The influence of low and high spatial frequency visual information on the anticipation of soccer penalty kicks

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Abstract

Research on anticipation within sport has been recently advanced by the isolation of visual spatial frequencies. The present study seeks to adapt this body of work for the context of anticipating penalty kicks within soccer. Across two experiments, participants had to anticipate the direction of pre-recorded penalty kicks that were occluded at the point of ball contact. The penalty kicks were presented with low (LSF; 'blurred'), high (HSF; 'edge detection' [i.e., sharp image outlines]) or unfiltered (i.e., original footage) spatial frequencies. Experiment 1 involved a lab-controlled setting using a life-sized display of the non-deceptive penalty kicks with outfield participants, which indicated no effect of visual condition. Experiment 2 involved a remote online protocol that displayed deceptive and non-deceptive penalty kicks with goalkeeper participants. While there was a decline in the anticipation of deceptive compared to non-deceptive kicks for the unfiltered condition, there was no such decline for the LSF and HSF conditions. We suggest that the LSF and HSF conditions were able to overcome deception because of the isolating global kinematic and local detailed cues, respectively.

Key words: perceptual-cognitive skill; blur; goalkeeper; deception;

1. Introduction

Perceptual-cognitive skills within sport have long been of interest based on the view that these skills can definitively discriminate different levels or standards of performance (Williams & Jackson, 2019). Perhaps the most empirically tested category of perceptual-cognitive skills is *anticipation*; that is, the ability to perceive key advance cues for a rapid and accurate response within a time-limited dynamic sport setting. In this instance, athletes are typically exposed to a real-life or video display of an initial opponent play prior to occlusion near or at the resulting action, thus requiring the use of prior visual information in order to make a judgement on the opponent's action; something otherwise known as, the *temporal occlusion paradigm* (Jones & Miles, 1978; Abernethy & Russell, 1987).

In order to learn more about the visual information that underpins anticipation, and with it, determine ways for training to improve performance, researchers have recently attempted to isolate particular visual spatial frequencies mostly by blurring the stimuli (e.g., refractive lenses, video-editing) (Mann et al., 2007, 2010a,b; Jackson et al., 2009; Ryu et al., 2018; Park et al., 2019; DeCouto et al., 2023). To elucidate, a standard visual array comprises a confluence of low-to-high spatial frequencies. Low spatial frequencies alone typically resemble visual blur, while high spatial frequencies alone can be characterised by discrete edges or contours (Figure 1) (Livingstone, 2000; see also, Musel et al., 2012). To-date, findings have shown that skilled performance in cricket-batting (+1.00 D, +2.00 D [equating to 0.00-0.74 logMAR]; Mann et al., 2010a,b) and tennis serve anticipation (20%, 40% blur; Jackson et al., 2009) can be sustained following a low spatial frequency filter to effectively elicit low-to-moderate levels of blur. In a similar vein, but using alternative video-editing techniques for filtering a wider range of spatial frequencies, it was shown that athletes can sustain (Park et al., 2019), or even improve (Ryu et al., 2018), their badminton stroke anticipation when presented with only low compared to high spatial frequencies (for the effects of a gaze-contingent central/peripheral blur, see also Ryu et al., 2016 and Limballe et al., 2022).

These findings may be explained by the prevalence of key discriminating cues in the form of global movement kinematics when low spatial frequencies are presented (e.g., opponent relative joint angles within real-time), although mere local fine details may only prevail when it comes to high spatial frequencies being presented (e.g., opponent head or gaze direction within the moment). This distinction has been loosely related to the proposed functional specialisation of neural pathways for the processing of different ranges of spatial frequencies. That is, low spatial frequencies combined with more rapid motion (high temporal frequency) are more closely associated with the magnocellular layers, while high spatial frequencies combined with slower motion (low temporal frequency) involve the parvocellular layers, of the lateral geniculate nucleus (LGN) (Ungerleider & Mishkin, 1982; Kaplan & Shapley, 1986; Merigan & Eskin, 1986; Livingstone & Hubel, 1987, 1988; Merigan et al., 1991; see also, Milner & Goodale, 1995; see also, van der Kamp et al., 2008; Mann et al., 2021).

The present study extends upon previous research on the visual spatial frequencies underpinning anticipation within sport. That is, we examine the visual spatial frequencies contributing to the anticipation of soccer penalty kicks over two separate experiments. Here, we had the spatial frequencies comprising pre-recorded penalty kicks either remain entirely unfiltered, or selectively filtered to present only a low or high range. This video footage was briefly exposed to participants with a view to them anticipating the direction of the kicks. As a result of this research, we may come to learn more about the processing of advance cues that are unique to soccer penalty kicks. However, perhaps more importantly, we may also corroborate previous research in the area of spatial frequency filtering for stimuli within dynamic or sporting contexts, which has been thus far comparatively limited. Indeed, if we are to adapt the filtering of spatial frequencies for a potential training tool, then it stands to reason that we both replicate and learn more about how it influences perceptual-cognitive skills across a variety of domains.

2. Experiment 1

2.1. Introduction

The filtering of visual spatial frequencies within anticipation research has been fairly widespread with evidence to suggest that athletes may be resilient to (e.g., Mann et al., 2010a,b), or benefitted by (e.g., Ryu et al., 2018), the presentation of low as opposed to high spatial frequencies. Broadly speaking, the suggestion is that low spatial frequencies expose key global movement kinematics, while high spatial frequencies allude only to the fine details that may be otherwise redundant.

This conjecture is highly relevant when we consider the anticipation of soccer penalty kicks. Here, the short time it takes for the ball to be kicked and reach the end goal (e.g., <700 ms; Dicks et al., 2010a) makes it necessary for the goalkeeper to pick up on advance cues if they are to successfully intercept the ball. Indeed, it has been shown that skilled players tend to fixate more on the kicking and non-kicking legs immediately prior to ball contact (Savelsbergh et al., 2002; see also, Savelsbergh et al., 2010). Likewise, detailed kinematic analyses of penalty kicks have shown that distributed information featuring a combination of angles of the non-kicking foot and knee of the kicking leg during the immediate build-up or preparation for kicking, can reliably predict or discriminate the direction of penalty kicks (Diaz et al., 2012; Lopes et al., 2014; see also, Lees & Owens, 2011).

Taken another way, we may question whether the filtering of visual spatial frequencies can help discriminant key advance cues, and in turn, influence the speed and accuracy of anticipating penalty kicks. Along these lines, a recent study showed that while the anticipation of penalty kicks was made worse by blurred compared to standard vision, it was better for blurred compared to a spatially occluded hips-only condition (DeCouto et al., 2023). The investigators attributed this finding to the importance of global over local level processing, but without necessarily isolating the wider range of spatial frequencies. Thus, the aim of the present experiment was to explore the influence of different visual spatial frequencies on the anticipation of soccer penalty kicks.

Skilled soccer participants anticipated the direction of penalty kicks within a temporal occlusion paradigm, where they responded to a video display of pre-recorded kicks by pressing an arrow key. The video included unfiltered spatial frequencies (original footage), or was pre-experimentally manipulated by separately filtering the low and high spatial frequencies (Figure 1). The kicks were made with no deceptive intent (i.e., appearing to kick in a direction that is consistent to the actual or intended direction) at least in the first instance in order to examine the influence of visual spatial frequencies on the anticipation of more conventional non-deceptive penalty kicks (for similar designs, see Jackson et al., 2009 and Mann et al., 2010a,b).

Based on the importance surrounding the global movement kinematics, it was predicted that performance would be upheld under the low spatial frequency, although may begin to decline for the high spatial frequency. Additionally, to check the severity of our low spatial frequency filter, participants had their static visual acuity tested under the low spatial frequency prior to the anticipation task (e.g., Mann et al., 2010a,b; see also, Roberts et al., 2020). In this regard, the subsequent anticipation responses to different spatial frequencies may be comparable to or interpreted in the context of other diagnostic assessments and (simulated) low vision research, which are each heavily reliant upon visual acuity measures.

2.2. Method

2.2.1. Participants

There were 21 participants who volunteered for the experiment (age range = 19-23 years, male (cis) = 15, female (cis) = 6). Participants were all outfield players who had a minimum of 5 years of competitive playing experience including 4 recreational/grassroots (*M* ±*SD* = 12.25 years ±3.59), 6 school/university (*M* ±*SD* = 9.83 years ±3.43), 3 county (*M* ±*SD* = 13.33 years ±1.53) and 8 elite/academy (*M* ±*SD* = 13.75 years ±2.31) as their highest level of competition. Participants provided written informed consent, and the study was approved by the institutional research ethics committee.

2.2.2. *Materials and Task*

The experiment involved a test of static visual acuity and penalty kick anticipation. With regard static visual acuity, this assessment could effectively quantify the level of blur reached with the potential to then cross-reference with separate diagnostic criteria (e.g., Allen et al., 2019) and (simulated) low vision research (e.g., Roberts et al., 2020). Here, participants initially stood opposite a TV screen (physical size = 124.0 x 70.8 cm, spatial resolution = 1920 x 1080 pix) at a distance of 4 m. A digital version of the ETDRS chart was displayed on the screen, which featured a series of letter optotypes comprising individual lines that became progressively smaller in size upon shifting further down. Participants were tasked with reading aloud the different optotypes from top-to-bottom until they obtained >2 (3 or more times) mistakes within a single line. Therein, the test was ceased and participants were scored by calculating their logarithmically transformed minimum angle of resolution (logMAR) (min. = -0.3 (20 / 10), max. = 1.0 (20 / 200)) with each optotype equating to 0.02 units (e.g., reaching 0.1 logMAR line including 4 errors = 0.18 (20 / 30)).

The penalty kick anticipation task involved participants initially standing opposite a large projector screen (physical size = 4.14 x 2.33 m, spatial resolution = 1920 x 1080 pix) at a distance of near standard or regulation soccer penalty kick spot of 10 m. Pre-recorded video footage (temporal resolution = 25 Hz, spatial resolution = 720 x 576 pix) was displayed on the screen with a real-life size player (physical height = 1.11 m, visual angle = 6.33°) preparing and running up to execute a penalty kick (approx. 5 secs), which then occluded at the point of ball contact (Causer et al., 2017, DeCouto et al., 2023). Participants were tasked with having to anticipate the direction of the penalty kick as if they were trying to save or intercept the ball. Participants responded as quickly and accurately as possible by pressing on arrows that overlaid keys on a handheld numeric keypad, which was connected to a computer via a universal serial bus (USB) cable (i.e., 7 = top-left, 9 = top-right, 1 = bottom-left, 3 = bottom-right). Responses were recorded using Psychtoolbox (v. 3.0.18.13) running in Matlab (v. 2022a) (MathWorks, Natick, MA).

The visual stimuli comprising each of the static visual acuity test and penalty kick anticipation task were manipulated in the same way. That is, they were unfiltered (i.e., standard viewing) (horizontally and vertically equating to 0-960 and 0-540 cycles, respectively) and pre-experimentally filtered to more closely isolate the contribution of both low (LSF) and high (HSF) visual spatial frequencies (Figure 1). The LSF and HSF stimuli were created by spatial domain filtering of the compilation of pixelated image arrays or individual frames that comprised the original unfiltered footage. Specifically, the LSF stimuli involved filtering images using a low-pass Gaussian function including the following parameters: sigma = 5, size = [9 9]. The HSF stimuli were formed by simply calculating the inverse of the low-pass filtered images with respect to the original unfiltered footage (i.e., HSF = unfiltered – LSF). While inverse or subtraction methods for high-pass filtering are susceptible to noise and potential artefact, it is generally well-accepted to broadly generate stimuli for edge detection (e.g., Difference of Gaussians [DoG]; McMahon et al., 2004). In addition, owing to the inherent loss of visibility from filtering, the HSF stimuli were further brightened. Taken together, the LSF and HSF stimuli comprised spatial frequencies of ≈ 0-9 and ≈ 9-43 cycles per degree for the penalty kick anticipation task, respectively. Stimuli were generated courtesy of the Computer Vision Toolbox within Matlab (v. 2022a).

Figure 1. Illustration of the different visual conditions for the penalty kick anticipation task including unfiltered (*left* panel), LSF (*middle* panel) and HSF (*right* panel) alone

2.2.3. Procedure

The experiment involved a single 1-hr visit to the lab where participants were initially adapted to dark settings, which was chosen to enhance the edge detection related to HSF stimuli. Participants first attempted the vision test on the TV screen with both a standard and blurred ETDRS chart being separately presented in a counter-balanced order between participants.

Therein, the participants were brought across the lab opposite the large projector screen to assume the goalkeeper viewpoint for the penalty kick anticipation task. Each trial commenced with a 150-ms auditory warning signal followed by an 800-2300-ms foreperiod until the initiation of each individual penalty kick stimulus. Participants had to anticipate the direction of the penalty kicks and immediately respond by pressing on the handheld numeric keypad that was provided to them. Following the penalty kick and related response, there was 1-sec delay prior to the start of the next trial.

For initial familiarisation/practice, only the standard footage of penalty kicks were presented featuring unfiltered spatial frequencies, where there were 12 trials comprising of 3 different penalty kick takers with each kicking in 4 different directions (i.e., top-left, top-right, bottom-left, bottom-right). This familiarisation/practice only featured the unfiltered stimuli because it was primarily intended to familiarise participants with trial proceedings (i.e., trial initiation, occlusion, temporally coupled response, etc) and not necessarily the visual conditions per se, while we also wanted to avoid any potential adaptation to the isolated spatial frequency conditions (LSF, HSF). Prior to the experimental trials, participants were advised that while the task was fundamentally the same as familiarisation/practice (i.e., anticipate and respond to the penalty kick direction), they would also be observing penalty kicks with additional visual conditions including "blur" (LSF) and "edges only" (HSF). These visual conditions were each presented separately in a blocked fashion with the order of blocks between participants being pseudo-randomized following a Latin-Square Design. There was a total of 108 trials presented in 3 blocks of 36 trials, which comprised of 3 different penalty kick takers kicking in the 4 different directions on 3 separate occasions. An 2-min break (approx.) was provided in between each of the blocks.

2.2.4. *Dependent Measures and Data Analysis*

The specific key and time at which it was pressed were recorded. Response accuracy was taken with respect to whether the response direction corresponded with the kick direction. Reaction time was calculated as the time difference between the onset of occlusion (i.e., ball contact) and the response, where a (near) negative value would indicate a more anticipatory response. The number of accurate trials (expressed as a proportion of the total trials) and median reaction times were calculated for each participant and subsequently forwarded to an inferential statistical analysis.

As a manipulation check, we first compared the static visual acuity results following the standard and blurred visual manipulations using a Wilcoxon-signed rank test (assuming non-parametric statistics following an initial evaluation of normality using a combination of the Shapiro-Wilk test, frequency-distribution histogram plots, and Q-Q plots). To ensure participants were sufficiently skilled to complete the anticipation task, we compared participants' response accuracy following the standard unfiltered block condition to a chance rating (25%) using a single-sample t-test. Next, we compared response accuracy and reaction time for each of the visual conditions using a one-way repeated-measures Analysis of Variance (ANOVA).

The assumption of Sphericity was evaluated using Mauchly's test, and if necessary, subsequently corrected using the Huynh-Feldt value when Epsilon (ε) was >.75, or the Greenhouse-Geisser value if otherwise (original Sphericity-assumed degrees-of-freedom reported). Any significant effects featuring more than two means were subsequently decomposed using Tukey HSD post hoc procedure. Effect sizes were indicated using a combination of r, Cohen's d (d_z) and partial eta squared (η_p^2) for the Wilxon signed-rank, t-test and ANOVA, respectively. Significance was declared at $p < .05$.

2.3. Results

For static visual acuity, the participants' standard vision scores ranged from -0.24 (20/12) to 0.04 (20/22), while the blurred vision scores ranged from -0.02 (20/19) to 0.18 (20/30). There was a significantly lower score (greater resolution) under the standard compared to blurred visual condition, $z = -4.02$, $p < .001$, $r = -.62$ (Figure 2).

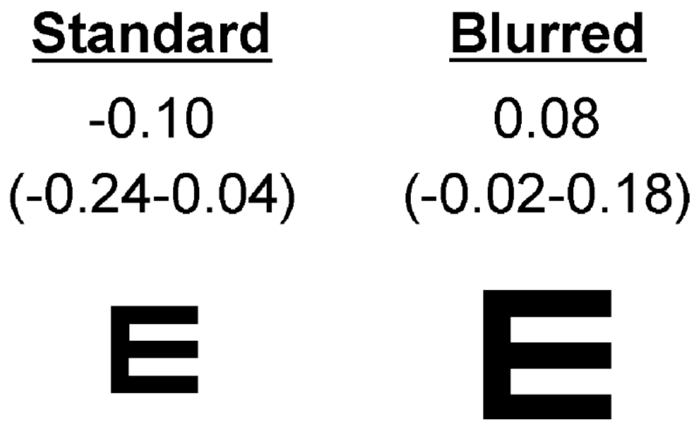

Figure 2. Relative size differences between the letter optotypes (example letter 'E') that were associated with the median static visual acuity under standard (*left* panel) and blurred (*right* panel) visual conditions.

For accuracy, participants completed the task as standard (unfiltered) with relative success having been significantly more accurate than chance alone (25%), $t(20) = 5.66$, $p < .001$, $d_z = 1.24$. However, there was no significant main effect of vision, $F(2,40) = 1.57$, $p = .23$, $\eta_p^2 = .07$ (Figure 3). For reaction time, there was also no significant main effect of vision, $F(2,40) = .05$, $p = .92$, $\eta_p^2 = .002$ (Table 1).

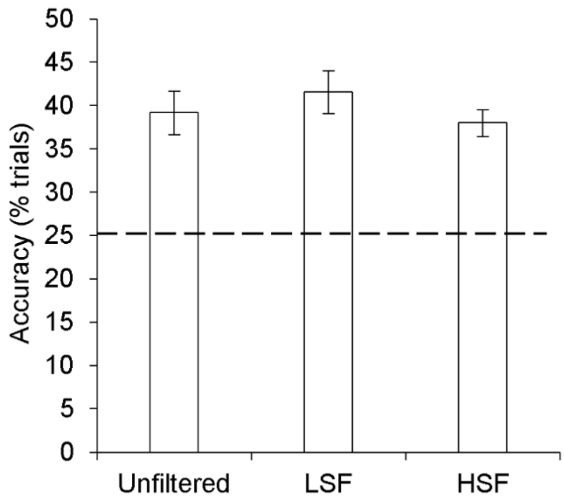

Figure 3. Mean number of accurate trials (expressed as a proportion of the total trials) as a function of vision. *Dotted line* indicates the score equivalent to chance (25%). Error bars indicate the standard error.

Table 1. Mean (±SE) reaction times (ms) as a function of vision.

Unfiltered	LSF	HSF
854 (±90)	845 (±91)	855 (±99)

2.4. Discussion

The present experiment had soccer participants anticipate penalty kicks when viewing under unfiltered, low and high spatial frequencies. There was no effect of isolating particular spatial frequencies on anticipation. Indeed, this was despite the low spatial frequency condition causing a decline in static visual acuity to sub-optimal levels of vision that would otherwise be considered in need of optometric correction (i.e., refracting to ≤0.00 logMAR).

The ability to sustain anticipation performance under the low spatial frequency is somewhat aligned with previous findings from other sport settings that indicate a resilience to visual blur (Mann et al., 2010a,b; see also, Bulson et al., 2008, 2015; Basevitch et al., 2015; van Biemen et al., 2018). This finding may be attributed to the prevalence of global movement kinematics when under low spatial frequencies, which provides the key advance cues for anticipation. Here, it is possible to pick-up on key distributed information such as the combined angles of the non-kicking foot and knee of the kicking leg in preparation in the lead-up to the kick (Diaz et al., 2012; Lopes et al., 2014).

Meanwhile, the ability to sustain performance under the opposite high spatial frequency may be the result of accessing other non-kinematic advance cues. Indeed, it is suggested that there are a series of local advance cues within the preparation of penalty kicks, which could discriminate their eventual direction (Diaz et al., 2012), as well as any anticipatory judgements (Causer et al., 2017; DeCouto et al., 2023) (see also, Savelsbergh et al., 2002). That said, the previous studies that have alternatively reported a decline in anticipation under a high spatial frequency are typically limited to contexts where an opponent's actions feature deceptive intent (Ryu et al., 2018; Park et al., 2019), although this was not possible within the present study because there were only conventional or non-deceptive penalty kicks displayed.

3. Experiment 2

3.1. Introduction

Previous evidence indicates that when an opponent's actions feature deceptive intent, anticipation performance can be either sustained or enhanced when the stimulus comprises low spatial frequencies, although begins to decline when it features high spatial frequencies, compared to a unfiltered or original spatial frequencies condition (Ryu et al., 2018; Park et al., 2019; see also, Abernethy et al., 2010). These findings can be explained by the perception of global movement kinematics from low spatial frequencies, whereas local finer details from the presence of high spatial frequencies may be regarded as somewhat superficial or misleading.

As a result, the present experiment examined the effect of isolating different spatial frequencies on the anticipation of soccer penalty kicks that were either with or without deceptive intent. In so doing, we can build upon the findings from Experiment 1 by examining whether the influence of spatial frequencies on anticipation is additionally contingent upon the deceptive intent of an opponent's action. Further still, while the previous sample was skilled or experienced within soccer (see also, the timeliness and accuracy of responses in Table 1 and Figure 3, respectively), one of the outstanding criticisms may be that they were outfield players with less knowledge and expertise surrounding penalty kicks compared to actual goalkeepers (e.g., Roca et al., 2013). Thus, we now introduce skilled goalkeepers with more suitable experience for the anticipation of penalty kicks. In order to recruit a reasonable number of goalkeepers where there is comparatively limited availability or access compared to outfield players, an adapted version of our temporal occlusion paradigm was completed using remote online methods (for similar virtual desktop methods, see Jackson et al., 2009; Farrow & Reid, 2012). Because of the continued availability of the global movement kinematics when under unfiltered and low spatial frequencies, it was predicted that there would be less of a decline in this instance following deception. Meanwhile, when accessing only the local finer details under a high spatial frequency, it was predicted that anticipation performance would start to become more susceptible to the deception (Ryu et al., 2018; Park et al., 2019).

3.2. Method

3.2.1. Participants

There were 15 participants who volunteered for the experiment (age range = 18-37 years, male (cis) = 15). Participants were all goalkeepers who had a minimum of 3 years of competitive playing experience including 4 recreational/grassroots (*M* ±*SD* = 8.67 years ±3.21), 5 school/university (*M* ±*SD* = 14.60 years ±1.52), 2 county (*M* ±*SD* = 19.00 years ±2.83) and 4 elite/academy (*M* ±*SD* = 19.00 years ±6.06) as their highest level of competition (1 unanswered). Participants provided written informed consent, and the study was approved by the institutional research ethics committee.

3.2.2. *Materials and Task*

In a similar vein to Experiment 1, this experiment involved a test of visual acuity and penalty kick anticipation, although each were adapted for online testing on a computer/laptop with a keyboard (no touch-screen devices) using Gorilla Experiment Builder (https://gorilla.sc/) (Anwyl-Irvine et al., 2020, 2021). Importantly, to ensure similarity in the stimulus viewing angle across participants, they were instructed to try to ensure the appropriate physical set-up of the screen including arms-length (approx. 700 mm) viewing distance, and 1280 x 1080 spatial resolution. For the visual acuity test, a single Landolt-C ring was displayed diagonally on the screen, and sized according to the visual angle that was associated with each unit change in logMAR (e.g., 0.8 logMAR subtends 0.52°). Participants were tasked with responding to the direction of the gap in the ring by pressing one of the keys in the corresponding direction (i.e., D = top-left, J = top-right, C = bottom-left, N = bottom-right) until they obtained >2 (3 or more times) mistakes at a single size of optototype. Therein, the test was ceased, and participants were scored by calculating their logMAR.

The penalty kick anticipation task involved participants remaining in the same physical set-up as the previous vision test. Newly recorded video footage (temporal resolution = 60 Hz, spatial resolution = 720 x 480 pix) was displayed on the screen with a player at a near real-life visual angle (visual angle ~4°) preparing and running up to execute a penalty kick, which then occluded at the point of ball contact (approx. 5 secs). However, on a select number of penalties, the penalty kick taker would try to deceive by implying that the ball was to be kicked in one direction when it was really being kicked in another. This deception manifested naturally from a variety of deceptive cues relating to gaze and head direction, angle of approach, smoothness or continuity of approach, and/or subsequent ball strike/spin. Participants had to respond to the anticipated direction of the kick as quickly and accurately as possible by pressing one of the keys from the same arrangement as the previous vision test.

Both the vision test and penalty kick anticipation task had their stimuli pre-experimentally manipulated in the same way as in Experiment 1.

3.2.3. *Procedure*

The experiment involved a single 45-min session that took place in a setting of the participants' own choosing. However, participants were advised to select a quiet area with no obvious distractions, and low/dim lighting that was not directly facing the screen (e.g., side lamp). Participants first attempted the vision test with standard and blurred Landolt-C rings being separately presented in a counter-balanced order between participants. Next, participants progressed to the penalty kick anticipation task. Each trial commenced with a prompt to press the spacebar when ready, followed by the presentation of a fixation cross-hair at screen-centre for 1300-2100 ms, and then each individual penalty kick stimulus. Following the penalty kick, there was a 2-sec delay prior to the start of the next trial.

Due to the remote online methods, we expected that participants might have trouble remaining engaged for a prolonged series of trials and thus decided to reduce the number of trials compared to Experiment 1. There were an initial 8 trials of familiarisation/practice comprising of 4 deceptive and 4 non-deceptive penalty kicks that were kicked in each of the 4 different directions. These trials were performed under standard vision featuring the original unfiltered footage. Prior to the experimental trials, participants were advised that they would be performing the same task as practice/familiarisation, but with further visual conditions including "blur" (LSF) and "edges only" (HSF). These different visual conditions were each presented separately in blocks of trials, the order of which was randomized between participants. There was a total of 48 trials received in 3 blocks of 16 trials. These blocks comprised of 8 deceptive and 8 non-deceptive penalty kicks, with the ball being kicked in each of the 4 different directions and repeated on 2 occasions. A prompt to take a short break was presented to participants following each of the blocks.

3.2.4. *Dependent Measures and Data Analysis*

We calculated the same dependent measures as in Experiment 1. For the statistical analyses, we first compared the vision test results from standard and blurred visual conditions using a Wilcoxon-signed rank test (assuming non-parametric statistics following an initial evaluation of normality using a combination of the Shapiro-Wilk test, frequency-distribution histogram plots, and Q-Q plots) for the purposes of a manipulation check. For the response data, we first compared the response accuracy following the unfiltered condition (non-deception kicks) with chance rating (25%) using a single-sample t-test to ensure that participants were at least skilled enough to complete the task. Despite the alternative methods, we also compared the response accuracy within the non-deception unfiltered condition (non-deception kicks) between Experiment 1 (outfielders) and Experiment 2 (goalkeepers) using a Mann-Whitney U test (assuming non-parametric statistics) in order to substantiate our recruitment of goalkeepers, and ensure that the present goalkeepers were in fact superior or better suited to the task compared to outfield players. Finally, we compared the response accuracy and reaction times for each of the visual conditions using a two-way repeated-measures ANOVA including factors of vision (unfiltered, LSF, HSF) and deception (deception, non-deception).

Any statistical effects featuring more than two repeated-measures levels were checked for the assumption of Sphericity using Mauchly's test, and if necessary, subsequently corrected using the Huynh-Feldt value when Epsilon (ε) was >.75, or the Greenhouse-Geisser value if otherwise (original Sphericity-assumed degrees-of-freedom reported). Any significant effects featuring more than two means were subsequently decomposed using

Tukey HSD post hoc procedure. Effect sizes were indicated using a combination of *r*, Cohen's d (d_z) and partial eta squared (η_p^2) for the non-parametric tests (Wilxon signed-rank, Mann-Whitney U), t-test and ANOVA, respectively. Significance was declared at $p < .05$.

3.3. Results

For visual acuity, the participants' standard vision scores ranged from -0.04 (20/18) to 0.10 (20/25), while the blurred vision scores ranged from 0.02 (20/21) to 0.44 (20/55). There was a significantly lower score (greater resolution) under the standard compared to blurred visual condition, $z = -3.41$, $p = .001$, $r = -.62$ (Figure 4).

Figure 4. Relative size differences between Landolt-C rings (example gap facing top-left) that were associated with the median visual acuity under standard (*left* panel) and blurred (*right* panel) visual conditions.

For accuracy, participants completed the task as standard (unfiltered and non-deception) with relative success having been significantly more accurate than chance alone (25%), $t(14) = 6.54$, $p < .001$, $d_z = 1.69$. Furthermore, there was significantly more accuracy for the goalkeepers (Experiment 2) (*mdn* = 50%, *range* = 25-86%) compared to the outfielders (Experiment 1) (*mdn* = 42%, *range* = 23-56%), *U* = 79.00, *z* = -2.53, *p* = .01, *r* = -.42.

However, there was no significant main effect of vision, $F(2,28) = .18$, $p = .84$, $\eta_p^2 = .01$, although there was a significant main effect of deception, $F(1,14) = 6.63$, $p = .02$, $\eta_p^2 = .32$, and a significant vision x deception interaction, $F(2,28) = 3.96$, $p = .03$, $\eta_p^2 = .22$ (Figure 5). Post hoc analysis (Tukey HSD value = 10%) indicated fewer accurate trials for the deception compared to non-deception penalty kicks, but only for unfiltered condition (*M diff* = 25%) with no such significant difference for LSF (*M diff* = 7%) and HSF (*M diff* = 8%) conditions. In order to substantiate these findings, we extended our previous comparison with chance rating to each of the remaining visual conditions, and found accuracy was significantly above chance for all of these conditions, $ts(14) = 2.88\text{-}5.85$, $ps = <.001\text{-}.01$, $d_z = .74\text{-}1.51$, with the exception of the deception penalty kicks in the unfiltered condition, $t(14) = 1.01$, $p = .33$, $d_z = .26$).

For reaction time, there was no significant main effect of vision, $F(2,28) = 1.46$, $p = .25$, $\eta_p^2 = .09$, and deception, $F(1,14) = .07$, $p = .80$, $\eta_p^2 = .005$, nor a significant vision x deception interaction, $F(2,28) = .05$, $p = .95$, $\eta_p^2 = .004$ (Table 2).

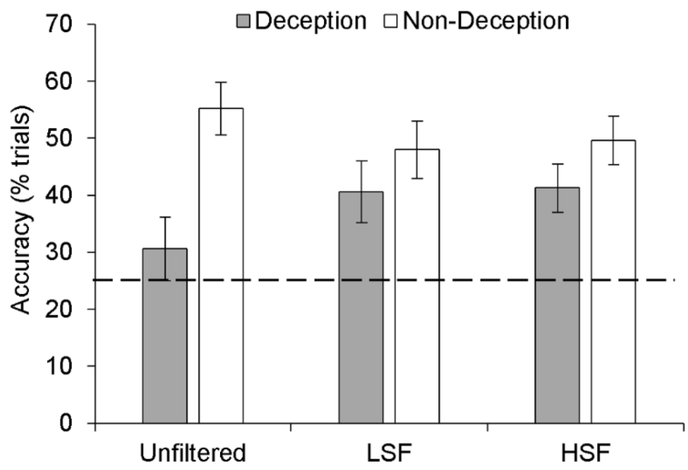

Figure 5. Mean number of accurate trials (expressed as a proportion of the total trials) as a function of vision and deception (see *legend*). *Dotted line* indicates the score equivalent to chance (25%). Error bars indicate the standard error.

Table 2. Mean (±SE) reaction times (ms) as a function of vision and deception.

	Unfiltered	LSF	HSF
Deception	738 (±115)	709 (±114)	618 (±155)
Non-Deception	736 (±126)	727 (±112)	624 (±137)

3.4. Discussion

The present experiment had goalkeepers anticipate deceptive and non-deceptive penalty kicks when viewing under unfiltered, low and high spatial frequencies. The findings indicated that the susceptibility to deception was contingent upon the filtering of spatial frequencies. That is, there was a decline in anticipation performance for deceptive compared to non-deceptive trials when the display comprised all original spatial frequencies, but there was no such decline when the display separately comprised of low and high spatial frequencies alone.

The ability to evade deceptive intent under a low spatial frequency concurs with previous evidence of a benefit when having prior training with (Ryu et al., 2018), or immediate access to (Park et al., 2019), low spatial frequencies. This benefit may be explained by having access to the global movement kinematics, which continue to prevail under low spatial frequencies and provide ample information for skilled anticipation (Dicks et al., 2010a,b; Causer et al., 2017; DeCouto et al., 2023). On the other hand, while we might have expected participants to be more susceptible to deceptive intent when under high spatial frequencies, they appeared equally capable of withstanding the deception. In this regard, we assume that the availability of local finer details under high spatial frequencies may have provided useful information for soccer penalty kicks that could be otherwise unrelated or misleading for other sport settings (for a detailed discussion, see later within the *General Discussion*).

Meanwhile, perhaps most surprisingly, the reduced ability to evade deceptive intent following unfiltered spatial frequencies was in direct conflict with previous evidence of standard vision being most or equally effective for anticipation performance (Park et al., 2019; see also, Mann et al., 2010a,b). Indeed, it stands to reason that the availability of a wider range of spatial frequencies, and with it, a coherent and natural percept that is more akin to the visual experience of a real-life encounter within sport (i.e., unfiltered), should be just as effective in providing the key cues for anticipation. Further still, the benefit of low and high spatial frequencies alone might lead one to assume that a wider range of frequencies should generate an even greater benefit (e.g., *additive factor logic*; Sternberg, 1969). However, there is an argument to suggest that it may sometimes be less effective with low and high spatial frequencies potentially interfering or masking one another. To elucidate, it has been suggested that a range of spatial frequencies can cause attention to become diverted away from the necessary sources of visual information (Mann et al., 2010b; Ryu et al., 2018; see also Ryu et al., 2016 and Limballe et al., 2022), and/or masking of visual spatial frequency channels that are each specialised in a particular frequency range (Di Lollo et al., 1981; Cleary & Braddick, 1990; Barton et al., 1996).

4. General Discussion

The present study aimed to examine the influence of isolating visual spatial frequencies on the anticipation of soccer penalty kicks, and in so doing, learn more about the visual information underpinning this setting. Despite changes in visual acuity, where it declined under a low spatial frequency, there was no effect of the spatial frequency manipulation for conventional or non-deceptive penalty kicks (unfiltered ≈ low ≈ high). However, the low and high spatial frequency alone showed less of a decline than the original unfiltered spatial frequencies for the deceptive compared to non-deceptive penalty kicks (unfiltered < low, high).

The benefit of low spatial frequencies could be explained by the prevailing visual information that is linked to the global movement kinematics, which are pivotal for the anticipation of an opponent's actions; and in particular, deceptive ones (Abernethy et al., 2010). Consistent with this logic, there are a growing number of studies to indicate resilience to blur during anticipation, where athletes must pick up on advance cues in order to successfully respond in time (Jackson et al., 2009; Mann et al., 2010a,b; Ryu et al., 2018; Park et al., 2019; see also, van Biemen et al., 2018). Along these lines, Para-athletes with congenital or acquired low vision, which can be often characterised by poor visual acuity that is synonymous with blur, have often shown comparatively limited adverse effects on their overall performance (Allen et al., 2019; Stalin et al., 2021).

Meanwhile, the failure to decline under high spatial frequencies may be somewhat counter to expectations because it is linked to the local finer details (non-kinematic) that may be otherwise regarded as superficial (Ryu et al., 2018; Park et al., 2019). Firstly, it is important to recognise that the present study may not be directly comparable to previous findings owing to the alternative methods used for the high spatial frequency filtering (e.g., frequency vs. spatial domain). Nonetheless, it is also possible that high spatial frequencies do indeed provide valuable insights into an opponent's action at least when it comes to the anticipation of penalty kicks. This conjecture is supported by recent evidence that skilled soccer players can adapt their pick-up of advance cues for the anticipation of penalty kicks by alternatively accessing local level processes (i.e., hips; DeCouto et al., 2023; see also, Diaz et al., 2012 and Causer et al., 2017). Along these lines, there are a growing number of studies to indicate that rather than anticipation performance relying on global movement kinematics from low spatial frequencies, skilled athletes are also able to draw upon contextual priors that can sometimes be associated with high spatial frequencies (e.g., initial opponent identification; Abernethy et al., 2010; Farrow & Reid, 2012; Navia et al., 2013; Gredin et al., 2023).

Perhaps most importantly, there was a disadvantage served by having access to a wider range of spatial frequencies. This somewhat surprising finding could be explained by the reallocation of attention to cause interference, where it may effectively detract from accessing the necessary visual information (Mann et al., 2010b; Ryu et al., 2018). Along these lines, a gaze-contingent central or peripheral field blur has been suggested to naturally cause athletes to divert their attention away from the visual field consisting of a low spatial frequency, and toward the visual field consisting of a high frequency (Ryu et al., 2016; Limballe et al., 2022). With this in mind, it has been recommended that by isolating visual spatial frequencies, then we could offer a valuable training tool for athletes to more comprehensively focus on the key advance cues for anticipation.

Alternatively, the disadvantage of the wider range of spatial frequencies may have manifested from the masking of spatial frequency channels that are exclusively linked to the processing of either low or high spatial frequencies (Kaplan & Shapley, 1986; Merigan & Eskin, 1986). Therefore, by isolating the low or high spatial frequencies, then we may more greatly utilise the related spatial frequency channels. For example, it has been shown that a low spatial frequency filter that predominantly removes high spatial frequencies using optical blur can enhance the sensitivity to visible persistence (Di Lollo & Wood, 1981), as well as the perception of apparent motion (Cleary & Braddick, 1990; Barton et al., 1996) and motion coherence (Zwicker et al., 2006; Burton et al., 2015; see also, Roberts et al., 2020). That said, it is important to recognise that more contemporary views would have it that at least some degree of cross-talk unfolds between the neural pathways associated with different spatial frequencies (de Haan & Cowey, 2011; Milner, 2017), while it has even been suggested that the neural network for lower-level visual processes is less functionally distinct and more widely distributed (Freud et al., 2016, 2017; Kravitz et al., 2011; see also, Skottun, 2015).

At this juncture, it is relevant to consider the potential limitations surrounding the present study. Indeed, Experiment 1 featured outfield players that—while skilled at soccer—may not have been a representative sample of athletes for the skilled anticipation of penalty kicks. That said, we observed timely responses and greater-than-chance accuracy in the anticipated direction of kicks from these particular players. Nevertheless, Experiment 2 introduced a perhaps more suitable sample of skilled goalkeepers that are more adept for facing penalty kick situations. However, in order recruit a sufficient number of participants within a reasonable time-frame, we adapted our methods to appear online in a remote data collection setting, which could be argued as not being an adequate enough 'representative design' (Araújo et al., 2007; Dicks et al., 2009). However, this is a long and outstanding debate throughout the literature, where researchers have tried to closely quantify perceptual-cognitive skills within an experimentally controlled setting. Likewise, the present methods are not entirely without precedence when we consider the virtual desktop settings of a number of other studies that have sort to adapt their subsequent findings as a proxy to perceptual-cognitive skills (e.g., Jackson et al., 2009). Thus, as a growing trend within the field of behavioural science (e.g., Anwyl-Irvine et al., 2020, 2021), we may suggest the possibility of further using these methods for any future studies on perceptual-cognitive skills within sport.

In summary, we found that the susceptibility to deception in soccer penalty kicks was reduced when isolating low and high spatial frequencies compared to having them unfiltered as per standard viewing. As a result, we suggest that the low and high spatial frequencies separately comprising advance cues can provide useful information for the anticipation of penalty kicks. At the same time, it is also possible for these different spatial frequencies to prohibit one another by way of interference and/or masking. As this was a perhaps a somewhat surprising finding, we only make this suggestion tentatively with a view to further investigating the possibility for interference and masking. While these findings may conflict with recent research surrounding the influence of different spatial frequencies on anticipation, we suggest this influence may vary according to the particular sport setting of interest.

Declaration of competing interests

None.

Data availability

Data will be made available upon reasonable request to the corresponding author (JWR).

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