post-test. The results indicated better

performance of the peripheral blur group compared to the normal vision group, with the former exhibiting increased performance on hazard discrimination from pre-test to post-test, and post-test to retention test. Performance of the normal vision group remained similar across all tests. However, no change was found on hazard detection time, leading the authors to suggest that training influenced only spatial perception. In addition, it was found that neural activity (indicated by a decrease of the high alpha power) of the peripheral blur group was more important in retention test compared to the other group, leading to the suggestion that attention was more focused on relevant visual processing. For the normal vision group, neural activity decreased (indicated by an increase of the high alpha power) from post-test to retention test in parietal cortex, which is consistent with less integration of visual information.

Although encouraging, it should be remarked that a driving task involving hazard perception while passively observing a video display is quite different from real world driving, as well as a dynamic sport situation in which the relationship between the participant and surrounds is actively (not passively) modified by movement of the participant (e.g., whole-body or individual limb) and/or object of interest (e.g., opponent). It is perhaps not surprising, then, that occluding central vision during the driving task significantly impaired performance of both inexperienced and experienced drivers, whereas in the sport tasks studied to date experts are less impaired because they use both central and peripheral vision (Hausegger et al., 2019; Ryu et al., 2016; Vater et al., 2019). Still, despite these differences, the use of a peripheral blur for training the perception is encouraging. The described changes in neural activity also support this idea and give a better understanding of the effect of the blur manipulation. That is, an increase of cortical activity is associated with processing cues in central vision that are more closely aligned with the line-of-gaze (Ryu et al., 2020).

3.7 Critical reflection

The primary aim of this article was to review the current research on how the artificial manipulation of blur influences perceptual-cognitive and perceptual-motor behaviour in sport, and to what extent the application of blur during training can facilitate learning and transfer. We presented a narrative review, which although sometimes considered to

be of lower status than a systematic review as it can contain bias (e.g., subjective selection of articles), was useful in this instance because it allowed us to bring together, summarise and critique articles from a new and hence small literature base. These articles included diverse methods of blurring (i.e., dioptric and gaussian blur applied to different tasks), different populations and varied experimental manipulations/questions. The narrative review allowed us to describe these differences in detail and to consider them in the wider context of how blur may be studied in future research using VR technology. As described in the previous sections, our review indicated that there are still unanswered questions regarding the underlying processing mechanisms that facilitate learning and transfer having been exposed to either a dioptric or gaussian blur while practicing a dynamic interceptive action. That aside, we agree with the authors that more work is required to better understand the effects of more prolonged training with a peripheral blur and if there is positive transfer from off-court training to on-court decision making performance. As we discuss below, and recognized by some of the authors of the studies described above, there are limitations of using pre-recorded 2D video clips with a non-adaptive 3rd person viewpoint. Similarly, although positive performance and learning effects of peripheral blur have been reported across a range of experimental tasks, some requiring no or a very limited motor response (i.e., button press), there are methodological issues that prevent the use of peripheral blur when training in more a natural sporting context. Part of the reason for the lack of work in such settings likely relates to the potential for injury that could occur if perception of an approaching object or person were disrupted. However, even if this were minimized (see D. L. Mann et al., 2010a), such training also does not lend itself to using a peripheral blur, which to date seems to be most effective in facilitating learning and transfer effects of novice participants (Ryu et al., 2020; Ryu et al., 2016). Related to this point, it is notable that the positive effects of a gaze-contingent blur have yet to be shown in expert populations. So far, it has only been shown that experts are resilient to the introduction of blur to the entire visual field (D. L. Mann et al., 2010b; Ryu et al., 2015), and that a short period of training (i.e., 70 video clips) with such a manipulation can facilitate decision making accuracy in expert referees (van Biemen et al., 2018). However, there are many facets of expert performance, and it could be that some experts would benefit from training with blurred vision. For example, anecdotal reports from boxers and coaches suggest that during a fight, vision deteriorates with fatigue and repetitive blows to the head. Thus, it could be the case that boxers might benefit from safely practicing in a blurred vision condition if this encourages enhanced pick-up of information and/or

provides an opportunity to familiarise to this specific situation. At the very least, the introduction of blur could be a new challenging situation that experts find stimulating, bringing a diversity to their training.

To overcome some of the limitations highlighted above, we are currently designing a methodology that uses virtual reality (VR) for training with a moving window in a more natural setting. According to Harris et al., 2019, "*virtual reality is a collection of technologies that allow the user to interact with a simulation of some environment, in real-time, using their own senses and motor skills*". The strength of VR is that the constructed environment can be representative of the sporting context, but importantly for the purpose of research, it can be completely reproducible, controlled and easily manipulated (Bideau et al., 2010; Craig, 2013; Faure et al., 2019; Harris et al., 2019; Miles et al., 2012; Renshaw et al., 2019; Stone et al., 2018; A. M. Williams et al., 2011). Unlike pre-recorded 2D video displays with a gaze-contingent blur (viewed from a 3rd person perspective), VR with integrated eye movement tracking (e.g., HTC Vive Eye Pro) ensures sufficient fidelity of binocular depth information in dynamic settings through viewpoint adaptation, while at the same time permitting a realistic, coupled motor response. This preservation of the normal perception-action loop means VR is not limited by the "*standard one-size-fits all practice schedule*" (Farrow, 2013; Renshaw et al., 2019; Stone et al., 2018). Instead, VR allows each individual to develop a particular interaction with the world and to experience it according to their skills, knowledge and morphology (Fajen & Warren, 2007; Gibson, 1979). In this way, VR offers the potential for individualised and targeted training that is respectful and adaptive to the level of the learner and the specific sporting context.

Using VR technology, we are studying the use of a gaze-contingent blur manipulation in boxing where the participant interacts with an opponent in a simulated fight setting. The technology developed allows the application of experimenter-determined Gaussian blur, and, will thus help us to identify the level of peripheral blur that facilitates learning and transfer when training with a peripheral blur. It can also help determine if the blur should be applied to the entire peripheral field (Ryu et al., 2016) or more specifically to areas of interest in the periphery that contains the relevant information. This could be relevant in combat sports such as boxing, where it is well known that participants fixate gaze around the chest/head of the opponent and use peripheral vision to pick-up information from the hands and/or feet (Hausegger et al., 2019; Martínez de Quel & Bennett,

2019; Vater et al., 2019). Moreover, once the VR environment has been developed, it is relatively straightforward to manipulate parameters that impact upon task difficulty. This means that training can be adapted to the current and changing level of participants' performance, thereby providing a stimulating and challenging context throughout learning. This is a major advantage compared to pre-recorded 2D videos, where the stimuli cannot be individually manipulated or matched to a participant's skill level. Indeed, by continually challenging the participant, it should be possible to maintain motivation and facilitate the rate of learning (Michalski et al., 2019).

Integrating the blur manipulation within a VR environment could be promising and open new possibilities; however some methodological and practical questions need to be considered. To reduce so-called cybersickness, and also enable depth perception similar to that experienced in the real world, it has been suggested that VR systems should ideally incorporate both depth of field (DoF) and foveated rendering techniques that introduce blur into the visual stimuli (Hussain et al., 2021). The former approach involves applying blur to visual stimuli that are located at different physical depths than the focal point. The applied blur is not uniform but follows a gradient such that it is stronger at more or less distant depths. The latter approach involves the application of blur in accord with the physiological properties of the retina (i.e., fovea, near periphery, mid-periphery); NB. Current HMDs do not typically enable presentation of objects in the far periphery. An object at the focal point that coincides with foveal vision is perceived with high acuity, whereas visual stimuli are increasingly blurred as they are located at more eccentric locations in the visual field.

Importantly, with dynamic, interactive VR stimuli, both DoF and foveated rendering require tracking of gaze location in order to optimally achieve the intended blur effect. The advent of eye tracking apparatus embedded within the HMD (e.g., Vive Pro Eye), has made this option more available. However, it does come at a cost in terms of purchasing the HMD and programming the VR stimuli. This could initially be problematic for practitioners and coaches but as the technology develops and interest grows, we envisage that low-cost, user-friendly solutions will be available. As for researchers, when applying a peripheral blur as suggested by the works of Ryu et al., 2020; Ryu et al., 2016, it will also be necessary to consider the potential interaction with DoF and foveated rendering. For example, the application of a high level of peripheral blur to a 3D VR stimuli could

impact upon depth perception more than when applied to a 2D video image viewed from a third-person perspective.

3.8 Conclusion

In this review, we have considered how blurring all or parts of the visual information available to participants impacts upon their performance and learning of sporting tasks. Given the claims that elite athletes have better vision than novices and/or the general population, and that various aspects of vision can be improved through training, it may be surprising to find that athletes of varying skill level can maintain performance on a range of sporting tasks under relatively high levels of blur. Moreover, it is interesting to see that novice participants can even benefit from practicing with blurred vision, particularly when the blur is selectively applied to the peripheral visual field. That said, there are a number of methodological issues with current approaches to applying blur in a dynamic sporting context, as well as a lack of research on learning effects of training with blur learning in elite athletes. We suggest that the immersive and adaptive 1st-person perspective of virtual reality can overcome many of these limitations and thereby offers an opportunity for sports scientists to improve understanding of the benefits of training with blurred stimuli in sporting contexts.

STUDY 1A: VIRTUAL REALITY BOXING: GAZE-CONTINGENT MANIPULATION OF STIMULUS PROPERTIES USING BLUR.

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4.1 Introduction

There have been a number of studies that have reconsidered the role of visual function in sport (Laby & Appelbaum, 2021). Rather than trying to improve performance by improving basic visual function, there has been interest in whether athletes can benefit from training in conditions that place different demands on the visual system. One such approach has been to consider whether experienced/skilled athletes can maintain, and even learn to improve their performance advantage under impoverished visual conditions. For instance, several studies have examined the effect of removing fine details by artificially blurring the visual stimulus. R. Jackson et al., 2009, used video recordings of a tennis serve to investigate the effect of blur, and thus the importance of detailed information (i.e., movement of specific features) compared to configural information available from movement kinematics, in groups of “poor anticipators” and “good anticipators”. The results indicated that performance of “poor anticipators” increased from the 0% blur to 20% blur video condition, whereas the “good anticipators” performance decreased. However, both groups increased their performance from the 20% to 40% blur condition. To explain the finding that blur can facilitate anticipation performance in some circumstances, the authors suggested there may have been a switch of visual strategy such that participants were more attuned to configural information in the presence of blur, and less focused on

high acuity information that can be distracting.

In a subsequent study, Ryu et al., 2018, presented novice badminton players with videos that showed either normal or blurred (i.e., low-pass Gaussian filter) badminton shots. Participants were divided into three training groups: low spatial frequency (i.e., blurred video), high spatial frequency (only detailed information conserved in the video) and normal vision. The video clips showed badminton shots with different occlusion times, plus a direct performance feedback. The authors reported different effects on anticipation accuracy and reaction time when comparing the type of video training. When facing deceptive actions, the low frequency training group improved the most from pre-test to post-test, and then kept this advantage in the retention test one week later. This observation is consistent with the performance improvement of novices reported by R. Jackson et al., 2009. It seemed that the blurred video encouraged participants to focus on kinematic information and thus they were more attuned to the deceptive intent. A similar statement was made by van Biemen et al., 2018, about the perception of deceptive information by skilled football referees who trained on a decision making task in a blurred or normal vision condition. The authors found that the blurred vision group improved their response accuracy to a greater extent than the normal vision group, and specifically that the skilled referees became more sensitive to genuine fouls.

Extending the work on blurred vision but now with the aim to distinguish between covert and overt attentional strategies, and thereby the role of central and peripheral vision, Ryu et al., 2013a, used a gaze-contingency display in which there was a moving window or moving mask. In the moving window condition, only a circle of 5° around the gaze fixation point was visible, whereas in the moving mask condition, central vision of 5° around the fixation point was removed from the video, leaving the participants with access to information in peripheral vision only. The authors found that expert basketball players exhibited better decision-making performance in all conditions compared to novices, thereby indicating that they possessed a better capacity to use both central and peripheral vision. To overcome the limitations of using an opaque mask (i.e., complete removal of central or peripheral vision), Ryu et al., 2015, revised their protocol by applying different levels of blur to the gaze-contingent location. The participants (18 skilled and 18 less skilled male basketball players) were required to click on a vacant court (response slide) to indicate the position of the most appropriate teammate to receive the

ball, with performance measured in terms of response accuracy and response time. They found that in both peripheral blur (clear central vision) and central blur (clear peripheral vision) conditions, performance of experts was better than novices for all levels of blur. Notably, when information from a part of the visual field was unavailable (opaque central vision or opaque peripheral vision), only experts were still able to perform above the level of chance. The authors suggested that experts were able to adapt and use information based on what was available. However, novices did improve their response accuracy with moderate and high blur applied in peripheral vision (NB there was no improvement for the experts in these conditions). This positive effect is in accordance with the previous results observed on novices (R. Jackson et al., 2009; D. L. Mann et al., 2010a; Ryu et al., 2018).

Although offering some promising findings, one limitation of manipulating blur on a 2D video display is that it decouples perception from the motor response. Indeed, it has been reported by D. L. Mann et al., 2010a, that the effect of a blurred visual stimulus is different when participants predict ball delivery direction from a real bowler by making a verbal response only (uncoupled) or verbal response plus batting movement (coupled). In the coupled condition, performance was more resistant to the blur manipulation, such that visual clarity was not essential to anticipation performance. However, in the uncoupled condition, performance increased a little for the lowest level of blur but deteriorated for the higher levels of blur. The authors suggested that a blur manipulation encourages participants to rely more on dorsal stream processing (vision for action), and thus is of greater benefit in tasks where there is a coupling between perception and the motor response. Following this logic, it is important to recognise that the use of 2D video displays to present blurred stimuli introduces a further decoupling of perception from action by preventing access to binocular information and associated vergence eye movements. Although not an issue when blur is achieved using lenses (i.e., dioptric blur) when performing tasks in real-life settings (D. L. Mann et al., 2010a), it is not practical using these methods to introduce a gaze-contingent manipulation. Therefore, to date, it remains to be determined if the application of blur to specific locations impacts upon the performance of tasks in which there is a natural perception-action coupling that occurs in close proximity to the participant.

Here, we examined the effect of different levels of blur on interception performance

and eye gaze data during an immersive virtual reality (VR) boxing task. VR offers a promising research tool as it permits the realistic simulation of real-world tasks (e.g., the presence of a feint prior to the onset of different combinations of punches thrown) with a high level of control and reproducibility (Bideau et al., 2010; Craig, 2013; Miles et al., 2012; Stone et al., 2018). Importantly, VR allows the user to interact with a first-person and adaptive viewpoint of the simulated environment in real-time (Harris et al., 2019). This preservation of the normal perception-action coupling means VR allows each individual to develop a particular interaction with the world and to experience it according to their skills, knowledge and morphology (Fajen & Warren, 2007; Gibson, 1979). In addition, advances in technology have made it possible to record eye gaze location in the VR environment, and thus introduce and determine the impact of a gaze-contingent blur manipulation. In the current study, we expected a gaze-contingent blur to central vision would have little or no negative impact on performance because it does not disrupt the perception of motion-related information from the periphery. In fact, it is possible that blurring central vision could encourage a shift of covert attention to peripheral locations, thus facilitating the pick-up of relevant information (Ryu et al., 2015; Ryu et al., 2016). Moreover, it could help the perception of deceptive intent by suppressing detailed information (e.g., facial expression) in the central vision thereby encouraging the use of basic kinematic information regarding movement feints. Following the above logic, we expected that a gaze-contingent blur to peripheral vision would not prevent participants from perceiving motion-related information from the periphery. However, it is possible that blurring peripheral vision might encourage a shift of attention to areas without blur such as central vision (see Ryu et al., 2015), thereby encouraging focus on less relevant or even distracting information. In this case, we can expect, the pick-up of motion-related information in the periphery to be inhibited and performance to decrease.

4.2 Materials and methods

4.2.1 Participants

Eighteen participants (5 female, 13 male) with a mean age of 29 years (± 11 years) completed the experiment. There were 9 athletes who practiced mixed martial arts (French boxing, judo, qwan ki do) and 9 who were expert boxers. All athletes had at least two

years of combat sports experience. Specifically, the mixed-martial athletes had an average experience of 12 (± 7) years, and the boxers an average experience of 7.8 (± 4) years. They performed at various levels from leisure to competitive and professional events (e.g., European championship). All participants were healthy, without injuries, and had normal or corrected-to-normal vision. They signed a written consent form and were free to withdraw from the experiment whenever they wanted. The experimental protocol was made in respect of the Declaration of Helsinki and accepted by the national ethical committee (CERSTAPS IRB00012476-2021-12-05-108).

4.2.2 Task and Stimuli

The experiment took place in a dark sports hall, large enough to avoid collision between the participant and the physical world. The virtual environment was built with Unity software (Version 5.6.6) and consisted of a boxing ring. The ring was of official size and participants were free to move within a space of 4m x 4m, with a virtual opponent. The origin of the scene was placed in the middle of the ring. Motion capture of a real professional boxer was performed to create the realistic animation of the virtual boxer. Participants were immersed in the virtual environment through the use of a Head-Mounted Display (HMD, model: HTC Vive Eye Pro, Field of View: 110 deg, image resolution: 2160*1200 pixels) and an HTC Vive tracker attached to each wrist. Participants' hands were reconstructed in the virtual environment so that they could see them and interact naturally with the scene. Using the eye tracking system integrated in the HTC Vive Eye Pro, we recorded eye movements (1 deg spatial resolution, 60 Hz temporal resolution)¹ and used the gaze location data to control in real-time the gaze-contingency manipulation. Calibration of gaze location within the virtual environment for each participant was done prior to each block, using the HTC Vive Eye pro calibration tool.

Participants faced a virtual male boxer (see Figure 4.1) in the virtual boxing ring. The virtual boxer was initially shown in a guard position 1m away from the participant and maintained a face-to-face orientation by rotating according to the participant's movement. Participants started the round (i.e., a block of trials) when they were ready by punching a red sphere located in front of them, after which the sphere disappeared.

1. The native temporal resolution of the eye tracker was 90 Hz, but it was only possible to record eye gaze at 60 Hz due to processing limitations when rendering the immersive 3D virtual environment.

The virtual opponent then launched an attacking sequence. Participants had to block the incoming punches (with their virtual hand) by intercepting the opponent's glove during the trajectory of the attack, and thus before it touched them, with a chasing parry. Participants were instructed to only block from the start of the punch to the moment when the opponent's arm was fully extended. Auditory feedback indicated to the participant if they succeeded. No other responses, such as throwing a punch after the attack, were allowed or scored. If the participant blocked too early or too late, it was considered as a failure. Irrespective of whether the participant successfully blocked any of the incoming punches or not, the sequence continued until all three attacking punches had been thrown.

To minimize the impact of familiarity and ensure participants could not easily predict the upcoming sequence of three successive punches, we recorded 12 attacking sequences in total. These were comprised of 4 variations in the type and order of the 3 punches thrown (i- left straight to face, right straight to face, left cross to face; ii – left uppercut to body, right uppercut to body, left cross to face; iii - left straight to face, left straight to face, right straight to face; iv – left uppercut to body, left cross to face, right straight to face) by 3 variations in “Feint Type”, which were defined according to whether the first punch was preceded by an arm feint, foot feint or no feint. The presence of a feint at the beginning of a sequence is commonly used by experienced boxers as a deceptive tactic to generate uncertainty regarding the onset of an attack and to create opportunities to land a successful punch. The 12 attacking sequences were presented in random order in each of the 5 blocks of trials, separated by a 2-minute break. In each block, participants performed the virtual boxing task in one of 3 Viewing Conditions. In the control condition, participants were presented with normal vision of the opponent and surrounds. For the other 2 Viewing Conditions, a gaze-contingent blur manipulation was made relative to the point of gaze fixation (for more detail see below and Figure 4.1), such that participants were presented with a peripheral blur or a central blur. The control condition consisted of a single block in which there were two repetitions of the 12 sequences, resulting in 24 trials. The peripheral and central blur conditions each comprised of one repetition of the 12 sequences under three levels of blur (light, medium, and strong blur), resulting in 36 trials per block. The peripheral and central blur conditions were performed twice, such that for each level of blur, there were two repetitions of the 12 attacking sequences.

4.2.3 Gaze-contingency manipulation

A 5° blurred circle around the gaze fixation point was used to create the central blur condition, whereas in the peripheral blur condition, the blur was only applied to stimuli outside of this 5° circle (see Figure 4.1). The control condition did not include any blur manipulation. A Gaussian blur, which is a 2D-convolution operator, was used to manipulate the display. It takes two inputs: the image of the participant’s viewpoint generated at each frame and the Gaussian kernel whose size defines the blur intensity. A Gaussian function G has the following form:

$$G(x) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2}{2\sigma^2}} \quad (4.1)$$

where σ is the standard deviation of the distribution, x is the distance from its centre.

This Gaussian is applied to each pixel of the rendered image that is to be blurred. It takes into account the neighbouring pixels with a weighting that is inversely proportional to its position (x,y) to the centre. The degree of blurring is thus determined by the standard deviation (σ) of the Gaussian: a stronger blur is obtained with a larger convolution kernel. It is important to note that Gaussian blur does not introduce noise in the image but instead simply acts as a low pass filter that makes transitions and edges between stimuli less prominent (for more details, see Limballe et al., 2022, chapter 3).

The parameters of the blur were the following: light blur ($\sigma = 100$, kernel size = 13), medium ($\sigma = 500$, kernel size = 19), strong ($\sigma = 10\,000$, kernel size = 25). These parameters were determined during pre-testing in which we first ascertained the strongest Blur Level that was achievable within the technological constraints (i.e., the Gaussian could be applied within the selected image refresh rate), and then decreased the kernel size and the associated sigma value, using a correspondence table. A similar approach has been used in previous work on blur (e.g., Ryu et al., 2015), where the authors used 20 units, 50 units and 100 units blur as specified by the filters in the software used to manipulate the images.

4.2.4 Data analysis

An interception was successful when the participant stopped the opponent’s incoming punch before complete extension of the opponent’s arm (end of the punch). We used the

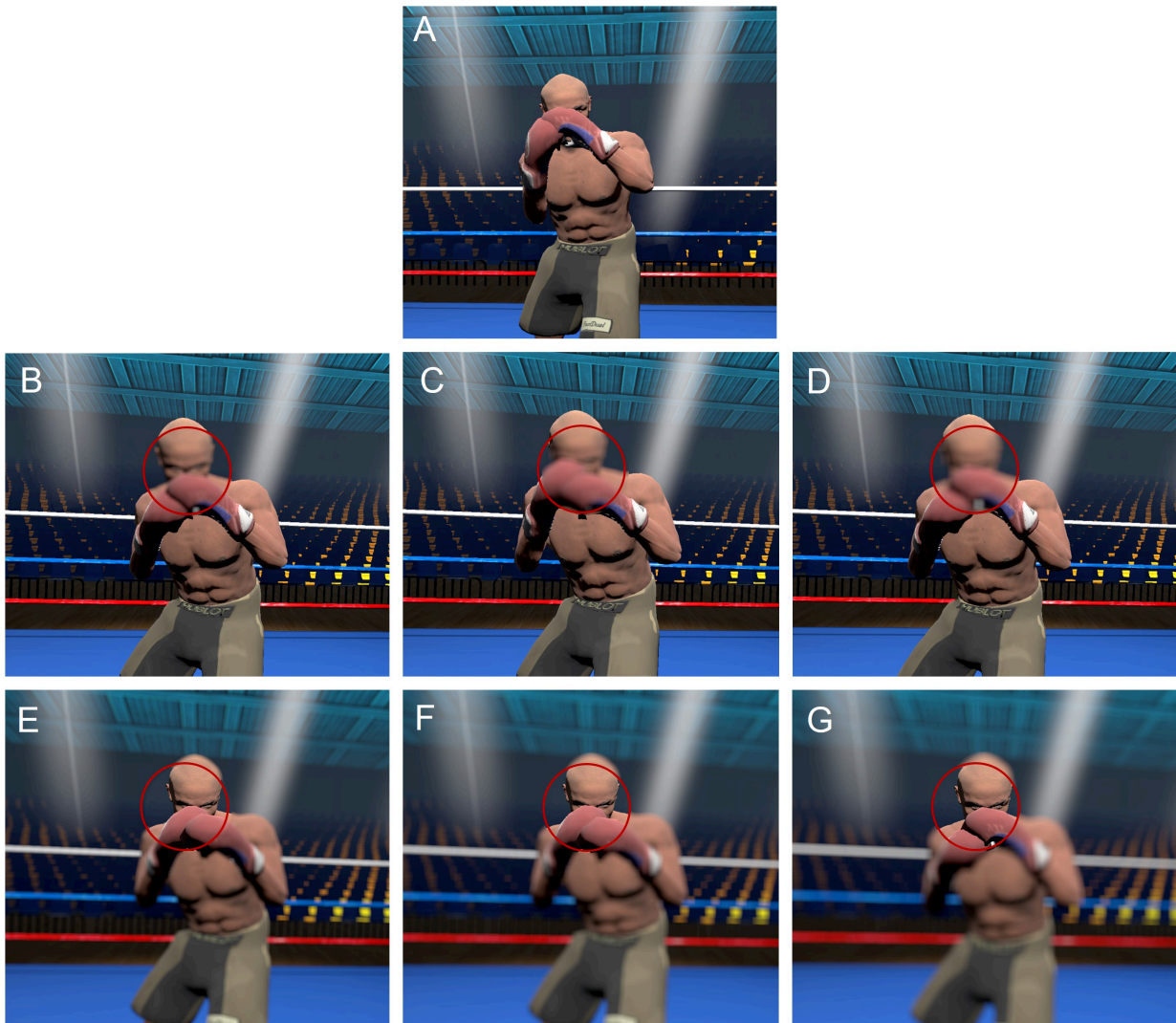


Figure 4.1 – Representation of the viewing conditions. (A) control, (B) central blur level 1, (C) central blur level 2, (D) central blur level 3, (E) peripheral blur level 1, (F) peripheral blur level 2, (G) peripheral blur level 3. VR user view. For emphasis, we have overlaid an outline to the gaze-contingent window but this was not visible to participants.

collider engine from Unity to detect collisions between the participant's hand and the opponent's glove. The performance data for each punch were expressed as either a 0 for no interception or 1 for a successful interception. The collider engine was also used to identify gaze location with respect to pre-determined areas of interest (AOIs). The analysis was performed on each trial (i.e., from onset of the first punch to end of the third punch within each sequence), prior to the replacement of missing data (see below). This resulted in a

percentage of the trial duration that gaze was located: i) within AOIs associated with the opponent's body; ii) on other areas away from the opponent; or iii) missing due to blinks or other technical problems that prevented pupil recognition.

To reflect the global distribution of gaze throughout the entire duration of the control, peripheral blur and central blur viewing conditions, the volume of a 3D ellipse containing 95% of the gaze data was calculated. The first stage in the process involved normalizing gaze data relative to the position of opponent's head in the 3D virtual world. Missing data (1.9% of the global observations) were then replaced using linear interpolation with the function `.interpolate()` from Panda Dataframe package in python. Next, the package `ellipse3d` from RGL (v. 0.108.3) in RStudio (v. 2022.02.3) was used to draw an ellipse surrounding 95% of the gaze data. This part of the process returned a 3D ellipse mesh, which was then converted into a triangular mesh using `triangulate_quads` from the `quadmesh` (v. 0.5.0) package in RStudio. Finally, the volume of the ellipse was calculated using `mesh_volume` from Lithics3D (v. 0.4.2) package in RStudio.

To provide a more precise measure of how participants fixated eye gaze during the attacking sequences, we used a dispersion-threshold algorithm to identify instances in which there was a change in the average position (greater than 1°) between consecutive windows (0.1 s) of eye position data (Llanes-Jurado et al., 2020). Such instances are equivalent to the start or end of a fixation. Using these data, we identified the occurrence of gaze fixations during the interval that the opponent was attacking with a punch (i.e., from the onset to the end of a punch). Having identified the start time and end time of each fixation, and hence the number of fixations, we also calculated each individual fixation duration.

4.2.5 Statistics

It was not the intention to determine if participants responded differently to the 4 variations in type and order of punches thrown, hence this was not considered as a factor in subsequent analysis. However, we did want to examine if participants' performance and gaze fixation data was influenced by the presence of different levels of blur in the peripheral and central conditions compared to control condition, as well as the inclusion of a feint (Feint Type). To provide a greater level of sensitivity, we also examined whether

any influence of these factors was present across the first, second and third punch (Punch Number) in an attacking sequence. Accordingly, performance and fixation data (i.e., number of fixations and mean fixation duration) were calculated from the response to 8 trials (2 repetitions of 4 variations in the type and order of punches) at each unique combination of Punch Number (1, 2, 3), Feint Type (arm, foot, none), Blur Level (1, 2, 3) and Viewing Condition (central, peripheral, control).

To analyse this partially crossed design and also take into account individual-participant variability in response to the different experimental manipulations, all data was analysed using linear mixed effects modelling (lme4 package in RStudio, v. 1.1-27.1). This is an iterative process that attempts to find the simplest model (i.e., random and fixed effects) that best fits the data. For performance and fixation data, we used a top-down strategy in which we first included all fixed effects (e.g., main and interaction terms) and a random effect of intercept and slope for Punch Number ($y = \text{Viewing condition} * \text{Feint Type} * \text{Punch Number} * \text{Blur Level} + (1 + \text{Punch Number} | \text{Participant})$). We then removed fixed effects sequentially based on their statistical significance determined using Wald Chi Squared tests (CAR package in RStudio, v. 3.0-12), and provisionally retained those that returned p-values of 0.1 or less. The reduced-effects model was compared to the full-effects model with conditional R^2 (MUMIn package in RStudio, v. 1.46.0) and AIC. It was also compared to a reduced model with the same fixed effects but only a random intercept. In the final reduced model, only fixed effects at $p \leq 0.05$ were deemed meaningful and further analysed using Bonferroni-corrected pairwise comparisons. To this end, we used the EMMEANS package (v. 1.7.2) to compare estimated marginal means, and thereby take account of the partially crossed design. Performance data (number of successful trials out of 8 per combination of independent variables) were modelled according to a binomial distribution with a logit link function. Number of fixations (total number of fixations across 8 trials per combination of independent variables) were modelled according to a Poisson distribution with a log link function. Fixation duration (mean fixation duration across 8 trials per combination of independent variables) were modelled according to a normal distribution with an identity link function.

To analyse the global measures of gaze distribution, linear mixed effects modelling with an identity link function was also used but with AOI and Viewing Condition as fixed effects for gaze location, and Viewing Condition as a fixed effect for 3D ellipse volume.

Each participant was initially modelled with a random intercept and slope for Viewing Condition. The same iterative approach to removing fixed and random effects was used as described above.

4.3 Results

4.3.1 Performance data

Having removed non-significant effects found in the full model (AIC=3835; conditional $R^2=0.56$), the final reduced model (AIC=3770, conditional $R^2=0.55$) indicated a main effect of Punch Number ($\chi^2(2)=138.545$, $p<.0001$), Viewing Condition ($\chi^2(2)=18.767$, $p<.001$) and Feint Type ($\chi^2(2)=46.830$, $p<.001$), as well as significant Punch Number by Feint Type interaction ($\chi^2(4)=63.872$, $p<.001$). Bonferroni-corrected pairwise comparisons indicated that performance in the central blur condition (0.442) was significantly ($p<.001$) better than the peripheral blur condition (0.392) but not the control condition (0.424) (see Figure 4.2).

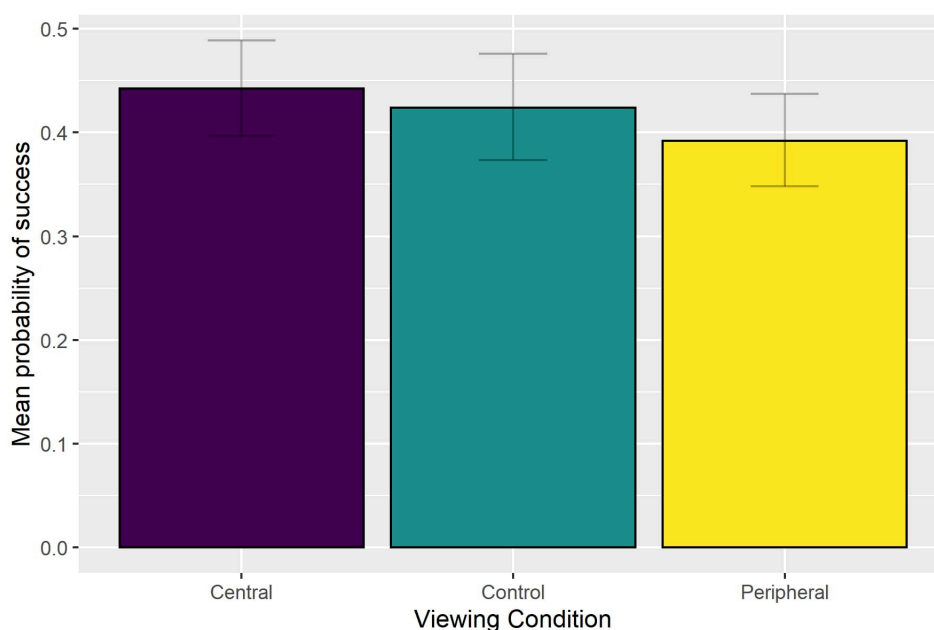


Figure 4.2 – Group mean probability of a successful interception as a function of Viewing Condition.

As can be seen in Figure 4.3, participants intercepted significantly more of the first punches in a sequence when they were preceded by a foot feint (0.353) than arm feint (0.197, $p < .0001$) or no feint (0.252, $p < .0001$). Still, their performance was significantly better on the second and third punch compared to the first punch within a sequence irrespective of whether a feint was present or not ($p < .0001$).

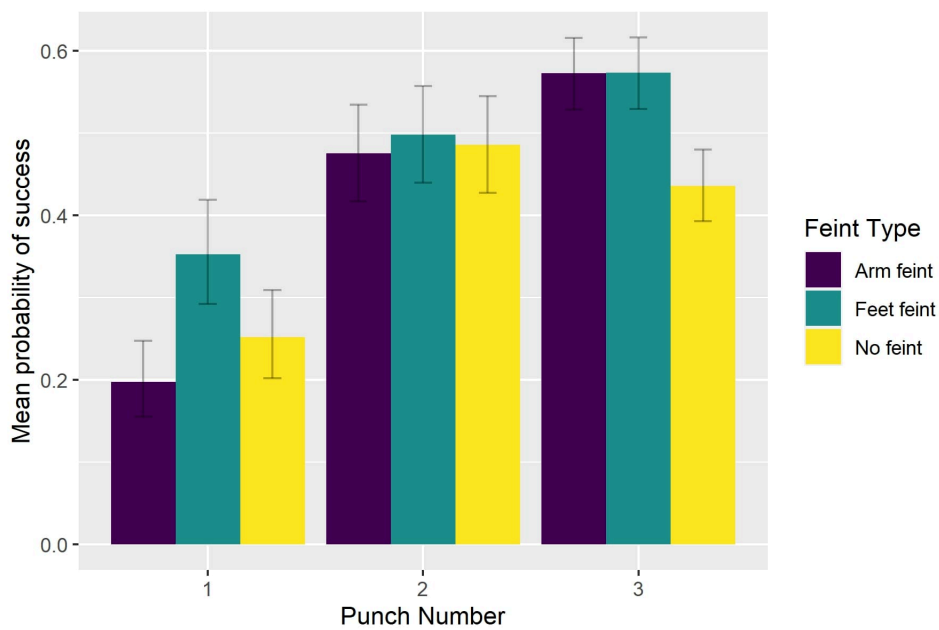


Figure 4.3 – Group mean probability of a successful interception as a function of Feint Type and Punch Number.

4.3.2 Eye gaze data

At a global level (i.e., across the entire block duration), a reduced model with a fixed effect of Viewing Condition ($\chi^2(2)=26.931$, $p<.0001$) and random intercept (AIC=32.749; conditional $R^2=0.87$) indicated a significantly better fit ($\chi^2(2) = 21.85$, $p<.0001$) of the 3D ellipse volume data than an intercept only model (AIC=768; conditional $R^2=0.76$). Bonferroni-corrected pairwise comparisons indicated that the 3D ellipse volume was smaller in the control condition (43.1 cm^3) compared to the peripheral blur (67.9 cm^3) and central blur (68.6 cm^3) conditions ($p<.0001$).

The finding of a relatively small volume that included 95% of eye gaze data across the entire duration of each viewing condition was confirmed by analysis of gaze location with respect to the AOIs within each trial. The full effects model (AIC=7598.499; conditional $R^2=0.803$) did not differ from the reduced model (AIC=7616.348, conditional $R^2=0.806$) in which there was a significant main effect of AOI ($\chi^2(15) = 5134.5$, $p<.0001$). Observation of the estimated marginal means revealed that 95% of eye gaze within each trial was located within 6 of the 16 AOIs, which were mostly distributed on the Head, Tunk and distal ends of the two arms (see Figure 4.4).

4.3.3 Fixation data

Number of Fixations: Having removed non-significant effects found in the full model (AIC=4743; conditional $R^2=0.50$), the reduced model (AIC=4665, conditional $R^2=0.49$) returned significant main effects of Punch Number ($\chi^2(2)=549.755$, $p<.0001$) and Feint Type ($\chi^2(2)=35.117$, $p<.0001$), and a significant interaction between Punch Number and Feint Type ($\chi^2(4)=60.066$, $p<.001$). Bonferroni-corrected pairwise comparisons indicated that the number of fixations (see Figure 4.5) decreased from the first to second punch ($p<.03$), and then again from the second to third punch ($p<.007$) for sequences that began with either no feint (8.70, 4.90, 3.88) or an arm feint (5.79, 4.85, 3.89). For sequences that began with a foot feint, there was a reduction ($p<.0001$) in the number of fixations from the first (7.85) to second punch (4.10), followed by a smaller decrease ($p=0.09$) from the second to third punch (3.39).

Fixation duration: The reduced model (AIC=-3892, conditional $R^2=0.47$) indicated significant main effects of Viewing Condition ($\chi^2(2)=19.822$, $p<.0001$), Feint Type (χ^2

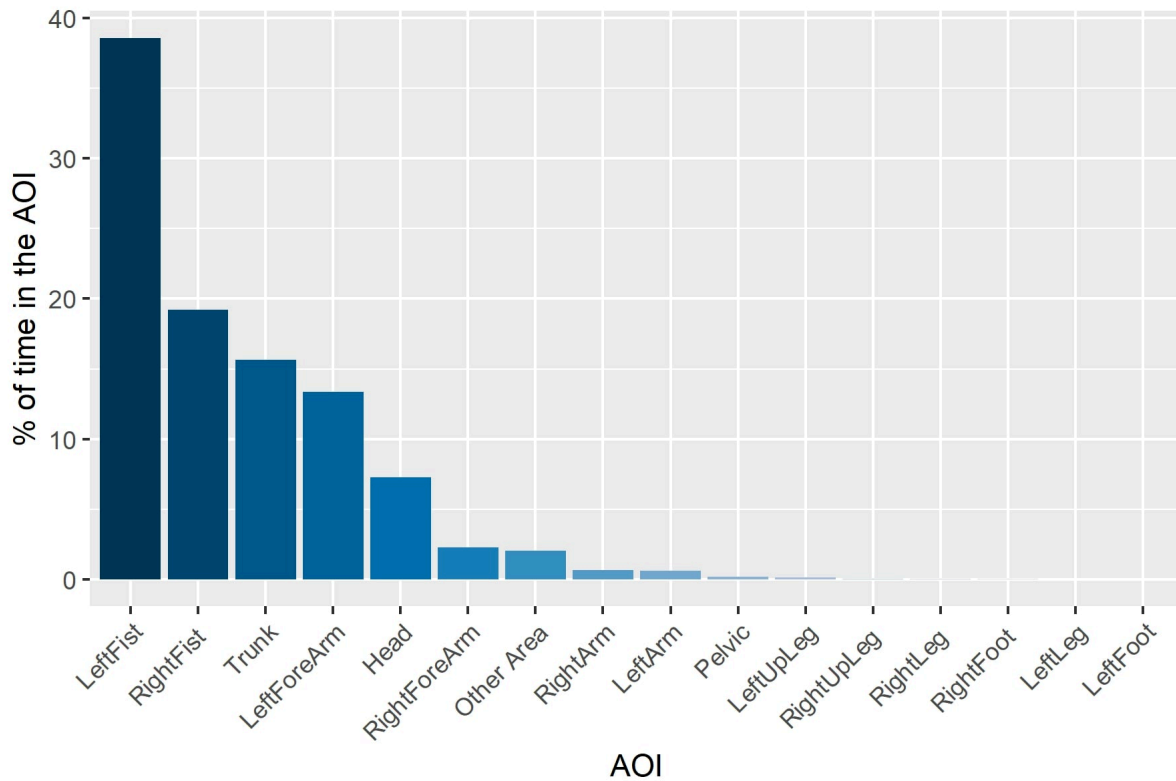


Figure 4.4 – Percentage of time that gaze was located in the AOIs.

(2)=10.356, $p < .006$), and Punch Number ($\chi^2 (2)=28.872$, $p < .0001$), which were superseded by significant interaction effects between Viewing Condition and Blur Level ($\chi^2 (4)=10.815$, $p < .025$), and Punch Number and Feint Type ($\chi^2 (4)=14.784$, $p < .006$). Bonferroni-corrected pairwise comparisons indicated that fixation duration was significantly ($p < .035$) longer in the peripheral viewing condition when faced with the strong level of blur (0.189 s) compared to the light level of blur (0.176 s). Fixation duration in the central viewing condition did not differ between the light (0.174 s), medium (0.172 s) or strong (0.172 s) levels of blur, or compared to the control condition (0.170 s). However, fixation duration in the central viewing condition and control condition was shorter (all $p < .004$) than that exhibited with the strong level of blur in the peripheral viewing condition (see Figure 4.6). Finally, fixation duration was significantly longer (all $p < 0.002$) on the first punch compared to the second punch for sequences that began with either no feint (0.191 s vs. 0.175 s) or a foot feint (0.200 s vs. 0.162 s). There was no decrease in fixation duration from the second to third punch irrespective of Feint Type (see Figure 4.7).

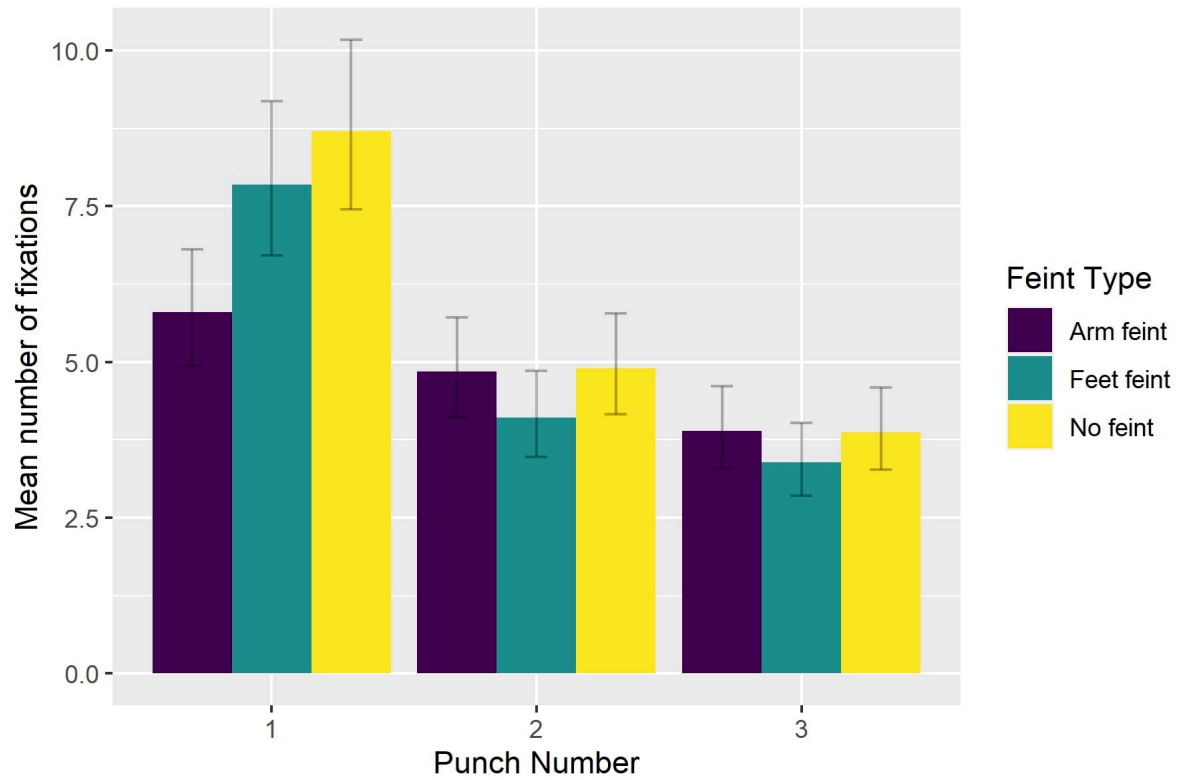


Figure 4.5 – Group mean number of fixations as a function of Feint Type and Punch Number.

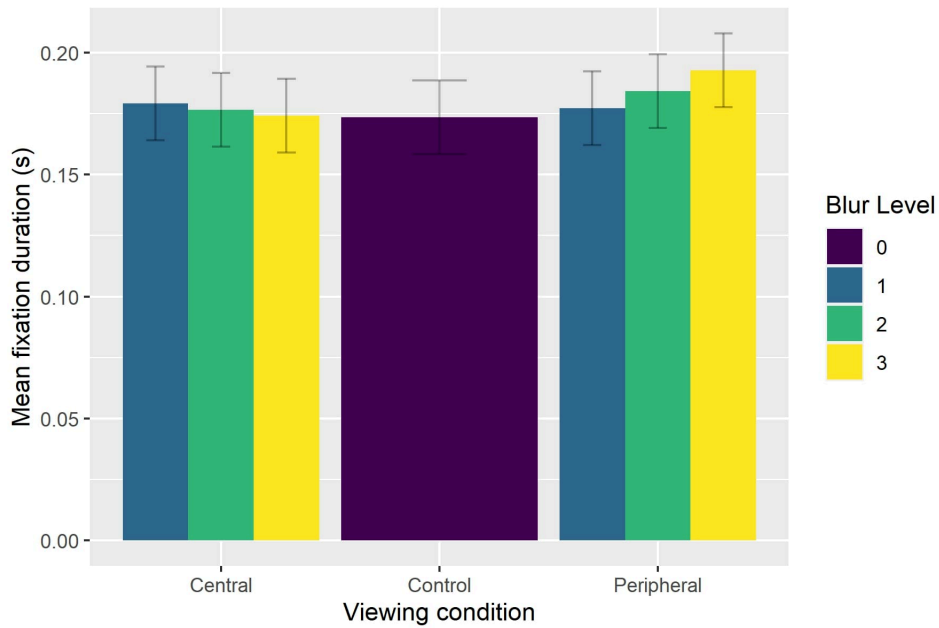


Figure 4.6 – Group mean fixation duration as a function of Viewing Condition and Blur Level.

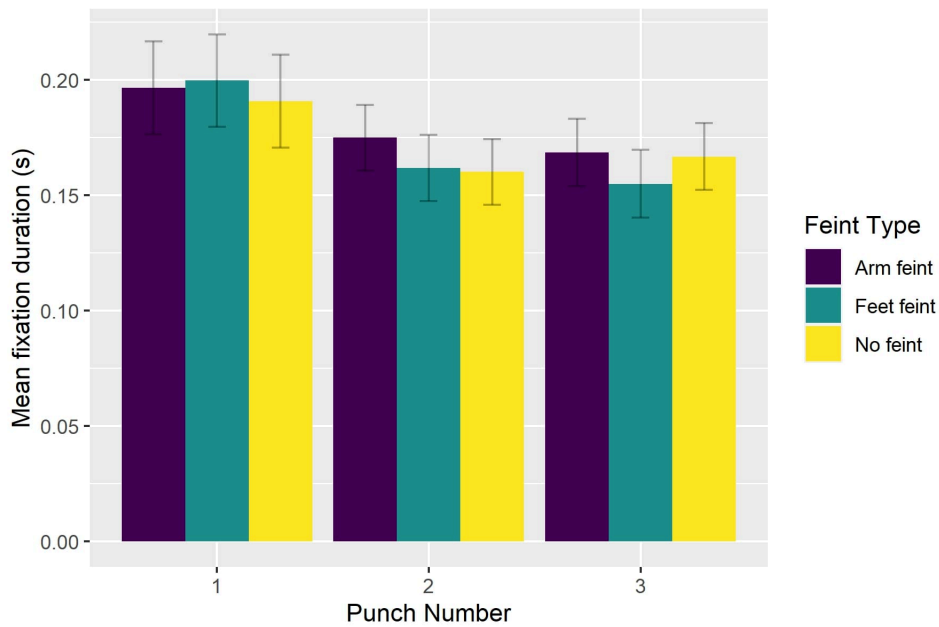


Figure 4.7 – Group mean fixation duration as a function of Feint Type and Punch Number.

4.4 Discussion

There have been a number of studies indicating that visual and visual-motor behaviour does not deteriorate (D. L. Mann et al., 2010b; Ryu et al., 2018; van Biemen et al., 2018), or can even be improved (R. Jackson et al., 2009; van Biemen et al., 2018), when the visual stimulus is artificially blurred. However, as was recently noted by Limballe et al., 2022 (see chapter 3), previous studies have included diverse approaches to blurring the visual stimulus (i.e., dioptric blur and Gaussian blur achieved using different methods), different populations and sporting tasks, as well as varied experimental manipulations that do not always preserve the normal perception-action coupling. Therefore, to improve upon the methodological limitations of previous work, in the current study we used an immersive VR boxing environment viewed through an HMD with an integrated eye tracker to examine if interception performance and eye gaze data of expert combat athletes are mediated by different levels of blur in the central or peripheral visual field, and whether this is influenced by the presence of deceptive information at the onset of an attack sequence.

In line with the finding that performance of expert basketball players (Ryu et al., 2015), badminton players (Ryu et al., 2018), cricketers (D. L. Mann et al., 2010b) and football referees (van Biemen et al., 2018) is relatively impervious to the presence of blur, we found that interception performance of expert combat athletes did not deteriorate significantly following a gaze-contingent blur manipulation in our virtual boxing environment. In fact, interception performance did not differ significantly between the central blur condition (0.442) and the control condition (0.424), or between the peripheral blur condition (0.392) and the control condition. The only significant difference was between the central blur and peripheral blur conditions. Moreover, we found that there was no main effect of Blur Level or interaction between Viewing Condition and Blur Level. The implication, therefore, is that the inferior interception performance in the peripheral blur condition compared to the central blur condition was evident at the lowest level of blur, and that even the highest level of blur in central vision did not impact negatively upon performance. Such findings may at first seem difficult to reconcile with reports that expert athletes make greater use of motion information available in peripheral vision (Vater et al., 2019; A. Williams & Jackson, 2019), which is more sensitive to low-spatial, high-temporal frequency visual stimuli, and thus should be less sensitive to the application of blur. However, as pointed out by Ryu et al., 2015, there are reports that blur causes participants to

shift attention towards areas of the visual field that are not blurred (Enns & MacDonald, 2013), which they suggested in their study encouraged novice participants to attend to more salient information in central vision. Following the same logic, it is possible in the peripheral blur condition of the current study that expert combat athletes' attention was drawn to the window of clear central vision. By doing so, participants may have been less aware of relevant information available from more peripheral locations and potentially more focussed on high acuity details such as facial expression, which can act as a distractor in combat sports (Petri et al., 2019b). Therefore, even though expert combat athletes may have been able to perceive and extract relevant information from peripheral vision in the presence of blur per se, they were less attentive to this area of the display and their performance deteriorated compared to the central blur condition.² A similar attentional mechanism could have been at play in the central blur condition, where it is possible that participants were less focussed on distracting, high acuity details, and instead attended to motion information about the attacking sequence of punches. Whether the presence of a gaze-contingent central blur in the current study encouraged expert combat athletes to focus on a reduced amount of information and/or the more salient information given their level of expertise remains to be determined.

Interestingly, the presence of blur in the current study did not impact upon participants' ability to intercept significantly more of the first punches in a sequence when they were preceded by a foot feint (0.353) than arm feint (0.197) or no feint (0.252). The facilitative effect of a foot feint was present in all Viewing Conditions but was no longer present for the second and third punch in the sequence. As might be expected given expert combat athletes' knowledge of how an attacking sequence would likely develop, interception performance was significantly better on the second and third punch compared to the first punch within a sequence irrespective of whether a feint was present or not. Why, then, if the peripheral and central blur conditions encouraged participants to shift attention to different areas of the display (e.g., to the window of clear central vision in peripheral blur), did they exhibit a similar benefit from the presence of a foot feint preceding the first punch? To answer this question, it is relevant to note that unlike a real boxing match, where a feint is used by the attacking boxer to deceive the opponent, in the current study

2. Also, it is possible that the application of a Gaussian blur in peripheral vision could have disturbed participants' spatial orientation in the ring. For example, although the presence of blur is a complementary depth cue (Held et al., 2012; Langer & Siciliano, 2015), we did not apply a blur gradient that changed as a function of depth or in accord with the physiological optics of the retina (see Limballe et al., 2022).

the feints were always followed by one of four pre-determined sequences. Thus, although participants would not have known which type of punch (e.g., straight left, straight right) to expect following a foot feint, they would have known that the feint was followed by an attacking sequence. Accordingly, it can be expected that simply becoming aware of the foot feint movement provided participants with an additional cue to the sequence onset as it clearly showed a forward movement of the opponent, and that this was still possible in the presence of a peripheral blur. Conversely, an arm feint was not associated with a clear forward body movement and thus did not provide an unambiguous cue concerning sequence onset.

To better understand how participants oriented overt visual attention in the current study, we quantified how eye gaze was located across the entire block duration (i.e., including intervals between attacking sequences). We found that eye gaze was located within a relatively small 3D ellipse volume data in the control condition (43.1 cm^3), which increased significantly in the presence of a peripheral blur (67.9 cm^3) and central blur (68.6 cm^3). However, the effect of Viewing Condition was not evident when eye gaze data across the entire block duration was expressed with respect to AOIs. Of 16 possible AOIs, 95% of eye gaze data was located on the Head, Trunk and distal ends of the two arms. This confirms previous findings regarding the relatively concentrated location of overt attention to the upper body and head in French boxers (Ripoll et al., 1995) and karateka (A. M. Williams & Elliott, 1999). To determine more precisely how participants fixated eye gaze, we next analysed the number and duration of fixations during only the three punches of attacking sequences. For the number of fixations, there was a decrease from the first to second punch, and then again from the second to third punch for all punch sequences, although the effect was less pronounced for punch sequences that began with a foot feint. There was also a decrease in fixation duration from the first punch compared to the second and third punch in sequences that began with no feint or a foot feint. As suggested above, this different pattern of fixations on the first compared to second and third punch could have resulted from expert combat athletes being better able to anticipate an attacking sequence once it had begun. Despite there being no difference in number of fixations per se, fixation duration was longer in the peripheral viewing condition when faced with the strong compared to the light level of blur. No effect of blur level on fixation duration was evident in the central viewing condition, which resulted in similar fixation duration as the control condition. Subsidiary classification of fixations according to their individual

duration (50-150 ms - ambient fixation; >250 ms - focal fixation, see Negi and Mitra, 2020) indicated that participants exhibited fewer ambient and more focal fixations in the peripheral blur conditions (i.e., 1204 and 458), compared to central blur conditions (i.e., 1373 and 436). In addition, there were more ambient and fewer focal fixations (i.e., 423 and 136) in the light peripheral blur condition, compared to the strong peripheral blur condition (374 and 178). Based on the suggestion that focal fixations reflect the conscious perception of objects in central vision, it follows that the increase when faced with a strong level of blur in the peripheral viewing condition could be associated with the proposed shift towards processing high acuity, distracting information from the opponent's facial expression (Petri et al., 2019b).

The notion that focal fixations and ambient fixations are processed through different but complimentary neural pathways (e.g., ventral and dorsal; see Pannasch and Velichkovsky, 2009), provides an interesting avenue for future research on the impact of refractive blur in sport. Indeed, it was previously suggested by D. L. Mann et al., 2010b, that the resilience of interception performance to refractive blur (i.e., to the entire visual field) could be explained by a reliance on visual information processed in the dorsal pathway, which is sensitive to visual-spatial motion and thus less affected by a reduction in visual acuity. In future work, it will be relevant to conduct more detailed analysis of eye movements in dynamic sports task to better understand the distribution of ambient and focal fixations as a proxy to underlying neural processing. For example, while we were able to determine fixation number and duration using a dispersion-threshold algorithm, there were limitations in the spatial (1 deg) and temporal (60 Hz) resolution of the eye tracking technology within the HMD. This prevented us from precisely quantifying saccadic eye movements, and particularly those with small amplitude (e.g., < 2-3 deg), which tend to precede focal fixations. As eye tracking technology embedded within HMDs improves, it will be possible to determine more precisely how eye gaze is moved between AOIs (e.g., use of a visual pivot; Vater et al., 2019) and thus the underlying processes associated with improved performance.

In an effort to control and standardize the parameters of the VR task in the current study, we chose to evaluate participants' performance based on the effectiveness of intercepting three punches within an attacking sequence. This required the use of a chased parry, which in a combat situation is not commonly used by experts. More typically, an expert boxer will try to avoid being hit and will therefore favour partial or total dodging

rather than defending with the hands (Davis et al., 2015), such as with a chased parry. Moreover, in English boxing, expert behaviour consists of systematically leaving the opponent's punching axis and not staying within his punching distance. In our virtual task, the attacking opponent did not move back and forth, but instead pivoted to keep their punch axis oriented toward the participant. As a result, the participant had to adjust their distance from the opponent in order to create a punching distance that enabled them to achieve an interception of the opponent's attacking punch. To provide a standardized performance evaluation, we took the number of intercepted punches in the sequence into account. However, in combat, a boxer can voluntarily accept to receive one or two blows, can counterattack from the first or second blow of the sequence, or can go out of the axis as quickly as possible. In combination, then, our effort to maintain internal validity may have reduced the realistic nature of the combat scenario for experts. Although probably suitable for novices, in future work with experts it could be relevant to modify the virtual boxing task such that the attacking opponent only delivers a single punch instead of a sequence but requiring a more complex and typical response (e.g., avoid the blow and counterattack).

4.5 Conclusion

Combined, these data from an immersive and adaptive first-person VR setting contribute to our understanding of how gaze-contingent blur influences interception performance and eye gaze of combat sport athletes when faced with a sequence of attacking punches. Moreover, these are the first findings to highlight the potential for using VR to provide a controlled manipulation of the visual environment while at the same time preserving a normal perception-action coupling. In future work, it will be relevant to consider whether VR training with a gaze-contingent blur can facilitate learning and transfer to a real boxing situation.

STUDY 1B. VIRTUAL REALITY BOXING: GAZE-CONTINGENT MANIPULATION OF STIMULUS PROPERTIES USING BLUR, ON DIFFERENT SKILLS GROUPS.

5.1 Introduction

The initial study of an expert population (i.e., experts boxers and combat sports athletes), revealed some potential limitations of the task, which may have influenced the effect of the gaze-contingent blur manipulation on performance. In particular, the task may have imposed constraints that did not encourage behaviour that would normally be exhibited by an expert in a real boxing match. That said, aspects of the task were representative, with real attacking sequences (i.e., from digitising an expert boxer) presented in an immersive VR environment. To better understand the experts' response in the study 1a, and potentially how to adapt the VR task, it was decided to make an additional comparison with a novice group of participants (i.e., expert-novice paradigm often used in previous works on perceptual-cognitive skills). Also, the expert population investigated in the study 1a was divided into two different groups based on their specific expertise. Here, then, the effect of a gaze-contingent blur in peripheral vision or central vision was examined in groups of Olympic boxers, combat sports athletes and novices.

5.2 Materials and methods

5.2.1 Participants

Twenty-eight participants (9 female, 19 male) with a mean age of 28 years (± 9.6 years) completed the experiment. The novice group comprised 10 participants who did not practice combat sports (but could have had limited experience, such as during physical education lessons). The combat sport group comprised 9 athletes who practiced mixed martial arts and combat sports (French boxing, judo, qwan ki do, judo) and the boxer group were 9 experts in Olympic boxing. All athletes had at least two years of combat sports experience. Specifically, the combat sport athletes had an average experience of 12 (± 7) years, and the boxers an average experience of 7.8 (± 4) years. They performed at various levels from leisure to competitive and professional events (e.g., European championship). All participants were healthy, without injuries, and had normal or corrected-to-normal vision. They signed a written consent form and were free to withdraw from the experiment whenever they wanted. The experimental protocol was made in respect of the Declaration of Helsinki and accepted by the national ethical committee (CERSTAPS IRB00012476-2021-12-05-108).

5.2.2 Data analysis and statistics

The data from the 3 groups were processed as explained in study 1a (see 4.2.4). Accounting for the skill factor, the design was as follows: Feint Type (arm, foot, none), Viewing Condition (central, peripheral, control), Punch Number (1, 2, 3), Blur Level (1, 2, 3) and Skills group (novices, combat sport, boxers).

For performance and fixation data, a top-down strategy was used in which all fixed effects (e.g., main and interaction terms) and a random effect of intercept ($y = \text{Viewing condition} * \text{Feint Type} * \text{Punch Number} * \text{Blur Level} * \text{Skill} + (1 | \text{Participant})$) were first included. To analyse the global measures of gaze distribution, linear mixed effects modelling with an identity link function was also used with AOI, Viewing Condition and Skill as fixed effects for gaze location, and Viewing Condition and Skill as a fixed effect for 3D ellipse Volume. Each participant was initially modelled with a random intercept. The same iterative approach to removing fixed and random effects was used as described above.

5.3 Results

5.3.1 Performance data

The full model with a random intercept (AIC=6112.079; conditional $R^2=0.55$) indicated a main effect of Punch Number ($\chi^2(2)=641.8822$, $p<0.001$), Viewing Condition ($\chi^2(2)=23.8613$, $p<0.001$), Feint Type ($\chi^2(2)=62.3371$, $p<0.001$), as well as significant Punch Number by Feint Type interaction ($\chi^2(4)=87.7986$, $p<0.001$), Blur Level by Viewing Condition interaction ($\chi^2(4)=10.3721$, $p=0.03$), Punch Number by Skill interaction ($\chi^2(4)=28.6651$, $p<0.001$), Skill by Viewing Condition interaction ($\chi^2(4)=9.5799$, $p=0.04$) and a three way Punch Number by Feint Type by Skill interaction ($\chi^2(8)=21.9564$, $p=.0041$).

For the Viewing Condition effect and the nested Blur Level effect, Bonferroni-corrected pairwise comparisons indicated that performance in the central blur condition (overall 0.446) was significantly better for the medium level of Blur (0.463) compared to almost all levels of blur in the peripheral blur condition (see Figure 5.1, overall 0.397; light level: 0.415, $p=0.07$; medium level: 0.402, $p=.004$; strong level: 0.375, $p<0.001$) but not the control condition (0.429, $p=0.78$). The light level of central blur condition (0.447) was not different from light blur (0.415, $p=0.054$), medium blur (0.402, $p=0.13$) in peripheral condition nor control condition (0.429, $p=1.00$). Performance in the strongest level of central blur condition (0.429) was greater compared to the strongest level of peripheral blur ($p=.022$) but not from other levels of peripheral blur or control condition. The light blur in peripheral condition (0.415) and the medium blur (0.402) were not different from control viewing condition (0.429, both $p=1.00$) but the strongest peripheral blur (0.375) was significantly worse than the control condition ($p=.02$).

Bonferroni-corrected pairwise comparisons indicated that performance for the boxer group in the central blur condition (0.419) was better compared to the peripheral blur condition (0.333, $p<0.001$) but not the control condition (0.370, $p=1.00$, see Figure 5.2). The performance of the boxers did not differ to the other groups in any condition. Performance of the combat sport and novice groups did not differ as a function of Viewing Condition, and was similar for both groups (Combat sport, central blur: 0.470, control: 0.479, peripheral: 0.452; Novice, central blur: 0.450, control: 0.438, peripheral: 0.409).

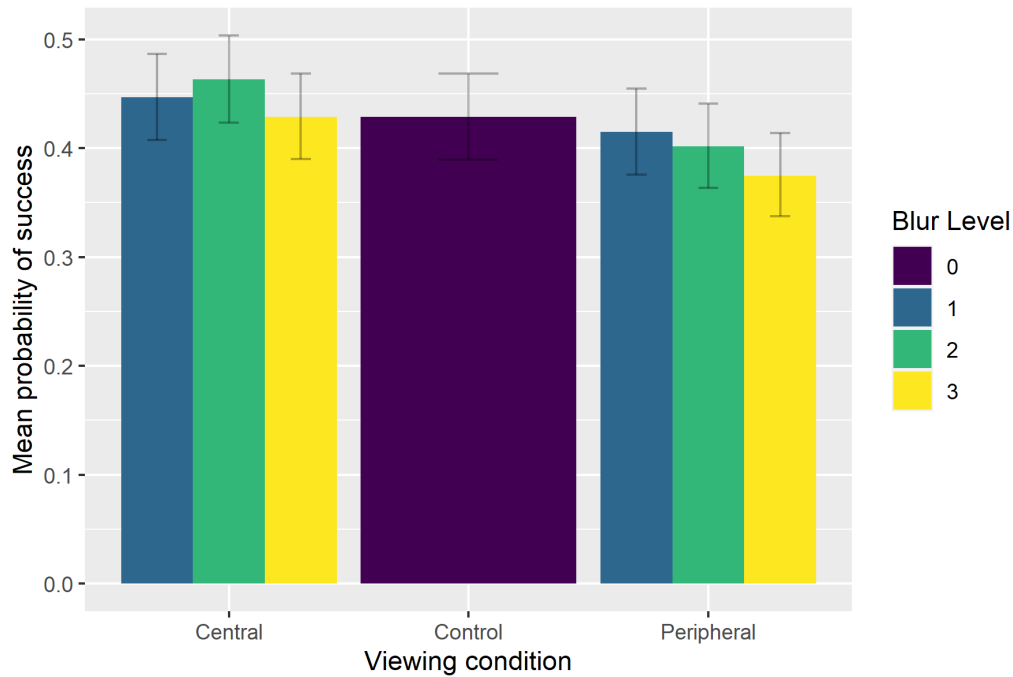


Figure 5.1 – Group mean probability of a successful interception as a function of Level of Blur and Viewing Condition.

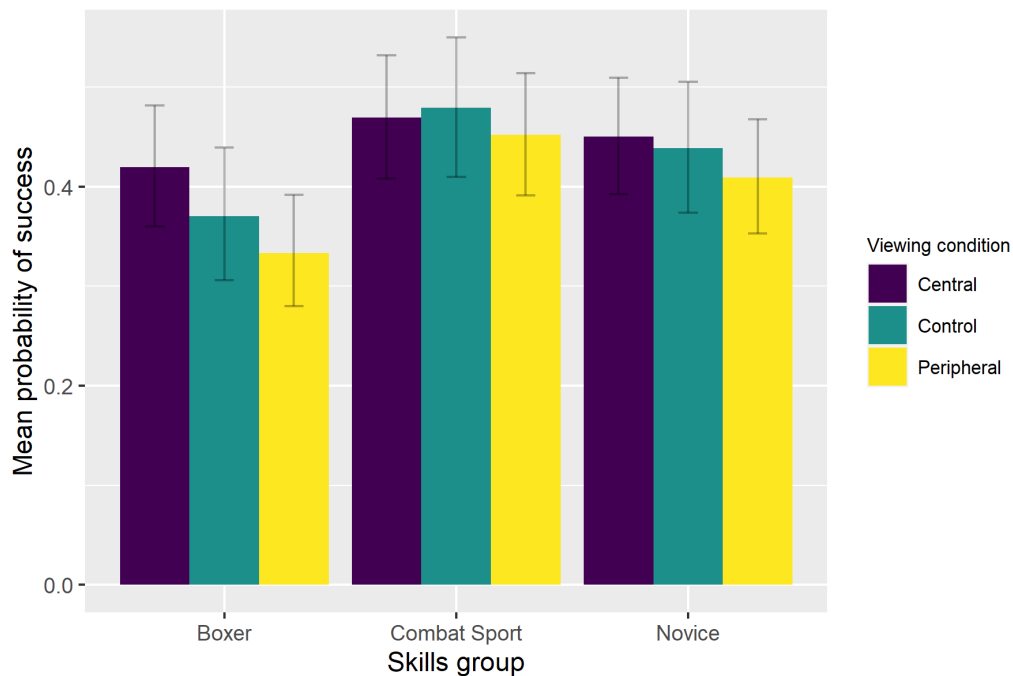


Figure 5.2 – Group mean probability of a successful interception as a function of Viewing Condition and Skill groups.

The first punch was better intercepted when it was preceded by a feet feint (0.368) compared to the first punch preceded by no feint (0.238, $p < 0.001$) or arm feint (0.218, $p < 0.001$) but this difference was not persistent for the second punch where the three Feint Type led to a similar percentage of success (0.499 for arm feint, 0.511 for feet feint and 0.507 for no feint, see Figure 5.3). For the third punch, the mean probability of success was similar for the arm feint (0.559) and the feet feint (0.555) but significantly lower for the sequences preceded by no feint (0.423, $p < 0.001$). For the sequences preceded by arm and feet feint, the mean probability of success significantly increased from the first to the second punch (all $p < 0.01$) and stay similar from the second to the third punch, whereas it was the case from the first (0.238) to the second punch of sequences without feint (0.507, $p < 0.001$), then decreased from the second to the third punch of the sequence without feint (0.423, $p = .002$).

Although there was a significant interaction between the Skill groups and Punch Number, Bonferroni-corrected pairwise comparisons indicated that all groups increased their probability of success from the first to the second punch of the sequence (all $p < 0.001$) but performance from the second to the third punch was similar.

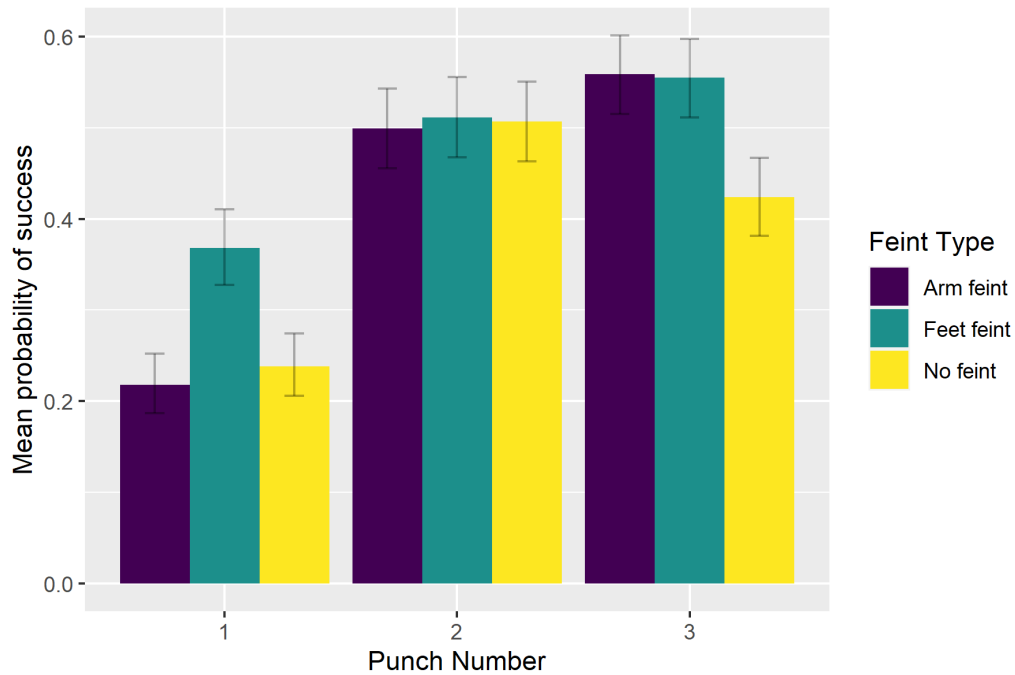


Figure 5.3 – Group mean probability of a successful interception as a function of Feint Type and Punch Number.

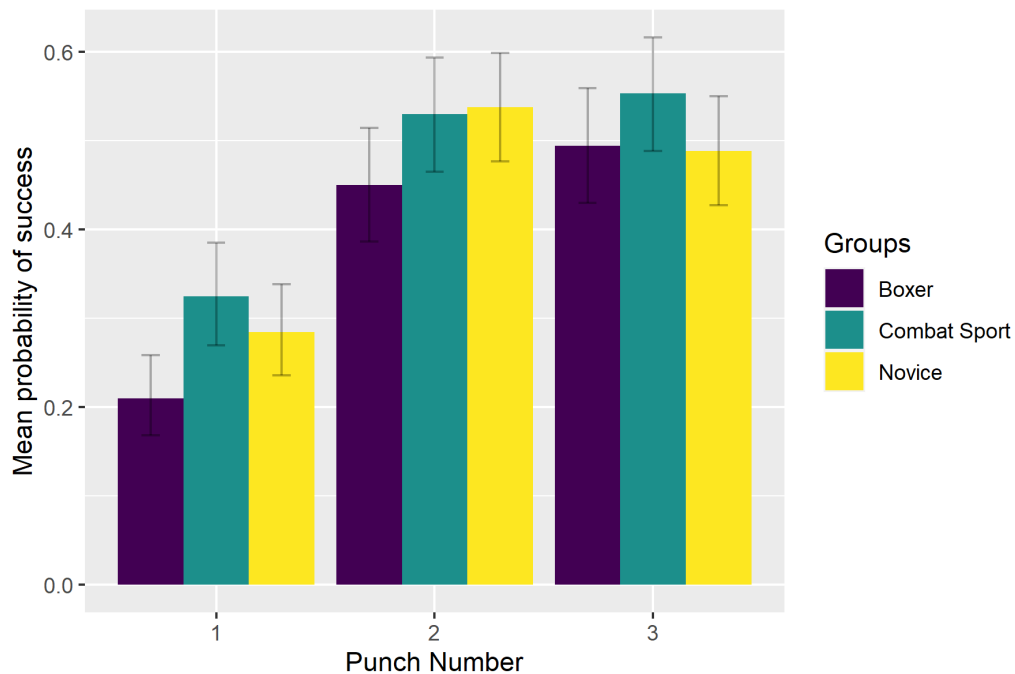


Figure 5.4 – Group mean probability of a successful interception as a function of Skill groups and Punch Number.

5.3.2 Eye gaze data

At a global level (i.e., across the entire block duration), having removed the non-significant Skill effect from the full model (AIC= 43.57; conditional $R^2= 0.87$), the reduced model (AIC= 19.92; conditional $R^2= 0.87$) indicated that the Viewing Condition made a significant contribution ($\chi^2(2)= 45.342$, $p<.0001$). Bonferroni pairwise comparisons indicated that the 3D ellipse Volume was smaller in the control condition (36.9 cm^3) compared to the peripheral blur (59.5 cm^3) and central blur (59.9 cm^3) conditions ($p<0.0001$).

Concerning the AOIs, the full fixed effects linear model (AIC=11052.71; conditional $R^2=0.76$) was reduced and the retained model (AIC=11181.29, conditional $R^2=0.77$) returned a significant main effect of AOI ($\chi^2(16) = 6030.1425$, $p<0.0001$) and an AOI and Skill interaction ($\chi^2(32) = 292.63$, $p<0.0001$). Observation of the estimated marginal means revealed that the majority of eye gaze within each trial was located within 6 of the 17 AOIs, which were mostly distributed on the Head, Trunk and distal ends of the two arms (see Figure 5.5).

More precisely, the major result was that boxers spent significantly more time looking at the trunk compared to other groups ($p<0.0001$). They also spent less time on the Head ($p=.003$) compared to novices, but not compared to combat sport athletes (see Figure 5.5). Novices spent an important percentage of time on the two fists, the head and the left forearm (front hand of the opponent) but spent less time on the trunk compared to the boxers.

Fixation count

Having removed non-significant effects found in the full model (AIC=7526.314; conditional $R^2=0.48$), the reduced model (AIC=7288.433, conditional $R^2=0.46$) returned a significant main effect of Punch Number ($\chi^2(2)=812.4118$, $p<.0001$), Feint Type ($\chi^2(2)=53.1443$, $p<.0001$), Skill ($\chi^2(2)=8.5768$, $p=.013$) and a significant interaction between Punch Number and Feint Type ($\chi^2(4)=76.0125$, $p<.0001$) and between Skill and Punch Number ($\chi^2(4)=10.9745$, $p=.026$). Bonferroni-corrected pairwise comparisons indicated that the number of fixations (see Figure 5.6) decreased from the first to second punch

($p < 0.001$), and then again from the second to third punch ($p < 0.05$) for punch sequences that began with either no feint (9.62, 5.83, 4.45) or a foot feint (8.84, 5.40, 3.66). For punch sequences that began with an arm feint, there was a small reduction similar ($p = 0.07$) in the number of fixations in the first (6.75) and second punch (6.17), followed by a significant decrease ($p < 0.0001$) from the second to third punch (4.18).

Regarding the interaction between Skill and Punch Number, significantly more fixations for all Skills group were observed on the first punch (8.39 for boxers, 6.52 for combat sport group, 7.99 for novices) compared to the second (5.42 for boxers, 3.91 for combat sport group, 5.20 for novices, all $p < 0.0001$) and the third (4.60 for boxers, $p = 0.0115$, 2.93 for combat sport group, $p < 0.0001$, 4.33 for novices, $p = .0014$). On the third punch, the combat sport group (2.93) made significantly less fixations than the boxer group (4.60, $p = 0.010$) and the novice group (4.33, $p = 0.048$).

Making more fixations on the first punch was also true when looking at the interaction effect with Feint type. The first punch of no feint sequences led to more fixations (8.94) compared to first punch of arm feint sequence (6.13, $p < 0.0001$) and the first punch of feet feint sequences (7.94, $p = 0.021$). Considering the second punch, arm feint sequences (5.09) and no feint sequences (5.05) led to more fixations than feet feint sequences (4.29, p respectively $p = .008$ and $p = .016$). For the third punch, there was no significant difference between arm feint sequence (4.01), feet feint sequences (3.51) and no feint condition (4.13). Still, there were a smaller number of fixations overall during the third punch of the sequence (3.88).

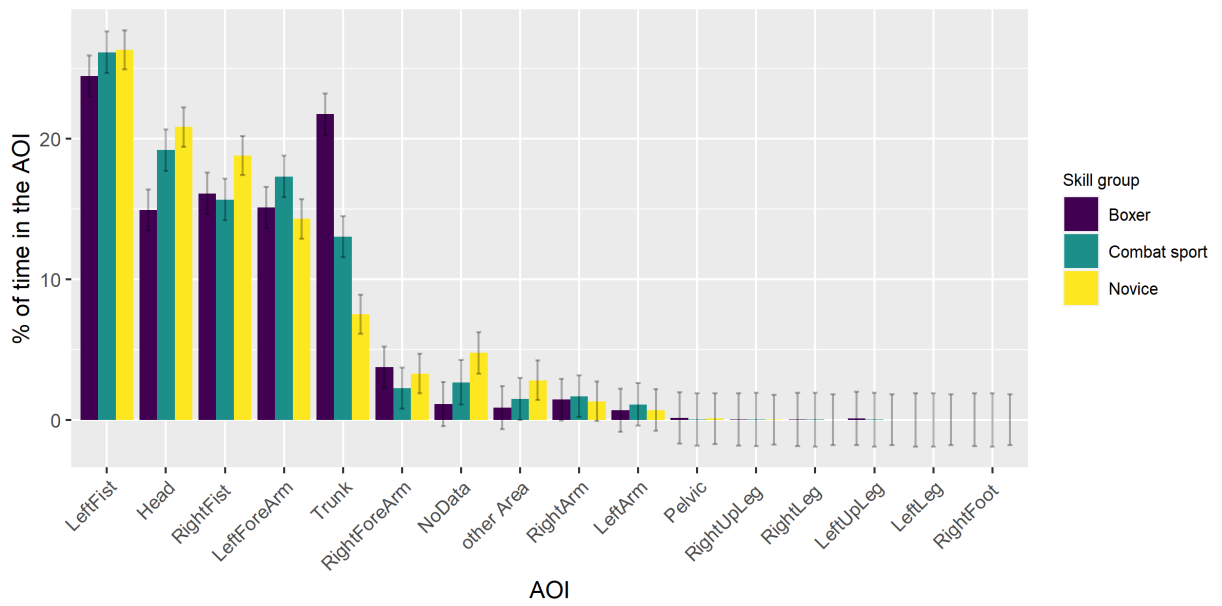


Figure 5.5 – Percentage of time that gaze was located in the AOIs as function of Skill groups.

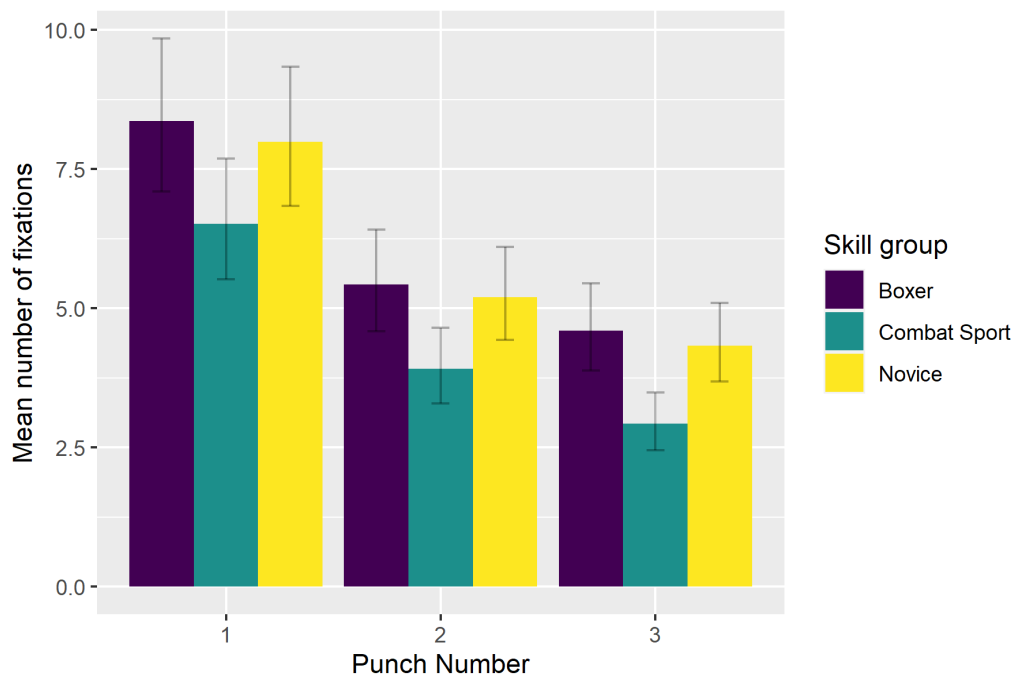


Figure 5.6 – Group mean number of fixations as a function of Punch Number and Feint Type.

Fixation duration

For fixation duration, the full model with intercept only (AIC=-5025.98, conditional $R^2=0.43$) indicated a significant main effect of Viewing Condition ($\chi^2(2)=18.4840$, $p<.001$), Punch Number ($\chi^2(2)=223.6448$, $p<.0001$), a significant interaction between Punch Number and Feint Type ($\chi^2(4)=26.8451$, $p<.001$), Feint Type and Skill ($\chi^2(4) =11.5073$, $p=.021$), as well as Punch Number and Skill ($\chi^2(4) =10.0198$, $p=.040$). The model revealed a 3-way interaction of Punch Number*Feint Type*Skill ($\chi^2(8)=18.3123$, $p=.019$), and 4-way interaction of Viewing Condition*Feint Type*Blur Level*Skill ($\chi^2(16)=29.2963$, $p=.022$), and Viewing Condition*Blur Level*Skill*Punch Number ($\chi^2(16)=26.8255$, $p=.043$). The reduced model removing the blur level effect did not indicate a better fit (AIC=-5803.269, conditional $R^2=0.40$).

Bonferroni-corrected pairwise comparisons indicated that fixation duration was significantly longer in the peripheral blur condition (0.176 s, $p<.001$) than the central blur condition (0.170 s, $p<.001$) and control condition (0.167 s), with fixation duration similar in control and central viewing condition (see Figure 5.8). Also, fixation duration was significantly longer on the first punch (0.190 s) of a sequence compared to the second (0.162 s, $p<.001$) and third (0.161 s, $p<.001$) punch of a sequence, irrespective of the Feint Type (see Figure 5.9). Fixation duration was similar for the first punch across Feint Type (0.188 s for arm feint, 0.193 s for feet feint and 0.189 s for no feint) but longer on the second punch for arm feint sequence (0.171 s) compared to feet feint (0.157 s, $p=0.021$) and no feint (0.158 s, $p=0.058$). The duration was again similar on the third punch (0.163 s for arm feint, 0.156 for feet feint and 0.164 s for no feint).

Boxers group tended to have longer fixation (0.185 s) than combat sport group (0.165 s) and novices (0.163 s). However, the Bonferroni-corrected pairwise comparisons did not indicate any significant differences in the Feint Type and Skill interaction. Similarly, the Bonferroni-corrected pairwise comparisons did not highlight major differences between groups for each number of punch.

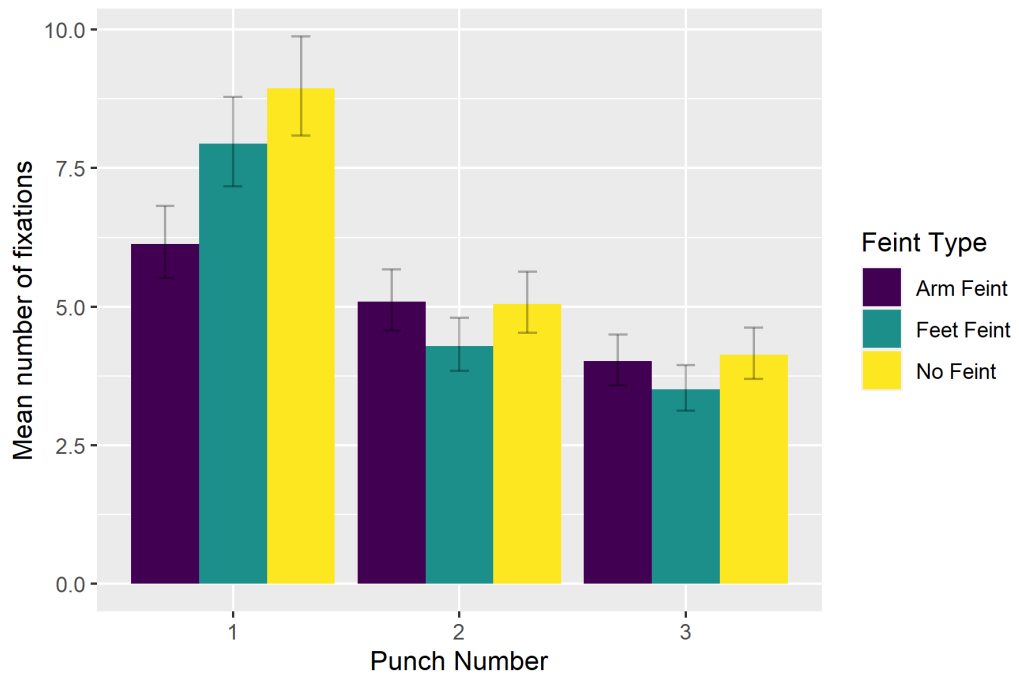


Figure 5.7 – Group mean number of fixations as a function of Punch Number and Skill group.

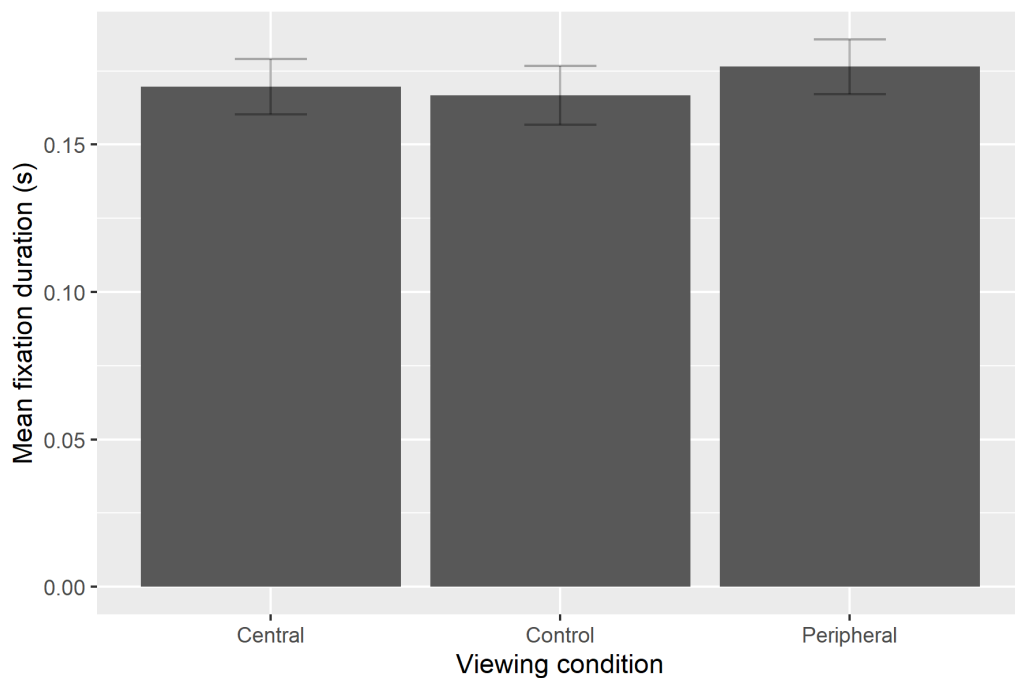


Figure 5.8 – Group mean fixation duration as a function of Viewing Condition.

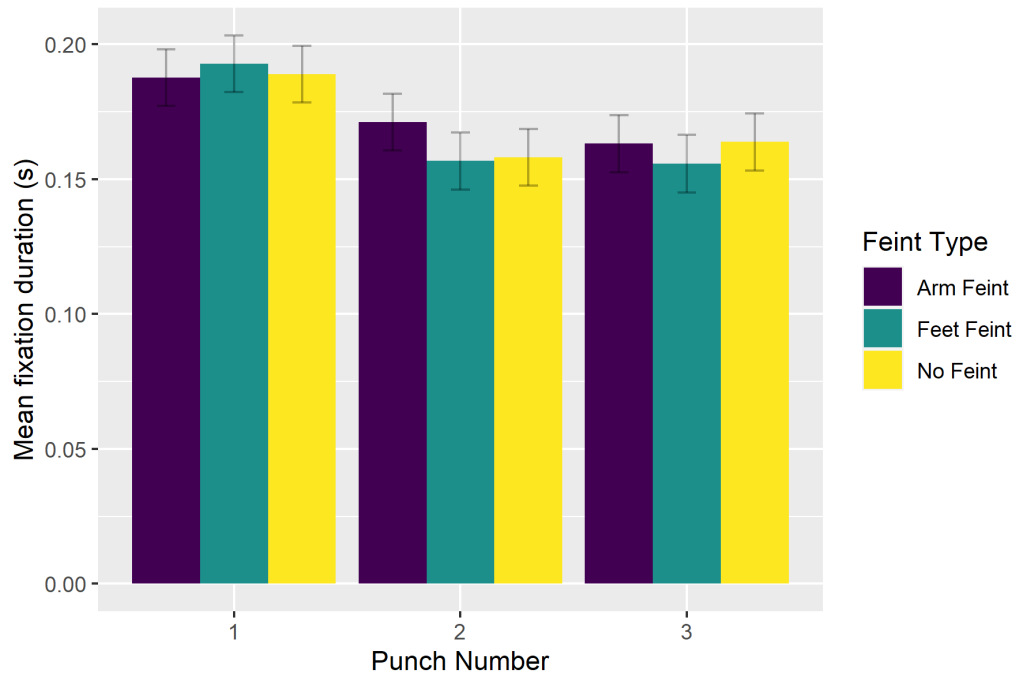


Figure 5.9 – Group mean fixation duration as a function of Punch Number and Feint Type.

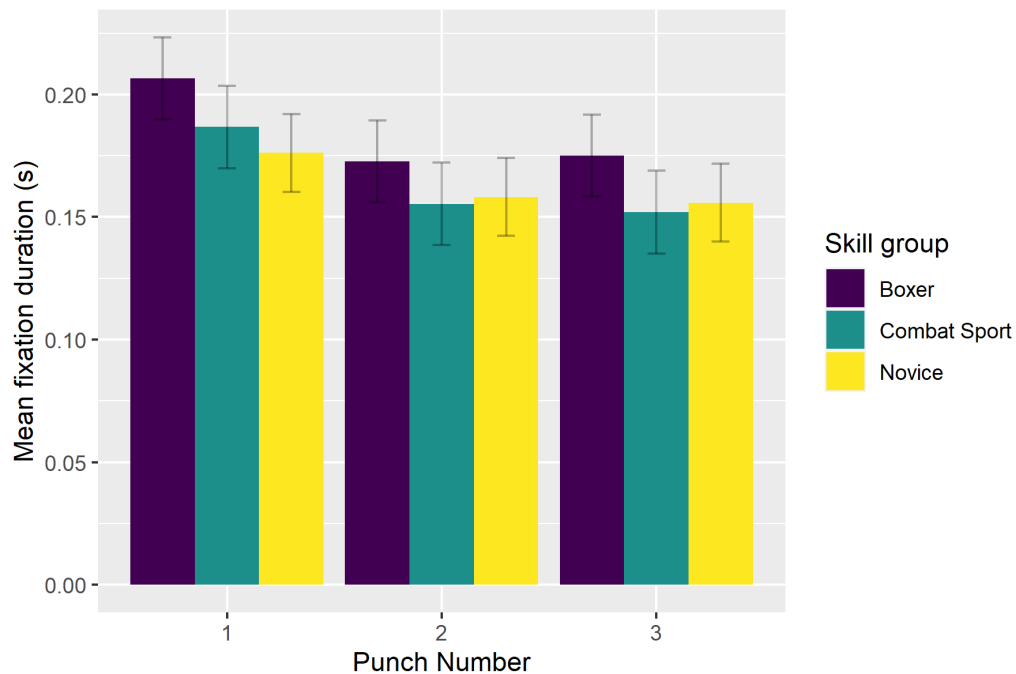


Figure 5.10 – Group mean fixation duration as a function of Punch Number and Skill groups.

5.4 Discussion

In extension to the first study on the effect of blur on anticipation performance of expert combat athletes in a VR boxing task, here an additional comparison was made between boxers, combat sport athletes and novice participants. The purpose was to gain more insight about the effect of blur depending on the level of expertise, as well as the potential limitations of the VR environment and the task.

It was found that there was an overall similar effect as study 1a of Punch Number, Feint type and the interaction between these two factors, on the performance and gaze data (number of fixation and mean duration). The results were also similar concerning the effect of the Viewing Condition on fixation duration, with a longer mean fixation duration in the peripheral condition compared to the central and control condition. The same effects were found for the total population of gaze location (i.e., the 3D ellipse containing 95% of the eye data). The introduction of a blur induced an increase 3D ellipse Volume of gaze location (to the same extent in the peripheral vision and central vision conditions) compared to the control condition.

Interestingly, there was a significant interaction between Viewing Condition and Blur Level. The main finding was a better performance observed in the central – medium blur level condition compared to peripheral (medium and strong blur) condition. The medium level of central blur was the condition where the best performance was observed (0.463 mean chance of success). This result is in line with the literature that has reported a facilitatory effect of the application of blur for perceptual and perceptual-motor tasks in novice populations (R. Jackson et al., 2009; D. L. Mann et al., 2010b; Ryu et al., 2018; van Biemen et al., 2018). Under a central blur (clear peripheral field of view), performance followed an inverted “U” shape similar to R. Jackson et al., 2009 (light blur: 0.447, medium blur: 0.463, strong blur: 0.429). It is possible that the medium level of blur could be a threshold, where we observed the maximum positive effect on performance when applied in central vision. The strong level may have been a cut-off threshold, where performance decreased and equalled the control condition. The increased performance with a medium blur in central vision could be explained by a reduction in high spatial frequency information, which could perturb and slow down information pick-up; for a similar explanation see R. Jackson et al., 2009; Petri et al., 2019b; Ryu et al., 2018. These authors suggested

the application of blur may have altered visual processing, with a greater use of the dorsal stream and peripheral vision. The current study also found that the introduction of blur in peripheral vision resulted in a deterioration in performance. The stronger the blur, the more performance decreased. Thus, it would seem that in the VR boxing task, a normal peripheral field of view was more important than clear central vision to maintain performance. Possible explanations for the impact of peripheral blur were discussed in study 1a. To recap, it could be that covert attention was drawn to the clear window of central vision when there was a peripheral blur, which resulted in greater reliance on distracting information. Notably, however, Ryu et al., 2015; Ryu et al., 2016, observed different results with novices, whose performance was improved more by a peripheral blur compared to a central blur. The positive effect of a medium central blur was not evident in the first analysis on experts' data (boxers and combat sport group) but was more present in the global population including novices. Although the 3-way interaction involving group was not significant, observation of the mean data indicated that the positive effect of the central blur was more pronounced in the boxers' group. At this stage, the positive influence of blur on performance in an immersive VR anticipation task is promising, particularly as it is the first such evidence in an expert population. However, this finding will need to be confirmed in additional experiments that facilitate the well-known expert advantage (see below for more details), and with less heterogeneous groups, before any firm conclusions can be drawn.

Given the expert advantage in tasks that depend on perceptual-cognitive expertise, it was instructive to observe that the lowest performance in the current study was exhibited by the expert boxers. Performance was in fact better for the novices than experts, but the combat sport group exhibited the best performance overall. These findings indicate that the VR boxing task did not enable expert boxers to demonstrate the normal sport-specific advantage. The use of VR, in this case, had probably revealed limitations concerning the task. On one side, novices possibly performed better than could have been expected. They were naïve about boxing, without specific motor patterns, strategy or experience of the pain caused by a punch. As such, the guard was not properly maintained in front of the head, which in a real task, would have been inappropriate and ineffective. In a real fight, they would have been knocked out quickly. Because these participants were unaware of the consequences of taking a punch, they moved in a way that although ineffective in a real boxing match, did produce a high performance when facing a chasing parry in the VR

environment. On the other side, the boxers and combat sport athletes kept their guard close, protected themselves and used movement and displacement representative to a real boxing situation. In addition to a realistic motor behaviour, observation of their gaze behaviour indicated similarities to experts' gaze described in the literature (Hausegger et al., 2019), with boxers making longer fixations, especially on the first punch of the sequence. Boxers also focused more their gaze on the trunk, which has been identified as a determinant AOI for performance of experts (Hausegger et al., 2019; Ripoll et al., 1995). That said, the task's constraints seemed to have led to an unexpected poor performance of boxers because it did not sufficiently represent boxing and resulted in the experts modifying their usual motor behaviour. In sum, this study has shown that a basic knowledge of boxing is necessary if participants are going to exhibit a normal boxing anticipation in a VR specific context. Having no haptic feedback is a strength of VR as it offers a safe practice environment but it may also be a weakness for the representativeness of boxing conditions and the potential to demonstrate expertise.

5.5 Conclusion

There was some evidence that a medium level of blur could improve performance (especially when blurring central vision), and potentially discriminate between other viewing conditions. However, this finding was evident in two successive analyses, where the chasing parry task may not have been representative of realistic boxing activity and the perceptual-motor skills involved. Also, it became clear that the lack of boxing knowledge in novice participants restricted their ability to have a realistic anticipation behaviour in a VR boxing specific context. To better understand the potential impact of blurring the visual surrounds, subsequent work should consider a modified VR boxing task that is more representative, and the use of homogeneous expert groups that have sport-specific expertise.

SECOND STUDY. ANTICIPATION PERFORMANCE IN VIRTUAL REALITY BOXING: IMPACT OF GAZE-CONTINGENT BLUR ON ELITE BOXERS.

6.1 Introduction

The first study demonstrated the possible use of an immersive and adaptative first-person VR to investigate the effect of blur on anticipation with expert boxers, combat sport athletes and novices. Yet, several potential limitations were highlighted in the task. Firstly, it became clear that some basic knowledge and experience in boxing are required if the aim is to observe a realistic behaviour. According to boxing rules, you must avoid to physically be touched by the opponent to win the fight. However, this haptic feeling is absent in VR, so the participants may not have realised they had been touched, hence explaining the lack of an expert advantage. In addition, the major threat that drives the behaviour in boxing is the fear to take a punch, which can result in severe pain or a knockout. This threat shapes the behaviour and how the boxer protects themselves with a guard and a defensive strategy. Experts are aware of this through experience but this is not the case for novices. Accordingly, novices tended not to exhibit a realistic boxing behaviour in the first study. Again, this may have contributed to the lack of an expert advantage. The implication is that the use of a defensive chasing parry task imposed constraints on novices and experts that may not have represented well a normal boxing experience.

A common behaviour observed during a real boxing match is to dodge or take a punch in the guard position (Davis et al., 2015). As a punch duration is typically shorter than

240 ms, and reaction time is similar (V. Bianco et al., 2017), being able to dodge an incoming punch means that early information, likely from the opponent's body kinematics before the onset of the punch, is key to anticipation skill. In addition, in both professional and Olympic boxing, the capacity to strike the opponent is judged (Romeas et al., 2022). That is, a boxer needs to avoid the punch from the opponent but also strike them to win at the end of the fight. For this reason, the requirement to counterattack after a dodging defensive gesture was introduced in this study to give a more suitable task to assess anticipation skill in boxing.

Taking into account the change in task requirement, and based on the findings of the first study, it was decided not to include a specific feint factor to give unwanted cues on the onset of the sequence. The number of punches in the sequences was also limited in order to better understand anticipation and early recognition of the opponent action. The first study showed that the success rate increased during the progression of the sequence, thus sequences of one and two punches were used for the second study. This ensured there was variability in the opponent behaviour that could not easily be predicted, which could have resulted in a ceiling effect. Here, then, based on the findings from study 1b, the effect of a medium level of blur on dodging and counterattack performance was examined during an immersive VR boxing task with elite boxers. Once again, it was expected the elite boxers' performance would be resilient to the presence of a gaze-contingent blur in central vision or peripheral vision as it does not disrupt the perception of motion-related information from the periphery. A possible small improvement of performance could be observed in the presence of a central blur.

6.2 Materials and methods

6.2.1 Participants

Eleven male participants with a mean age of 23 years (± 2.44 years) completed the experiment. They were elite athletes from French boxing federation, who competed at national to international level. All participants were healthy, without injuries, and had normal or corrected-to-normal vision. They signed a written consent form and were free to withdraw from the experiment at any time. The experimental protocol was made in

respect of the Declaration of Helsinki and accepted by the national ethical committee (CERSTAPS IRB00012476-2022-31-10-202).

6.2.2 Task and stimuli

The set-up was very similar and adapted from the first study. The VR environment was updated using a new version of Unity (v. 2020.3.29f1), which resulted in an avatar that had slightly different appearance to the avatar in first study, while keeping the same running structure. The delta time of the refreshing environment within the HMD apparatus (HTC Vive Eye Pro, see 4.2.2) was fixed at 0.011 s. The virtual boxing ring was of official size and matched the real ring in which participants did the experiment. Realism was increased by the inclusion of real ropes in the physical and virtual boxing rings. Participants were free to move within this ring but were also constrained by the ropes. A new motion capture (compared to the first study) was conducted on two high level boxers (one male, one female) to provide 3D coordinate data to animate the virtual opponent. The virtual opponent avatar was the same in the whole experiment; a male avatar whose proportions were not affected by the real two boxers' characteristics. The virtual opponent was resized according to the participant size in order to ensure that the view of the virtual opponent within the participant visual field was similar and that the virtual opponent launched punch to similar body target (head or body).

As previous, participants faced a virtual male boxer (see Figure 6.1) in the virtual boxing ring. The virtual boxer was initially shown in a guard position 1 m away from the participant and maintained a face-to-face orientation by rotating according to the participant's movement. In this experiment, the virtual opponent moved toward the participant and launched an attacking sequence when he was at punching distance. This distance was pre-determined and adapted for each sequence based on punch extension to make sure that every punch touched the participant if he didn't move. Participants started the round (i.e., a block of trials) when they were ready by punching the starting sphere in the scene (a red sphere located in front of them to trigger the onset of the block; then, the sphere disappeared).

The virtual opponent then launched successive attacks, comprising the 20 sequences (10 sequences of one punch and 10 of two punches) described below. Each participant com-



Figure 6.1 – Representation of the Viewing Conditions. (A) control, (B) central blur, (C) peripheral blur. VR user view. For emphasis, we have overlaid a red outline to the gaze-contingent window but this was not visible to participants.

pleted three blocks of 60 trials that were presented in a random-blocked order separated by a 2-minute break. Participants had to avoid the incoming punches by dodging and counterattacking to touch the virtual opponent with their virtual hand. Auditory feedback indicated to the participant if they had been touched and/or touched the opponent. A successful dodge scored 1 point, whereas a successful dodge followed by a successful counterattack scored 2 points. No other responses, such as throwing a punch before or too late after the attack, were allowed or scored. If the participant was touched by any punch in the sequence, it was considered as a failure and received a score of 0 points. After a sequence, the virtual opponent moved backward then started a new sequence as he was at punch distance.

Based on the findings of the first study, a specific feint factor at the onset of the sequence was not included as a factor. Instead, the sequence started with the opponent in an idle posture with arm movements (of various time length to minimize the familiarity) before he attacked with either one or two punches. These were 10 sequences of one punch (5 starting with left front hand, 5 with right back hand) and 10 sequences of two punches (4 starting with left front hand, 6 with right back hand, see description table 6.1). The 20 attacking sequences were presented 3 times per block in random order (60 trials per block). In each block, participants performed the virtual boxing task in one of 3 Viewing Conditions. In the control condition, participants were presented with normal vision of the opponent and surrounds. For the other two Viewing Conditions, a gaze-contingent blur manipulation was made relative to the point of fixation (for more detail see below

Sequence Number	Number of punches (Sequence Type)	Description
1	1	Left straight to the head
2	1	Right cross to the head
3	1	Right straight to the head
4	1	Left straight to the head
5	1	Left straight to the head
6	1	Right straight to the head
7	1	Left cross to the head
8	1	Left cross to the body
9	1	Right cross to the head
10	1	Right straight to the head
11	2	Left straight - right straight to the head
12	2	Left straight - left straight to the head
13	2	Right straight - right straight to the head
14	2	Left straight - right cross to the head
15	2	Right straight - left cross to the head
16	2	Right cross - left straight to the head
17	2	Left straight - right cross to the head
18	2	Right cross to the head - left cross to the body
19	2	Right cross to the body - left cross to the head
20	2	Right straight - left cross to the head (exit left)

Table 6.1 – Description of the attacking sequences.

and Figure 6.1), such that participants were presented with a peripheral blur or a central blur. In sum, the participants completed 180 trials, which took approximately 10 min in the virtual environment.

6.2.3 Gaze-contingent manipulation

The blur gaze-contingency manipulation was the same as the first study (see section 4.2.3). However, based on the first study results, only the medium level of blur ($\sigma = 500$, kernel size = 19) was used here in both the entire peripheral and central blocks of trials.

6.2.4 Data analysis

The distance between the user and the virtual opponent was calculated based on both head positions. The collider engine from Unity was used to detect a collision between a participant’s body and the opponent’s gloves (for dodging) and the participant’s hand and the opponent’s body (for counterattack). The *GazeFocusChanged* function in the *IGazeFocusable* interface from the software development kit’s application programming interface (SDK’s API) was used to determine the time a participant spent with their gaze in each AOI of the opponent. The time spent with gaze away from the opponent, or when gaze data was missing, were calculated a posteriori (Time in “other” AOI = total time of the block – sum of the time in every AOI on the virtual opponent). In sum, there were 17 AOI, with 16 AOI located on the virtual opponent and 1 AOI defined as “Other”. This method, similar to what was done in the first study, used a ray cast from the user’s gaze origin with a machine-learned selection algorithm to produce more accurate output (see Tobii XR, Tobii G2OM documentation¹). Global distribution of the gaze (i.e., the volume of a 3D ellipse containing 95% of the gaze data), as well as fixation data, were also extracted as per the first study. Here, fixation rate, rather than number of fixations, was calculated during only the attacking sequences in order to take into consideration the different length of the Sequence Type (i.e., mean number of fixations per sequence divided by the time of each sequence).

6.2.5 Statistics

The primary interest was to examine if participants’ performance, the average distance between the participant and opponent over the block and trial, and gaze fixation data was influenced by the inclusion of blur in the peripheral and central conditions compared to the control condition. To provide a greater level of sensitivity, any influence of blur was also considered across the length of the attacking sequence (Sequence Type: one punch sequence and two punch sequence). Accordingly, performance and fixation data were calculated from the response to 3 trials (3 repetitions of 20 sequences) at each unique combination of Sequence Type (1, 2) and Viewing Condition (central, peripheral, control).

To analyse this crossed design and also to take into account individual-participant variability in response to the different experimental manipulations, all data was anal-

1. <https://developer.tobii.com/xr/solutions/tobii-g2om/>

ysed using linear mixed effects modelling (lme4 and ordinal package in R). Performance data (ordinal multinomial data, ranked 0, 1 or 2 for each trial) were modelled using a cumulative link mixed model (*clmm* function from Ordinal package, v. 2022.11-16). A top-down strategy was used in which all fixed effects were first included (e.g., main and interaction terms), as well as a random effect of intercept and slope for Viewing Condition ($y = \text{Viewing Condition} * \text{Sequence Type} + (1 + \text{Viewing Condition} | \text{Participant})$). Fixed effects were sequentially removed based on their statistical significance determined using Wald Chi Squared tests (CAR package in R), and provisionally retained if they returned p-values of 0.1 or less. The reduced-effects model was compared to the full-effects model with conditional R^2 (MUMIn package) and AIC. It was also compared to a reduced model with the same fixed effects but only a random intercept. In the final reduced model, only fixed effects at $p \leq 0.05$ were deemed meaningful and further analysed using Bonferroni-corrected pairwise comparisons. To this end, the EMMEANS package was used to compare estimated marginal means, and thereby take account of the partially crossed design. The *rating.emmeans()* function (see RVAideMemoire, v. 0.9-81-2) was also used to get the probability of each rating score. Number of fixations (total number of fixations across 3 trials per combination of independent variables) were modelled according to a Poisson distribution with a log link function. Fixation duration (mean fixation duration across 3 trials per combination of independent variables) was modelled according to a normal distribution with an identity link function.

To analyse the global measures of gaze distribution, linear mixed effects modelling with an identity link function was also used but with AOI and Viewing Condition as fixed effects for gaze location, and Viewing Condition as a fixed effect for 3D ellipse Volume. Each participant was initially modelled with a random intercept and slope for Viewing Condition. The same iterative approach to removing fixed and random effects was used as described above.

6.3 Results

6.3.1 Performance data

Having removed non-significant effects found in the full model (AIC=3798.191; conditional $R^2=0.07$), the final reduced model (AIC=3795.597, conditional $R^2=0.066$) indi-

cated a main effect of Sequence Type ($\chi^2(1)=21.44$, $p\leq 0.0001$). Performance was better when participants faced sequences of one punch compared to sequences of two punches. The mean probability to be touched by the opponent was 0.500 for one punch sequences and increased to 0.656 for two punch sequences. The mean probabilities revealed that the number of dodging and counterattack responses was similar when facing one punch sequences (0.255 chance of dodging, 0.244 chance of counterattack response) but the number of counterattacks decreased more when facing a two punch sequences (0.145 chance of counterattack response) compared to the chance of dodging response (0.198) (see Figure 6.2).

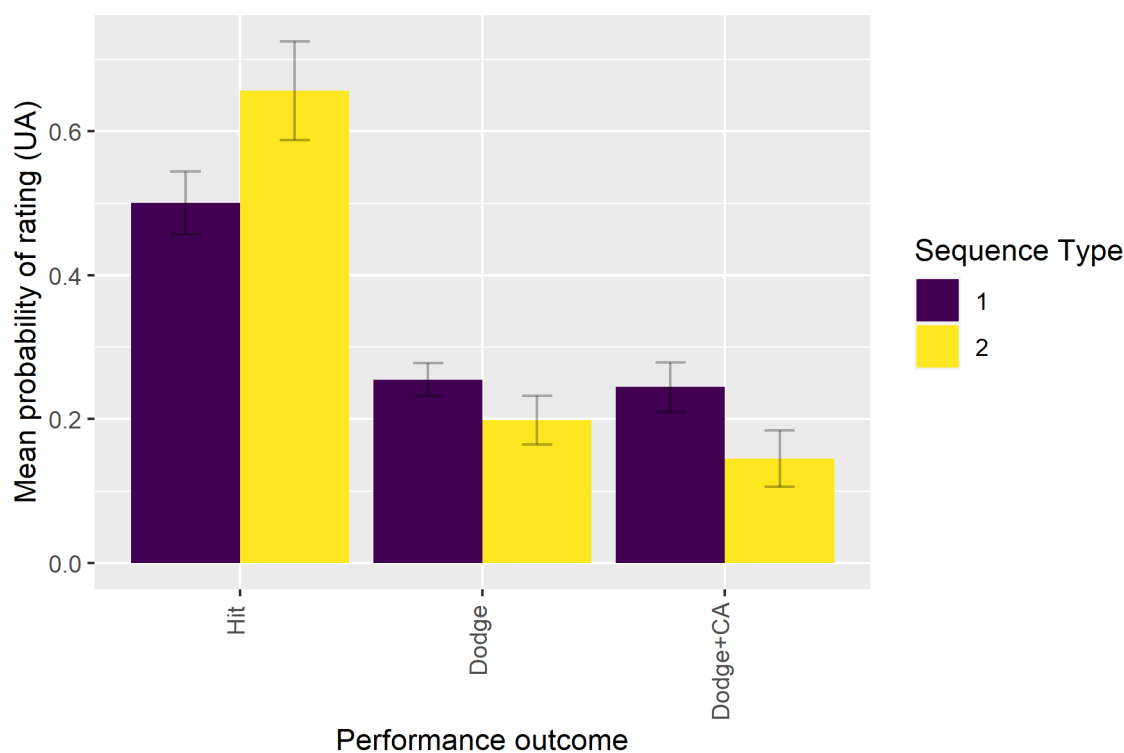


Figure 6.2 – Group mean probability of a performance outcome (hit, dodge, counterattack – CA) as a function of Sequence Type.

As predicted, there was no significant effect of Viewing Condition. In the central blur condition, the mean probability of dodging was 0.236 and 0.200 of CA (see Figure 6.3). In the peripheral condition, the mean probability of dodging was 0.222 and 0.177 of CA. In the control condition, the mean probability of dodging equalled 0.230 and 0.190 of CA.

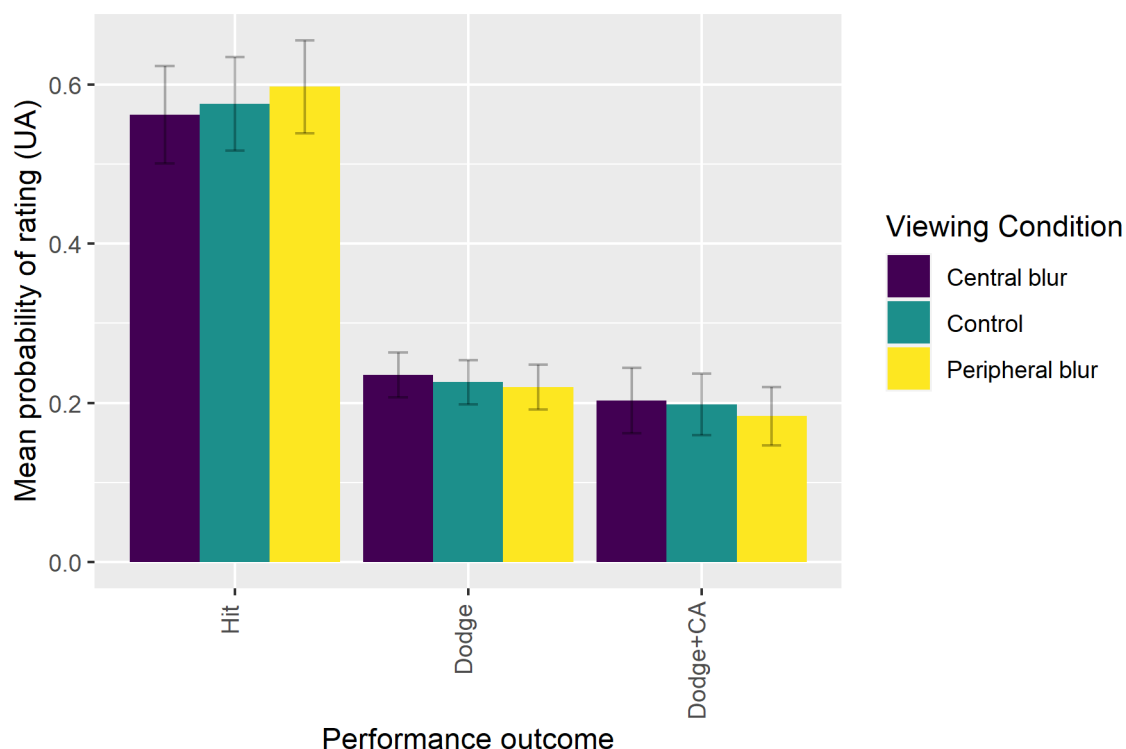


Figure 6.3 – Group mean probability of a performance outcome (hit, dodge, counterattack – CA) as a function of Viewing Condition. Nb: the means were taken from the full model.

To better understand if and how participants adapted their motor behaviour to the experimental manipulations, the distance between the participant and the opponent was investigated during the task. The full model including Viewing Condition as a random slope (AIC=-7.990, conditional $R^2=0.81$) indicated a significant interaction between Sequence Type and Viewing Condition ($\chi^2(2)=6.929$, $p=.03$). No main effect of Viewing Condition or Sequence Type were found. Bonferroni-corrected pairwise comparisons did not indicate significant differences between relevant comparisons. However, the participant-opponent distance tended to be smaller in peripheral blur condition, especially when facing two punch sequences (1.27 m), compared to control two punch (1.36 m) or central blur two punches (1.47 m). Overall, the mean distance was 1.36 m.

The correlation between the number of counterattacks per Viewing Condition and the participant-opponent distance did not reveal any significant correlation. The correlation coefficients were 0.034 in the control condition ($p=.877$), 0.241 in central blur condition ($p=.279$), and 0.381 in the peripheral blur condition ($p=.087$).

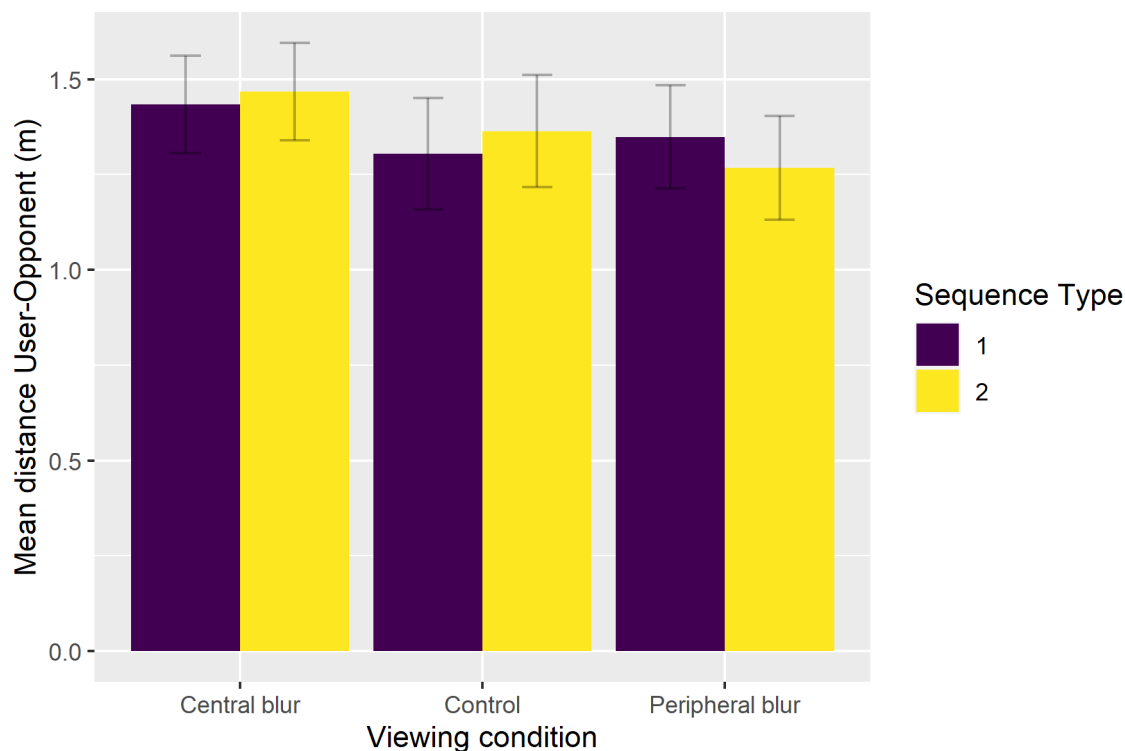


Figure 6.4 – Group mean distance participant-opponent as a function of Viewing Condition and Sequence Type.

6.3.2 Eye gaze data

At a global level (i.e., across the entire block duration), there was a significant main effect ($\chi^2= 7.254$, $p=.02$) of Viewing Condition (AIC= 36.935; conditional $R^2= 0.73$). Bonferroni-corrected pairwise comparisons did not indicate any significant differences. The 3D ellipse Volume was 96 cm^3 in the control condition, 96.5 cm^3 in the central blur condition and 121.8 cm^3 in the peripheral blur (respectively $p=.090$ and $p=.098$).

For the analysis of gaze location with respect to the AOIs over the block, the full effects model including a random slope for Viewing Condition (AIC= 2547.333; conditional $R^2=0.84$) did not differ from a reduced model with a random intercept (AIC=2537.333, conditional $R^2=0.84$) in which there was a significant main effect of AOI ($\chi^2(16) = 2442.404$, $p\leq 0.0001$), as well as a significant interaction AOI by Viewing Condition ($\chi^2(32) = 84.134$, $p\leq 0.0001$). Observation of the estimated marginal means collapsed across the 3 Viewing Conditions, the time spent on the left hand and the plexus was reduced in favour

of the head and areas outside the boxer in peripheral blur condition compared to the central blur and control conditions. Consistent with the increase of the 3D ellipse Volume, the location of the gaze outside the boxer increased in the peripheral condition (23.76%) compared to the control condition (14.72, $p=.0002$) and the central blur condition (13.58, $p\leq 0.0001$, see Figure 6.5).

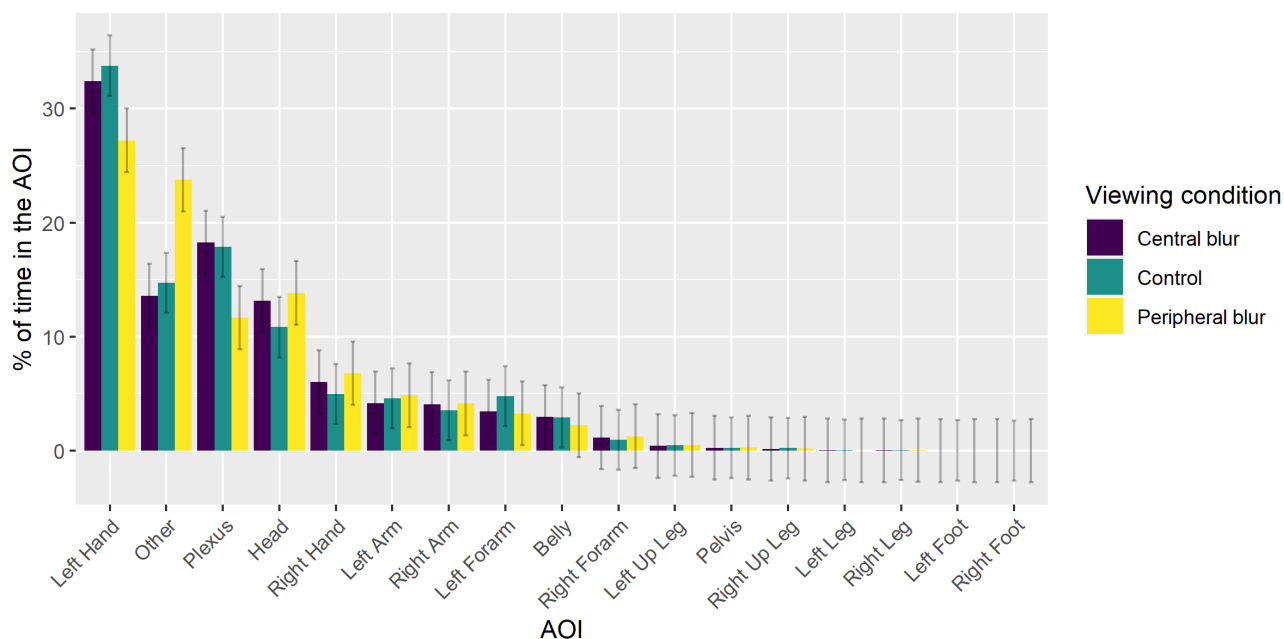


Figure 6.5 – Percentage of time that gaze was located in the AOIs in function of Viewing Condition.

Fixation data

Having removed non-significant effects found in the full model (AIC= 156.0865; conditional $R^2= 0.91$), the reduced model (AIC= 150.0821, conditional $R^2=0.91$) returned a significant main effect of Sequence Type ($\chi^2(1)=77.269$, $p\leq 0.0001$) and Viewing Condition ($\chi^2(2)=11.246$, $p=.003$) on the fixation rate. Bonferroni-corrected pairwise comparisons indicated that the fixation rate (see Figure 6.6) was greater when facing a central blur (5.14) compared to a peripheral blur (4.04, $p=.02$) but not different from the control condition (4.60). The pairwise comparisons also indicated that the fixation rate was greater when facing sequence of one punch (5.05) compared to sequence of two punches (4.14, $p\leq 0.0001$).

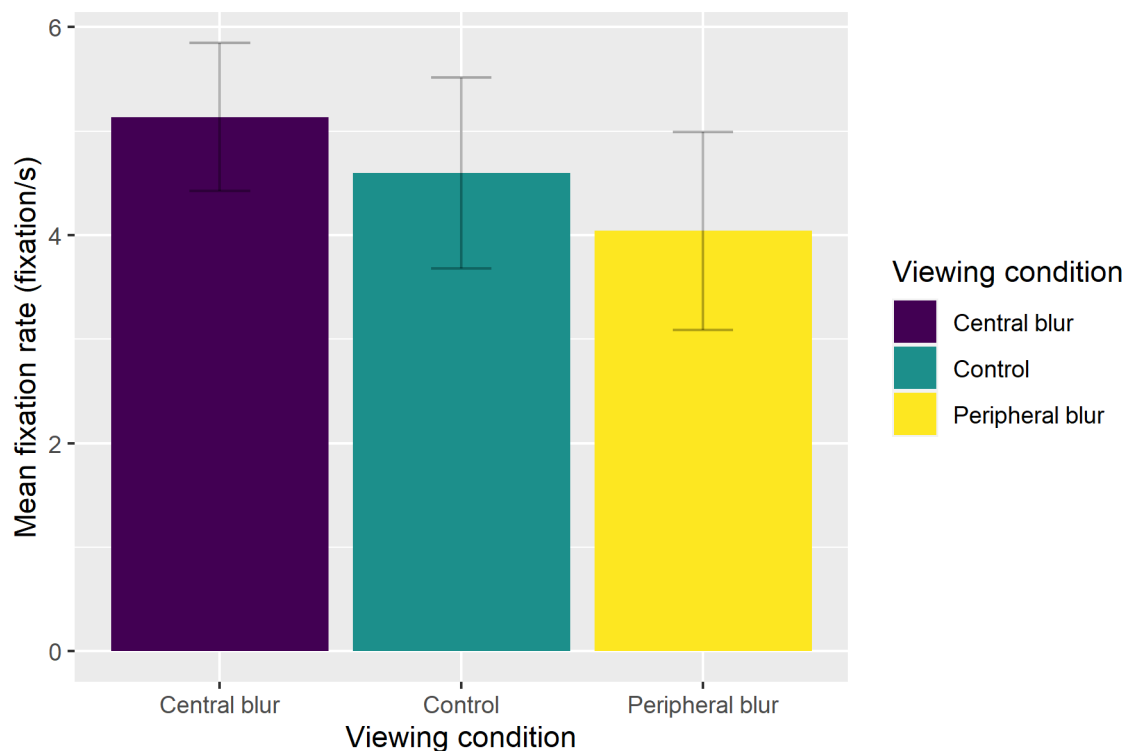


Figure 6.6 – Group mean fixations rate as a function of Viewing Condition.

For fixation duration, the full model (AIC= -311.348, conditional $R^2=0.65$) indicated no significant effect of any factors on the fixation duration. Overall, the mean fixation duration was 159 ms. Indeed, there was no difference between the full or any reduced model and the intercept-only model. Subsidiary classification of fixations according to their individual duration (50–150 ms—ambient fixation; ≥ 250 ms—focal fixation, see Negi and Mitra, 2020) indicated, in total, that participants exhibited fewer ambient and focal fixations in the peripheral blur conditions (969 ambient identified and 139 focal, ratio ambient/focal= 6.97. Mean ambient duration= $0.120 \text{ s} \pm 0.010$, mean focal duration= $0.321 \text{ s} \pm 0.07$), compared to central blur conditions (1,322 ambient and 205 focal, ratio ambient/focal= 6.44. Mean ambient duration= $0.119 \text{ s} \pm 0.014$, mean focal duration= $0.324 \text{ s} \pm 0.077$) and control condition (1,164 ambient and 177 focal, ratio ambient/focal= 6.57. Mean ambient duration= $0.118 \text{ s} \pm 0.014$, mean focal duration= $0.345 \text{ s} \pm 0.10$). Overall, the fixations were mainly ambient fixations.

A generalised linear mixed model applied to the number of ambient fixations confirmed the effect of the Viewing Condition as well as the Sequence Type effect. Having removed

the non-significant interaction effect found in the full model (AIC= 475.5477; conditional $R^2= 0.89$), the reduced model (AIC= 471.638, conditional $R^2=0.89$) returned a significant main effect of Sequence Type ($\chi^2(1) = 155.244$, $p \leq .0001$) and Viewing Condition ($\chi^2(2) = 11.356$, $p = .003$) on the number of ambient fixations. Bonferroni-corrected pairwise comparisons indicated that the mean number of ambient fixations per participant was higher in central blur condition (63.6) compared to the peripheral blur condition (44.7, $p = .002$). In the control condition, the mean number of ambient fixation (55.0) was higher compared to the peripheral condition ($p = 0.03$) but not different from the central condition ($p = 0.13$). The mean number of ambient fixations was also significantly higher when facing the two punch sequences (66.9) compared to the one punch sequences (43.4, $p \leq .0001$).

Concerning the mean number of focal fixations, the full model including random slope for Viewing Condition failed to converge. The reduced model with intercept only (AIC= 340.069, $R^2=0.73$) returned a significant main effect of Sequence Type ($\chi^2(1) = 23.94$, $p \leq .0001$) and Viewing Condition ($\chi^2(2) = 12.144$, $p = .002$) on the number of focal fixations. Bonferroni-corrected pairwise comparisons indicated that the mean number of focal fixations was higher in central blur condition (8.74) compared to the peripheral blur condition (6.13, $p = .004$). No other differences were present compared to the control condition (7.58). The mean number of focal fixations was also significantly higher when facing the two punch sequences (9.13) compared to the one punch sequences (6.00, $p \leq .0001$).

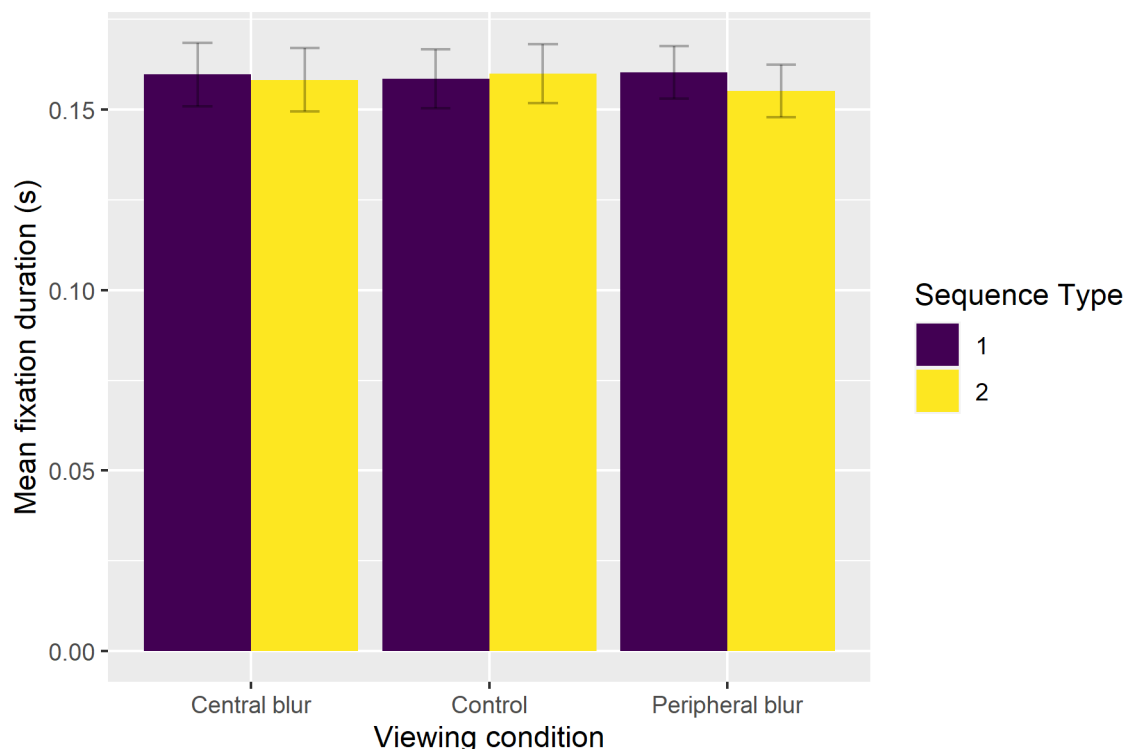


Figure 6.7 – Group mean fixation duration as a function of Viewing Condition and Sequence Type.

6.4 Discussion

This study was designed to improve upon several potential limitations identified in the first study, including the use of a chasing parry task, which although achievable by novices and experts alike, may not reflect the behaviour typically experienced in a boxing match. To better understand the effect of gaze-contingent central or peripheral blur on anticipation performance in a boxing task in elite athletes, the task was updated by asking participants to dodge and counterattack the thrown punch by the virtual opponent. Having made these changes, the positive effect of a central blur found in the first study or in R. Jackson et al., 2009; van Biemen et al., 2018, was not observed in this experiment. The Viewing Condition manipulation did not affect outcome performance, which was similar in the blur conditions compared to the control condition. Observation of the non-significant effect of Viewing Condition indicated that performance decreased slightly in peripheral condition, mainly when considering the counterattack response. Also, the dodging response was slightly better in the central blur condition compared to the control

condition. Overall, though, the finding with elite boxers in a realistic VR task is consistent with previous studies, which have reported that performance of experts was resilient to the presence of blur in basketball (Ryu et al., 2015), badminton (Ryu et al., 2018), cricket (D. L. Mann et al., 2010b) and football refereeing tasks (van Biemen et al., 2018).

Although the presence of blur in the current study did not significantly impact upon performance, there was a significant effect of Sequence Type. To reiterate, two types of sequence were presented, comprised of one or two punches. To be successful, all punches in the sequence needed to be avoided. Interestingly, the mean probability of dodging was similar when facing a one punch and two punch sequence. However, the probability of making a counterattack decreased more when facing two punch sequences compared to one punch sequences. This shows that, irrespective of the presence of blur, it was more difficult to punch the virtual opponent after avoiding two punches compared to one punch. It is possible that the elite boxers were able to anticipate the first punch using visual cues from the opponent's body before the onset of the punch, giving them time to avoid the punch and put themselves in the best situation to counterattack. That is, they were able to avoid a single punch while keeping a suitable distance between themselves and the opponent to make a successful counterattack. As one punch and two punch sequences were randomly played, there was uncertainty about the presence of a second punch.

To better understand how elite boxers maintained outcome performance, a measure of the evolving motor behaviour (participant-opponent distance) was analysed. This indicated there was a significant effect between Viewing Condition and Sequence Type, but post-hoc testing did not reveal any significant pairwise differences. Observation of the mean data showed that the greatest distance was observed in the central blur condition (1.45 m) compared to control (1.33 m) and peripheral blur (1.31 m) conditions. It was interesting to note that the smallest participant-opponent distance occurred in the peripheral blur condition when facing two punch sequences (1.27 m), and further that a small (and non-significant) decrease of CA probability was observed in this condition. It was also found that performance (number of successful counterattacks) and the participant-opponent distance were not significantly correlated. Observation of the correlation coefficients per Viewing Condition showed the strongest association was in the peripheral blur condition. The decrease of the counterattack probability could be, in part, explained by the decrease in this distance. In this sense, being too close to the opponent

does not give enough time and space to avoid the punches and counterattack. An optimal distance needs to be maintained and may depend on depth perception, which could have been impaired in the peripheral blur condition.

Eye gaze location across the entire block duration was investigated to understand how participants oriented overt visual attention. The 3D ellipse Volume increased significantly in the presence of a peripheral blur (121.8 cm^3) compared to the central blur and control condition's values (96.5 and 96 cm^3). This possibly suggests that the peripheral blur resulted in a broader visual search. This was confirmed by the analysis of eye gaze data across the entire block duration with respect to AOIs. In the peripheral blur condition, the time spent on the left hand and the plexus dropped in favour of the head and areas outside the boxer, compared to the central blur and control conditions. Consistent with the increase of the 3D ellipse Volume, the location of gaze outside the boxer increased in the peripheral blur condition (23.76%) compared to the control condition (14.72%) and the central blur condition (13.58%). In central blur and control conditions, the findings were in line with the relatively concentrated location of overt attention on upper body and head observed in French boxing (Ripoll et al., 1995) and karate (A. M. Williams & Elliott, 1999), as well as in the first study. To determine more precisely how participants fixated eye gaze, fixation rate and duration of fixations during only the attacking sequences was analysed. For fixation rate, there was a decrease in peripheral blur condition ($4.04 \text{ fixations.s}^{-1}$) compared to central blur ($5.14 \text{ fixations.s}^{-1}$) and control ($4.60 \text{ fixations.s}^{-1}$) conditions. Also, the fixation rate was greater when facing sequences of one punch ($5.05 \text{ fixations.s}^{-1}$) compared to sequences of two punches ($4.14 \text{ fixations.s}^{-1}$). No differences were found in the fixation duration, which was overall 159 ms. For the distribution of fixation duration according to the focal-ambient classification (Negi & Mitra, 2020), it was found that fixations were mainly ambient. Also, there were more ambient fixations in the central blur condition compared to the peripheral blur and the control conditions. However, the ambient/focal ratio was very similar between the three conditions, with the fixation rate being globally more important in the central blur condition. Associated with the fixation rate and performance regarding the Sequence Type effect, the more effective visual strategy seemed to be to use more fixations on the opponent of short duration. That is, a greater fixation rate could coincide with a better performance when facing a one punch vs two punch sequence. In addition, the findings for the 3D ellipse Volume and the time spent on the AOIs, seemed to indicate that eye gaze was more widely located in

peripheral blur condition. As well, participants exhibited a lower fixation rate, comprising of fewer ambient and focal fixations. They did not, however, exhibit a longer mean fixation duration. The decreased fixation rate could explain the subtle decrease of performance in peripheral blur condition as previous works stated that performance in many sports is associated with more and longer fixations compared to poorer performance (e.g. novices or less experts) (D. Mann et al., 2007; Romeas et al., 2022).

There have been a number of studies reporting that expert athletes make greater use of peripheral vision (Vater et al., 2019). One reason could be that peripheral vision is more sensitive to low-spatial and high temporal frequency visual input such as that related to moving stimuli, which is key to early anticipation. Accordingly, it could be expected that experts should not be affected by the application of a peripheral blur as this does not impact negatively upon the perception of movement information in peripheral vision. However, as observed in the first study of this thesis on experts (boxers and combat sports), there was evidence that a gaze-contingent peripheral blur tended to result in decreased performance. Yet, the elite boxer population in the current study maintained a similar level of performance, suggesting that elite boxers were unaffected by the peripheral blur and adapted their information pick-up to the available information. Decreased performance when faced with a peripheral blur could be explained by a covert shift of visual attention toward clear areas of the visual display (i.e., central vision), as suggested by (Enns & MacDonald, 2013; Ryu et al., 2015) and discussed in the study 1a. In this way, participant's covert visual attention in a peripheral blur condition could be drawn to highly detailed information like facial expression, which possibly acted as a distractor that impacted negatively upon performance (Petri et al., 2019b). Yet, this negative effect on performance was not evident in elite boxers, so little differences were observed. In a central blur condition, following the same logic, possible distracting information would not be present in central vision. Instead, participants could overtly attend to relevant information from the opponent such as fist and head movement, as well covertly attend to the peripheral visual field where other useful movement and depth-related information would be present. Moreover, it corroborated with an ambient mode of fixation suggesting a dorsal stream processing (Negi & Mitra, 2020; Pannasch & Velichkovsky, 2009), more sensitive to low frequency and visual-spatial information, and hence more resilient to blur. Nevertheless, as commented in the first study, it is possible that the application of the peripheral blur could have disturbed the participants' spatial orientation in the ring (see

footnote first study).

6.5 Conclusion

This study contributes to understanding of how a gaze-contingent blur impacts upon on dodging and counterattack performance, as well as eye gaze, during a realistic boxing task with an elite population, in an immersive and adaptive first-person VR setting. A realistic boxing behaviour was permitted by the use of a VR set-up, with a controlled manipulation of the visual environment while at the same time preserving a normal perception-action coupling. A resilience to the presence of blur was found in the elite population, suggesting a potential use of low spatial frequency motion information. Characteristics of eye gaze of expert behaviour such as more fixations on the important parts of the opponent's body (head, plexus, upper body extremities) could explain the maintenance of performance in the central blur condition. The peripheral blur led to a perturbation of the fixation rate and the time spent on major AOIs. In future work, it will be relevant to consider whether VR training with a gaze-contingent blur can facilitate learning and transfer to a real boxing situation.

THIRD STUDY. ANTICIPATION PERFORMANCE IN VIRTUAL REALITY BOXING: IMPACT OF LOCAL BLUR.

7.1 Introduction

A general resilience to the introduction of blur within the visual surrounds has been reported in previous studies on basketball (Ryu et al., 2015), badminton (Ryu et al., 2018), cricket (D. L. Mann et al., 2010b), and football refereeing (van Biemen et al., 2018). Notably, a positive effect of blur on performance has been reported with novice participants (R. Jackson et al., 2009; Ryu et al., 2015; Ryu et al., 2018). Thus, it would seem that the effect of blur on outcome performance is skill level dependent and likely related to the different information used by novices and experts. In study 1a of the current thesis, the limited negative effect of blur on outcome performance was confirmed in expert boxers and expert combat sports athletes performing an immersive, first-person perspective VR boxing task. A small but significant positive effect of a central blur was found in study 1b, which compared groups of expert boxers, combat sports expert and novice participants. It was suggested that the effect of blur depends on the task, which for novices and experts alike in the current thesis (i.e., a chasing parry) did not facilitate a typical response expected in a real boxing match. Having modified the task such that a counterattack was also required, the second study found that outcome performance of elite boxers was resilient to a gaze-contingent blur in central or peripheral vision. Although not significant, the elite boxers did exhibit their best performance in the central blur condition, and worse performance in the peripheral blur condition. In central blur condition, the gaze behaviour was similar to the control condition, with a slightly (but not significant) higher fixation rate. There was also evidence that the peripheral blur impacted upon eye gaze behaviour. Participants exhibited a lower fixation rate, comprising of fewer ambient and

focal fixations in the peripheral blur condition. Still, there were 6-7 times more ambient than focal fixations, which is suggestive of dorsal stream visual processing, and has been associated with increased sensitivity to low spatial frequency information in peripheral vision (D. L. Mann et al., 2010b; Negi & Mitra, 2020; Pannasch & Velichkovsky, 2009). Interestingly, eye gaze in the peripheral blur condition was located within a larger 3D ellipse Volume, due to greater percentage of the trial spent with eye gaze on the head and AOIs outside the opponent's body. Combined with evidence that the participant-opponent distance tended to decrease by a small amount, it was suggested the peripheral blur could have disrupted participants' depth perception and thus their spatial orientation in the ring. Accordingly, it could be that the adapted gaze location in the peripheral blur condition was an attempt by elite boxers to still perceive information from relevant AOIs, while also providing opportunity to perceive more reliable information on the opponent's location and spatial layout of the ring.

In normal vision, blur is a complementary depth cue (Held et al., 2012; Langer & Siciliano, 2015). It is known that VR can disrupt depth perception, often leading to cue conflict and cybersickness. The incorporation of depth of field and foveated rendering techniques are a solution to limit the disruption of depth perception (Held et al., 2012; Hussain et al., 2021). That is, artificial blur is applied to the visual stimuli to reconstruct the different physical depths relative to the focal point, determined using eye tracking technology. The applied blur is non-uniform, varying as a function of the different depths of visual stimuli, with a stronger blur indicating stimuli at greater depth. This approach involves the application of blur in accordance with the physiological properties of the retina (i.e., fovea, near periphery, mid-periphery, see Figure 1.3 in literature review, Hussain et al., 2021) and uses the “*circle of confusion*” concept from optical imaging (Hussain et al., 2021). Foveated rendering uses a different approach that is biased toward reducing processing load of image rendering in immersive VR environments. High acuity stimuli are visible near the user's point of fixation, whereas blurred stimuli are visible in the periphery. Fixed parameters such as the blur kernel and diameter of the blur circle are used, and are determined manually or imposed by the HMD manufacturer. In this way, foveated rendering does not provide a natural coupling (i.e., consistent with physiological properties of the retina) between the point of fixation and blur-related depth cues. However, depending on the diameter of the blur circle, it does provide a coarse indication that objects beyond the point of fixation are at a greater depth. Also, it may still offer

the opportunity for depth perception based on pictorial cues such as occlusion, size and perspective.

The approach used in the previous chapters of this thesis was similar to foveated rendering in the sense that it did not attempt to model blur in accord with depth-of-field and/or eccentricity from gaze location. Instead, a gaze-contingent protocol was used in which parameters of the blur (i.e., kernel and diameter) were manually determined based on previous research and pilot testing. In this way, a uniform blur was applied to central or peripheral vision contingent upon the evolving location of eye gaze. In the current chapter, the same VR boxing task was studied but now with blur applied on the opponent or the entire visual field surrounding the opponent. It was expected that youth elite boxers would be resilient to the presence of blur on the opponent as they should still have access to movement information (i.e., low spatial frequency) and depth. Conversely, in the environment blur condition, a shallow depth of field in which the opponent is in focus (clear), could disrupt depth perception and orientation on the ring by altering the pictorial and blur depth cues from the background. This misperception could affect distance to the opponent and eye gaze behaviour.

7.2 Participants

Thirteen participants (one female, 12 males) with a mean age of 16 years (± 1.19 years) completed the experiment. They were youth elite athletes from French boxing federation, who competed at youth levels from national to international. All participants were healthy, without injuries, and had normal or corrected-to-normal vision. The experiment was included in the athletes' training program by the coach, the French federal structure and is part of the agreement between the parents and the federation. The participants were free to withdraw at any moment. The experimental protocol was made in respect of the Declaration of Helsinki, under responsibility of the federal structure and accepted by the national ethical committee (CERSTAPS IRB00012476-2022-31-10-202).

7.3 Materials and methods

The implementation of the third study was modelled on the same design as in the second study, except that a medium level of blur ($\sigma = 500$, kernel size = 19) was applied to a different location (see Figure 7.1). Specifically, blur was applied only to the virtual opponent's body (boxer blur condition) or the environment surrounding the virtual opponent (environment blur condition); there was also a control condition without blur. The Gaussian blur applied was not contingent on the participant's gaze location. Accordingly, the task and stimuli, data analysis and statistics were identical to that of the second study (see part 6.2), but with central and peripheral blur Viewing Condition replaced by boxer and environment blur conditions.

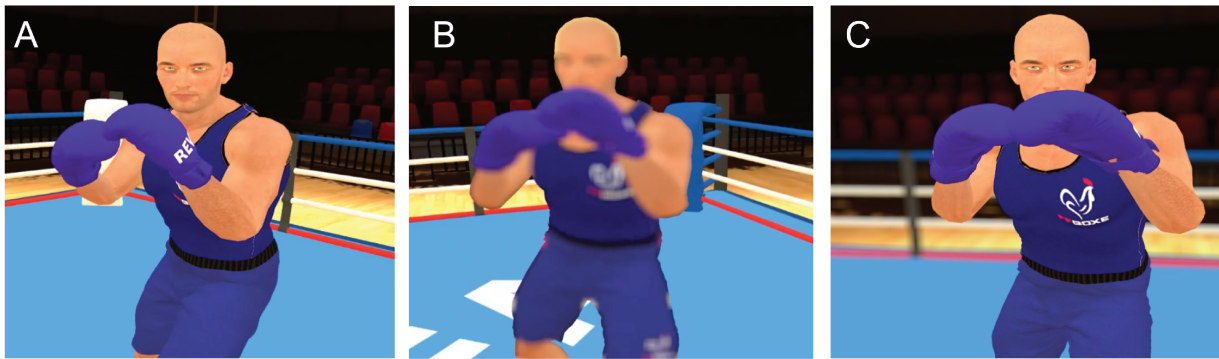


Figure 7.1 – Representation of the Viewing Conditions. (A) control, (B) boxer blur, (C) environment blur. VR user view.

7.4 Results

7.4.1 Performance data

The full model (AIC=5059.204; conditional $R^2=0.058$) indicated a main effect of Sequence Type ($\chi^2(1) = 24.5884$, $p \leq .0001$) and a close to significant Sequence Type by Viewing Condition interaction ($\chi^2(2)=5.8089$, $p=.054$). Performance was better when facing sequences of one punch compared to sequences of two punches ($p \leq .0001$). The mean probability to be touched by the opponent (i.e. to fail) was 0.310 for one punch sequences and increased to 0.397 for two punch sequences. The mean probabilities revealed that the number of dodges and counterattacks stayed similar when facing one

punch sequences (0.305 chance of dodging, 0.384 chance of counterattack response) but the number of counterattacks decreased more when facing two punch sequences (0.298 chance of counterattack response) compared to the chance of a dodge response (0.303) (see Figure 7.2).

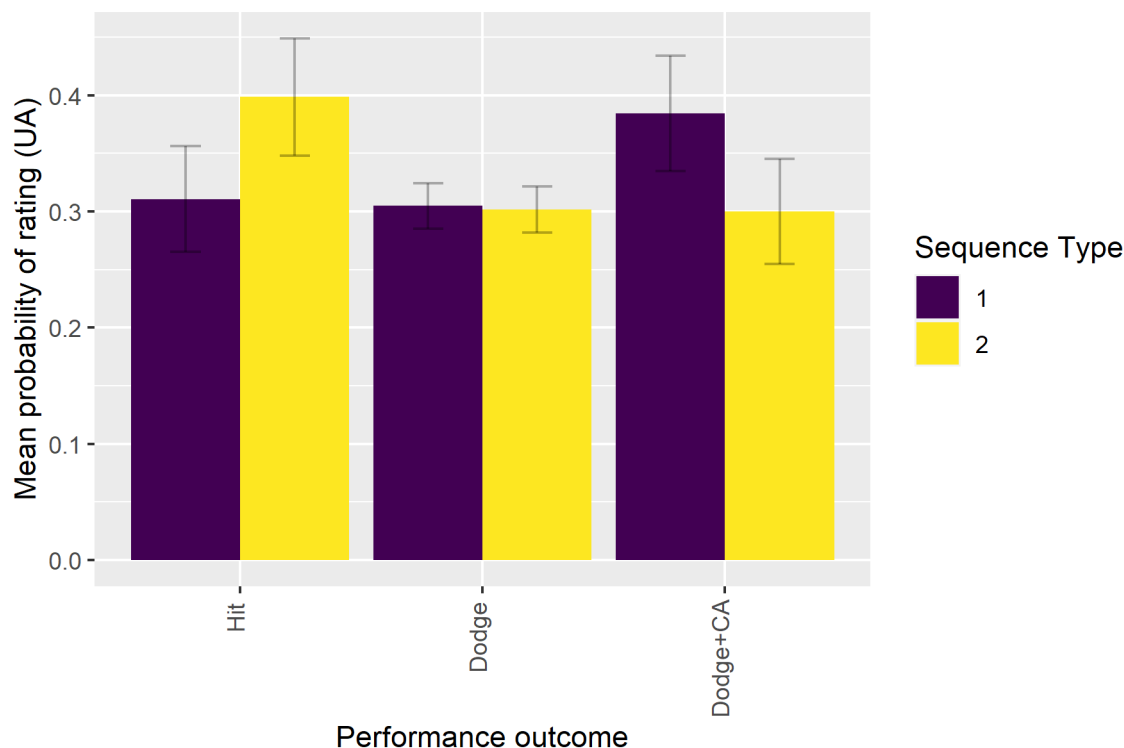


Figure 7.2 – Group mean probability of a performance outcome (hit, dodge, counterattack – CA) as a function of Sequence Type

Bonferroni-corrected pairwise comparisons did not indicate other significant differences in the close to significant interaction between Viewing Condition and Sequence Type. However, it is interesting to note that the probabilities of a dodging response were consistent across all the Viewing Conditions for level of Sequence Type, whereas the counterattack response probabilities were lowest when facing two punch sequences in the boxer blur condition (0.250 chance of CA response in boxer blur, compared to 0.319 in environment and 0.329 in control, see figure 7.3). Also, the probabilities of being hit were highest when facing two punch sequences in the boxer blur condition (0.456 chance of being hit in two punches boxer blur, compared to 0.375 in two punches environment blur and 0.364 in two punches control conditions, see Figure 7.3).

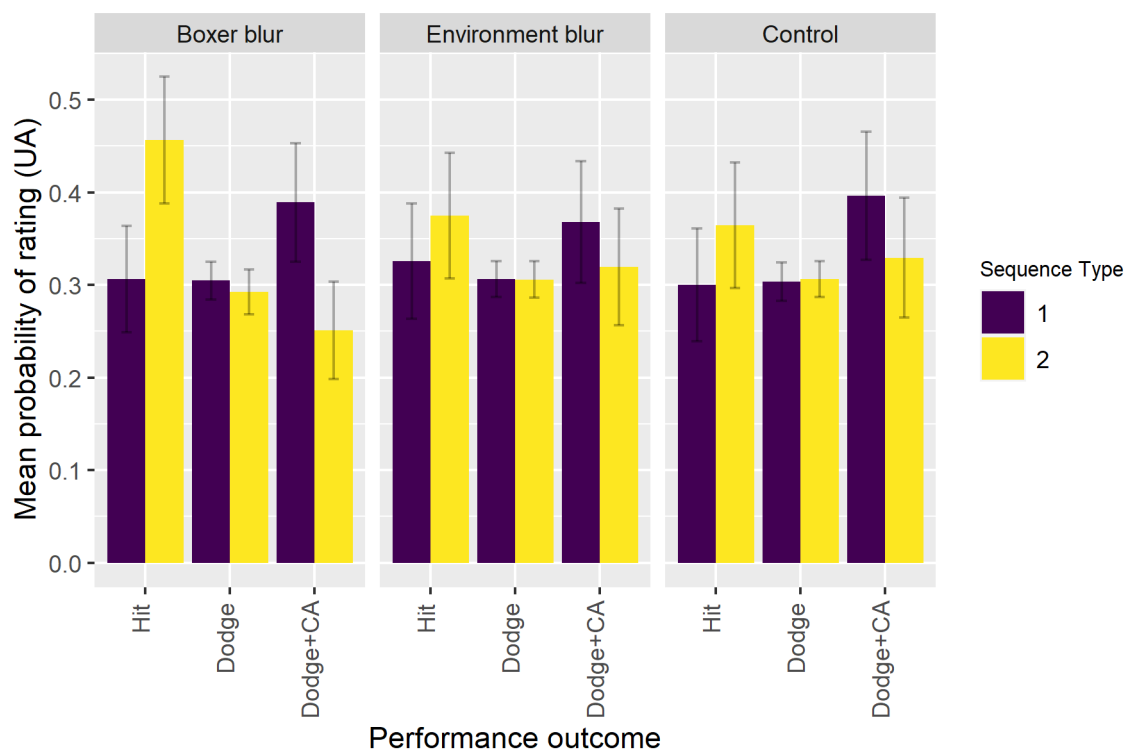


Figure 7.3 – Group mean probability of a performance outcome (hit, dodge, counterattack – CA) as a function of Sequence Type and Viewing Condition

For the distance between the participant and the opponent, the full model (AIC=25.784, conditional $R^2=0.92$) did not indicate any significant main or interaction effects, although the main effect of Sequence Type was approaching significance ($\chi^2(1) = 5.8089$, $p=.059$). The reduced model with a random intercept but no random slope indicated a worse fit (AIC=77.828, conditional $R^2=0.33$). The reduced model (AIC=6.128, conditional $R^2=0.89$) including only the Sequence Type effect and random slopes for Viewing Condition did not return a significant main effect of Sequence Type ($\chi^2(1)=3.6479$, $p=.056$). Although non-significant, the participant-opponent distance tended to be smaller in boxer blur condition (1.44 m) and environment blur condition (1.42 m) compared to control condition (1.55 m). The mean distance participant-opponent when facing one punch sequences equalled 1.45 m whereas the mean distance was 1.49 m when facing two punch sequences. Overall, the mean distance was 1.47 m.

The correlation between performance score per Viewing Condition and the participant-

opponent distance did not reveal any significant correlation in any Viewing Condition. In the control condition, the coefficient correlation equal -0.165 ($p=.24$), it was -0.130 in boxer blur condition ($p=.35$) and the coefficient was greater in environment condition 0.168 ($p=.23$).

7.4.2 Eye gaze data

At a global level (i.e., across the entire block duration), a model with a fixed effect of Viewing Condition (AIC=42.594; conditional $R^2=0.67$) indicated a significant main effect ($\chi^2=11.748$, $p=.002$). Bonferroni-corrected pairwise comparisons indicated that the 3D ellipse Volume was smaller in the control condition (88.8 cm^3) compared to the boxer blur (129.8 cm^3 , $p=.015$) and the environment blur condition (123.4 cm^3 , $p=.04$).

Concerning the analysis of gaze location with respect to the AOIs within each trial, the full effects model (AIC= 2904.519; conditional $R^2=0.82$) did not differ from the reduced model (AIC= 2894.519, conditional $R^2=0.82$) in which there was a significant main effect of AOI ($\chi^2(16) = 2349.035$, $p\leq 0.0001$), as well as a significant interaction between AOI and Viewing Condition ($\chi^2(32) = 89.042$, $p\leq 0.0001$). Observation of the estimated marginal means revealed the eye gaze within each trial was located a majority of the time within 6 of the 17 AOIs, which were mostly distributed on the Head (20.05%), the plexus (7.96) and distal ends of the two arms (left hand, 21.53%; left arm 2.67, left forearm 1.87%, right hand 5.99%). A larger percentage of time (33.89%) was also spent with eye gaze away from the virtual opponent (Other, see Figure 7.4). In the boxer and environment conditions, the time spent on the left hand, the plexus and the head dropped in favour of the areas outside the boxer, compared to the control condition. Consistent with the smallest volume of the 3D ellipse Volume observed in control condition, the location of the gaze outside the boxer increased in the environment blur condition (36.38%) and the boxer blur condition (40.46%) compared to the control condition (24.84%, both $p\leq 0.0001$).

Fixation data

The full model (AIC= 152.3198; conditional $R^2= 0.86$) returned a significant main effect of Sequence Type ($\chi^2(1) = 21.9296$, $p\leq 0.0001$) and a close to significant inter-

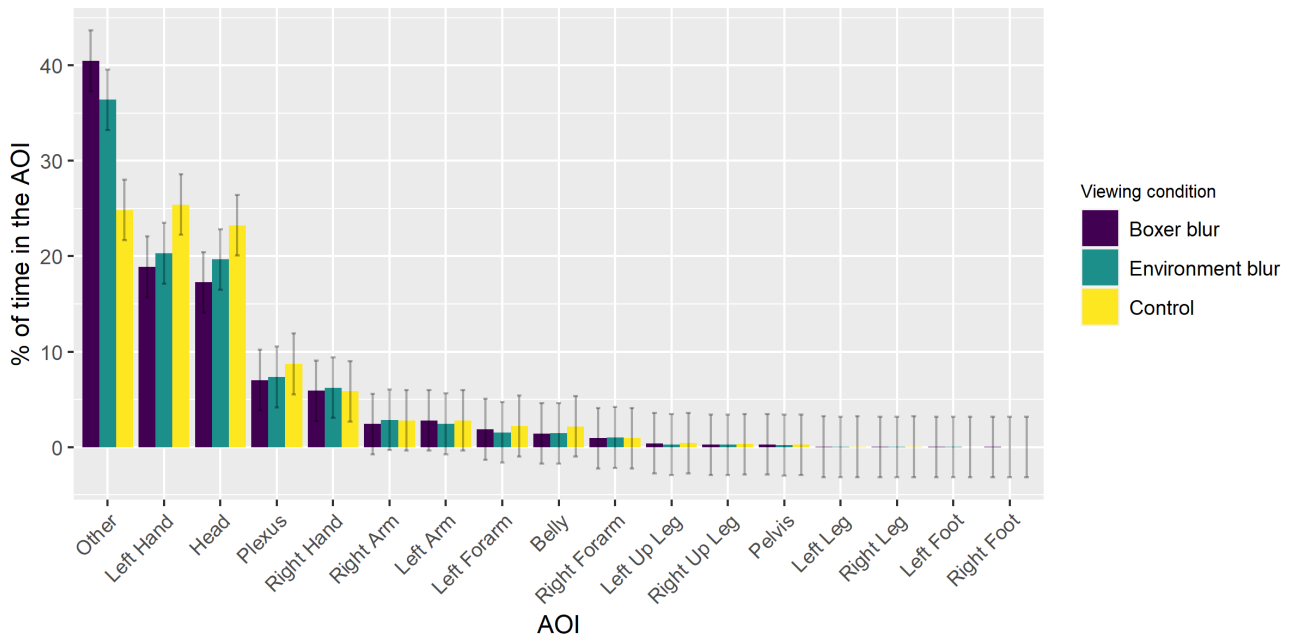


Figure 7.4 – Percentage of time that gaze was located in the AOIs in function of Viewing Condition.

action between Viewing Condition and Sequence Type ($\chi^2(2)=5.6699$, $p=.058$) on the fixation rate. Bonferroni-corrected pairwise comparisons indicated that the fixation rate was greater when facing a sequence of one punch (3.60) compared to sequence of two punches (3.09). The interaction between Viewing Condition and Sequence Type was not significant but the fixation rate tended to be lower in blurred conditions (see Figure 7.5), especially in the boxer blur condition with sequences of two punches (lowest fixation rate, 2.83 compared to 3.38 in two punch sequences control condition).

For fixation duration, the full model ($AIC=-280.1056$, conditional $R^2=0.78$) indicated no significant effect of any factors. Overall, the mean fixation duration was 160 ms. A close to significant main effect of Sequence Type ($\chi^2(1) = 3.501$, $p=.061$) was returned, with fixation duration being a bit shorter in one punch sequences (158 ms) compared to two punches sequences (162 ms, $p=.072$).

Subsidiary classification of fixations according to their individual duration (50–150 ms—ambient fixation; ≥ 250 ms—focal fixation, see Negi and Mitra, 2020) indicated that, in total, participants exhibited fewer ambient and more focal fixations in the environment

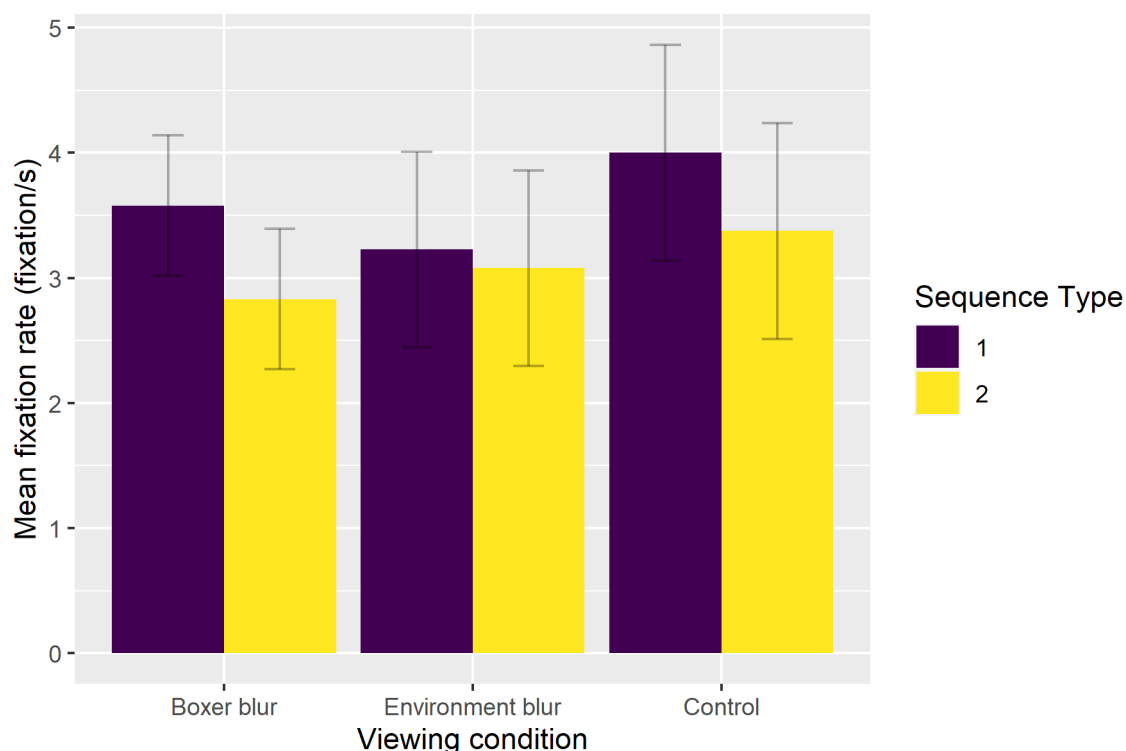


Figure 7.5 – Group mean fixations rate as a function of Viewing Condition and Sequence Type.

blur condition (701 ambient and 139 focal, ratio ambient/focal= 5.04. Mean ambient duration= 0.122 s \pm 0.009, mean focal duration= 0.322 s \pm 0.08), compared to boxer blur condition (728 ambient and 111 focal, ratio ambient/focal= 6.55. Mean ambient duration= 0.121 s \pm 0.010, mean focal duration= 0.312 s \pm 0.111). In control condition (ratio ambient/focal= 7.40), there were more ambient fixations (992) compared to the two blur conditions. There were also more focal fixations (134) compared to the boxer blur condition (111), and a similar number of focal fixations compared to environment blur condition (139. Mean ambient duration= 0.120 s \pm 0.014, mean focal duration=0.355 s \pm 0.163). Overall, participants exhibited mainly ambient fixations.

A generalised linear mixed model applied to the number of ambient fixations confirmed the effect of the Viewing Condition as well as the Sequence Type effect. The full model including random slope for Viewing Condition failed to converge. The reduced model with intercept only (AIC= 485.875, conditional $R^2=0.82$) returned a significant main effect of Sequence Type ($\chi^2(1)=85.376$, $p \leq .0001$) and Viewing Condition ($\chi^2(2)=63.602$, $p \leq .0001$)

on the number of ambient fixations. Bonferroni-corrected pairwise comparisons indicated that the mean number of ambient fixations was higher in control condition (47.3) compared to the boxer blur condition (34.7, $p \leq .0001$) and the environment condition (33.4, $p \leq .0001$). The mean number of ambient fixations was also significantly higher when facing the two punch sequences (46.0) compared to the one punch sequences (31.4, $p \leq .0001$).

Concerning the mean number of focal fixations, the full model including random slope for Viewing Condition failed to converge. The reduced model with intercept only (AIC=318.54, $R^2=0.63$) returned a significant main effect of Sequence Type ($\chi^2(1)=28.31$, $p \leq .0001$). Bonferroni-corrected pairwise comparisons indicated that the mean number of focal fixations was higher when facing the two punches sequences (8.01) compared to the one punch sequences (4.54, $p \leq .0001$).

7.5 Discussion

This study aimed to extend the results observed in the second study (which included a gaze-contingent blur), by investigating a youth elite population who performed the realistic VR boxing task in presence of a local or global blur. In particular, the aim was to better understand the effect of the previously used gaze-contingent blur window on performance and eye gaze behaviour. The observed results in this study highlighted that there was no significant effect of blur on participants' ability to dodge and counterattack a single or two punches thrown by the opponent. Still, the interaction between Viewing Condition and Sequence Type was close to conventional levels of significance. Further observation indicated that the probability of a dodging response was consistent across all the Viewing Conditions irrespective of Sequence Type. The probability of a counterattack response was lowest and the the probability of being hit was highest, when facing a two punch sequence in the boxer blur condition compared to environment blur and control conditions. Thus, contrary to the initial expectation, it would seem that elite boxers' spatial orientation in the ring was not sufficiently disrupted by the presence of the environment blur to impact negatively upon performance. This was in line with the findings that Viewing Condition did not impact significantly on the participant-opponent distance.

Observation of the eye gaze indicated an increased 3D ellipse Volume and an increased percentage of time spent with eye gaze on locations other than the opponent in the boxer

and environment blur conditions compared to the control condition. Fixation rate also tended to be lower in the boxer blur condition when facing two punch sequences, although this was not significant. Thus, it would seem that overt visual attention was drawn more often to the visual surrounds in both the boxer blur and environment blur conditions compared to the control condition. In the second study, it was suggested that moving gaze to the visual surrounds in the peripheral blur condition could have been an adaptive strategy to perceive depth and spatial layout. The same explanation could fit with the eye gaze data exhibited by youth boxers in the current study when the environment was blurred. However, it is less obvious why participants shifted eye gaze to the clear visual surrounds in the boxer blur condition. One possibility is that being able to perceive relevant motion-related information from the blurred opponent, “freed” overt attention to be drawn more often to the clear visual surrounds in order to recover other relevant information on depth and spatial layout. Interestingly, the ambient/focal fixation ratio decreased with the application of blur compared to the control condition, especially in environment blur condition. That is, in the boxer blur and environment blur conditions, participants spent proportionally more time making focal fixations (and less time making ambient fixations) than in the control condition. Although the current analysis did not consider where the focal fixations occurred, they are suggestive of more cognitive involvement, such as could be expected with ventral stream processing (Negi & Mitra, 2020; Pannasch & Velichkovsky, 2009).

As the majority of the time is spent with eye gaze located on the opponent (especially the head and upper body’ extremities), overt attention could have been more solicited in the environment condition and aligned with the line of gaze. On contrary, in control condition, the ratio indicated a more pronounced ambient mode of fixation. As observed in the second study then, better performance seemed related to ambient fixation mode and a covert attention preference, ambient mode being overall adopted. That is, removing the high frequency information (and possibly distracting information) from the whole opponent could not benefit to the performance. Instead, it could be more favourable to remove this high frequency information from the central vision like the previous experiments and not to affect the perception of blur depth cue around the gaze location (Held et al., 2012; Hussain et al., 2021). To go further, it could mean to encourage the dorsal processing of information, using the peripheral vision and the covert attention. Globally, as observed in previous works on blur (Ryu et al., 2015; Ryu et al., 2018; Ryu et al., 2016),

the introduction of blur, gaze-contingent or local, impacts the gaze behaviour.

7.6 Conclusion

This study sought to better understand the effect of blur on dodging and counter-attack performance, as well as eye gaze, in a youth elite population performing an immersive and adaptive first-person realistic VR boxing task. The aim was to disambiguate the possible disruption of depth perception and spatial orientation in the ring due to the gaze-contingent blur method. It was found that blurring the opponent boxer or the surrounding environment did not impact on performance, yet some influences were found on counterattack response and eye gaze. The results suggested that the spatial orientation in the ring was not disrupted by the presence of blur on the background. Blurring the entire opponent, however, was not favourable to the performance as expected. It would be interesting to compare the performance of this same population to the gaze-contingent blur experiment and conclude about the implication of central and peripheral vision on anticipation performance, as well as the possible disruption of the depth perception around the gaze location. The long-term effect of blur and the transfer to a real boxing situation would be also relevant to extend the understanding.

GENERAL DISCUSSION

From the outset, the PhD thesis was interested in several broad questions: What is the effect of blur in a virtual reality where a motor response is involved? Is the effect mediated by expertise? And does it matter what level of blur is applied to different parts of the visual field? To gain some initial insight, the first aim was to review and synthesise previous work that had investigated the effect of blur on perceptual-cognitive performance in sports tasks. The review indicated that there were somewhat ambiguous results, particularly concerning the effect of expertise, and limited studies that had examined the effect of blur in representative settings. Therefore, a series of studies were conducted to investigate the influence of a computer-generated Gaussian blur on anticipation performance of different skill level groups in an immersive virtual reality boxing context. Importantly, the virtual reality environment was presented in an HMD with embedded eye tracking, which made it possible for eye gaze to be both measured and used to locate the Gaussian blur. In the first study, the effect of low, medium and high levels of a gaze-contingent blur during a chasing parry task was examined in three groups of different expertise (boxers, combat sport athletes and novices). Although the VR stimuli were realistic, immersive and required a motor response, the results highlighted some limitations with the task concerning the discrimination of expert and novice groups. Therefore, in the second study, the effect of a medium level of a gaze-contingent blur on dodging and counterattack performance was examined with elite boxers. This was followed by a third study that examined the impact of a local or global blur (non gaze-contingent) on youth elite boxers dodging and counterattack performance. In the following sections, the main findings of the three studies will be considered together in order to better understand the effects of blur found in the current PhD thesis. Limitations, future directions and implications for high level practice will also be discussed.

8.1 Comparison between the three studies

8.1.1 Performance data

The main concern of this work was to understand the effect of blur on anticipation performance in a virtual boxing task. Initially, based on the literature review (R. Jackson et al., 2009; D. L. Mann et al., 2010b; Ryu et al., 2015; Ryu et al., 2018; Ryu et al., 2016; van Biemen et al., 2018), it was expected that expert boxers would exhibit resilience to the presence of blur in either central or peripheral vision, and that performance may even increase in the presence of a central blur.

In study 1a, performance of a chasing-parry task in experts in various combat sports was examined in three Viewing Conditions (control, central blur and peripheral blur) with different levels of blur (light, medium, strong). Performance in the blurred conditions did not improve significantly, nor did it deteriorate significantly, compared to a control condition. Overall, then, there was a general resilience to the presence of blur irrespective of level and location in the visual field. That said, there was a small but significant difference in performance between the peripheral blur condition (0.392) and the central blur condition (0.442). To further understand the effect of the blur given the constraints of the chasing parry task, study 1b compared performance of novices, boxers and combat sport athletes. The results were surprising as the novices outperformed the boxers in the boxing-specific VR task. This confirmed the limitations of the chasing-parry like task and the fact that it lacked representativeness of the specific boxing context. Interestingly, this extended analysis of three skill groups revealed a significant interaction between Viewing Condition and Blur Level. In particular, a small positive effect of the central medium blur was observed compared to the control condition. In the peripheral blur viewing condition, performance tended to decrease, especially with the strongest level of blur. Therefore, across study 1a and 1b, there was some evidence of a negative effect of a peripheral blur, but a positive effect of a central blur was observed only on study 1b. Also, it was noted that the level of sport-specific practice was heterogeneous in the boxers and combat sport groups. For example, the expert boxers had 2-15 years practice, and competed at leisure to European level. The heterogeneity was similar for the combat sport group, and thus could have impacted upon the results.

To resolve the limitations identified in study 1a and 1b related to the task, the sec-

ond and third studies considered dodging and counterattack performance, which is more representative of a typical response in a real boxing match. A direct comparison between the performance results of study 1a/1b and the second and third studies was not conducted as the dependant measures of performance were quite different. However, a direct comparison of performance between the two populations in the second and third studies can be made. The control condition was identical in these two studies, but the blurred conditions differed. In the second study, a gaze-contingent medium blur was applied to investigate the performance of elite boxers. All boxers were from the same structure (i.e., the elite French group), and thus their training practice, coaches and level of performance were homogeneous. The positive effect of a medium central blur, observed in study 1b, was not present in the second study. However, consistent with study 1a and 1b, as well as previous published work, a general resilience to blur was observed. Although a small decrease in performance of elite boxers was observed in the presence of a peripheral blur, this effect was not significant. In the third study, performance of youth elite boxers in the presence of a local (boxer) or global (background) blur did not differ, again indicating a resilience to the presence of blur. The maintenance of performance in presence of a blurred background was suggested to indicate that the boxers' spatial orientation in the ring was not disrupted enough to have a significant effect. The finding of no positive effect of blurring the boxer indicated that removing superficial and distracting information did not benefit performance in the virtual reality boxing task on expert/elite boxer.

Together, the experiments conducted in this PhD did not unequivocally confirm the previously reported positive effect of the presence of blur when applied in central vision, or when a modified protocol was used where blur was applied locally on the opponent and thus where gaze tends to be located. Also, although a general resilience to the presence of blur was observed across the different populations of boxers, if there was a decrease in performance it would seem to occur with the introduction of blur in peripheral vision. However, this was not the case with the elite adult boxers in the second study. Possibly, the perceptive-cognitive skills in the elite group may have reached a peak where the blur disturbance was not strong enough to impact on the performance. To conclude if the resilience was due to expertise, the investigation of the effect of central/peripheral blur on homogeneous various skills levels' population would be useful. It would be interesting for instance to cross the population between the second and the third study to compare the effect of blur between the youth and the elite boxers.

The effect of blur on performance was investigated in this PhD using a cross-sectional protocol, where different groups performed a single testing session. Therefore, it remains to be determined if the general resilience to the presence of blur, and the limited evidence of a performance decrease in the peripheral blur condition, would be similar in a learning protocol. Indeed, Ryu et al., 2016, observed improved decision-making performance in a perceptual-cognitive task after training in a peripheral blur condition. It is possible that a peripheral blur presents a challenging situation, which encourages participants to adapt their perceptual-cognitive strategy to maintain performance. If this then transfers positively back to a normal vision condition, it follows that performance will improve. It would be interesting to consider for future study the dodging and counterattack performance over more prolonged training, comparing different skills groups, under the conditions of central and peripheral blur. As discussed previously in the thesis, attention may have been drawn to the clear part of the display to avoid the blur. This observation can be used to target a specific learning strategy which could orient attention to specific important areas (like the trunk or the head). That is, it could be interesting to blur the visual field and keep clear some key AOI on the opponent.

Additionally, comparing performance between the second and the third studies, it was observed that the youth boxers performed better than the elite group. This is surprising as it would be expected that elite boxers would outperform the youth boxers. However, it is notable that the elite boxers were summoned for the experiment between two of their daily training sessions. It is possible that the elite boxers approached the task as an alternative way of practicing perceptual skills, or a warm-up similar to shadow boxing situation, and thus managed their effort for the proper training session. On contrary, the youth athletes completed the task during their training sessions, in the presence of the coach, who provided feedback about their defensive behaviour. This may have encouraged more effort and involvement in the task than the elite adult boxers, which could have impacted upon the results.

To better understand the adaptation of motor behaviour in the second and the third studies, the participant-opponent distance was investigated. The variation of the counter-attack response in relation to this distance, as discussed in the second and third studies, could indicate the importance of fighting distance for performance, especially the proba-

bility of counterattack (yet no correlation was found). Indeed, although non-significant, a small decrease of the participant-opponent distance was observed in the second study when facing sequences of two punches in the peripheral blur condition, dropping to 1m27 from 1m45 in the central blur condition where counterattack performance was maintained. In the third study on youth boxers, the introduction of blur on the opposing boxer or the surroundings lead to a small, but non-significant decrease of the participant-opponent distance to 1m43 from 1m55 in the control condition. Comparing the two studies, it is interesting to note that the adult elite participants adopted a shorter participant-opponent distance (overall 1m36) compared to the youth elite boxers (overall 1m47), even though the adult elite boxers were taller. Considering that the adult elite boxers tended to perform worse than the youth elite boxers (some reasons were discussed above), the analysis of dodging and counterattack as dependant variable may need to be put in perspective. Indeed, the optimal fighting distance is an important aspect of performance in combat sports (Martínez de Quel & Bennett, 2019). That is, observing only dodging and counterattack response may be too reductionist, and hence an incomplete way to consider the complex dynamic and interactive performance during a fight. This was confirmed in post-testing debriefing exchange with coaches, who explained that youth athletes have more difficulties in defensive situations to accept the close fighting distance and tend to move backward. A detailed categorisation of the dodging response (i.e., left dodge, right dodge, parade or retreat) was not examined in this thesis, but qualitatively there appeared to be more retreat behaviours in the youth boxer group. Future work should recognise the potential for optimal fighting distance to be a characteristic of expertise, and hence consider in more detail how it is influenced by the blur manipulation.

8.1.2 Individual sensitivity to the presence of blur

In the second and third studies, the main effect of blur was not present (or limited) in the group mean performance. Linear mixed modelling was used in order to take account of individual variability, but it still considers the overall group mean response and may not reveal individual patterns of response to blur. In the second study, some participants performed better in the control condition, whereas some performed better in central blur and others in peripheral blur (see Figure 8.1). The completion order of the conditions was randomised, and subsequent checks indicated that it did not explain the variable response to the presence of blur. The same individual variability was observed in the third study

and confirmed post-hoc to be unrelated to condition order (see Figure 8.2). It was not expected to find such individual variability and hence it was not planned to test several participants on more than one occasion to determine if this variability was replicated. In fact, this would not have been a trivial task given the elite nature of the boxers and associated difficulty recruiting participants across repeated sessions. It was also complicated to increase the sample while keeping the group homogeneous in skill level as the entire elite French team and youth French team were tested. Therefore, although it is not possible at this stage to confirm if the effect of blur in the current thesis was unstable, or if participants exhibited a different but stable sensitivity to the presence of blur, this will be an important consideration for future work.

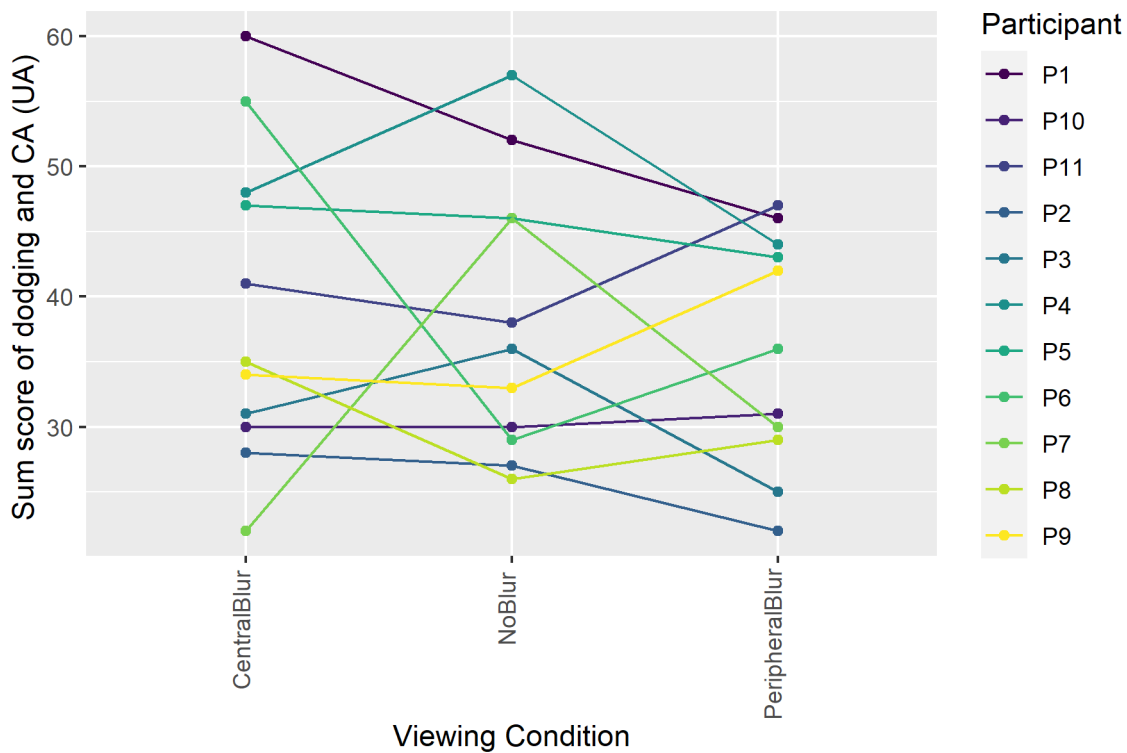


Figure 8.1 – Individual pattern of performance in the second study as function of Viewing Condition in the second study. In sum score, dodging scored one and CA scored two.

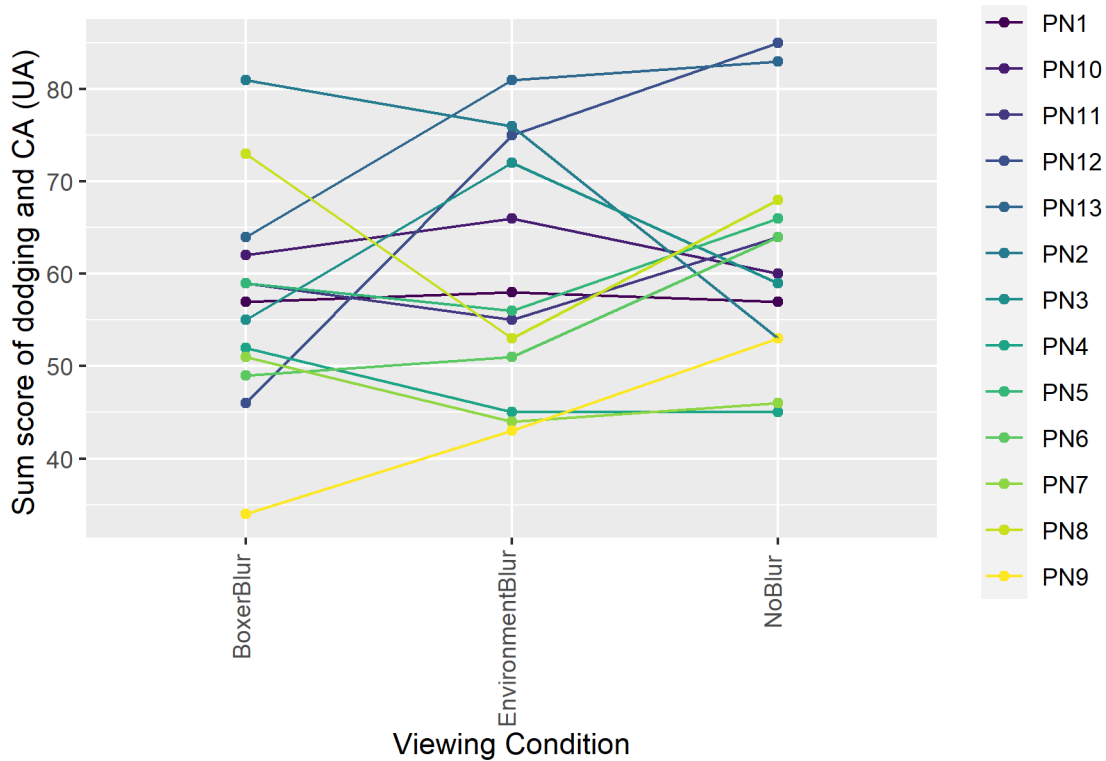


Figure 8.2 – Individual pattern of performance in the third study as function of Viewing Condition in the second study. In sum score, dodging scored one and CA scored two.

8.1.3 Eye gaze data

In order to better understand the effect of blur on performance, eye gaze data was investigated in each of the studies in this thesis. Given the spatial and temporal resolution of the eye tracking device embedded with the HMD, it was decided to present the time spent in AOIs, the 3D ellipse Volume containing 95% of the gaze data, the number of fixations (or fixation rate in the second and third studies), fixation duration and the number of ambient and focal fixations.

Overall, the time spent in the AOIs confirmed previous observations in the literature on combat sports, with a majority of the time spent on the trunk, head and the two upper limbs (Hausegger et al., 2019; Ripoll et al., 1995). In study 1a and 1b, the introduction of peripheral or central blur did not impact on the time spent in AOIs. However, differences regarding the skills level were observed in study 1b, with boxers gazing more at the trunk and the head compared to novices. This observation was also consistent with previous

work (Hausegger et al., 2019; Ripoll et al., 1995). In the second and third studies, an effect of blur on the time spent in the different AOIs was observed. In the second study, the time spent on the left hand and the plexus was reduced in favour of the head and areas outside the boxer in peripheral blur condition compared to the central blur and control conditions. In the third study, again, the time spent on the left hand, the plexus and the head dropped in favour of the areas outside the opposing boxer in the boxer and environment conditions, compared to the control condition. Surprisingly, the areas outside the opposing boxer registered the greater percentage of time in the third study. This was particularly true for both blurred conditions, which could indicate that participants tried to adapt their information pick-up differently in the two blurred conditions to maintain performance.

Here, it is worth noting that the method to process the percentage of time on AOIs was slightly different between study 1a/1b and the second and third studies. In study 1a/1b, a basic ray with the line of gaze cast was used to output the object encountered in the scene, which gave the AOI for each frame. In the second and third studies, the *GazeFocusChanged* function in the *IGazeFocusable* interface from the software development kit's application programming interface (SDK's API) was used. This function is a ray-cast but, according to Tobii documentation, a machine learning correction is applied to gain in accuracy. The function outputs information when an object gains and loses the gaze focus, allowing to determine, at the end, the focused object in each frame. The area outside the boxer was not output directly from this function but calculated in the post-processing as the difference between total time of the block and total time spent on the opponent's AOI. The different methods could explain why more time outside the boxer was observed in these studies compared to the study 1a/1b. That said, the same process was used in the second and third studies, so it is interesting to note that youth boxers spent more time outside the opponent boxer, even in the control condition, compared to the elite group. This pattern could be indicative of a visual expertise.

In study 1a and 1b, as well as the third study, the introduction of blur leads to a significant increase in the 3D ellipse Volume compared to the control condition. However, in the second study, only the peripheral blur condition induced an increased 3D Volume, which was quasi equal between central blur and control conditions. In study 1a and 1b, the volume was smaller overall (52.1 cm^3) compared to the second (104.7 cm^3)

and the third study (114 cm^3). The virtual opponent was more mobile in the second and third studies, exhibiting more backwards and forwards movements, which could explain the overall increased volume. In consideration of the different studies, it is possible that maintaining a 3D Volume close to the control condition value helped to maintain task performance. Conversely, the perturbation of task performance may have been associated with an increased 3D Volume, in line with the observation made on the time spent outside the boxer. It was clear that the more time was spent on the trunk and the head, the more it seems to facilitate task performance.

The number of fixations and fixation duration were analysed independent of gaze location. In study 1a and 1b, the number of fixations was not influenced by the presence of blur, but it was influenced by other factors such as Feint Type, Punch Number and the group in study 1b. More fixations were observed for boxers especially on the last punch of the sequence. In the second and third studies, however, fixation rate was influenced by the introduction of blur. In the second study, fixation rate was slightly higher in the central blur condition compared to the control condition and significantly higher than the peripheral blur condition. In the third study, fixation rate tended to be lower in the boxer blur condition when facing two punch sequences, although this was not significant. The elite adult group in the second study had an overall higher fixation rate (4.59) compared to the elite youth boxers in the third study (3.34). As was found for the 3D Volume, elite boxers exhibited gaze behaviour with more fixations, which is consistent with previous observations on experts' gaze behaviour (Hausegger et al., 2019; D. L. Mann et al., 2010b; Vater et al., 2019; A. Williams & Jackson, 2019). Possibly, the observed resilience to the presence of blur may be related to the maintenance of a high number of fixation on the opponent's major AOIs. Indeed, the conditions where the best performance was observed (or maintenance of the performance in blurred conditions) seemed to coincide with the highest fixation rate. In particular, the strongest resilience was observed in the elite group in the second study. It was clear that the elite boxers presented a higher fixation rate compared to the youth boxers, along with more time spent on the head, trunk and upper limbs of the opponent.

Concerning fixation duration, an effect of blur (and level) was observed in study 1a and 1b but not in the second and third studies. The gaze was considered "fixed" when the average position stayed within an area of 1° for 100 ms minimum. In study 1a, fixation

duration was longer when facing a strong peripheral blur (189 ms) compared to a light peripheral blur (176 ms). In central blur condition, irrespective of level, fixation duration (172 ms) was similar to the control condition. In study 1b, fixation duration was again longer in the peripheral blur condition (176 ms) compared to the central blur (170 ms) and control condition (167 ms). It was interesting to note in study 1b that boxers produced longer fixations (185 ms) than other groups. In the second study, the overall mean fixation duration was 159 ms for the adult elite boxers, and 160 ms for the youth elite boxers in the the third study. In sum, fixation duration was quite similar in the different studies, especially in the second and third studies. Recollect with the fixation rate, a possible optimal strategy observed in elite group, could be to increase the number of rather short fixations. This was confirmed in the second study by observation of the number of ambient fixations. More ambient fixations (fixations of duration from 100 ms to 150 ms) were observed in the central blur and control conditions compared to the peripheral blur condition. The number of focal fixations (fixations of duration longer than 250 ms) was also higher in the central blur condition compared to the peripheral blur condition. In the third study, the number of ambient fixations was greater in the control condition compared to the two blurred conditions, and there were no differences in the number of focal fixations between the three Viewing Conditions. The number of ambient fixations was higher overall in adult elite boxers compared to the youth elite boxers. Overall, for both elite and youth boxers, a dominant ambient mode of fixation was observed, suggesting a dorsal stream processing, more sensitive to low frequency and visual-spatial information, and hence more resilient to the presence of blur (Negi & Mitra, 2020; Pannasch & Velichkovsky, 2009).

Summing up, it is possible that the resilience to blur observed in performance could be underpinned by a resilience of gaze behaviour. Indeed, elite boxers in the second study, who exhibited the strongest resilience, maintained a similar gaze behaviour in the central blur condition and control condition. In the peripheral condition, where a small non-significant decrease in performance was observed, gaze behaviour also tended to be negatively impacted. Overall, the suitable visual strategy in the current VR boxing task seemed to be to make more fixations of short duration on the trunk or the head of the opponent. However, it should be recognized that the type of gaze analysis reported in this thesis was dictated by the properties of the eye tracking device. The sampling rate of the eye tracker was synchronised to the display refresh rate, and was thus 0.011 s in

the second and third studies. It was lower in study 1a and 1b, where the display refresh rate was impacted slightly by the computation cost of achieving a strong level of blur in the peripheral blur condition. Therefore, with sampling rates of this level, it was deemed inappropriate to determine saccadic eye movements, which could have provided a more accurate representation of eye gaze fixation parameters. For example, although it was possible to describe gaze fixation, it was not possible to know what the eyes were doing the rest of the time. An increased eye tracking sampling rate would enable the determination of saccades and gain in precision regarding the fixation location. The scan path, saccade duration and saccade amplitude, often investigated in perceptual-cognitive studies, could then have been determined to describe more precisely the gaze behaviour. In future consideration, it would be useful to investigate more precisely the gaze behaviour with a higher frequency sampling rate. A characterisation of differences between elite and youth boxers' gaze behaviour based on these additional parameters would be of major interest to understand the effect of expertise on gaze behaviour and the possible implication on the performance.

As observed on the previous works (Ryu et al., 2015; Ryu et al., 2018; Ryu et al., 2016), the introduction of blur altered gaze behaviour in the different studies of this PhD thesis. In particular, it seemed that the introduction of blur on a part of the visual display may have drawn participant's overt attention to the clear part of the visual display. In the central blur condition, the adaptation may have facilitated the use of peripheral information (low frequency motion information). In the peripheral blur condition, participants may have overtly focussed on distracting information, such as the opponent's facial expression, instead of the low frequency information. Interestingly, Ryu et al., 2015; Ryu et al., 2016, observed a different effect on decision making performance of the peripheral blur with a novice population (i.e., improved performance). Yet, in their basketball task, the court was viewed from a third-person perspective and the response was a button-click. In their study, overtly attending to the ball carrier and limiting the information (possibly distracting) from the periphery seemed to help novices' performance. Conversely, in the current work, information on the opponent in central vision seemed to be distracting. As discussed for the performance findings, the current study used a cross-sectional protocol. The use of training intervention may reveal different effects of the presence of blur on performance and/or gaze behaviour. Nevertheless, knowing that attention could be drawn to the clear part of the display, future work may use specific blur locations to target an

education of attention. Indeed, some works previously investigated perceptual training methods to guide the attention of novice/less skilled participants to improve and accelerate information pick-up and visual search behaviour, based on the experts' efficient skills (Abernethy et al., 2012; Klostermann et al., 2015; Martínez de Quel & Bennett, 2019; Ryu et al., 2013a). Implicit learning methods, using cue highlighting, mainly on 2D displays, presented the more promising long-term results (Farrow & Abernethy, 2002; Milazzo et al., 2016b; Ryu et al., 2013b; N. J. Smeeton et al., 2005). Colour cueing, for example, was investigated as a means to draw overt attention to specific locations, but the results were somewhat mixed (Abernethy et al., 2012; Klostermann et al., 2015; Ryu et al., 2013b; Savelsbergh et al., 2010). Possibly, the limitation of the findings may be related to the use of a the 2D display and the lack of perception-action coupling, as well as a possible visual feedback dependence of the colour cueing presentation in the transfer of learned skills (Klostermann et al., 2015). Interestingly, Milazzo et al., 2016b, tried to preserve the perception-action coupling in a training study of combat athletes (i.e., using a video display) and found an improvement of performance and gaze behaviour. The investigation of the use of blur for (implicit) learning and guiding attention could be interesting. As we observed an impact of blur on gaze behaviour, this investigation would need particular attention to the transfer of gaze behaviour to the real situation to prevent possible negative transfer or dependency on the blur acting like a visual feedback.

In this work, fixation was determined according to traditional definition, widely used in the investigation of 2D gaze behaviour (Salvucci & Goldberg, 2000). In our case, 3D coordinates of the gaze data were investigated, using a dedicated, published algorithm for fixation identification (Llanes-Jurado et al., 2020). Moreover, the task and the visual stimuli were dynamic and the participant was free to move the head. As discussed by Clay et al., 2019, fixations in VR *“are not as well defined as during eye tracking when looking at a static 2D scene. A clear way to differentiate fixations from smooth pursuit or optokinetic nystagmus needs to be established. It has to be kept in mind that for eye tracking in a 3D environment established concepts like fixations and saccades are not as clearly defined as in front of a 2D screen anymore.”* (Clay et al., 2019). The comprehension of 3D gaze behaviour, including vergence movements, in a dynamic and realistic VR boxing task, and how this is influenced by expertise may need further investigation, taking into consideration the vergence-accommodation conflict in VR (Dits et al., 2013; Eadie et al., 2000; Fulvio & Rokers, 2017; Gerig et al., 2018; Klinghammer et al., 2016).

8.2 Application to high-level practice

The second and third studies were carried out with high-level athletes and thus provide an opportunity to discuss the acceptance of VR and its inclusion in daily training. Globally, the athletes reported that they felt immersed in the task and found the environment realistic. The immersion was reinforced by the correspondence of the virtual ring and the real ring where they were completing the task. Being able to touch the real ropes, which matched with the virtual ropes of the ring, was appreciated by the boxers and gave them a sense of security when moving around and wearing the HMD. The athletes reported that the opponent threw realistic punches and that they tried, as they do in a real fight, to find the weak point of the opponent and the opportunity to counterattack. It was interesting to note that the situation was physically engaging. Participants moved around the ring, made realistic behaviours with quick movements according to the opponent, and also sweated (many were surprised by this). Therefore, it can be concluded that VR boxing was not only a perceptual task. The athletes reported they were able to adapt accurately their distance to the opponent, they reported an accuracy of their fists position, and they felt that the opponent launched their punches from a correct punching distance. Also, although the athletes perceived that the punches sequences were randomly distributed, it meant that they proceeded without logical progression. From these comments, it is clear that contextual information about the sequence and previous moves by the opponent are used in a boxing real situation. This has also been described in other sports (Murphy et al., 2016; Murphy et al., 2018). An interesting perspective would be to implement contextual sequences where the punch sequences evolve in a boxing realistic way. Yet, this would need, in first instance, the identification of the patterns of evolving punch sequence in real competitions, which could vary as a function of the opponent and situational probabilities of the fight. Then, motion capture or computer generation of these actions will be needed to create the virtual movements. Creating an intelligent and realistic opponent would be a great challenge, possibly based on machine learning/artificial intelligence protocols to predict the behaviour from a large database of real fights.

Another comment was that the peripheral blur resulted in a perceptual experience similar to that of a mild concussive event that occurs when taking heavy blow to the head. Although not an aim of the thesis, this specific situation in practice, which is impossible to safely reproduce in a real setting, was of interest to elite boxers and coaches. VR could

offer a way to simulate, and thus safely experience this situation. First, the boxers could improve their defensive skills and learn how to better protect themselves, without the risk to take a punch when they make an inappropriate response. Second, they could practice maintaining their performance (keep protecting themselves while keep attacking) when their perception of the environment is blurred. This very specific context of practice is sometimes recreated by the coaches by provoking the disorientation of the boxers, making them turn on themselves before an exercise. This of course impacts upon the vestibular apparatus, causing a more general balance disorientation, which is not the case with the use of blur in VR.

For coaches and boxers, a primary concern is the management of injury of any kind (e.g. traumatic or mild concussive) and return to combat. In this respect, VR brings an alternative modality, which is safe and allows the boxer to recover from the injury while being able to practice in a setting that presents realistic information on the opponent, including the temporal and spatial constraints of their attacking sequences. VR offers a smooth transition between shadow work or the punch bag, without visual stimuli and adaptation to the opponent behaviour, and sparring where the punches come quickly. Moreover, while injured, boxers report that they miss the feeling of being in the ring and the opportunity to interact with an opponent. The feeling of presence in the VR environment was strong, with participants reporting that they “felt” the ring and experienced a realistic information intake. The absence of the haptic consequence of a punch is an asset to the use of VR, especially to offer this safe way of practice. Yet, it is also a limitation, as it will never replace the actual fight. Indeed, boxers commented that the essential point of boxing was missing in VR, which is the danger and impact of taking/giving a punch.

The second main interest reported by the coaches and boxers was the possibility of being able to train against their future real opponent in a virtual setting in preparation for the fight. It was suggested they would benefit from experiencing a simulation of the specific favoured sequences, movements, stature, and appearance of a specific real opponent. Yet, the tool developed in this PhD was not designed for this purpose. Another related comment was the interest to reproduce a specific context of practice, like the future location of a fight. To fulfil these requests, a major investment would be needed in the development of the VR environment, including importation of the specific movements and graphism to design this individual training. For sure, major limitations will be raised

from the creation of a “smart” opponent, able to adapt themselves to the real boxer’s behaviour and thereby reproduce realistic boxing strategy and the evolving dynamic. The future works in this direction will have to segment this objective in progressive steps to ensure each of the steps’ validity, before designing the complexity of the whole tasks. It comes, obviously, with a strong economic, technical, and human resources cost.

This PhD was completed under a very specific period of COVID19. The pandemic altered the progress of this work and the opportunities for experimental testing, especially with the elite population. However, these particular times inadvertently confirmed the interest of VR in helping to maintain realistic training. A VR boxing environment can bring diversity to training when the number or level of sparring partners are limited, when being unable to train during travelling, or in extreme cases of lock-down. In addition, VR offers a new and complementary way of practice, which is challenging, possibly individualized and engaging.

The major limitations exposed by coaches of its use are the complexity of the set-up and the limited opponent’s behaviour. Coaches traditionally prioritise actual boxing during practice and are not comfortable with these new technologies. To be accepted by coaches and boxers, the VR device must be easy and quick to use, without the need for configuration or calibration, and to take a place in daily training. The output data report must be short, with key highlighted indicators that are easy to read and interpret. In addition, the athletes and coaches were expecting an interactive opponent, which will react like a real boxer. This kind of virtual opponent is obviously technologically difficult to recreate. The environment in this PhD was designed for a specific scientific purpose, with limitations in the participants-opponent interaction. The conflict between scientific standardisation, tool validation and on-field use of the VR tool will remain a challenge in the coming years.

CONCLUSION

Boxing is a combat sport characterized by very strong spatio-temporal and event constraints. The speed of the opponent's attacking punches coupled with the short participant-opponent distance, make perceptual-cognitive skills, and in particular anticipation, key to successful performance. Underpinning this skill is likely to be the rapid pick-up and use of low frequency movement-related information from the opponent. Indeed, expert boxers rely more on peripheral vision, possibly associated with dorsal stream processing. This is reflected in their gaze location, which tends to be around the trunk or the head of the opponent, thus facilitating the use of covert attention to perceive information from the opponent's fists. However, learning these important perceptual-cognitive skills through repeated practice in a real world boxing environment is dangerous and could lead to unwanted injuries. Therefore, this PhD thesis aimed to develop and apply a VR tool to identify and assess anticipation in boxing. It was deemed relevant based on an initial review, to investigate the effect of blur on anticipation performance. The principle of using blur is to remove the highly detailed information, which can be unnecessary or even disturbing, and thereby to direct participants to perceive basic kinematic information on the opponent and thus their upcoming attacking response. Using VR, the limitations of previous research on the effect of blur on perceptual-cognitive skills can also be overcome. Indeed, VR presents an opportunity to preserve the perception-action loop and the representativeness of the context in order to simulate perceptual-cognitive skill involved in a real context.

Across the three studies reported in this thesis, there was a general resilience to the presence of blur, irrespective of level and location in the visual field, as well as participant expertise. If there was a decrease in performance, it would seem to occur with the introduction of blur in peripheral vision. This effect was also present in the gaze data, which showed an increase in the 3D ellipse Volume and a decreased fixation rate in presence of the peripheral blur or a blurred opponent. Overall, though, an ambient mode of visual processing was dominant, with participants exhibiting more fixations of rather short duration on the important parts of the opponent's body (head, plexus, upper body

extremities). Together, the results indicate the use of low spatial frequency motion information, which could explain the maintenance of performance in the presence of blur. Future work on larger populations of elite athletes will be needed to better understand the individual sensitivity to blur and whether this is stable across repeated sessions. Indeed, it could be that the observed resilience, or subtle negative effect of a peripheral blur, may even facilitate learning if it can be used to orient attention to specific locations (e.g. head, trunk and the upper limb extremities). Importantly, such work with elite athletes needs their engagement, as well as that of the coaches. It is promising, then, to note that the VR boxing task used in the latter studies was received positively. The boxers reported feeling immersed in the task and commented that it represented well a boxing situation. Therefore, the realistic and representative VR boxing tool developed in this PhD thesis offers an alternative, safe practice environment, which could also be used with injured boxers as they prepare to return to fight.

BIBLIOGRAPHY

- Abernethy, B., Schorer, J., Jackson, R. C., & Hagemann, N., (2012), Perceptual training methods compared: The relative efficacy of different approaches to enhancing sport-specific anticipation., *Journal of Experimental Psychology: Applied*, *18*(2), 143–153, <https://doi.org/10.1037/a0028452>
- Appelbaum, L. G., & Erickson, G., (2018), Sports vision training: A review of the state-of-the-art in digital training techniques, *International Review of Sport and Exercise Psychology*, *11*(1), 160–189.
- Applegate, R. A., & Applegate, R. A., (1992), Set Shot Shooting Performance and Visual Acuity in Basketball: *Optometry and Vision Science*, *69*(10), 765–768, <https://doi.org/10.1097/00006324-199210000-00004>
- Badau, D., Baydil, B., & Badau, A., (2018), Differences among Three Measures of Reaction Time Based on Hand Laterality in Individual Sports, *Sports*, *6*(2), 45, <https://doi.org/10.3390/sports6020045>
- Bahill, A., Clark, M. R., & Stark, L., (1975), The main sequence, a tool for studying human eye movements, *Mathematical Biosciences*, *24*(3-4), 191–204, [https://doi.org/10.1016/0025-5564\(75\)90075-9](https://doi.org/10.1016/0025-5564(75)90075-9)
- Baldwin, T. T., & Ford, J. K., (1988), Transfer of training: A review and directions for future research [Place: United Kingdom Publisher: Blackwell Publishing], *Personnel Psychology*, *41*, 63–105, <https://doi.org/10.1111/j.1744-6570.1988.tb00632.x>
- Barnes, G., (2008), Cognitive processes involved in smooth pursuit eye movements, *Brain and Cognition*, *68*(3), 309–326, <https://doi.org/10.1016/j.bandc.2008.08.020>
- Belling, P. K., Suss, J., & Ward, P., (2015), Advancing theory and application of cognitive research in sport: Using representative tasks to explain and predict skilled anticipation, decision-making, and option-generation behavior, *Psychology of Sport and Exercise*, *16*, 45–59, <https://doi.org/10.1016/j.psychsport.2014.08.001>
- Bianco, M., Ferri, M., Fabiano, C., Scardigno, A., Tavella, S., Caccia, A., Manili, U., Faina, M., Casasco, M., & Zeppilli, P., (2008), Comparison of Baseline Neuropsychological Testing in Amateur Versus Professional Boxers, *The Physician and Sportsmedicine*, *36*(1), 95–102.

-
- Bianco, V., Di Russo, F., Perri, R. L., & Berchicci, M., (2017), Different proactive and reactive action control in fencers' and boxers' brain, *Neuroscience*, *343*, 260–268, <https://doi.org/10.1016/j.neuroscience.2016.12.006>
- Bideau, B., Kulpa, R., Vignais, N., Brault, S., Multon, F., & Craig, C., (2010), Using virtual reality to analyze sports performance, *IEEE Comput Graph Appl*, *30*(2), 14–21.
- Blascheck, T., Kurzhals, K., Raschke, M., Burch, M., Weiskopf, D., & Ertl, T., (2014), State-of-the-Art of Visualization for Eye Tracking Data [Artwork Size: 20 pages ISBN: 9783038680284 Publisher: The Eurographics Association], *EuroVis - STARS*, 20 pages, <https://doi.org/10.2312/EUROVISSTAR.20141173>
- Bracht, G. H., & Glass, G. V., (1968), The External Validity of Experiments, *American Educational Research Journal*, *5*(4), 437–474, <https://doi.org/10.3102/00028312005004437>
- Brault, S., Bideau, B., Kulpa, R., & Craig, C. M., (2012), Detecting deception in movement: the case of the side-step in rugby, *PLoS ONE*, *7*(6), e37494.
- Broadbent, D. P., Causer, J., Williams, A. M., & Ford, P. R., (2015), Perceptual-cognitive skill training and its transfer to expert performance in the field: Future research directions, *European Journal of Sport Science*, *15*(4), 322–331, <https://doi.org/10.1080/17461391.2014.957727>
- Bulson, R. C., Ciuffreda, K. J., & Hung, G. K., (2008), The effect of retinal defocus on golf putting, *Ophthalmic and Physiological Optics*, *28*(4), 334–344, <https://doi.org/10.1111/j.1475-1313.2008.00575.x>
- Burdea, G., Coiffet, P., & Burdea, G., (2003), *Virtual reality technology* (2. ed), Wiley.
- Causer, J., Hayes, S. J., Hooper, J. M., & Bennett, S. J., (2017), Quiet eye facilitates sensorimotor preprogramming and online control of precision aiming in golf putting, *Cognitive Processing*, *18*(1), 47–54, <https://doi.org/10.1007/s10339-016-0783-4>
- Clay, V., König, P., & König, S. U., (2019), Eye tracking in virtual reality, *Journal of Eye Movement Research*, *12*(1), <https://doi.org/10.16910/jemr.12.1.3>
- Craig, C., (2013), Understanding perception and action in sport: how can virtual reality technology help?, *Sports Technology*, *6*(4), 161–169.
- Davis, P., Benson, P. R., Pitty, J. D., Connorton, A. J., & Waldock, R., (2015), The Activity Profile of Elite Male Amateur Boxing, *International Journal of Sports Physiology and Performance*, *10*(1), 53–57, <https://doi.org/10.1123/ijsp.2013-0474>

-
- Diaz, G., Cooper, J., Rothkopf, C., & Hayhoe, M., (2013), Saccades to future ball location reveal memory-based prediction in a virtual-reality interception task, *J Vis*, *13*1.
- Dits, J., King, W. M., & van der Steen, J., (2013), Scaling of compensatory eye movements during translations: virtual versus real depth, *Neuroscience*, *246*, 73–81, <https://doi.org/10.1016/j.neuroscience.2013.04.029>
- Eadie, A. S., Gray, L. S., Carlin, P., & Mon-Williams, M., (2000), Modelling adaptation effects in vergence and accommodation after exposure to a simulated virtual reality stimulus, *Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic Opticians (Optometrists)*, *20*3, 242–251.
- Enns, J. T., & MacDonald, S. C., (2013), The role of clarity and blur in guiding visual attention in photographs., *Journal of Experimental Psychology: Human Perception and Performance*, *39*2, 568–578, <https://doi.org/10.1037/a0029877>
- Fajen, B. R., & Warren, W. H., (2007), Behavioral dynamics of intercepting a moving target, *Experimental Brain Research*, *180*2, 303–319.
- Farrow, D., (2013), Practice-enhancing technology: a review of perceptual training applications in sport, *Sports Technology*, *6*4, 170–176, <https://doi.org/10.1080/19346182.2013.875031>
- Farrow, D., & Abernethy, B., (2002), Can anticipatory skills be learned through implicit video based perceptual training?, *Journal of Sports Sciences*, *20*6, 471–485, <https://doi.org/10.1080/02640410252925143>
- Farrow, D., & Abernethy, B., (2003), Do Expertise and the Degree of Perception—Action Coupling Affect Natural Anticipatory Performance?, *Perception*, *32*9, 1127–1139, <https://doi.org/10.1068/p3323>
- Faubert, J., (2013), Professional athletes have extraordinary skills for rapidly learning complex and neutral dynamic visual scenes, *Scientific Reports*, *3*1, <https://doi.org/10.1038/srep01154>
- Faure, C., Limballe, A., Bideau, B., & Kulpa, R., (2019), Virtual reality to assess and train team ball sports performance: A scoping review, *Journal of Sports Sciences*, 1–14, <https://doi.org/10.1080/02640414.2019.1689807>
- Fulvio, J. M., & Rokers, B., (2017), Use of cues in virtual reality depends on visual feedback, *Scientific Reports*, *7*1, <https://doi.org/10.1038/s41598-017-16161-3>
- Galley, N., (1989), Saccadic eye movement velocity as an indicator of (de)activation. A review and some speculations, *Journal of Psychophysiology*, *3*, 229–244.

-
- Gerig, N., Mayo, J., Baur, K., Wittmann, F., Riener, R., & Wolf, P., (2018), Missing depth cues in virtual reality limit performance and quality of three dimensional reaching movements, *PloS One*, *13*(1), e0189275, <https://doi.org/10.1371/journal.pone.0189275>
- Gibson, J., (1979), *The Ecological Approach to Perception*, Boston : Houghton Mifflin.
- Goodale, M. A., (2017), Duplex Vision: Separate Cortical Pathways for Conscious Perception and the Control of Action, In S. Schneider & M. Velmans (Eds.), *The Blackwell Companion to Consciousness* (1st ed., pp. 648–661), Wiley, <https://doi.org/10.1002/9781119132363.ch46>
- Goodale, M. A., & Milner, A., (1992), Separate visual pathways for perception and action, *Trends in Neurosciences*, *15*(1), 20–25, [https://doi.org/10.1016/0166-2236\(92\)90344-8](https://doi.org/10.1016/0166-2236(92)90344-8)
- Gray, R., (2017), Transfer of Training from Virtual to Real Baseball Batting, *Frontiers in Psychology*, *8*, 2183, <https://doi.org/10.3389/fpsyg.2017.02183>
- Gray, R., (2019), Virtual environments and their role in developing perceptual-cognitive skills in sports [Num Pages: 17]. In *Anticipation and Decision Making in Sport*, Routledge.
- Harris, D. J., Buckingham, G., Wilson, M. R., Brookes, J., Mushtaq, F., Mon-Williams, M., & Vine, S. J., (2020), The effect of a virtual reality environment on gaze behaviour and motor skill learning, *Psychology of Sport and Exercise*, *50*, 101721, <https://doi.org/10.1016/j.psychsport.2020.101721>
- Harris, D. J., Buckingham, G., Wilson, M. R., & Vine, S. J., (2019), Virtually the same? How impaired sensory information in virtual reality may disrupt vision for action, *Experimental Brain Research*, *237*(11), 2761–2766, <https://doi.org/10.1007/s00221-019-05642-8>
- Harris, D. J., Hardcastle, K. J., Wilson, M. R., & Vine, S. J., (2021), Assessing the learning and transfer of gaze behaviours in immersive virtual reality, *Virtual Reality*, *25*(4), 961–973, <https://doi.org/10.1007/s10055-021-00501-w>
- Harris, D. J., Wilson, M. R., Holmes, T., de Burgh, T., & Vine, S. J., (2022), Eye Movements in Sports Research and Practice: Immersive Technologies as Optimal Environments for the Study of Gaze Behavior [Series Title: Neuromethods], In S. Stuart (Ed.), *Eye Tracking* (pp. 207–221), Springer US, https://doi.org/10.1007/978-1-0716-2391-6_12

-
- Hausegger, T., Vater, C., & Hossner, E.-J., (2019), Peripheral Vision in Martial Arts Experts: The Cost-Dependent Anchoring of Gaze, *Journal of Sport and Exercise Psychology*, *41* 3, 137–146.
- Held, R. T., Cooper, E. A., & Banks, M. S., (2012), Blur and Disparity Are Complementary Cues to Depth, *Current Biology*, *22* 5, 426–431, <https://doi.org/10.1016/j.cub.2012.01.033>
- Hodges, N. J., Wyder-Hodge, P. A., Hetherington, S., Baker, J., Besler, Z., & Spring, M., (2021), Topical Review: Perceptual-cognitive Skills, Methods, and Skill-based Comparisons in Interceptive Sports, *Optometry and Vision Science*, *98* 7, 681–695, <https://doi.org/10.1097/OPX.0000000000001727>
- Hristovski, R., Davids, K., Araujo, D., & Passos, P., (2011), Constraints-induced emergence of functional novelty in complex neurobiological systems: a basis for creativity in sport, *Nonlinear Dynamics, Psychology, and Life Sciences*, *15* 2, 175–206.
- Hukkanen, E., & Häkkinen, K., (2017), Effects of Sparring Load on Reaction Speed and Punch Force During the Precompetition and Competition Periods in Boxing, *Journal of Strength and Conditioning Research*, *31* 6, 1563–1568, <https://doi.org/10.1519/JSC.0000000000001885>
- Hussain, R., Chessa, M., & Solari, F., (2021), Mitigating Cybersickness in Virtual Reality Systems through Foveated Depth-of-Field Blur, *Sensors*, *21* 12, 4006, <https://doi.org/10.3390/s21124006>
- Jackson, R., Abernethy, B., & Wernhart, S., (2009), Sensitivity to fine-grained and coarse visual information: the effect of blurring on anticipation skill., *Int J Sport Psychol*, *40* 4, 461–475.
- Jackson, R. C., Barton, H., Ashford, K. J., & Abernethy, B., (2018), Steppovers and Signal Detection: Response Sensitivity and Bias in the Differentiation of Genuine and Deceptive Football Actions, *Frontiers in Psychology*, *9*, <https://doi.org/10.3389/fpsyg.2018.02043>
- Klimesch, W., (2012), Alpha-band oscillations, attention, and controlled access to stored information, *Trends in Cognitive Sciences*, *16* 12, 606–617, <https://doi.org/10.1016/j.tics.2012.10.007>
- Klinghammer, M., Schütz, I., Blohm, G., & Fiehler, K., (2016), Allocentric information is used for memory-guided reaching in depth: A virtual reality study, *Vision Research*, *129*, 13–24, <https://doi.org/10.1016/j.visres.2016.10.004>

-
- Klostermann, A., & Mann, D. L., (2019), Editorial: Current Issues in Perceptual Training: Facing the Requirement to Couple Perception, Cognition, and Action in Complex Motor Behavior, *Frontiers in Psychology*, *10*, 2680, <https://doi.org/10.3389/fpsyg.2019.02680>
- Klostermann, A., Vater, C., Kredel, R., & Hossner, E.-J., (2015), Perceptual Training in Beach Volleyball Defence: Different Effects of Gaze-Path Cueing on Gaze and Decision-Making, *Frontiers in Psychology*, *6*, <https://doi.org/10.3389/fpsyg.2015.01834>
- Klostermann, A., Vater, C., Kredel, R., & Hossner, E.-J., (2020), Perception and Action in Sports. On the Functionality of Foveal and Peripheral Vision, *Frontiers in Sports and Active Living*, *1*, 66, <https://doi.org/10.3389/fspor.2019.00066>
- Krabben, K., Orth, D., & van der Kamp, J., (2019), Combat as an Interpersonal Synergy: An Ecological Dynamics Approach to Combat Sports, *Sports Medicine*, *49* 12, 1825–1836, <https://doi.org/10.1007/s40279-019-01173-y>
- Krauzlis, R. J., (2004), Recasting the smooth pursuit eye movement system, *J. Neurophysiol.*, *91* 2, 591–603, <https://doi.org/10.1152/jn.00801.2003>
- Kredel, R., Vater, C., Klostermann, A., & Hossner, E.-J., (2017), Eye-Tracking Technology and the Dynamics of Natural Gaze Behavior in Sports: A Systematic Review of 40 Years of Research, *Frontiers in Psychology*, *8*, <https://doi.org/10.3389/fpsyg.2017.01845>
- Krejtz, K., Duchowski, A., Krejtz, I., Szarkowska, A., & Kopacz, A., (2016), Discerning Ambient/Focal Attention with Coefficient K, *ACM Transactions on Applied Perception*, *13* 3, 1–20, <https://doi.org/10.1145/2896452>
- Kwon, M., Liu, R., & Chien, L., (2016), Compensation for Blur Requires Increase in Field of View and Viewing Time (K. Paterson, Ed.), *PLOS ONE*, *11* 9, e0162711, <https://doi.org/10.1371/journal.pone.0162711>
- Laby, D. M., & Appelbaum, L. G., (2021), Review: Vision and On-field Performance: A Critical Review of Visual Assessment and Training Studies with Athletes, *Optometry and Vision Science: Official Publication of the American Academy of Optometry*, *98* 7, 723–731, <https://doi.org/10.1097/OPX.0000000000001729>
- Langer, M. S., & Siciliano, R. A., (2015), Are blur and disparity complementary cues to depth?, *Vision Research*, *107*, 15–21, <https://doi.org/10.1016/j.visres.2014.10.036>

-
- Lesiakowski, P., Lubiński, W., & Zwierko, T., (2018), Evoked potentials in diagnosis of visual dysfunction in amateur boxers, *The Physician and Sportsmedicine*, *46*(4), 449–459, <https://doi.org/10.1080/00913847.2018.1496763>
- Limballe, A., Kulpa, R., & Bennett, S., (2022), Using Blur for Perceptual Investigation and Training in Sport? A Clear Picture of the Evidence and Implications for Future Research, *Frontiers in Psychology*, *12*, retrieved March 8, 2022, from <https://www.frontiersin.org/article/10.3389/fpsyg.2021.752582>
- Llanes-Jurado, J., Marín-Morales, J., Guixeres, J., & Alcañiz, M., (2020), Development and Calibration of an Eye-Tracking Fixation Identification Algorithm for Immersive Virtual Reality, *Sensors*, *20*(17), 4956, <https://doi.org/10.3390/s20174956>
- Lounis, C., Peysakhovich, V., & Causse, M., (2021), Visual scanning strategies in the cockpit are modulated by pilots' expertise: A flight simulator study (P. J. Hills, Ed.), *PLOS ONE*, *16*(2), <https://doi.org/10.1371/journal.pone.0247061>
- Lucas, J. W., (2003), Theory-Testing, Generalization, and the Problem of External Validity, *Sociological Theory*, *21*(3), 236–253, <https://doi.org/10.1111/1467-9558.00187>
- Ma, K., Fu, H., Liu, T., Wang, Z., & Tao, D., (2018), Deep Blur Mapping: Exploiting High-Level Semantics by Deep Neural Networks, *IEEE Transactions on Image Processing*, *27*(10), 5155–5166, <https://doi.org/10.1109/TIP.2018.2847421>
- Mallek, M., Benguigui, N., Dicks, M., & Thouvarecq, R., (2017), Sport expertise in perception–action coupling revealed in a visuomotor tracking task, *European Journal of Sport Science*, *17*(10), 1270–1278, <https://doi.org/10.1080/17461391.2017.1375014>
- Mann, D. L., Abernethy, B., & Farrow, D., (2010a), Visual information underpinning skilled anticipation: The effect of blur on a coupled and uncoupled in situ anticipatory response, *Attention, Perception & Psychophysics*, *72*(5), 1317–1326, <https://doi.org/10.3758/APP.72.5.1317>
- Mann, D. L., Abernethy, B., & Farrow, D., (2010b), The resilience of natural interceptive actions to refractive blur, *Human Movement Science*, *29*(3), 386–400, <https://doi.org/10.1016/j.humov.2010.02.007>
- Mann, D. L., Ho, N. Y., De Souza, N. J., Watson, D. R., & Taylor, S. J., (2007), Is optimal vision required for the successful execution of an interceptive task?, *Human Movement Science*, *26*(3), 343–356, <https://doi.org/10.1016/j.humov.2006.12.003>
- Mann, D., Williams, A. M., Ward, P., & Janelle, C. M., (2007), Perceptual-cognitive expertise in sport: a meta-analysis, *Journal of Sport & Exercise Psychology*, *29*(4), 457–478.

-
- Marteniuk, R. G., (1976), *Information processing in motor skills*, Holt, Rinehart; Winston.
- Martínez de Quel, Ó., & Bennett, S. J., (2019), Perceptual-cognitive expertise in combat sports: a narrative review and a model of perception-action., *RICYDE. Revista internacional de ciencias del deporte*, *15* 58, 323–338, <https://doi.org/10.5232/ricyde2019.05802>
- Michalski, S. C., Szpak, A., & Loetscher, T., (2019), Using Virtual Environments to Improve Real-World Motor Skills in Sports: A Systematic Review, *Frontiers in Psychology*, *10*, 2159, <https://doi.org/10.3389/fpsyg.2019.02159>
- Milazzo, N., Bernier, M., Rosnet, E., Farrow, D., & Fournier, J., (2016a), L'entraînement cognitivo-perceptif basé sur la vidéo et ses modes d'instructions, *Psychologie Française*, *61* 4, 273–289.
- Milazzo, N., Farrow, D., & Fournier, J. F., (2016b), Effect of Implicit Perceptual-Motor Training on Decision-Making Skills and Underpinning Gaze Behavior in Combat Athletes, *Perceptual and Motor Skills*, *123* 1, 300–323, <https://doi.org/10.1177/0031512516656816>
- Miles, H. C., Pop, S. R., Watt, S. J., Lawrence, G. P., & John, N. W., (2012), A review of virtual environments for training in ball sports, *Computers & Graphics*, *36* 6, 714–726, <https://doi.org/10.1016/j.cag.2012.04.007>
- Milner, A., & Goodale, M., (2008), Two visual systems re-viewed, *Neuropsychologia*, *46* 3, 774–785, <https://doi.org/10.1016/j.neuropsychologia.2007.10.005>
- Mishra, V., Sreenivasan, K., Banks, S. J., Zhuang, X., Yang, Z., Cordes, D., & Bernick, C., (2018), Investigating structural and perfusion deficits due to repeated head trauma in active professional fighters, *NeuroImage. Clinical*, *17*, 616–627, <https://doi.org/10.1016/j.nicl.2017.11.013>
- Moriarty, J., Collie, A., Olson, D., Buchanan, J., Leary, P., McStephen, M., & McCrory, P., (2004), A prospective controlled study of cognitive function during an amateur boxing tournament, *Neurology*, *62* 9, 1497–1502, <https://doi.org/10.1212/WNL.62.9.1497>
- Moriarty, J. M., Pietrzak, R. H., Kutcher, J. S., Clausen, M. H., McAward, K., & Darby, D. G., (2012), Unrecognised ringside concussive injury in amateur boxers, *British Journal of Sports Medicine*, *46* 14, 1011–1015, <https://doi.org/10.1136/bjsports-2011-090893>
- Müller, S., Dekker, E., Morris-Binelli, K., Piggott, B., Hoyne, G., Christensen, W., Fadde, P., Zaichkowsky, L., Brenton, J., & Hambrick, D. Z., (2022), Attributes of Expert

-
- Anticipation Should Inform the Design of Virtual Reality Simulators to Accelerate Learning and Transfer of Skill, *Sports Medicine*, <https://doi.org/10.1007/s40279-022-01735-7>
- Murphy, C. P., Jackson, R. C., Cooke, K., Roca, A., Benguigui, N., & Williams, A. M., (2016), Contextual information and perceptual-cognitive expertise in a dynamic, temporally-constrained task., *Journal of Experimental Psychology: Applied*, *22*(4), 455–470, <https://doi.org/10.1037/xap0000094>
- Murphy, C. P., Jackson, R. C., & Williams, A. M., (2018), The role of contextual information during skilled anticipation, *Quarterly Journal of Experimental Psychology*, *71*(10), 2070–2087, <https://doi.org/10.1177/1747021817739201>
- Murray, S. O., Schallmo, M.-P., Kolodny, T., Millin, R., Kale, A., Thomas, P., Rammsayer, T. H., Troche, S. J., Bernier, R. A., & Tadin, D., (2018), Sex Differences in Visual Motion Processing, *Current Biology*, *28*(17), 2794–2799.e3, <https://doi.org/10.1016/j.cub.2018.06.014>
- Negi, S., & Mitra, R., (2020), Fixation duration and the learning process: an eye tracking study with subtitled videos, *Journal of Eye Movement Research*, *13*(6), <https://doi.org/10.16910/jemr.13.6.1>
- Neumann, D. L., Moffitt, R. L., Thomas, P. R., Loveday, K., Watling, D. P., Lombard, C. L., Antonova, S., & Tremeer, M. A., (2018), A systematic review of the application of interactive virtual reality to sport, *Virtual Reality*, *22*(3), 183–198, <https://doi.org/10.1007/s10055-017-0320-5>
- North, J. S., Hope, E., & Williams, A. M., (2017), The Role of Verbal Instruction and Visual Guidance in Training Pattern Recognition, *Frontiers in Psychology*, *8*, <https://doi.org/10.3389/fpsyg.2017.01473>
- Oleskiw, T. D., Nowack, A., & Pasupathy, A., (2018), Joint coding of shape and blur in area V4, *Nature Communications*, *9*(1), 466, <https://doi.org/10.1038/s41467-017-02438-8>
- Ottoboni, G., Russo, G., & Tessari, A., (2015), What boxing-related stimuli reveal about response behaviour, *Journal of Sports Sciences*, *33*(10), 1019–1027, <https://doi.org/10.1080/02640414.2014.977939>
- Pannasch, S., & Velichkovsky, B. M., (2009), Distractor effect and saccade amplitudes: Further evidence on different modes of processing in free exploration of visual images, *Visual Cognition*, *17*(6-7), 1109–1131, <https://doi.org/10.1080/13506280902764422>

-
- Pastel, S., Chen, C.-H., Martin, L., Naujoks, M., Petri, K., & Witte, K., (2021), Comparison of gaze accuracy and precision in real-world and virtual reality, *Virtual Reality*, 25 1, 175–189, <https://doi.org/10.1007/s10055-020-00449-3>
- Pastel, S., Marlok, J., Bandow, N., & Witte, K., (2022), Application of eye-tracking systems integrated into immersive virtual reality and possible transfer to the sports sector - A systematic review, *Multimedia Tools and Applications*, <https://doi.org/10.1007/s11042-022-13474-y>
- Petri, K., Bandow, N., Masik, S., & Witte, K., (2019a), Improvement of Early Recognition of Attacks in Karate Kumite Due to Training in Virtual Reality, *Journal Sport Area*, 4 2, 294, [https://doi.org/10.25299/sportarea.2019.vol4\(2\).3370](https://doi.org/10.25299/sportarea.2019.vol4(2).3370)
- Petri, K., Bandow, N., Salb, S., & Witte, K., (2019b), The influence of facial expressions on attack recognition and response behaviour in karate kumite, *European Journal of Sport Science*, 19 4, 529–538, <https://doi.org/10.1080/17461391.2018.1536170>
- Petri, K., Emmermacher, P., Danneberg, M., Masik, S., Eckardt, F., Weichelt, S., Bandow, N., & Witte, K., (2019c), Training using virtual reality improves response behavior in karate kumite, *Sports Engineering*, 22 1, <https://doi.org/10.1007/s12283-019-0299-0>
- Petri, K., Masik, S., Danneberg, M., Emmermacher, P., & Witte, K., (2019d), Possibilities to Use a Virtual Opponent for Enhancements of Reactions and Perception of Young Karate Athletes, *International Journal of Computer Science in Sport*, 18 2, 20–33, <https://doi.org/10.2478/ijcss-2019-0011>
- Pinder, R. A., Davids, K., Renshaw, I., & Araújo, D., (2011), Representative learning design and functionality of research and practice in sport, *Journal of Sport and Exercise Psychology*, 33 1, 146–155.
- Raab, M., Bar-Eli, M., Plessner, H., & Araújo, D., (2019), The past, present and future of research on judgment and decision making in sport, *Psychology of Sport and Exercise*, 42, 25–32, <https://doi.org/10.1016/j.psychsport.2018.10.004>
- Rauter, G., Sigrist, R., Koch, C., Crivelli, F., van Raaij, M., Riener, R., & Wolf, P., (2013), Transfer of Complex Skill Learning from Virtual to Real Rowing (A. Szolnoki, Ed.), *PLoS ONE*, 8 12, e82145, <https://doi.org/10.1371/journal.pone.0082145>
- Renshaw, I., Davids, K., Araújo, D., Lucas, A., Roberts, W. M., Newcombe, D. J., & Franks, B., (2019), Evaluating Weaknesses of “Perceptual-Cognitive Training” and “Brain Training” Methods in Sport: An Ecological Dynamics Critique, *Frontiers in Psychology*, 9, <https://doi.org/10.3389/fpsyg.2018.02468>

-
- Ripoll, H., Kerlirzin, Y., Stein, J.-F., & Reine, B., (1995), Analysis of information processing, decision making, and visual strategies in complex problem solving sport situations, *Human Movement Science*, *14* 3, 325–349, [https://doi.org/10.1016/0167-9457\(95\)00019-0](https://doi.org/10.1016/0167-9457(95)00019-0)
- Roca, A., Ford, P. R., McRobert, A. P., & Williams, A. M., (2013), Perceptual-Cognitive Skills and Their Interaction as a Function of Task Constraints in Soccer, *Journal of Sport and Exercise Psychology*, *35* 2, 144–155, <https://doi.org/10.1123/jsep.35.2.144>
- Roca, A., Ford, P. R., & Memmert, D., (2018), Creative decision making and visual search behavior in skilled soccer players (A. Antonietti, Ed.), *PLOS ONE*, *13* 7, e0199381, <https://doi.org/10.1371/journal.pone.0199381>
- Romeas, T., & Faubert, J., (2015), Soccer athletes are superior to non-athletes at perceiving soccer-specific and non-sport specific human biological motion, *Frontiers in Psychology*, *6*, <https://doi.org/10.3389/fpsyg.2015.01343>
- Romeas, T., More-Chevalier, B., Charbonneau, M., & Bieuzen, F., (2022), Virtual-Reality Training of Elite Boxers Preparing for the Tokyo 2020 Olympics During the COVID-19 Pandemic: A Case Study, *Case Studies in Sport and Exercise Psychology*, *6* 1, 21–35, <https://doi.org/10.1123/cssep.2021-0027>
- Rooney, K. K., Condia, R. J., & Loschky, L. C., (2017), Focal and Ambient Processing of Built Environments: Intellectual and Atmospheric Experiences of Architecture, *Frontiers in Psychology*, *08*, <https://doi.org/10.3389/fpsyg.2017.00326>
- Russo, G., & Ottoboni, G., (2019), The perceptual – Cognitive skills of combat sports athletes: A systematic review, *Psychology of Sport and Exercise*, *44*, 60–78, <https://doi.org/10.1016/j.psychsport.2019.05.004>
- Ryu, D., Abernethy, B., Mann, D. L., & Poolton, J. M., (2015), The contributions of central and peripheral vision to expertise in basketball: How blur helps to provide a clearer picture., *Journal of Experimental Psychology: Human Perception and Performance*, *41* 1, 167–185, <https://doi.org/10.1037/a0038306>
- Ryu, D., Abernethy, B., Mann, D. L., Poolton, J. M., & Gorman, A. D., (2013a), The Role of Central and Peripheral Vision in Expert Decision Making, *Perception*, *42* 6, 591–607, <https://doi.org/10.1068/p7487>
- Ryu, D., Abernethy, B., Park, S. H., & Mann, D. L., (2018), The Perception of Deceptive Information Can Be Enhanced by Training That Removes Superficial Visual Information, *Frontiers in Psychology*, *9*, <https://doi.org/10.3389/fpsyg.2018.01132>

-
- Ryu, D., Cooke, A., Bellomo, E., & Woodman, T., (2020), Watch out for the hazard! Blurring peripheral vision facilitates hazard perception in driving, *Accident Analysis & Prevention*, *146*, 105755, <https://doi.org/10.1016/j.aap.2020.105755>
- Ryu, D., Kim, S., Abernethy, B., & Mann, D. L., (2013b), Guiding Attention Aids the Acquisition of Anticipatory Skill in Novice Soccer Goalkeepers, *Research Quarterly for Exercise and Sport*, *84* 2, 252–262, <https://doi.org/10.1080/02701367.2013.784843>
- Ryu, D., Mann, D. L., Abernethy, B., & Poolton, J. M., (2016), Gaze-contingent training enhances perceptual skill acquisition, *Journal of Vision*, *16* 2, 2, <https://doi.org/10.1167/16.2.2>
- Salvucci, D. D., & Goldberg, J. H., (2000), Identifying fixations and saccades in eye-tracking protocols, *Proceedings of the symposium on Eye tracking research & applications - ETRA '00*, 71–78, <https://doi.org/10.1145/355017.355028>
- Savelsbergh, G. J. P., van Gastel, P. J., & van Kampen, P. M., (2010), Anticipation of penalty kicking direction can be improved by directing attention through perceptual learning [Place: Italy Publisher: Edizioni Luigi Pozzi], *International Journal of Sport Psychology*, *41*, 24–41.
- Schmidt, R. A., & Young, D., (1986), Transfer of movement control in motor skill learning. *In Transfer of learning* (Orlando: Academic press).
- Schorer, J., Rienhoff, R., Fischer, L., & Baker, J., (2013), Foveal and Peripheral Fields of Vision Influences Perceptual Skill in Anticipating Opponents' Attacking Position in Volleyball, *Applied Psychophysiology and Biofeedback*, *38* 3, 185–192, <https://doi.org/10.1007/s10484-013-9224-7>
- Shima, N., Markowitz, S. N., & Reyes, S. V., (2010), Concept of a functional retinal locus in age-related macular degeneration, *Canadian Journal of Ophthalmology*, *45* 1, 62–66, <https://doi.org/10.3129/i09-236>
- Slater, M., (2009), Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments, *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364* 1535, 3549–3557, <https://doi.org/10.1098/rstb.2009.0138>
- Slater, M., & Sanchez-Vives, M. V., (2016), Enhancing Our Lives with Immersive Virtual Reality, *Frontiers in Robotics and AI*, *3*, <https://doi.org/10.3389/frobt.2016.00074>
- Smeeton, N. J., Williams, A. M., Hodges, N. J., & Ward, P., (2005), The Relative Effectiveness of Various Instructional Approaches in Developing Anticipation Skill., *Journal*

-
- of *Experimental Psychology: Applied*, 112, 98–110, <https://doi.org/10.1037/1076-898X.11.2.98>
- Smeeton, N., Page, J., Causer, J., Wilson, M., Gray, R., & Williams, A. M., (2013), The BASES Expert Statement on the Effectiveness of Vision Training Programmes., *The Sport and Exercise Scientist*, 38, 12–13.
- Stone, J. A., Strafford, B. W., North, J. S., Toner, C., & Davids, K., (2018), Effectiveness and efficiency of virtual reality designs to enhance athlete development: an ecological dynamics perspective (M. Dicks, J. O'Halloran, & M. Navarro, Eds.), *Movement & Sport Sciences - Science & Motricité*, 102, 51–60, <https://doi.org/10.1051/sm/2018031>
- Strasburger, H., Bach, M., & Heinrich, S. P., (2018), Blur Unblurred—A Mini Tutorial, *i-Perception*, 92, 204166951876585, <https://doi.org/10.1177/2041669518765850>
- Sundstedt, V., & Garro, V., (2022), A Systematic Review of Visualization Techniques and Analysis Tools for Eye-Tracking in 3D Environments, *Frontiers in Neuroergonomics*, 3, 910019, <https://doi.org/10.3389/fnrgo.2022.910019>
- Tirp, J., Steingröver, C., Wattie, N., Baker, J., & Schorer, J., (2015), Virtual realities as optimal learning environments in sport—A transfer study of virtual and real dart throwing [Place: Germany Publisher: Pabst Science Publishers], *Psychological Test and Assessment Modeling*, 57, 57–69.
- Todorov, E., Shadmehr, R., & Bizzi, E., (1997), Augmented Feedback Presented in a Virtual Environment Accelerates Learning of a Difficult Motor Task, *Journal of Motor Behavior*, 292, 147–158, <https://doi.org/10.1080/00222899709600829>
- Van der Kamp, J., Rivas, F., Van Doorn, H., & Savelsbergh, G., (2008), Ventral and dorsal system contributions to visual anticipation in fast ball sports, *International Journal of Sport Psychology*, 392, 100.
- Van der Stigchel, S., Bethlehem, R. A. I., Klein, B. P., Berendschot, T. T. J. M., Nijboer, T. C. W., & Dumoulin, S. O., (2013), Macular degeneration affects eye movement behavior during visual search, *Frontiers in Psychology*, 4, <https://doi.org/10.3389/fpsyg.2013.00579>
- van Biemen, T., Koedijker, J., Renden, P. G., & Mann, D. L., (2018), The Effect of Blurred Perceptual Training on the Decision Making of Skilled Football Referees, *Frontiers in Psychology*, 9, <https://doi.org/10.3389/fpsyg.2018.01803>
- Vater, C., Kredel, R., & Hossner, E.-J., (2017a), Detecting target changes in multiple object tracking with peripheral vision: More pronounced eccentricity effects for

-
- changes in form than in motion., *Journal of Experimental Psychology: Human Perception and Performance*, 43 5, 903–913, <https://doi.org/10.1037/xhp0000376>
- Vater, C., Kredel, R., & Hossner, E.-J., (2017b), Examining the functionality of peripheral vision: From fundamental understandings to applied sport science [Publisher: University of Bern], https://doi.org/10.15203/CISS_2017.010
- Vater, C., Williams, A. M., & Hossner, E.-J., (2019), What do we see out of the corner of our eye? The role of visual pivots and gaze anchors in sport, *International Review of Sport and Exercise Psychology*, 1–23, <https://doi.org/10.1080/1750984X.2019.1582082>
- Vickers, J. N., (2007), *Perception, cognition, and decision training: The quiet eye in action* [Pages: xii, 267], Human Kinetics.
- Vignais, N., Kulpa, R., Brault, S., Presse, D., & Bideau, B., (2015), Which technology to investigate visual perception in sport: Video vs. virtual reality, *Human movement science*, 39, 12–26.
- Warren, W. H., (1984), Perceiving affordances: visual guidance of stair climbing, *J Exp Psychol Hum Percept Perform*, 10 5, 683–703.
- Watson, A. B., & Ahumada, A. J., (2011), Blur clarified: A review and synthesis of blur discrimination, *Journal of Vision*, 11 5, 10, <https://doi.org/10.1167/11.5.10>
- Williams, A., & Jackson, R., (2019), Anticipation in sport: Fifty years on, what have we learned and what research still needs to be undertaken?, *Psychology of Sport and Exercise*, 42, 16–24, <https://doi.org/10.1016/j.psychsport.2018.11.014>
- Williams, A. M., (2009), Perceiving the intentions of others: how do skilled performers make anticipation judgments? *In Progress in Brain Research* (pp. 73–83), Elsevier, [https://doi.org/10.1016/S0079-6123\(09\)01307-7](https://doi.org/10.1016/S0079-6123(09)01307-7)
- Williams, A. M., (2013), *Science and soccer: developing elite performers* (3rd ed), Routledge.
- Williams, A. M., & Elliott, D., (1999), Anxiety, Expertise, and Visual Search Strategy in Karate, *Journal of Sport and Exercise Psychology*, 21 4, 362–375, <https://doi.org/10.1123/jsep.21.4.362>
- Williams, A. M., Ford, P. R., Eccles, D. W., & Ward, P., (2011), Perceptual-cognitive expertise in sport and its acquisition: Implications for applied cognitive psychology, *Applied Cognitive Psychology*, 25 3, 432–442, <https://doi.org/10.1002/acp.1710>
- Williams, A. M., Ward, P., Smeeton, N. J., & Allen, D., (2004), Developing Anticipation Skills in Tennis Using On-Court Instruction: Perception versus Perception and

Action, *Journal of Applied Sport Psychology*, 164, 350–360, <https://doi.org/10.1080/10413200490518002>

Zhang, Z., Piras, A., Chen, C., Kong, B., & Wang, D., (2022), A comparison of perceptual anticipation in combat sports between experts and non-experts: A systematic review and meta-analysis, *Frontiers in Psychology*, 13, 961960, <https://doi.org/10.3389/fpsyg.2022.961960>

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Titre : Impact du flou Gaussien sur le comportement perceptivo-moteur en boxe : une évaluation en réalité virtuelle.

Mot clés : Réalité virtuelle, anticipation, flou Gaussien, boxe, capacités perceptivo-cognitives.

Résumé : Les compétences perceptivo-cognitives sont essentielles à la performance en boxe mais restent peu entraînées. Ce projet vise à exploiter les propriétés de la réalité virtuelle (standardisation des stimuli, reproductibilité, préservation du couplage perception-action, quantification de la performance en interaction...) afin de proposer de nouveaux outils pour l'évaluation et l'optimisation des processus perceptivo-cognitifs sous-jacents à la performance. En particulier, cette thèse s'intéresse à l'impact d'un flou visuel sur les capacités d'anticipation (prise d'information) des boxeurs. Le flou altère les informations de détail qui peuvent agir comme des distracteurs mais préserve les informations essentielles telles que le mouvement cinématique de base des membres de l'adver-

saire par exemple. Les premières études ont été réalisées dans des contextes perceptifs limités (vidéo en vision monoscopique), avec des effets disparates sur la performance et ne permettent donc pas de conclure sur son influence. L'objectif est donc d'évaluer l'impact du flou visuel sur les capacités d'anticipation de boxeurs de différents niveaux en réalité virtuelle. De plus, en raison du lien entre le flou et la vision périphérique, ce projet étudie l'impact du flou 1) en vision centrale par rapport à la vision périphérique (en utilisant le flou conditionné par le regard) ou 2) sur l'adversaire par rapport à l'environnement. Globalement, les résultats de trois expériences montrent un impact limité du flou sur la performance avec une résilience au flou pour les participants experts.

Title: Impact of Gaussian blur on perceptual-motor behaviour in boxing: A virtual reality assessment.

Keywords: Virtual reality, anticipation, Gaussian blur, boxing, perceptual-cognitive skills.

Abstract: Perceptual-cognitive skills are essential to performance in boxing but remain poorly trained. This project is aiming at exploiting the properties of virtual reality (standardization of stimuli, reproducibility, preservation of perception-action coupling, quantification of performance in interaction...) in order to propose new tools for the assessment and optimization of perceptual-cognitive processes underlying performance. Particularly, this PhD was interested in the impact of a visual blur on the boxers' anticipation capacities (information pick-up). The blur alters the fine details information that can act as distractors but preserves essential information such as the basic kinematic movement of the opponent's limbs for example. Initial studies have

been carried out in limited perceptual settings (video in monoscopic vision), with disparate effect on performance and therefore do not allow to conclude on its influence. The objective is therefore to evaluate the impact of visual blur on the anticipation capacities of boxers of different levels in virtual reality. Moreover, because of the link between blur and peripheral vision, this project investigates blur impact 1) in central compared to peripheral vision (using gaze-contingent blur) or 2) on the opponent compared to the surrounding environment. Overall, the results of three experiments show limited impact of the blur on performance with a resilience to blur for experts' participants.