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Using blur for perceptual investigation and training in sport? A clear picture of the evidence and implications for future research

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2 ABSTRACT

3 **Dynamic, interactive sports require athletes to identify, pick-up and process relevant**
4 **information in a very limited time, in order to then make an appropriate response.**
5 **Perceptual-cognitive skills are therefore a key determinant of elite sporting performance.**
6 **Recently, sport scientists have investigated ways to assess and train perceptual-**
7 **cognitive skills, with one such method involving the use of blurred stimuli. Here, we**
8 **describe the two main methods used to generate blur (i.e., dioptric and Gaussian) and**
9 **then review the current findings in a sports context. Overall, it has been shown the use**
10 **of blur can enhance performance and learning of sporting tasks in novice participants,**
11 **especially when the blur is applied to peripheral stimuli. However, while intermediate and**
12 **expert level participants are relatively impervious to the presence of blur, it remains to be**
13 **determined if they are positive effects on learning. In a final section, we describe some of**
14 **the methodological issues that limit the application of blur and then discuss the potential**
15 **use of virtual reality to extend the current research base in sporting contexts.**

16 **Keywords:** Blur, sport, perceptual -cognitive skills, virtual reality.

1 INTRODUCTION

17 For more than two decades, sport scientists have investigated the contribution of perceptual-cognitive
18 skills such as anticipation, attention and decision making to expertise, and thereby expert performance
19 (Mann et al., 2007b; Williams and Jackson, 2019; Williams et al., 2011). It is now well accepted that
20 experienced/skilled athletes in dynamic and interactive sports are better at anticipating an opponent's
21 movement (Williams and Jackson, 2019) and consequently make earlier and more appropriate decisions
22 (Raab et al., 2019). In addition, they can achieve high levels of performance on the basis of less information,
23 whether that be due to temporal (e.g., information determined earlier) or spatial (e.g., information
24 determined from fewer stimuli) constraints (Mann et al., 2007b; Williams and Jackson, 2019; Williams
25 et al., 2011). Compared to novices, overall performance of experts is better when the environment is
26 impoverished, thus indicating that the experts' ability to extract basic kinematic information is more
27 resistant to visual stimuli deterioration. In part based on such findings, the role of visual functions such
28 as acuity and contrast sensitivity have often been overlooked. Indeed, it is found in most sports that there

29 is no additional advantage of supra-threshold levels of visual function (i.e., above the general population
30 average), and thus little or no benefit of general visual training programmes aimed at improving vision to
31 above-normal levels (Williams and Jackson, 2019). Somewhat counterintuitively, however, several studies
32 have shown that perceptual and perceptual-motor behaviour does not deteriorate (Mann et al., 2010a; Ryu
33 et al., 2018; van Biemen et al., 2018), or can even be improved (Jackson et al., 2009; van Biemen et al.,
34 2018), when the visual stimulus is artificially blurred by the experimenter. Early signs of an improvement
35 of performance in the presence of blur (Jackson et al., 2009) has led to several studies on the use of blur to
36 improve perception, anticipation and decision making, with the largest improvements typically found in
37 novices and/or less skilled participants (Jackson et al., 2009; Ryu et al., 2013, 2015, 2016). However, it
38 seems there is less evidence for a positive impact of blur on performance of experts (van Biemen et al.,
39 2018), and even a negative effect in some studies and particular tasks (Ryu et al., 2013, 2015, 2016).

40

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

2 DIOPTRIC VS GAUSSIAN BLUR – CONCEPTUAL ASPECT

51 Normal healthy vision typically involves a seamless integration of high acuity and low acuity (i.e., blurred)
52 inputs from the central and peripheral retina. Indeed, one does not normally notice that objects located
53 away from the point of fixation are in fact blurred, even though this can provide useful information on
54 spatial location (e.g., depth from crossed and uncrossed disparity). In normal or corrected-to-normal vision,
55 high acuity input is perceived from cone cells that are concentrated at the centre of the eye in the area
56 known as the fovea. Cone cells detect light of different wavelengths, which is the basis of colour perception,
57 operate best in bright light, and enable perception of fine details (i.e., high spatial frequency). They thus
58 play a critical role in being able to distinguish shapes and details of objects in our surrounds. The other
59 main photoreceptor cells, known as rods, are not attuned to the same light wavelengths as cones, but they
60 are more sensitive to light and are located mainly in the peripheral region outside the fovea. Although more
61 numerous than cone cells, multiple rod cells converge onto single retinal ganglion cells, thus resulting in
62 a specialisation for processing low spatial frequency visual stimuli, as well as motion. **More, the blur is
63 considered to be a depth cue allowing a strong estimation, associated with disparity. (Held et al., 2012;
64 Hussain et al., 2021; Langer and Siciliano, 2015). Indeed, the binocular disparity gives consistent indication
65 of depth in the area close to the fixation point but become less relevant for estimation away from the
66 fixation location, as an increase gradient (Sprague et al., 2016). To accurately estimate away from it, the blur
67 integrated in the vision proposes good support (Langer and Siciliano, 2015; Held et al., 2012).** Accordingly,
68 in those with normal healthy vision, individuals fixate gaze location in a way to best combine high acuity
69 and low acuity input. For example, in combat sports such as French boxing (Ripoll et al., 1995) and Karate
70 (Milazzo et al., 2016; Williams and Elliott, 1999), experts direct their eye gaze mainly to the head and
71 trunk of the opponent, whereas less experienced individuals tend to look at the opponent's fist and arms.

72 Presumably, fixating gaze on a relatively static location (i.e., the center of the opponent's body) facilitates
73 perception of information from central and peripheral vision. Indeed, minimizing the number of saccades
74 to distal locations (i.e., opponent's fists and feet) would result in fewer periods of saccadic suppression,
75 and thus a more continuous input of information.

76

77 In the presence a partial central blur (e.g., macular degeneration), and hence the removal or alteration
78 of high spatial frequency stimulus characteristics, individuals often respond by changing gaze fixation to
79 a location that still enables a reasonable perception of object characteristics (Shima et al., 2010; Van der
80 Stigchel et al., 2013). Similar effects on gaze location and outcome performance have been reported when
81 a partial central blur has been artificially introduced by the experimenter (Ryu et al., 2015, 2016). Even
82 when there is a full blur applied across central and peripheral vision, individuals can still exhibit high levels
83 of performance in some tasks (Mann et al., 2010a) presumably from processing low spatial frequency input
84 such as motion and spatial layout. Importantly, however, while the impact of both experimenter-imposed
85 partial and full blur has been studied in a sporting context, this has been achieved using two different
86 methods (i.e., dioptric blur and Gaussian blur). As we highlight below, these methods do not influence the
87 stimulus in the same way and could thus impact upon the experimental findings.

88

89 A dioptric blur is equivalent to optical defocus caused by a visual impairment (e.g., myopia) or inaccurate
90 accommodation. Experimentally, this is achieved using lenses (i.e., contact lenses or glasses) that alter
91 focal length, thereby increasing focal length error and creating a so-called blur disk on the retina that
92 is a function of defocus (in diopters) and pupil diameter. The consequence of wearing such lenses is a
93 perturbation of high spatial frequency information, and thus a reduction in contrast sensitivity and visual
94 acuity due to the stimulus edges being more difficult to discriminate (Kwon et al., 2016; Strasburger et al.,
95 2018; Watson and Ahumada, 2011). The relative reduction in visual acuity (i.e., acuity with blur / best
96 corrected acuity) can be derived as $1 / 1 + D^2$, where D is the spherical error in diopters. Accordingly, as
97 was reported by Bulson et al. (2008), it is possible to create different conditions of optical defocus, using
98 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
99 90 and +10 D) and estimate the corresponding level of visual acuity (20/20, 20/25, 20/60 20/100, 20/180,
100 20/25, 20/60 and 20/2000). Improving on this relative course estimation, Mann et al. (2010b) recognized
101 the importance of taking into account best corrected visual acuity, although they did rely on the mean
102 habitual visual acuity across participants (i.e., 6/5.3) when estimating the effect of three dioptric lenses
103 (i.e., +1.00D, +2.00D, +3.00D) on mean visual acuity (i.e., 6/11, 6/20 and 6/49).

104

105 The other experiments described in this review applied a Gaussian blur on images viewed on a computer
106 monitor. A Gaussian blur is the result of an image or video processing procedure, whereby the optical
107 system of the eye is unperturbed but the displayed stimuli are altered by removing the high frequency
108 information (Kwon et al., 2016; Ma et al., 2018; Oleskiw et al., 2018; Strasburger et al., 2018; Watson and
109 Ahumada, 2011). A Gaussian blur is different from dioptric blur in the sense that it does not create spurious
110 resolution (see below) and does have a simple relationship with visual acuity. In terms of computation,
111 the method requires the calculation of the transformation that needs to be applied to each pixel when
112 rendering the image; it is the result of applying a Gaussian function to the pixel matrix. The Fourier
113 transform decomposes the domains of frequencies contained in the image. Applying a Fourier transform to
114 a Gaussian results in another Gaussian, and is thus similar to a low pass filtering to remove the high spatial
115 frequencies (Ma et al., 2018; Strasburger et al., 2018). The new pixel coloration is the weighted average of

116 the neighbored pixel characteristics included in the computation. Different software can be used to apply
117 the processing, with directly implemented tool or custom processing. For example, Jackson et al. (2009)
118 added 20% and 40% blur in both horizontal and vertical dimensions using the special effects module in
119 Pinnacle editing software. Unfortunately, details on this method of applying the Gaussian were scant, thus
120 making it difficult to compare both the experimental condition and results to other studies. van Biemen
121 et al. (2018) also used software (Premiere Pro CC software) and the camera blur option to create their
122 blur video, whereas Ryu et al. (2015, 2016) used the Adobe Premiere CS 4 software to apply a low-pass
123 Gaussian filter with the 20, 50 and 100 units option.

125 It is often assumed that the dioptric and Gaussian blur are equivalent because they both alter the spatial
126 frequencies of an image. However, as described by Strasburger et al., (2018), dioptric blur is a consequence
127 of naturally occurring or experimenter-imposed alterations in physiological optics and is not identical
128 to low-pass filtering (i.e., Gaussian blur) of a computer image. This becomes particularly evident when
129 considering the point-spread function (PSF) that results from different methods of blur, and the resulting
130 spurious resolution that is available in conditions of dioptric blur (see figure 1). For example, Strasburger
131 et al. showed that high spatial frequencies are detectable under dioptric blur, meaning that the orientation
132 of a sine-wave grating may still be discernible but the appearance of blurred optotypes are likely too
133 dissimilar from the original unblurred counterparts to permit identification without extended practice. No
134 such spurious resolution is present when blur is created by low-pass Gaussian filtering (Strasburger et al.,
135 2018). Consequently, while dioptric blur is easy to implement and is closest to the naturally-occurring blur
136 caused by some visual impairments (e.g., myopia, presbyopia), it is debatable whether it is suitable for
137 experimentation in a sporting context unless the study aims to investigate the effect of a visual impairment.
138 That said, the application of Gaussian blur is not without limitations, such as the use of diverse software
139 and computer algorithms, as well as a lack of coherence between the level of induced blur and visual acuity.
140 These differences between dioptric and Gaussian blur have not been explicitly recognised in most research
141 to date on blur in a sport context.

143 Insert figure 1 here.

3 THE EFFECT OF BLUR ON ANTICIPATION AND DECISION MAKING

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

153 An interaction was found between anticipation skill (“good anticipators” vs. “poor anticipators”) and
154 the level of blur. Performance of “good anticipators” was more disturbed with a low level of blur,
155 such that performance declined significantly from the 0% to 20% blur condition (approximately -0.2
156 mean transformed accuracy). In contrast, performance of “poor anticipators” was slightly better in the
157 20% compared to 0% blur condition (approximately +0.03 mean transformed accuracy). Despite these

158 significant group differences between the 0% and 20% blur conditions, performance of both groups was
159 equal in the 20% blur condition. Moreover, both groups exhibited a similarly small increase in performance
160 from the 20% to 40% blur condition. Overall, then, participants who were better at anticipating in the normal
161 vision condition did not maintain this advantage with the introduction of the blur, as the authors expected.
162 Only participants who were less competent in the normal vision condition exhibited an improvement in
163 performance following the introduction of 20% and 40% blur, thus providing some preliminary support
164 for the suggestion that the application of blur can make participants more attuned to basic kinematic
165 information (i.e., motion).

166

167 According to the Jackson et al. (2009), an explanation for the non-linear effects of blur could be a change
168 in participant's strategy. That is, in 20% blur condition, better anticipators could have still been looking
169 for the high spatial frequency visual information, which was missing and thus performance declined.
170 However, in 40% blur condition, participants may have changed strategy and thereby become more attuned
171 to the essential movement kinematics that was present in the low spatial frequency information. While
172 a reasonable account for the findings, the strategies used by players, whether unconscious or conscious,
173 cannot be determined based on the recording of performance alone. Moreover, because there was only a
174 single testing session, it is likely that blur acted as a momentary perturbation.

175

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

188

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

200

201 In terms of gaze behaviour, no changes were noted in fixation duration and breadth of search after training.
202 A small change in saccadic amplitude was reported ($p=0.058$), with larger saccades during retention test
203 compared to pre-test and post-test, but this was the same for all groups. The time spent on the area of
204 interest revealed some more notable differences between groups. The low frequency group (blurred video)
205 spent more time with gaze located on racquet-shuttle contact in post-test and retention compared to normal
206 group. However, they also spent less time fixating on the head compared to normal group but in the
207 retention test only. The high frequency group spent less time fixating the head, compared to normal group
208 but only in the post-test. There were no differences between these two groups at pre-test and retention test.
209

210 As described above, the trials used in training did not contain deceptive intent. Still, such training seemed
211 to help participants recognise deceptive movement in post-test and retention, even though they did not
212 face any examples of deceptive actions. According to the authors, the training intervention encouraged
213 participants to rely more on the meaningful information, which they were then able to disambiguate from
214 deceptive information in the post-test. This was supported by the finding that the low frequency training
215 group decreased the time spent directing gaze toward the face of the opponent, instead locating gaze
216 toward the racquet-shuttle contact, presumably to extract the most useful information. This pattern can
217 be considered an improvement of visual strategy, and is consistent with the pattern of eye movement
218 observed in experts (Mann et al., 2007a). Indeed, gaze direction and facial expression can be used to
219 fake one's intention and mislead an opponent, thus indicating that the head area could be a source of
220 distracting information (Petri et al., 2019). Conversely, the racquet-shuttle contact point contains important
221 information about the direction of the shuttle and the type of shot.
222

223 The studies discussed up to this point were primarily based on novice populations (Bulson et al., 2008;
224 Applegate and Applegate, 1992; Jackson et al., 2009; Ryu et al., 2018) and indicated some evidence
225 that blur can improve anticipation performance, and potentially maintain this improvement following a
226 relatively short, 7-day intervention ((Ryu et al., 2018). These positive effects on performance and learning
227 could have occurred because blur alters the process of visual information extraction. That is, applying a
228 blur removes some irrelevant or even distractive information, which helps novices avoid an overload in
229 visual processing when confronted with a multitude of stimuli. In the blur condition, the task could in effect
230 become easier as participants are guided to the most useful information. However, such positive effects of
231 manipulating blur are more limited for experts, and could even be detrimental. For example, it could be
232 that experts have already learned to extract useful kinematic information from the environment, and as such
233 removing high frequency information conveys no advantage, or even a disadvantage if experts use some
234 aspect of high frequency information to support their perceptual-motor behaviour. One such study of an
235 expert population was reported by (van Biemen et al., 2018), who investigated decision making of skilled
236 football referees in a blurred condition. This represents an interesting population because although they are
237 not skilled in performing the motor activity per se, referees are skilled in observing and detecting deceptive
238 intent and movement of players. The 22 participants in this study were divided into two training groups:
239 normal vision training and blurred vision training. The training took 45 minutes and was run the same day
240 as a pre-test and post-test, which required the referees to make judgments on whether the situation shown
241 in a video clip was a foul or not (26 clips, 13 foul and 13 no foul). The training intervention comprised
242 70 clips in which all situations showed a foul. In this phase, the referees had to judge the severity of the
243 foul, choosing to award a red card, yellow card, or no card as quickly as possible. Feedback on the correct
244 response was given after each trial.
245

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

4 PERCEPTUAL-MOTOR BEHAVIOUR IN THE PRESENCE OF BLUR

257 In an early investigation, Applegate and Applegate (1992) compared basketball shooting performance
258 under five conditions in which dioptric blur was achieved using 6/6, 6/12, 6/24, 6/48 and 6/75 diopter
259 lenses. The 19 male participants (all with a visual acuity of 6/6) performed 25 shots from one position in
260 each condition. The authors observed a small drop in performance as a function of dioptric blur from 6/6 to
261 6/12. However, the decrease was not significant, and participants were still able to shoot the basket even
262 with strong level of blur. Moreover, performance remained constant across all other levels of blur (from
263 6/12 to 6/75), thus showing that a static aiming task does not depend on high acuity information.
264

265 In another static aiming task (i.e., golf putting), Bulson et al. (2008) examined the effect of dioptric blur
266 on 16 young participants. Similar to Applegate and Applegate (1992), participants performed the task
267 while wearing different lenses: PLANO, +0.50 D, +1.00 D, +1.50 D, +2.00 D, +1.00 D, +2.00 D and
268 +10 D. These corresponded to visual acuity levels of approximately 20/20, 20/25, 20/60 20/100, 20/180,
269 20/25, 20/60 and 20/2000. It was found that the different levels of blur had little or no effect on completion
270 of the golf putting task. The authors suggested that an adaptation to the blur could have explained the
271 maintenance of performance. In addition, they suggested that automaticity related to repetition of practice
272 at a fixed distance could have minimised the effect of a low level of blur. In fact, it is notable that in both
273 Applegate Applegate (1992) and Bulson et al., (2008), the target was fixed and there was no need to
274 consider information from moving teammates and/or opponents. Thus, it is questionable whether these
275 findings generalise to dynamic sport situations where it is important to follow moving stimuli and anticipate
276 future events.
277

278 To this end, Mann and colleagues conducted a series of studies using a cricket batting interception task,
279 with intermediate to skilled cricket batters (Mann et al., 2007a, 2010a,b). In the first study Mann et al.
280 (2007a), 11 intermediate batters faced a bowling machine under five conditions of refractive blur (PLANO,
281 +1.00D, +2.00D, +3.00D, and normal correction lenses to control the effect of wearing lenses), with four
282 different ball end locations. The authors confirmed that the performance of the cricket batting task did not
283 require normal levels of visual acuity. In fact, there was even a tendency for better performance in +1.00D
284 and +2.00D conditions compared to the PLANO condition. The only decrement in performance was found
285 in +3.00D blur condition, which is recognised as the point of legal blindness.
286

287 In the second study, Mann et al. (2010a) compared the performance of 10 skilled male cricket batters when
288 receiving balls delivered by a real bowler vs. a projection machine. Participants faced 196 trials, comprised
289 of the two ball projection conditions, four blur conditions (PLANO, +1.00D, +2.00D, +3.00D, see figure
290 2) and three different paced ball deliveries (medium-pace only for the machine, slow and fast-pace for
291 the bowler). They found no differences in batting performance between the projection machine and real
292 bowler, irrespective of the blur condition. Again, a significant decrease in batting performance was only
293 found in the +3.00D blur condition. The authors suggested that the resilience of interception to refractive
294 blur could be explained by the batting task being regulated by visual information processed in the dorsal
295 stream, which is sensitive to motion and thus less affected by reduction in visual acuity. Moreover, they
296 concluded that visual acuity is not a primary limiting factor in cricket batting and thus called into question
297 whether there is benefit to improve visual acuity above an average level.
298

299 Insert Figure 2 here.

300 At this point, Mann and colleagues considered whether the effect of blur depended on the type of response
301 required by the participant. To this end, Mann et al. (2010b), examined the influence of refractive blur in
302 conditions where participants (10 skilled male cricket batters) responded to real ball deliveries by verbal
303 response only (uncoupled) or verbal response plus batting movement (coupled). Two ball speed conditions
304 were included (fast and slow), as well as four levels of blur (PLANO, +1.00D, +2.00D, +3.00D). In the
305 uncoupled condition, performance (response accuracy) improved slightly from normal vision to the lowest
306 level of blur, consistent with previous observations (Jackson et al., 2009; Ryu et al., 2018; van Biemen et al.,
307 2018) and remained quite constant as the level of blur was increased. In the coupled condition, performance
308 did not change from normal vision to the lowest level of blur and was better than the uncoupled condition.
309 However, performance did deteriorate at the greater level of blur such that it was no better than performance
310 in the uncoupled condition with the +2.00D blur manipulation, and somewhat worse than the uncoupled
311 condition with the +3.00D blur manipulation.
312

313 Overall, then, the findings again indicate that anticipation performance can be improved (uncoupled
314 condition) or maintained (coupled condition) in conditions of blur, and further that coupled anticipation
315 is better than uncoupled anticipation (Farrow and Abernethy, 2003; Milner and Goodale, 2008; Van der
316 Kamp et al., 2008). The authors suggested that the improvement in performance of the uncoupled task
317 (fast-pace bowler) in some conditions of refractive blur could be explained by a shift in contribution from
318 ventral to dorsal stream processing. A greater reliance on dorsal stream processing could also explain the
319 maintenance of performance in the coupled condition. This interpretation is consistent with the notion
320 that perceptual and perceptual-motor tasks are not dependent on a single processing stream and that the
321 contribution from ventral and dorsal stream processing depends on the task demands and nature of the
322 visual stimuli. For example, although in Mann et al. (2010) there was no need to regulate a complex motor
323 response when giving a verbal response, performance was influenced by the ability to anticipate motion of
324 a fast moving visual object. Accordingly, while blurring the visual stimuli could impact negatively upon
325 perceptual or perceptual-motor tasks that depend on normal levels of visual acuity to identify features and
326 characteristics, this may not be the case if low spatial, high temporal frequency information such as object
327 motion played a major role.
328

5 PERIPHERAL AND CENTRAL BLUR

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

339

340 As the perception of an object or limb as it moves through peripheral vision is based on processing of
341 low spatial, high temporal frequency visual inputs, there should be minimal impact of applying a refractive
342 blur to the entire visual field (Mann et al., 2007a, 2010a,b). In addition, it follows that blurring the entire
343 visual field has limited ability to identify the contribution of specific sources and types of information that
344 experts use to regulate perceptual-motor tasks in dynamic sport settings. This can potentially be overcome
345 using a gaze-contingent blur manipulation (Ryu et al., 2015, 2013, 2016). The general idea is that because
346 eye gaze does not necessarily coincide with covert attention, simply reporting spatial-temporal patterns eye
347 gaze (i.e., visual search behaviour) does not actually indicate what information is being extracted. Indeed,
348 without additional manipulation, it can only be assumed that relevant information is picked-up in peripheral
349 vision. With a gaze-contingent manipulation on a video display, the content of the video is adapted relative
350 to gaze location, with an image artefact applied to a specific area of the display. For example, this method
351 allows the experimenter to alter (e.g., occlude or blur) central vision whilst preserving normal peripheral
352 vision, and vice versa.

353

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

370

371 To overcome the limitations of using an opaque mask, Ryu et al. (2015) revised their earlier 2013 protocol
372 by applying a different level of blur to the gaze-contingent location. In total, there were 19 different viewing
373 conditions (see figure 3) comprised of 5 levels of blur (no blur, low, moderate, high blur and opaque mask)
374 and 5 configurations of visual alteration (see figure 3, i. Moving window – clear/blur. ii. Moving mask
375 -blur/clear. iii. Moving window – blur/opaque. iv. Moving mask – opaque blur. v. Central + peripheral blur,
376 complete blur). **The moving window condition will be referred as peripheral blur and the moving mask as**
377 **central blur**. Only one aspect of vision was altered in conditions a to i (peripheral blur or central blur). In
378 condition j to o, two aspects of vision were altered by combining the gaze-contingent blur manipulation
379 with an opaque mask (e.g., condition j – low level central blur and opaque peripheral vision). In condition
380 p to r, the combination of central and peripheral blur resulted in a uniform blur across the entire visual
381 field. In experiment 4 of the paper, the video clips were occluded at a critical moment (i.e., when the ball
382 carrier had to make a decision to which teammate to pass the ball). The participants (18 skilled and 18
383 less skilled male basketball players) were required to click on a vacant court (response slide) to indicate
384 the position of the most appropriate teammate to receive the ball. Performance was measured in terms of
385 response accuracy and response time.

386

387 Insert figure 3 here.

388

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

402

403 In terms of the conditions where a part of vision was occluded by an opaque mask and the other part was
404 blurred (see panel j. to o.), it was found that performance accuracy of experts was better than novices when
405 a central blur (low and moderate blur) was applied (i.e., peripheral vision opaque). However, experts still
406 performed better when there was no alteration of central vision. Performance of the novices was below
407 the level of chance with blurred central vision and no peripheral vision. Moreover, when the opaque mask
408 was applied to central vision, performance of experts was above the level of chance (contrary to novices),
409 although it did decrease with the introduction of a peripheral blur. For both expert and novice participants,
410 there was an increase in response time in the presence of blur (central or peripheral). Analysis of gaze
411 behaviour revealed somewhat mixed findings. Overall, fixation duration was affected to the same extent by
412 central or peripheral blur when remaining visual field was occluded by an opaque mask, although there
413 were some subtle differences for some levels of central blur. For example, fixation duration increased for
414 the low and moderate central blur but decreased for the high level of central blur, all of which were still

415 longer than the no-blur level. As for saccadic amplitude, both expert and novice participants exhibited an
416 increase when there was a high blur applied to central vision and an opaque mask in the periphery. Finally,
417 saccadic amplitude of novice participants decreased with the levels of blur.
418

6 FROM PERFORMANCE TO LEARNING

419 As described above, while intermediate and expert level participants are relatively impervious to the
420 presence of blur, it seems that there is a facilitatory effect on performance of novices when blurring the
421 entire visual field (Mann et al., 2007a) or only the periphery (Ryu et al., 2013, 2015). The next important
422 question to be considered was whether these performance effects could enhance learning and ultimately
423 be retained. To this end, Ryu et al. (2016) conducted a training study using the gaze contingent blur
424 manipulation. Based on the materials and apparatus reported in Ryu et al. (2013, 2015), the previous
425 study design was extended to include a pre-test (Day 1), intervention (Day 2-4), post-test (Day 5) and
426 retention test (two weeks after the post-test). Fifty novice basketball players (recreational level) completed
427 the pre, post and retention tests in three different conditions (see figure 4): full vision, **peripheral blur** and
428 **central blur**. The response was recorded by clicking on a vacant court slide to indicate the position of the
429 most appropriate teammate to receive the ball. For the intervention, the population was divided into four
430 groups that received different types of training: full vision, **peripheral blur**, **central blur** and control group.
431 Video clips taken from NBA gameplay were viewed in the respective training condition (occlusion at a key
432 passing time), and participants had to decide as quickly and accurately as possible the most suitable action.
433 Feedback on their response accuracy was provided after every trial. The exception was the control group,
434 who watched an NBA dunk contest video, which did not involve any action play or decision-making.
435

436 Insert figure 4 here.
437

438 The authors reported that in the retention test after training, the **peripheral blur** group (clear central vision,
439 blurred peripheral vision) exhibited a slightly better improvement of performance (in terms of response
440 accuracy) than the other 3 groups. They were also the only group to improve from pre-test to post-test, and
441 then from post-test to the retention test in all viewing conditions. Conversely, performance of **central blur**
442 group (blurred central vision, clear peripheral vision) decreased significantly from post-test to retention
443 test, and almost back to the baseline, pre-test level. These results were observed across all the three viewing
444 test conditions, that is, independently of the training modalities they received. Thus, training with the
445 **peripheral blur** manipulation also led to an improvement in the full vision and **central blur** testing condition.
446 Regarding eye behaviour, the specific training regimen did not influence fixation duration. However, taking
447 part in the training intervention per se (i.e, irrespective of training group), led to an overall increase of
448 fixation duration. The authors suggested that the enhanced learning (i.e., best retention) following training
449 in the **peripheral blur** condition was in part a result of the peripheral blur enhancing participants' use of
450 information available in central vision. It was reasoned this occurred because the peripheral blur guided
451 overt attention to information in central vision and away from potential distracting information in peripheral
452 vision, thereby attenuating the overall attentional demands. Then, when transferring to the full vision
453 condition, it was suggested that participants who had trained with a moving window were able to combine
454 their newly learned enhanced use of central visual information with the unrestricted peripheral visual
455 information now available, and thereby further improve decision-making performance.
456

457 More recently, Ryu et al. (2020) applied the gaze contingency manipulation to the detection of hazards in
458 newly licenced drivers compared to experienced drivers. To better determine the mechanism involved in
459 training using blur, the authors also measured cortical activity using EEG (i.e., alpha wave power). The
460 logic is that an increase in alpha wave power reflects an increase in inhibitory control, whereas a decrease
461 in alpha wave power suggests a neural activation. In this way, the high alpha wave power gives a view
462 of basic cognitive processes, and in particular attention suppression and attention selection (Klimesch,
463 2012). Thus, in the situation of driving with blur, a decrease in alpha power would reflect a greater attention
464 dedicated to visual processing (Klimesch, 2012; Ryu et al., 2020). In the first study of the experiment,
465 performance of newly licenced drivers was compared to experienced drivers under full vision, **central**
466 **blur** and **peripheral blur** conditions. Video clips were presented to participants that showed a non-adaptive
467 first-person viewpoint. One or two hazards appeared in the visual field and participants had to identify them
468 as quickly as possible by clicking on the video with a computer mouse. Overall, hazard discrimination and
469 detection time were impaired in the **central blur** condition, while no differences were found between the
470 other two conditions. The **peripheral blur** condition produced longer fixation duration and smaller saccadic
471 amplitudes than the full vision and **central blur** conditions. Regarding the EEG findings, alpha wave power
472 decreased in the **peripheral blur** condition and full viewing condition (e.g., more cortical activation). There
473 was even some evidence that the **peripheral blur** condition offered the most benefit over some parameters
474 like hazard processing time, with longer fixation on hazard and no difference in response time. According
475 to the authors, the **peripheral blur** condition favoured an efficient fixation leading to faster information
476 processing, reflective of a visual search strategy that was more focused on central vision. This statement
477 was supported by evidence of an increase of neural activation in cortical areas involved in perceptual-motor
478 decision making information processing and motor response programming.

479

480 In the second study of the experiment, the authors conducted a training intervention on unlicensed trainee
481 drivers. Based on the findings of the first study, the **central blur** condition was not included, so the design
482 involved a comparison between a **peripheral blur** group (i.e., clear central vision and blurred peripheral
483 vision) and a normal vision group. The study comprised a pre-test (Day 1), the training intervention
484 (Day 2-5), post-test (Day 6) and a retention test one month after the post-test. The results indicated better
485 performance of the **peripheral blur** group compared to the normal vision group, with the former exhibiting
486 increased performance on hazard discrimination from pre-test to post-test, and post-test to retention test.
487 Performance of the normal vision group remained similar across all tests. However, no change was found
488 on hazard detection time, leading the authors to suggest that training influenced only spatial perception. In
489 addition, it was found that neural activity (indicated by a decrease of the high alpha power) of the **peripheral**
490 **blur** group was more important in retention test compared to the other group, leading to the suggestion
491 that attention was more focused on relevant visual processing. For the normal vision group, neural activity
492 decreased (indicated by an increase of the high alpha power) from post-test to retention test in parietal
493 cortex, which is consistent with less integration of visual information.

494

495 Although encouraging, it should be remarked that a driving task involving hazard perception while
496 passively observing a video display is quite different from real world driving, as well as a dynamic
497 sport situation in which the relationship between the participant and surrounds is actively (not passively)
498 modified by movement of the participant (e.g., whole-body or individual limb) and/or object of interest
499 (e.g., opponent). It is perhaps not surprising, then, that occluding central vision during the driving task
500 significantly impaired performance of both inexperienced and experienced drivers, whereas in the sport
501 tasks studied to date experts are less impaired because they use both central and peripheral vision (Hausegger

502 et al., 2019; Ryu et al., 2016; Vater et al., 2019). Still, despite these differences, the use of a peripheral blur
503 for training the perception is encouraging. The described changes in neural activity also support this idea
504 and give a better understanding of the effect of the blur manipulation. That is, an increase of cortical activity
505 is associated with processing cues in central vision that are more closely aligned with the line-of-gaze (Ryu
506 et al, 2020).

507

7 SUMMARY AND CRITICAL REFLECTION

508 The primary aim of this article was to review the current research on how the artificial manipulation
509 of blur influences perceptual-cognitive and perceptual-motor behaviour in sport, and to what extent
510 the application of blur during training can facilitate learning and transfer. Having first described the
511 two methods of blurring the visual stimulus (i.e., dioptric vs. Gaussian), we then provided a summary
512 of studies in which blur was applied to the entire visual field while participants performed lab-based
513 anticipation and decision-making tasks. A consistent finding was that performance of novices improved
514 in the presence of moderately blurred vision (Jackson et al., 2009; Jackson et al., 2018). Next, we reported
515 on studies of basketball shooting (Applegate and Applegate, 1992) and golf putting (Bulson et al., 2008),
516 which found participants were able to maintain outcome performance in the presence of a dioptric
517 blur. Similar effects were found in a series of studies by Mann and colleagues on a dynamic, cricket
518 batting interreception task. Irrespective of whether the participant faced a bowling machine or a real
519 bowler, it was reported that batting performance was resilient to dioptric blur, and hence that visual
520 acuity is not a primary limiting factor in cricket batting. Mann et al. (2010b) found similar effects when
521 participants responded to real ball deliveries by verbal response only (uncoupled) or verbal response plus
522 batting movement (coupled). The authors suggested that cricket batting performance can be improved or
523 maintained in conditions of blur because participants were able to rely on dorsal stream processing to
524 perceive the necessary and sufficient information, which in this task was likely from low spatial, high
525 temporal frequency input related to the bowler and/or object motion. Based on the suggestion that experts
526 and novices tend to attend to different parts of the visual field, Ryu et al. (2015) adapted an earlier protocol
527 (Ryu et al., 2013) such that either a mask or a window of blur was applied contingent upon gaze location.
528 Once again, it was shown that experts were able to perform above level of chance even when there was
529 limited information available (i.e., masked central vision and highly blurred peripheral vision). While this
530 was not the case for novices, they did exhibit improved performance when they had clear central vision
531 combined with moderately or highly blurred peripheral vision. Ryu et al. suggested this confirmed the use
532 of central vision by novice participants, and that this may be facilitated by the application of a peripheral
533 blur.

534 Having shown that expert level participants are relatively impervious to the presence of blur and that
535 novices can even benefit from blurring the entire visual field or only the periphery, we next reported on
536 studies that examined whether these performance effects could enhance learning. Using a gaze-contingent
537 blur manipulation, Ryu et al. (2016) reported that novice basketball players benefited most from training
538 on a lab-based decision-making task with clear central vision combined with blurred peripheral vision
539 (i.e., **peripheral blur** group). Moreover, training with a **central blur** (no central vision, normal peripheral
540 vision) was no better than training on an unrelated task with unrestricted vision. Similar effects were then
541 reported by Ryu et al. (2020), who used a gaze-contingent blur manipulation in a training intervention on
542 unlicensed trainee drivers. Training with clear central vision and blurred peripheral vision resulted in better
543 hazard perception performance compared to a group that trained with normal vision group. These findings
544 of enhanced learning, and transfer (Ryu et al., 2016), are promising but as acknowledged by the authors,

545 many questions remain unanswered. For example, while Ryu et al. (2016) favoured the suggestion that
546 the peripheral blur could have encouraged novices to focus attention to information in central vision, it is
547 not clear this mechanism can explain why these participants exhibited positive transfer to a **central blur**
548 condition in which central vision was blurred and peripheral vision was clear. We suspect a more likely
549 explanation is that a **peripheral blur** facilitates novice participants' ability to perceive and then combine
550 the relevant information from both central vision and peripheral vision.

551

552 **The literature described in the review present different results, some unanswered question and limitation.**
553 **They exposed the interest of using blur for perceptual-motor skills but to consider with cautious.** In addition
554 to questions regarding the underlying processing mechanisms that facilitate learning and transfer, we
555 agree with the authors that more work is required to better understand the effects of more prolonged
556 training with a **peripheral blur** and if there is positive transfer from off-court training to on-court decision
557 making performance. As we discuss below, and recognized by some of the authors of the studies described
558 above, there are limitations of using pre-recorded 2D video clips with a non-adaptive 3rd person viewpoint.
559 Similarly, although positive performance and learning effects of peripheral blur have been reported across
560 a range of experimental tasks, some requiring no or a very limited motor response (i.e., button press), there
561 are methodological issues that prevent the use of peripheral blur when training in more a natural sporting
562 context. Part of the reason for the lack of work in such settings likely relates to the potential for injury
563 that could occur if perception of an approaching object or person were disrupted. However, even if this
564 were minimized (see Mann et al. (2010b)), such training also does not lend itself to using a **peripheral blur**,
565 which to date seems to be most effective in facilitating learning and transfer effects of novice participants
566 (Ryu et al., 2020, 2016). Related to this point, it is notable that the positive effects of a gaze-contingent
567 blur have yet to be shown in expert populations. So far, it has only been shown that experts are resilient to
568 the introduction of blur to the entire visual field (Mann et al., 2010a; Ryu et al., 2015), and that a short
569 period of training (i.e., 70 video clips) with such a manipulation can facilitate decision making accuracy in
570 expert referees (van Biemen et al., 2018). However, there are many facets of expert performance, and it
571 could be that some experts would benefit from training with blurred vision. For example, anecdotal reports
572 from boxers and coaches suggest that during a fight, vision deteriorates with fatigue and repetitive blows to
573 the head. Thus, it could be the case that boxers might benefit from safely practicing in a blurred vision
574 condition if this encourages enhanced pick-up of information and/or provides an opportunity to familiarise
575 to this specific situation. At the very least, the introduction of blur could be a new challenging situation
576 that experts find stimulating, bringing a diversity to their training.

577

578 To overcome some of the limitations highlighted above, we are currently designing a methodology that
579 uses virtual reality (VR) for training with a moving window in a more natural setting. According to Harris
580 et al. (2019), "virtual reality is a collection of technologies that allow the user to interact with a simulation
581 of some environment, in real-time, using their own senses and motor skills". The strength of VR is that
582 the constructed environment can be representative of the sporting context, but importantly for the purpose
583 of research, it can be completely reproducible, controlled and easily manipulated (Bideau et al., 2010;
584 Craig, 2013; Faure et al., 2019; Harris et al., 2019; Miles et al., 2012; Renshaw et al., 2019; Stone et al.,
585 2018; Williams et al., 2011). Unlike pre-recorded 2D video displays with a gaze-contingent blur (viewed
586 from a 3rd person perspective), VR with integrated eye movement tracking (e.g., HTC Vive Eye Pro)
587 ensures sufficient fidelity of binocular depth information in dynamic settings through viewpoint adaptation

588 ¹, while at the same time permitting a realistic, coupled motor response. This preservation of the normal
589 perception-action loop means VR is not limited by the "standard one-size-fits all practice schedule" (Stone
590 et al., 2018; Renshaw et al., 2019; Farrow, 2013). Instead, VR allows each individual to develop a particular
591 interaction with the world and to experience it according to their skills, knowledge and morphology (Fajen
592 and Warren, 2007; Gibson, 1979). In this way, VR offers the potential for individualised and targeted
593 training that is respectful and adaptive to the level of the learner and the specific sporting context.

594

595 Using VR technology, we are studying the use of a gaze-contingent blur manipulation in boxing where
596 the participant interacts with an opponent in a simulated fight setting. The technology developed allows
597 the application of experimenter-determined Gaussian blur, and, will thus help us to identify the level of
598 peripheral blur that facilitates learning and transfer when training with a **peripheral blur**. It can also help
599 determine if the blur should be applied to the entire peripheral field (Ryu et al., 2016) or more specifically
600 to areas of interest in the periphery that contains the relevant information. This could be relevant in combat
601 sports such as boxing, where it is well known that participants fixate gaze around the chest/head of the
602 opponent and use peripheral vision to pick-up information from the hands and/or feet (Hausegger et al.,
603 2019; Martínez de Quel and Bennett, 2019; Vater et al., 2019). Moreover, once the VR environment has
604 been developed, it is relatively straightforward to manipulate parameters that impact upon task difficulty.
605 This means that training can be adapted to the current and changing level of participants' performance,
606 thereby providing a stimulating and challenging context throughout learning. This is a major advantage
607 compared to pre-recorded 2D videos, where the stimuli cannot be individually manipulated or matched
608 to a participant's skill level. Indeed, by continually challenging the participant, it should be possible to
609 maintain motivation and facilitate the rate of learning (Michalski et al., 2019).

610

611 **Integrating the blur manipulation within a VR environment could be promising and open new possibilities;**
612 **however some questions need to be consider. The VR display now integrates a "foveal rendering". This**
613 **method consists in keeping the center of the field of view clear, where the user is supposed to look and**
614 **decrease the level of details away. It is necessary to have a tracking of gaze location to activate this**
615 **manipulation. Another computation investigated is blurring the background, that is away from the focal**
616 **point (Hussain et al., 2021). The applied blur is not uniform, it follows a gradient. The blur is stronger at the**
617 **far eccentricity of the visual field. These methods were developed, in a computer sciences way, to minimize**
618 **the computation cost and increase user comfort (Nie et al., 2020). This user comfort is increased because,**
619 **supposedly, the displays match better the normal vision integrated both high and low spatial frequencies**
620 **stimuli. The manipulation is not noticed as it is at the edge of peripheral vision and away from the focal**
621 **point. In line, a part of the computer sciences field used the blur to minimize the cybersickness which can**
622 **be induced by VR (Nie et al., 2020). Another solution investigated was to decrease the field of view: a**
623 **limited field of view resulted in less cybersickness (Fernandes and Feiner, 2016). VR also raised a problem**
624 **of vergence accommodation conflict (Dits et al., 2013; Fulvio and Rokers, 2017; Klinghammer et al., 2016;**
625 **Eadie et al., 2000; Gerig et al., 2018) which could disrupt the normal vision processes. These different**
626 **points need to be taken in consideration all together, as we need a large field of view to best represent and**
627 **investigate the role of central and peripheral vision in sport setting. More, we want, to fulfill this aim, to**
628 **include blur; thus, the integration of an additional blur could interaction with the cybersickness effect.**

¹ Despite the many advantages of VR, it should be acknowledged that there are some limitations such as the quality of depth perception due to accommodation-vergence regulation (Dits et al., 2013; Fulvio and Rokers, 2017; Klinghammer et al., 2016; Eadie et al., 2000; Gerig et al., 2018)

8 CONCLUSION

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

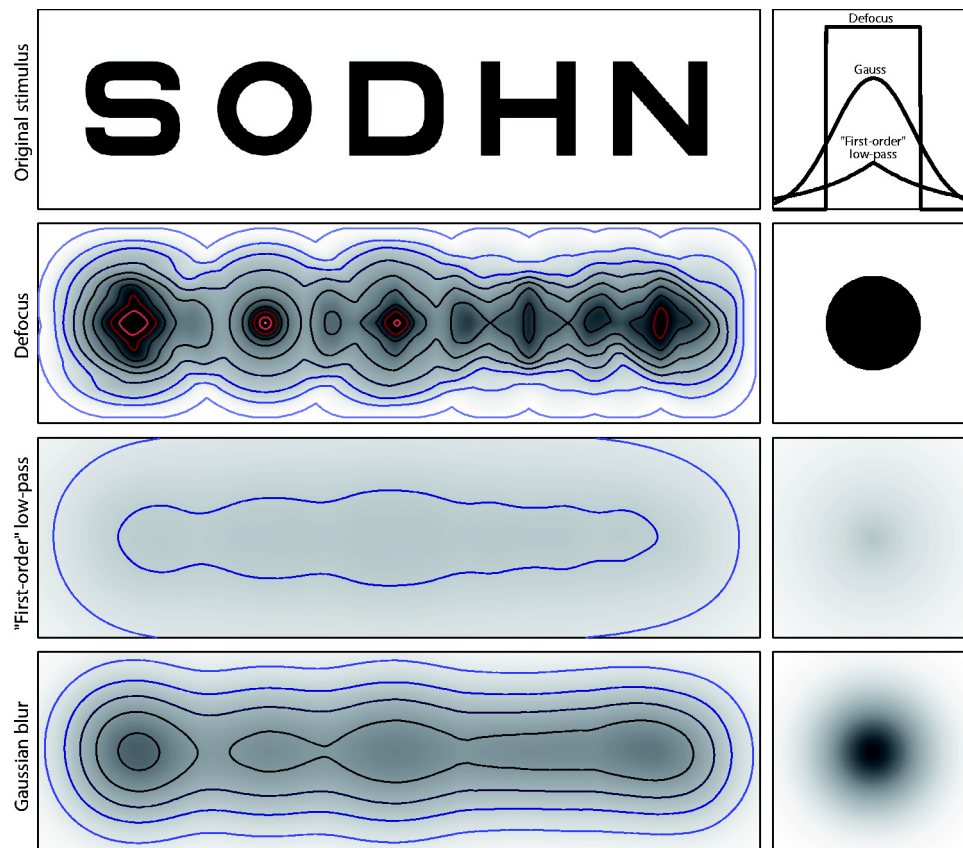


Figure 1. Illustration from Strasburger et al. (2018) of the effect of blur on Sloan letters. Top row: original, unblurred letters, together with point-spreadfunction profiles (right) for the lower rows. FWHMs of the three PSFs are equal. Note that PSF amplitudes are necessarily different since their 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).

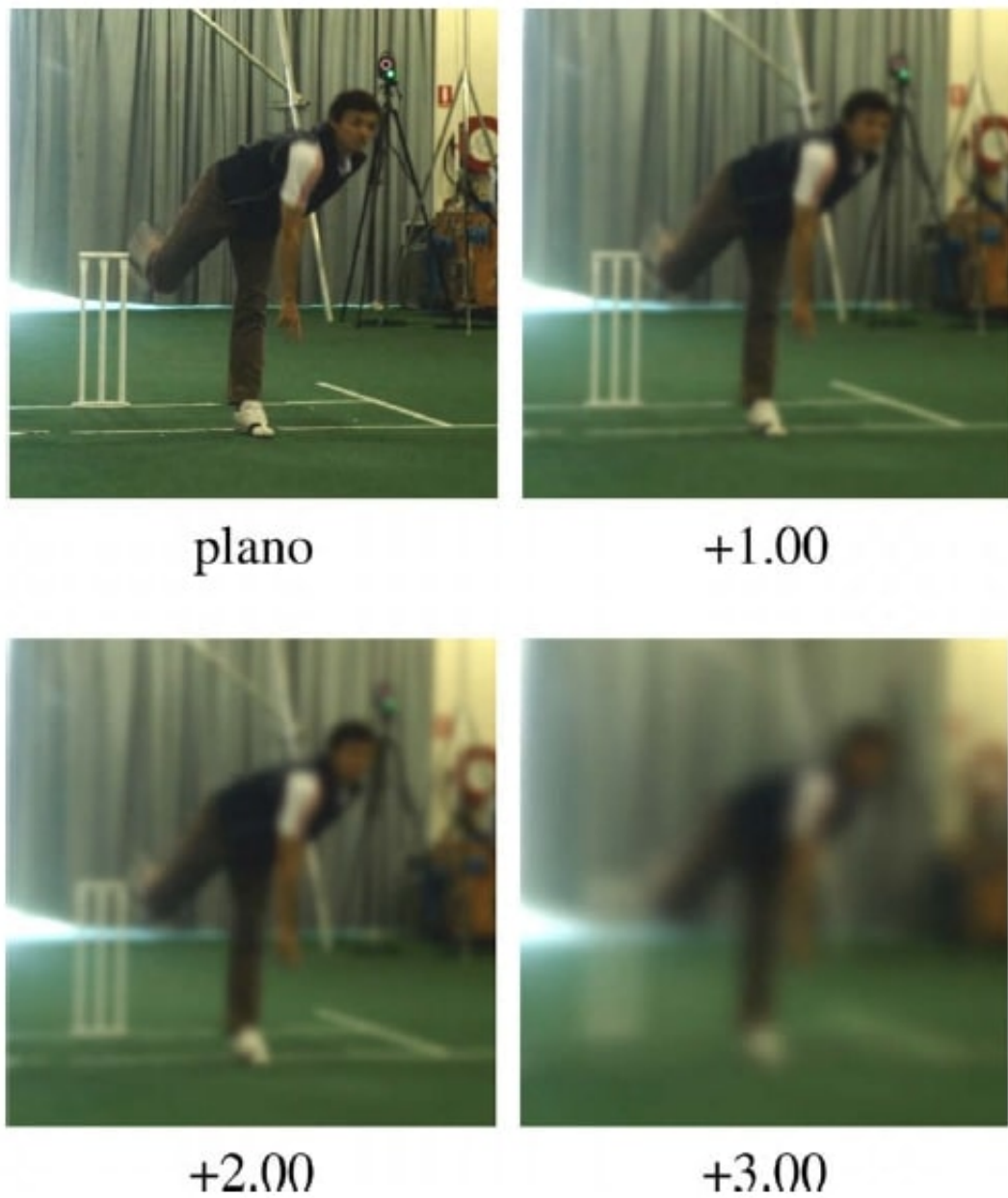


Figure 2. Illustration of Mann et al. (2010a)'s experiment : simulation of the four refractive blur conditions experienced by the participants.

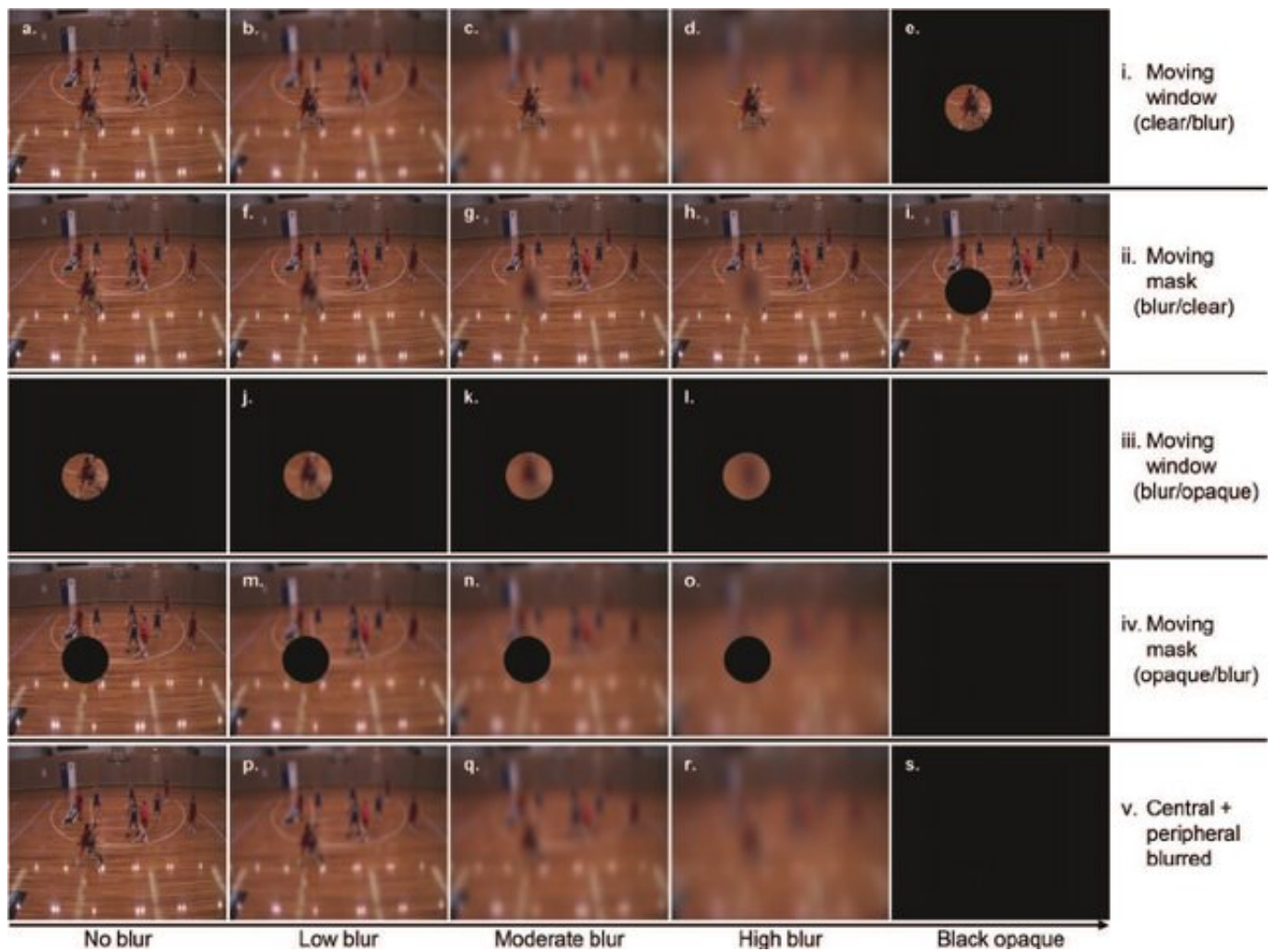


Figure 3. Screenshots of the 19 different viewing condition studied by Ryu et al. (2015): (a) full-clear, (b-e) moving window (clear/blur) conditions (low, moderate, high, and opaque, respectively), (f-i) moving mask (blur/clear) conditions (low, moderate, high, and opaque, respectively), (j-l) moving 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).



Figure 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.

CONFLICT OF INTEREST STATEMENT

641 The authors declare that the research was conducted in the absence of any commercial or financial
642 relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

643 AL, RK and SB explored literature and wrote the original draft. AL, RK and SB review and edited the final
644 manuscript. All authors approved the final version of this manuscript.

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