



Skill and experience impact neural activity during global and local biological motion processing

B.S. DeCouto^{a,b,*}, N.J. Smeeton^c, A.M. Williams^{a,b}

^a Florida Institute for Human & Machine Cognition, Human Health, Resilience & Performance, 40 South Alcaniz St. Pensacola, FL 32502, USA

^b University of Utah, College of Health, Department of Health & Kinesiology, 383 Colorow Drive, Suite 260, Salt Lake City, UT. 84112, USA

^c University of Brighton, School of Sport and Health Sciences, Sport and Exercise Science and Sports Medicine Research and Enterprise Group, 1 Denton Road, Eastbourne BN22 7SR, Brighton, England, UK

ARTICLE INFO

Keywords:

EEG
Parietal
Processing
Brain
Low spatial frequency
Anticipation

ABSTRACT

During biological motion perception, individuals with perceptual experience learn to use more global processing, simultaneously extracting information from multiple body segments. Less experienced observers may use more local processing of individual body segments. The parietal lobe (e.g., alpha and beta power) has been shown to be critical to global and local static stimulus perception. Therefore, in this paper, we examined how skill impacts motion processing by assessing behavioral and neural responses to degrading global or local motion information for soccer penalty kicks. Skilled ($N = 21$) and less skilled ($N = 19$) soccer players anticipated temporally occluded videos of penalty kicks under normal, blurred (degraded local information), or spatially occluded (hips-only; degraded global information) viewing conditions. EEG was used to measure parietal alpha and beta power. Skilled players outperformed less skilled players, albeit both skill groups were less accurate in the blurred and hips-only conditions. Skilled performers showed significant decreases in bilateral parietal beta power in the hips-only condition, suggesting a greater reliance on global motion information under normal viewing conditions. Additionally, the hips-only condition elicited significantly greater beta relative to alpha power (beta – alpha), lower beta power, and lower alpha power than the control condition for both skill groups, suggesting spatial occlusion elicited a shift towards more local processing. Our novel findings demonstrate that skill and experience impact how motion is processed.

1. Introduction

Biological motion perception is influenced by viewing experience (Jacobs et al., 2004; Lieberman, 1984; Pratt, 1950). When observing point-light walking displays (PLDs), individuals are better at detecting gait characteristics (e.g., walking direction, walker identity, changes in speed) for gait patterns resembling human motion rather than non-human or impossible gait patterns, presumably due to more perceptual experience observing human motion (Chang and Troje, 2009b; Jacobs et al., 2004; Ueda et al., 2018). Furthermore, younger infants prefer looking at PLDs that are non-biologically specific, developing a preference for human displays later in development (Bidet-Ildes et al., 2014; Fox and McDaniel, 1982; Simion et al., 2008). It is postulated that greater experience with a stimulus develops this holistic motion processing ability (Chang and Troje, 2009b; Troje and Chang, 2023). In sporting domains, skilled athletes, who possess significant

experience actively viewing and responding to domain-specific movements of opponents, utilize motion information distributed across an opponent's body, while less skilled athletes localize attention towards movement endpoints (e.g., arm-racquet for a tennis serve; Huys et al., 2009; Smeeton et al., 2019; Williams et al., 2009). Thus, skilled athletes might be processing motion more holistically or globally than less skilled athletes, which could be advantageous considering that the severe time constraints frequently encountered in sport will limit the amount of motion information that can be extracted to guide actions. Given that skilled and less skilled athletes have measurable differences in experience observing domain-specific movements, sport provides an effective vehicle to examine how skill impacts biological motion processing. Therefore, in this paper, we examine skill-related preferences for global and local motion information during a time-constrained anticipation task.

Previous reports suggest that two distinct processes are involved in

* Corresponding author. Institute for Human and Machine Cognition, Human Health, Resilience & Performance, 40 South Alcaniz St., Pensacola, FL 32502, USA.
E-mail address: bdecouto@ihmc.org (B.S. DeCouto).

biological motion perception: local and global processing (Troje and Chang, 2023; Troje and Westhoff, 2006). *Local processing* is biologically innate and pre-attentive, serving to quickly detect motion from animals or humans that may present danger or that may be critical to achieve a given goal in time-sensitive scenarios. Local processing enables perceivers of scrambled PLDs to identify walking direction by focusing attention locally towards the foot, which carries the most salient information for walking direction due to its downward gravitational acceleration (Chang and Troje, 2009a). *Global processing* involves the perception of spatiotemporal relationships between different body segments to identify more complex visual information such as gender, facing direction, and emotion (Barclay et al., 1978; Hirai and Senju, 2020; Lee and Kim, 2017). Critically, only global processing is thought to be susceptible to learning effects (Chang and Troje, 2009b; Troje and Chang, 2023), which is potentially corroborated by evidence from studies in sport and motor learning (Huys et al., 2009). For example, in observational learning studies using PLDs, novices replicate movements better after training with endpoint displays (e.g., only arm is visible during throwing) compared to full body displays (Breslin et al., 2009; Hayes et al., 2007; Hodges et al., 2007), suggesting that initial learning stages may be facilitated by simpler informational constraints that depend on more localized attention.

Relatedly, results from studies involving the blurring of vision during anticipation are highly suggestive that global processing is learned by skilled athletes. Mann and colleagues (Mann et al., 2007, 2010b, 2010a) showed that when anticipating the actions of cricket bowlers, skilled batters are generally unaffected by blur. This resilience to blur is explained through their greater use of the dorsal visual pathway, since visual blur preserves the motion and contrast information that the dorsal pathway specializes in detecting (Corbetta et al., 2008; Mann et al., 2010a; Ryu et al., 2018). In studies evaluating the perception of static images, visual blur has been associated with global perception (Flevaris and Robertson, 2016; Kauffmann et al., 2014). For instance, attending to a global stimulus structure facilitates subsequent detection of gratings with a low spatial frequency (LSF) filter (Shulman and Wilson, 1987). Furthermore, both global processing and LSF information processing are reported to occur in shared brain regions (Flevaris and Robertson, 2016). Thus, skilled athletes' resilience to visual blur could be due to their predominant use of global processing, which would involve LSF information processing. In this framework, blur degrades fine details for local processing of single body segments and directs attention towards more salient global motion features. For skilled athletes, visual blur would redundantly highlight motion features that are already predominantly extracted through global processing in normal viewing conditions. In contrast, visual blur could impair perceptual judgments for less skilled athletes since they do not have adequate observational experience to quickly extract relevant global motion information that is highlighted in blurred conditions.

Traditionally, researchers have used high spatial frequency (HSF) filters to contrast LSF filters in studies assessing static image perception since local processing is linked to HSF information extraction (Flevaris and Robertson, 2016; Ryu et al., 2018). However, for motion perception, HSF filters still allow biological motion to retain a global movement structure, in that all body segments are visible to process the spatiotemporal relationship between segments. To reduce global motion information in a biological motion display, spatial occlusion may be more functional than HSF filters since body segments can be occluded and replaced with the background or a black box, forcing performers to rely on fewer kinematic cues (Loffing and Hagemann, 2014; Williams and Davids, 1998). For example, Causer et al. (2017) used spatial occlusion to isolate an opponent's hips during soccer penalty kicks, and only skilled goalkeepers could accurately predict kicking direction above chance level, presumably due to their greater experience observing how localized motions at the hips are related to different action outcomes. Similar to how observers of scrambled PLDs use local processing of the foot to determine walking direction, performers in the spatially occluded

soccer task must use local processing to determine kicking direction in the absence of more global information. Therefore, spatial occlusion is a suitable manipulation to contrast visual blur for the assessment of how local and global motion processing are impacted by skill level in sport.

The recording of neural measures can further elucidate global and local motion processing. Neural networks for global and local processing of static images may also be involved during motion processing. Perception of biological motion, like an image, depends upon the binding of local features into a global stimulus structure (Lange et al., 2006; Thirkettle et al., 2009). Scientists have used PLDs with different objects replacing points (e.g., stick figures, inverted faces), and perceivers are asked to discriminate walking direction. Perceivers are slower to determine walking direction when local stimuli contain information conflicting with the global structure (e.g., left-facing walker made up of smaller right-facing walkers; Hunt and Halper, 2008; Kerr-Gaffney et al., 2016; Wittinghofer et al., 2012). These local interference effects are similar to what is reported in object recognition literature, where incongruent global and local stimulus structures can slow recognition of attended features (Navon, 1977; Pang et al., 2020; Song and Hakoda, 2012). The posture-temporal filter model of biological motion perception asserts that neurons attuned to static postural forms during perception of PLDs are active when interpreting motion characteristics (Lappe et al., 2015; Theusner et al., 2014). Thus, the perception of motion and static images may be governed by similar neural networks to those responsible for detecting global and local stimulus features.

Scientists using neural measures or lesion studies have demonstrated shared brain structures for global and local processing across perceptual tasks. Specifically, there is evidence for hemispheric specialization of global and local processing. Patients with left temporo-parietal lesions have trouble reproducing (drawing) local stimulus features and show a global advantage when viewing Navon stimuli (i.e., large letter made up of smaller congruent or incongruent letters), and patients with right temporo-parietal lesions have trouble reproducing global stimulus features and show a local advantage when viewing Navon stimuli (Delis et al., 1986; Lamb et al., 1990; Robertson et al., 1988). In studies using EEG or fMRI with Navon stimuli, right and left temporo-parietal activation are associated with enhanced global and local processing, respectively (Fink et al., 1997; Flevaris et al., 2011; Volberg et al., 2009; Weissman and Woldorff, 2005). Romei et al. (2012) also showed that during a Navon task, rhythmic transcranial magnetic stimulation (TMS) in the alpha frequency range (8–13 Hz) impaired global processing when applied to the right parietal region, and impaired local processing when applied to the left parietal region. Furthermore, LSF (related to global perception) and HSF information (related to local perception) are predominantly processed in the right and left hemisphere, respectively (Flevaris and Robertson, 2016). Thus, previous evidence across domains of research indicates a hemispheric specialization for global and local processing, which may include how biological motion is processed.

Alpha and beta power could indicate global or local processing dominance. Alpha power is inversely related to cortical activation and reflects suppression of task-irrelevant brain regions for neural efficiency (Baumeister et al., 2008; Deeny et al., 2009). Therefore, greater alpha activity could reduce the relative contribution of the left or right hemisphere for motion processing. Moreover, bilateral beta activity may facilitate local perception (Liu and Luo, 2019; Pitchford and Arnell, 2019; Romei et al., 2011). Parietal beta activity is conjectured to be functional for endogenously orienting top-down attention and evoking states of vigilance or alertness before local processing tasks (Battaglini et al., 2020; MacLean et al., 2012; Zaretskaya and Bartels, 2015). Beta activity oscillates at a higher frequency (14–30 Hz), making it useful for detecting momentary changes in the environment with shorter and more frequent temporal processing windows (Kloosterman et al., 2015; Liu and Luo, 2019; Riddle et al., 2019). Furthermore, researchers have observed enhanced local perception when higher beta power is coupled with lower alpha power (e.g., beta – alpha power) in posterior brain

regions (MacLean et al., 2012; Pitchford and Arnell, 2019).

In this study, we investigate if skilled performers process motion more globally and less skilled performers process motion more locally using a video-based temporal occlusion paradigm. We use neural markers from previous perceptual research to distinguish global and local processing, namely reduced right parietal alpha power for global processing, and reduced left parietal alpha power, increased bilateral beta power, and greater bilateral beta – alpha power for local processing (Pitchford and Arnell, 2019; Volberg et al., 2009; Zaretskaya and Bartels, 2015). Additionally, we created viewing conditions that emphasize global (visual blur) and local (spatial occlusion) motion information to further delineate skill-based differences in neural activity. We measured neural activity during a preparatory period before motion processing, which is consistent with methodologies adopted in previous work on local and global processing (Flevaris et al., 2011; Volberg et al., 2009). However, since motion processing is a continuous task in which global and local visual attention can be continuously utilized, we also explored neural activity during the motion processing period.

We hypothesized that skilled players would outperform less skilled players across conditions. Yet, we expected only less skilled performers to be negatively impacted by blur (Mann et al., 2010a; Ryu et al., 2015). We expected skilled and less skilled observers would demonstrate neural activity indicative of global and local processing, respectively, and the blurred and spatial occlusion conditions would elicit neural activity indicative of global and local processing, respectively. We also expected that less skilled individuals would show a more dramatic shift in neural activity from local to global processing from the control to blurred (global) condition than skilled observers, and skilled performers would show a more dramatic shift in neural activity from global to local processing from the control to spatial occlusion (local) condition.

2. Materials and methods

2.1. Participants

We recruited 21 skilled (M age = 29.8 ± 8.5 , 7 females) and 19 less skilled (M age = 28.2 ± 5.0 , 7 females) soccer players with normal or corrected-to-normal vision. Skilled players had participated in organized and semi-professional leagues, had at least 10 years of competitive experience (23.3 ± 9.6 years) and reported regularly playing 1.9 ± 1.4 times per week. Less skilled players played infrequently and only at the recreational level (1.1 ± 1.2 years, play 0.01 ± 0.02 times per week). Three participants reported having goalkeeper experience. A sensitivity analysis in G*Power was conducted to determine the effect size that our sample size was powered to detect, showing that 30–40 participants were sufficient to detect small-to-medium effect sizes ($f = 0.20$ – 0.25) with 80% statistical power. This effect size range assumes a moderate correlation in brain activity across conditions for individuals ($r = 0.60$), which is reasonable given individual correlations in alpha asymmetry across tasks in other work (Leiker et al., 2019; Metzen et al., 2021). For EEG analyses, we removed three participants who were over 40 years of age because older populations have distinct neural activity in oscillatory frequencies from younger adults (Hong et al., 2015; Voytek et al., 2015). For behavioral performance analyses, we kept the three older participants and removed one younger skilled participant due to corrupted performance measurements. There were three left-handed participants that we kept in our analyses since hemispheric-specific functions are likely not impacted by handedness (Packheiser et al., 2020). We include an analysis without left-handed participants in Appendix A. Participants received monetary compensation for their participation in the research. Informed consent was obtained for all participants, and ethical approval was granted by the University of Utah's Institutional Review Board (IRB). Additionally, individuals in experimental footage gave informed consent for publication of identifying images in an online open-access publication. All methods were performed in accordance with the Declaration of Helsinki.

2.2. Stimuli

We used video clips of soccer penalty kicks from the work of Causer and colleagues (Causer et al., 2017; Causer and Williams, 2015). These videos were recorded from the perspective of a goalkeeper standing in the center of the goal at eye height 1.7 m off the ground. Videos consisted of penalty kicks from four full-time players at a professional club in England. Each player had three kicks at four possible targets (top left, bottom left, top right, or bottom right of the goal), making up a total of 48 video clips. The film clips included the player's approach to the ball and continued throughout the kicking action. Film was edited using Adobe Premiere Pro 2020 (Adobe Systems Incorporated, San Jose, CA). We used the Gaussian blur feature in Adobe Premiere to set the blur to 20% intensity after piloting different blur intensities aimed at allowing skilled players to still perform above chance.

The spatially occluded footage was from Causer et al. (2017) and consisted of all body segments being replaced with the background except for the hips. We temporally occluded (i.e., stopped) footage at 80ms before ball contact because this interval elicited scores between 61 and 72% accuracy for skilled players, and 39–50% accuracy for less skilled players in the work by Causer et al. (2017). The 80ms occlusion interval should have been challenging enough for both skill levels so the more skilled players would not experience a ceiling effect for performance, and less skilled players could score above chance. Finally, each video clip was preceded by a still frame of the clip's first frame for 1000ms so we could record EEG during a preparatory period and compare this to the motion processing period. Each video clip was approximately 1400ms long. Penalty kickers moved towards the ball closer to the camera during each video clip, so the stimulus size was approximately 11.8–13.79 cm, resulting in a visual angle of 10.87–12.69°. We used PsychoPy v2021.3 (Peirce et al., 2019) to present study stimuli. The computer monitor used was 53×32 cm with a refresh rate of 60 Hz and pixel resolution of 1920×1080 pixels. The computer and monitor were stationed in the corner of a laboratory, where only the participant and experimenter were present. The computer was equipped with an Intel Core i7-7700 K CPU, 32 Gb of RAM, and an NVIDIA Quadro P4000 graphics card. Sample stimuli are displayed in Fig. 1.

2.3. Procedures

Participants filled out demographic questionnaires and were seated 62 cm in front of the computer monitor. Participants were asked to avoid head and body movements throughout data acquisition to mitigate muscular and motion artifact in EEG signals. EEG data were collected during a 30-s baseline period with participants' eyes open staring at a blank monitor. A familiarization period was presented consisting of four video trials (2 normal, 1 blurred, and 1 occluded). Each trial consisted of: 1) a still-image of the first video frame for 1000ms; 2) a video with temporal occlusion at 80ms before ball contact; and 3) a black screen for 2000ms during which participants were told to make a keyboard response to guess the kick location in the goal. 'Enter' signified top right, 'right Ctrl' bottom right, 'Caps Lock' top left, and 'left Ctrl' bottom left. Feedback on performance was provided during familiarization but not during the study. The study consisted of 8 blocks of 34–35 trials (276 total) with normal, blurred, and spatially occluded clips randomly interleaved (92 trials of each condition). Participants had a 30-s break between blocks. The study in total took about 42 min to complete.

2.4. Measurements

Anticipation. Performance was measured by comparing predicted versus actual kick location. Performance was analyzed as the percentage (%) of trials answered correctly for kick direction, kick height, and combined kick direction and kick height (total).

Brain Activity. Brain activity was analyzed using BrainVision

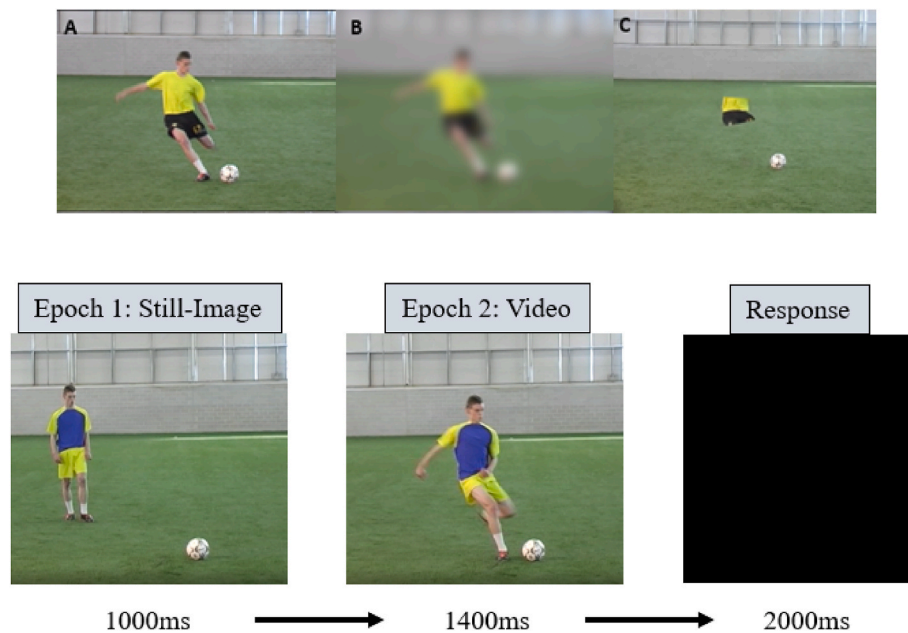


Fig. 1. **Top:** Video stimuli used in the study. **A)** Normal condition (normal), **B)** Blurred condition (blur), and **C)** Spatially occluded condition (hips-only). **Bottom:** Schematic of trials. At the start of each trial, participants viewed a still-image of the video's first frame for 1000ms, then watched the video of the penalty kick. Following the kick, a blank screen was presented for 2000ms during which participants had to use the keyboard to predict where the ball would end up.

Recorder (Brain Products, GmbH, Munich, Germany). We used 32 channels in a 64-channel actiCAP system labeled in accordance with the international 10–20 system (Jasper, 1958). Signals were amplified with a BrainAmp DC amplifier. The system collects data at 1000 Hz, and impedances at each electrode were kept below 25 k Ω . The ground electrode was placed on the right earlobe, and the reference electrode was placed directly anterior to Cz. We used frontotemporal (FT9, FT10) and temporoparietal (TP9, TP10) electrodes on the cap as vEOG and hEOG electrodes.

The data were processed through BrainVision Analyzer (Brain Products, GmbH, Munich, Germany). We resampled the data to 256 Hz, and an infinite impulse response (IIR) filter was applied with a high-pass filter at 0.1 Hz and a low-pass filter at 60 Hz (4th order). EEG data were visually inspected to flag major blink and muscle artifacts. We used independent component analysis (ICA) with vEOG and hEOG to correct for ocular artifacts across trials per subject. We removed components that were significantly influenced by ocular activity from the data, correlating the resulting independent components from the ICA time source with the vertical and horizontal ocular sensor activity. If the sum of squared correlations was greater than 5, independent components were considered artifactual. To enhance source localization, we transformed the data using surface Laplacian (SL). SL entails calculations subtracting the voltages from neighboring electrodes according to distance (Kayser and Tenke, 2015). We used a 4th order spline for SL due to its proven flexibility with lower density arrays (Kayser and Tenke, 2015). We manually inspected data for major muscular and blink artifacts that the ICA did not correct. Fast Fourier transformation (FFT) was applied to analyze oscillatory rhythms in the alpha (8–13 Hz) and beta (14–30 Hz) frequency ranges. Specifically, we examined activity at parietal electrodes (P3, P4, P7, P8) because this region participates in global and local perception as well as action observation (Balsler et al., 2014; Flevaris et al., 2011; Volberg et al., 2009). We averaged activity in the left (P3 and P7) and right (P4 and P8) hemisphere. Brain activity was measured at two epochs to assess a preparatory period (still-image) in addition to the motion processing period because most global/local processing work has used preparatory periods to infer about subsequent processing mechanisms (Flevaris et al., 2011; Volberg et al., 2009). Epoch 1 consisted of a 1-s baseline period with a still-image of the first

video frame, and Epoch 2 consisted of the video portion of the trial. We subtracted each participant's EEG data from their 30-s baseline period.

2.5. Data analysis

The EEG data were log10 transformed to achieve a more normal distribution, so interpretations of our data should consider that total alpha or beta power is on a different scale. The log10 transformation of EEG data resulted in more normal distribution of residuals in subsequent analyses as indexed by visual inspection of q-q plots. We used linear mixed effect regressions (LMERs) in our analyses given their robustness to violations of normally distributed data (Schielzeth et al., 2020). LMERs also allow for the control of individual differences in intercepts within each condition since random effects can control for individual responses to conditions (Boisgontier and Cheval, 2016; Kristensen and Hansen, 2004). Thus, the ability of LMERs to account for random effects while maintaining a general robustness to violations of normality allows for more accurate statistical estimates compared to non-parametric tests. We created a variable to assess relative differences between beta and alpha power (beta power minus alpha power, or beta – alpha) because higher beta power accompanied by lower alpha power has been associated with local processing dominance (Pitchford and Arnell, 2019). The LMER assessing anticipation performance (% correct) included factors of Skill (skilled, less skilled) and Condition (normal, blur, occlusion), interaction terms, and random effects for Participant:

$$\text{Performance} \sim \text{Skill} \times \text{Condition} + (1|\text{Participant})$$

LMERs for each EEG variable (alpha power, beta power, beta – alpha power) included factors of Skill (skilled, less skilled), Hemisphere (right, left), and Condition (normal, blur, occlusion), interaction terms, and random effects of Participant and Participant crossed with Condition and Hemisphere:

$$\text{EEG} \sim \text{Skill} \times \text{Hemisphere} * \text{Condition} + (1|\text{Participant}) + (1|\text{Hemisphere:Participant}) + (1|\text{Condition:Participant})$$

We used separate models to analyze data in each epoch. For mixed models, we calculated effect sizes as partial eta-squared (η^2) values, and confidence intervals (CI) are reported for η^2 values. We reported model

performance as the marginal R^2 values for LMERS which provides the variance explained by fixed effects of the model (Jaeger et al., 2017). Post hoc follow-up tests were conducted using contrast analyses with Benjamini-Hochberg corrections for multiple testing, and we report Cohen's d effect sizes. In communicating our EEG results, we first address the preparatory period (epoch 1), then the motion processing period (epoch 2). We place statistical results testing our main hypotheses at the beginning of each section, and subsequent results exploring other outcomes are reported afterwards. Data analyses were conducted using R Studio v2023.4.2.3 (Barton, 2022; Lüdtke, 2019; Wickham, 2016; Wickham and Golemund, 2020).

3. Results

3.1. Anticipation

Direction. There were significant main effects of Skill ($p < .001, \eta^2 = .141$) and Condition ($p < .001, \eta^2 = .397$), which were superseded by an interaction between Skill and Condition ($p = .018, \eta^2 = .083$). Skilled players performed significantly better than less skilled players in the normal ($p < .001, d = .50$) and blurred conditions ($p = .009, d = .33$), but not in the hips-only condition, ($p = .205, d = .15$). For both skill groups, performance was significantly worse in the hips-only condition compared to the control (p 's $< .011, d$'s $> .33$) and blurred conditions (p 's $< .011, d$'s $> .34$). Performance was significantly above chance level in the normal (Skilled: $p < .001$; Less Skilled: $p < .001$), blurred (Skilled: $p < .001$; Less Skilled: $p < .001$), and hips-only conditions (Skilled: $p < .001$; Less Skilled: $p = .003$).

Height. There was a significant main effect of Condition, ($p < .001, \eta^2 = .176$). Performance was significantly worse in the hips-only compared to the normal ($p < .001, d = .48$) and blurred conditions ($p = .001, d = .41$), but no difference emerged between the control and blurred condition ($p = .543, d = .07$). Performance was significantly above chance level for only the normal condition ($p = .014$), but not significantly above chance level for the blurred ($p = .145$) and hips-only conditions ($p = .999$). Thus, comparisons involving the blurred and hips-only condition for height performance should be interpreted with caution. There was no main effect for Skill ($p = .705, \eta^2 = .001$) or interaction between Condition and Skill ($p = .153, \eta^2 = .035$).

Total. There were significant main effects of Skill ($p = .011, \eta^2 = .067$) and Condition ($p < .001, \eta^2 = 0.391$). Skilled players performed significantly better than less skilled players across conditions ($p = .013, d = .29$). Both skill groups performed better in the control condition compared to the blurred ($p = .013, d = .30$) and hips-only condition ($p <$

$.001, d = .91$). Additionally, participants were more accurate in the blurred condition compared to the hips-only condition ($p < .001, d = .60$). No significant interaction emerged between Skill and Condition ($p = .011, \eta^2 = .067$). Total performance was significantly above chance level in the normal (Skilled: $p < .001$; Less Skilled: $p < .001$) and blurred conditions (Skilled: $p < .001$; Less Skilled: $p < .001$), but for the hips-only condition, only skilled players performed above chance (Skilled: $p = .004$; Less Skilled: $p = .059$). Performance data are depicted in Fig. 2, and detailed statistical outputs for performance data can be found in Table 1 and Table 2.

3.2. Brain activity

Alpha Power Epoch 1 (1000 ms). No significant interactions emerged between Skill, Condition, and Hemisphere, ($p = .303, \eta^2 = .031$), or between Skill and Hemisphere ($p = .621, \eta^2 = .003$), indicating no hemispheric specialization for global or local processing according to skill. There was no interaction between Skill and Condition ($p = .726, \eta^2 = .008$), indicating that viewing conditions did not impact neural activity according to skill level. Other main effects and interactions did not reach significance (p 's $> .090$).

Table 1

Mixed model results for analyses on performance measurements. Significant results are highlighted in bold.

Dependent Variable	Fixed Effect	df	F	p	η^2	R^2
Direction	Skill	1,	15.38	<	.141	.377
		40		.001		
	Condition	2,	30.89	<	.397	
		80		.001		
Skill x Condition	2,	4.24	.018		.083	
	80					
Height	Skill	1,	.15	.705	.001	.163
		40				
	Condition	2,	11.45	<	.176	
		80		.001		
Skill x Condition	2,	1.92	.153		.035	
	80					
Total	Skill	1,	7.04	.011	.067	.334
		40				
	Condition	2,	31.64	<	.391	
		80		.001		
Skill x Condition	2,	1.28	.283		.025	
	80					

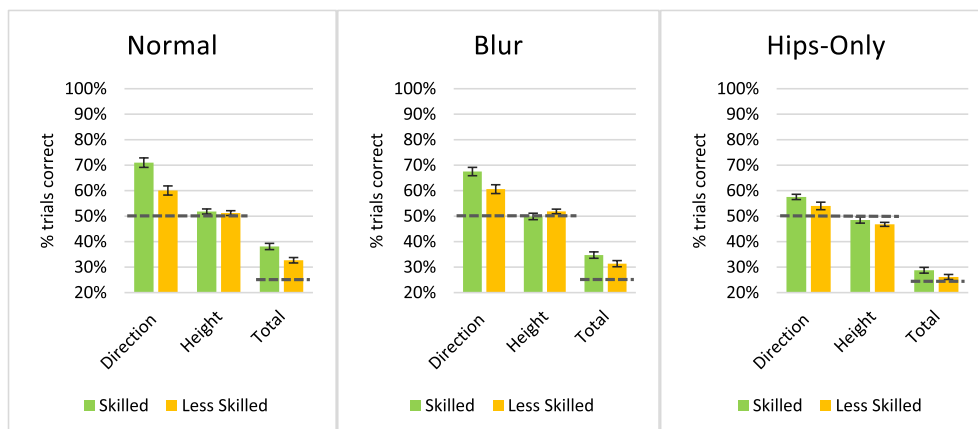


Fig. 2. Performance accuracy scores for normal, blurred, and hips-only conditions (in %). Grey dashed lines represent chance-level performance. Skilled players anticipated direction significantly better than less skilled players in the normal and blurred conditions. No skill differences were evident for anticipation of height. Skilled players anticipated combined direction and height (total) better than less skilled players across all conditions. For both skill groups, performance was significantly worse in the hips-only compared to the normal and blurred condition for each performance measurement. Anticipation of height was not greater than chance level for the blurred and hips-only viewing conditions.

Table 2
Post hoc comparisons for performance models.

Dependent Variable	Effect/Interaction	Factor Levels	Post hoc comparison	β	SE	p	d	
Direction	Skill x Condition	Control	Skilled > Less Skilled	.102	.026	< .001	.50	
			Blur	Skilled > Less Skilled	.067	.024	.009	.33
			Hips-only	Skilled \approx Less Skilled	.031	.018	.205	.15
			Skilled	Control \approx Blur	.033	.017	.077	.21
				Control > Hips-only	.126	.017	< .001	.81
		Less Skilled	Blur > Hips-only	.093	.017	< .001	.60	
			Control \approx Blur	.002	.018	.930	.01	
			Control > Hips-only	.055	.018	.011	.33	
			Blur > Hips-only	.056	.018	.011	.34	
			Control \approx Blur	.006	.009	.543	.07	
Height	Condition		Control > Hips-only	.040	.009	< .001	.48	
			Blur > Hips-only	.034	.009	.001	.41	
		Total	Skill	Skilled > Less skilled	.031	.012	.013	.29
				Condition	Control > Blur	.025	.010	.013
		Control > Hips-only	.076	.010	< .001	.91		
		Blur > Hips-only	.050	.010	< .001	.60		

“Effect/Interaction” refers to the significant main effect or interaction found in the mixed model.

“Factor Levels” refer to levels within a factor in which post hoc comparisons are being made. “ β ” refers to the estimated difference between two groups. “ \approx ” denotes nonsignificant difference. Effect sizes are displayed as Cohen’s d . Significant results are highlighted in **bold**.

Alpha Power Epoch 2 (~1400 ms). No significant interactions emerged between Skill, Condition, and Hemisphere, ($p = .390, \eta^2 = 0.023$), or between Skill and Hemisphere ($p = .691, \eta^2 = .002$), indicating no hemispheric specialization for global or local processing according to skill. There was no interaction between Skill and Condition ($p = .066, \eta^2 = .066$), indicating that viewing conditions did not impact neural activity according to skill level. There was a significant main effect of Condition ($p < .001, \eta^2 = .299$), revealing that the hips-only condition induced significantly less alpha power than the control ($p < .001, d = .65$), and blurred condition ($p < .001, d = .44$), but no significant difference emerged between the control and blurred condition ($p = .084, d = .20$) (Fig. 3). Other main effects and interactions did not

reach significance (p 's > .343).

Beta Power Epoch 1 (1000 ms). No significant main effect was observed for Skill ($p = .094, \eta^2 = .038$), and no significant interaction was observed between Skill and Condition ($p = .796, \eta^2 = .006$), indicating that bilateral parietal beta power did not differ according to skill or condition as we hypothesized. Other effects and interactions failed to reach significance (p 's > .107).

Beta Power Epoch 2 (~1400 ms). There was no main effect for Skill, ($p = .306, \eta^2 = .014$), but there was a significant interaction between Skill and Condition ($p = .022, \eta^2 = .094$). For only skilled performers, there was lower beta power in the hips-only condition compared to the control ($p < .001, d = .54$), and blurred condition ($p < .001, d = .48$), but

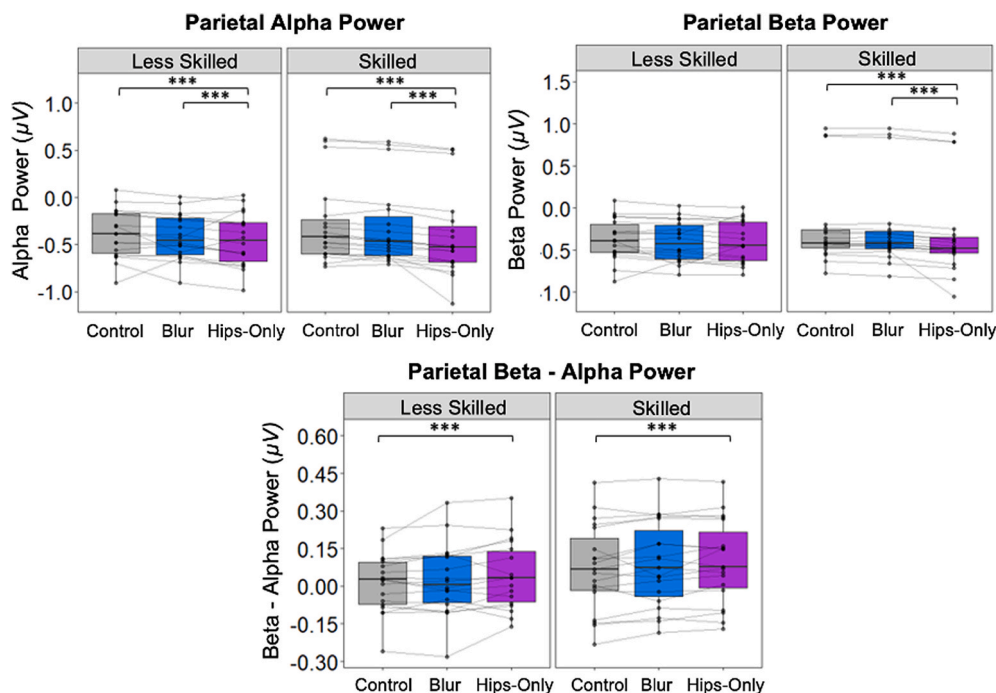


Fig. 3. Log-transformed parietal beta and alpha power for each visual condition and skill group. Negative values reflect desynchronization from a baseline period. Individual data points and lines represent each subject’s change between conditions. **Top Left)** Both skill groups showed significantly lower alpha power in the hips-only compared to the control and blurred condition. **Top Right)** Only skilled performers showed significant reductions in beta power in the hips-only compared to control and blurred conditions. **Bottom)** Both skill groups had higher beta relative to alpha power (beta – alpha power) in the hips-only compared to the control condition. * denotes $p < .05$, ** denotes $p < .01$, and *** denotes $p < .001$. There were no skill interactions for alpha power and beta – alpha power plots, meaning that comparisons are averaged across groups in these plots and replicated in both skill boxes for uniformity.

no differences emerged between the control and blurred condition ($p = .651, d = .06$) (Fig. 3). These findings are divergent from our predictions about neural activity for global or local processing since we predicted greater beta for the hips-only condition for skilled players. Other main effects and interactions did not reach significance (p 's > .248).

Beta – Alpha Power Epoch 1 (1000 ms). There was no main effect of Skill ($p = .725, \eta^2 = .001$) or Condition ($p = .790, \eta^2 = .005$), but there was a significant interaction between Condition and Hemisphere ($p = .032, \eta^2 = .073$) and between Skill, Condition, and Hemisphere ($p = .038, \eta^2 = .070$). However, post hoc tests did not reveal any significant differences after correcting for multiple comparisons, indicating that p -value corrections eliminated type I error (see Appendix B for post hoc results). Other main effects and interactions did not reach significance (p 's > .105).

Beta – Alpha Power Epoch 2 (~1400 ms). In testing whether greater beta – alpha power would be associated with less skilled motion perception, we did not find a main effect of Skill ($p = .224, \eta^2 = .017$). We also expected beta – alpha power to be impacted by viewing condition, and we found a significant main effect for Condition ($p = .001, \eta^2 = .155$) (Fig. 3). The hips-only condition produced significantly greater beta – alpha power than the control condition ($p < .001, d = .46$), but no difference emerged between control and blur ($p = .075, d = .21$), or between blur and hips-only ($p = .075, d = .25$). Other main effects and interactions did not reach significance (p 's > .100). The detailed statistical outputs for EEG data can be found in Table 3 and Table 4.

4. Discussion

We examined skill-related differences in motion processing during anticipation using a penalty kick task with viewing conditions that reduced access to global and local motion information. We expected skilled players to outperform less skilled players across conditions, and that only less skilled players would be adversely affected by visual blur. We hypothesized that skilled players would generally show more neural activity indicative of global processing (i.e., greater left parietal alpha power; less bilateral beta power) than less skilled players, particularly in the blurred condition, while less skilled players would show the opposite trend. We also expected less skilled players to show greater bilateral beta – alpha power than skilled players, which would evidence more local processing. Finally, we expected skilled players' neural activity to be more impacted by the hips-only condition and less skilled players to be more impacted by visual blur.

Skilled players had superior performance to less skilled players for anticipating combined kick direction and height across conditions, and performance declined from the control to the blurred to the hips-only conditions for both skill groups (control > blur > hips-only). In accordance with our hypothesis, neural findings showed an effect of viewing condition on motion processing for both skill groups. The hips-only condition induced significantly lower bilateral alpha power and greater bilateral beta – alpha power which are both neural markers of enhanced local processing (Pitchford and Arnell, 2019; Zaretskaya and

Table 3
Mixed model results for analyses on EEG measurements.

DV	Ep.	Fixed Effect	df	F	p	η^2	R^2
Alpha Power	1	Skill	1, 37	3.30	.077	.042	.074
		Hemisphere	1, 37	.07	.789	.001	
		Condition	2, 74	.43	.655	.011	
		Skill x Hemisphere	1, 37	.25	.621	.003	
		Skill x Condition	2, 74	.32	.726	.008	
		Condition x Hemisphere	2, 74	2.49	.090	.062	
		Skill x Condition x Hemisphere	2, 74	1.21	.303	.031	
	2	Skill	1, 37	.44	.511	.005	.025
		Hemisphere	1, 37	.92	.343	.011	
		Condition	2, 74	17.06	< .001	.299	
		Skill x Hemisphere	1, 37	.16	.691	.002	
		Skill x Condition	2, 74	2.82	.066	.066	
		Condition x Hemisphere	2, 74	.44	.646	.011	
		Skill x Condition x Hemisphere	2, 74	.96	.390	.023	
Beta Power	1	Skill	1, 37	2.95	.094	.038	.068
		Hemisphere	1, 37	.52	.476	.007	
		Condition	2, 74	.34	.716	.009	
		Skill x Hemisphere	1, 37	.83	.370	.011	
		Skill x Condition	2, 74	.23	.796	.006	
		Condition x Hemisphere	2, 74	.41	.666	.011	
		Skill x Condition x Hemisphere	2, 74	2.30	.107	.058	
	2	Skill	1, 37	1.08	.306	.014	.035
		Hemisphere	1, 37	1.01	.322	.013	
		Condition	2, 74	10.59	< .001	.215	
		Skill x Hemisphere	1, 37	.84	.365	.011	
		Skill x Condition	2, 74	4.02	.022	.094	
		Condition x Hemisphere	2, 74	.12	.892	.011	
		Skill x Condition x Hemisphere	2, 74	1.42	.248	.035	
Beta – Alpha Power	1	Skill	1, 37	.13	.725	.001	.029
		Hemisphere	1, 37	1.40	.245	.015	
		Condition	2, 74	.24	.790	.005	
		Skill x Hemisphere	1, 37	2.76	.105	.029	
		Skill x Condition	2, 74	.85	.431	.018	
		*Condition x Hemisphere	2, 74	3.59	.032	.073	
		*Skill x Condition x Hemisphere	2, 74	3.42	.038	.070	
	2	Skill	1, 37	1.53	.224	.017	.050
		Hemisphere	1, 37	.04	.844	.001	
		Condition	2, 74	8.17	.001	.155	
		Skill x Hemisphere	1, 37	2.85	.100	.031	
		Skill x Condition	2, 74	.12	.882	.003	
		Condition x Hemisphere	2, 74	.51	.606	.011	
		Skill x Condition x Hemisphere	2, 74	.04	.963	.001	

Significant results are highlighted in **bold**.

*Post hoc analyses with corrected p values showed no significant Condition, Skill, or Hemispheric differences. See text and Appendix B for detail.

Table 4
Post hoc comparisons for EEG mixed models.

DV	Effect / Interaction	Factor Levels	Post hoc comparison	β	SE	<i>p</i>	<i>d</i>		
Alpha Power Epoch 2	Condition		Control \approx Blur	.029	.017	.084	.20		
			Control > Hips-only	.093	.017	< .001	.65		
			Blur > Hips-only	.063	.017	< .001	.44		
Beta Power Epoch 2	Skill x Condition	Control	Skilled \approx Less Skilled	.153	.136	.451	.13		
			Skilled \approx Less Skilled	.165	.136	.451	.14		
		Blur	Skilled \approx Less Skilled	.088	.136	.651	.08		
			Control \approx Blur	.010	.022	.651	.06		
		Hips-only	Control > Hips-only	.097	.022	< .001	.54		
			Blur > Hips-only	.087	.022	< .001	.48		
		Skilled	Control \approx Blur	.022	.021	.451	.12		
			Control \approx Hips-only	.032	.021	.651	.17		
		Beta – Alpha Power Epoch 2	Condition	Less Skilled	Blur \approx Hips-only	.010	.021	.416	.05
					Control \approx Blur	.013	.007	.075	.21
Control < Hips-only	.028				.007	< .001	.46		
Blur \approx Hips-only	.015				.007	.075	.25		

“Effect/Interaction” refers to the significant main effect or interaction found in the mixed model.

“Factor Levels” refer to levels within a factor in which post hoc comparisons are being made for interactions. “ β ” refers to the estimated difference between compared groups. “ \approx ” denotes nonsignificant difference. Effect sizes are displayed as Cohen’s *d*. Significant results are highlighted in **bold**.

Bartels, 2015). We found no support for our hypothesis that less skilled players would show greater beta power than skilled players. However, for skilled performers, the hips-only condition elicited *lower* bilateral beta power than the control and blurred condition during motion processing, suggesting that skilled motion processing was altered by removing global motion information (Nurislamova et al., 2019). Overall, the neural results did not support our hypothesized outcomes related to skill and traditional neural markers of global and local processing (e. g., hemispheric lateralization), indicating that neural activity for global and local processing of static images may be distinct from neutral activity for global and local motion processing. Yet, despite the results not matching our hypotheses for neural activity, our findings still suggest that skilled observers may be more reliant upon global motion information than less skilled observers.

The role of beta power during cognitive processing has been investigated and contested in numerous contexts including motor preparation (Tzagarakis et al., 2010, 2015), visual alertness (Battaglini et al., 2020; MacLean et al., 2012), cortical inhibition (Arif et al., 2020; Scheeringa et al., 2011), and local stimulus processing (Dale and Arnell, 2013; Zaretskaya and Bartels, 2015). However, beta power has not been studied on tasks involving global and local biological motion processing. Beta power is associated with “maintaining the status quo,” or regulating top-down attention in anticipation of an expected stimulus outcome (Antzoulatos and Miller, 2014; Pagnotta et al., 2020; Spitzer and Haegens, 2017). In this framework, beta power desynchronization reflects reduced contributions from top-down attentional networks to facilitate processing of exogenous information when action outcomes are less certain (Pagnotta et al., 2020). Moreover, alpha power reductions facilitate exogenous information processing by releasing inhibition of cortical regions (Jensen and Mazaheri, 2010; Pagnotta et al., 2020, 2022). Our neural results fit with these latter conjectures because during the motion processing period, alpha and beta power (for only skilled performers) were reduced under spatial occlusion, the condition with which participants were generally least familiar. Participants should be most familiar with conditions containing both global and local motion information, but the removal of global information under spatial occlusion likely caused a shift away from top-down neural networks to track the evolving dynamics of the isolated hip movement (Nurislamova et al., 2019; Palacios-García et al., 2021; van Helvert et al., 2021). These neural shifts likely contributed to performance decrements in the hips-only condition. Thus, decreases in alpha power across skill groups suggest that degraded global motion information caused some uncertainty and enhanced bottom-up processing (Benedek et al., 2014; Spitzer and Haegens, 2017).

Only skilled performers showed significantly lower bilateral parietal beta power in the hips-only condition compared to blur and control

conditions. Less beta power could signal a shift from global to local processing through greater parietal activation (Samaha et al., 2017; Scheeringa et al., 2011). Furthermore, greater bilateral beta – alpha power in the hips-only condition across skill groups suggests that spatial occlusion increased local motion processing demands. High beta with low alpha power has been associated with heightened vigilance and local processing for an upcoming stimulus (MacLean et al., 2012; Pitchford and Arnell, 2019; Zaretskaya and Bartels, 2015). Thus, the hips-only condition may have demanded more local processing which disrupted global processing in skilled performers. Less skilled performers did not show significant bilateral parietal beta power decreases in the hips-only condition, so removing global motion information may not have been as disruptive to their motion processing strategy as it was for skilled performers.

Limited work has made explicit conjectures about the role of beta oscillations during biological motion processing. Denis and colleagues (Denis et al., 2017) looked at sensorimotor oscillations in the alpha and beta frequency bands during a tennis anticipation task. Significant beta power reductions were found only for skilled observers in sensorimotor regions but not in parietal regions. The authors suggested that beta desynchronization in sensorimotor regions of skilled players reflects greater certainty about action outcomes during motor preparation (Denis et al., 2017; Tzagarakis et al., 2015). In contrast, we observed skill-related *parietal* beta reductions in more difficult visual conditions, suggesting that the role of beta power is likely task-specific, skill-dependent, and serves different functions according to brain region.

We expected left hemispheric lateralization of alpha power to be evident in skilled players to indicate global processing dominance (Romei et al., 2012), but our findings did not support a particular role for left or right parietal specialization during motion processing. Previous reports showing hemispheric specialization for global and local processing may be specific to the static stimuli employed (i.e., Navon letters). Given the conceptual overlap between global and local processing for different perceptual categories (e.g., biological motion, objects), it is logical to presume a shared underlying cognitive construct for performance on these tasks. However, some researchers have refuted this idea (Agnew et al., 2016, 2020; Chamberlain et al., 2017). Behavioral performance on different perceptual tasks has been compared (e.g., Navon letters, face discrimination), and generally, no relationships are found for performance between tasks (Chamberlain et al., 2017; Dale and Arnell, 2013). These findings indicate that global and local processing biases may be very task specific, which fits in with the framework that experience with a stimulus will modulate perceptual strategies. Notably, researchers who have compared global and local processing across tasks have used behavioral measures, so our investigation is the first to assess perception of different stimulus categories

with neural (EEG) data. The lack of hemispheric specialization in our results suggests that global and local motion processing may involve different neural pathways and activity than what has previously been observed in studies using static images. Brain activity may exhibit more rapid changes in dynamic real-world tasks. More work is needed to thoroughly assess neural networks involved in global and local motion processing.

It is perhaps noteworthy that significant neural findings were only evident during the motion processing period rather than during the preparatory period. Previous investigations looking at neural correlates of global and local processing have predominantly assessed alpha and beta power immediately before stimulus presentation (Flevaris et al., 2011; Volberg et al., 2009). Given the absence of significant results during the preparatory period in the present study, it is possible that global and local processing of movement depends on observation of the movement itself. For instance, the perception of walking direction in PLD studies is contingent upon the motion of the stimulus to determine how individual points are moving in relation to one another (Chang and Troje, 2009a, 2009b). With this reasoning, skill and condition differences in neural activity would arise primarily during the period where motion is being observed, so individuals can attend to global or local features of the movement. Furthermore, preparatory periods in other studies typically entail a fixation cross (Flevaris et al., 2011; Volberg et al., 2009), and studies using event-related potentials in response to a spatial frequency stimulus typically involve a behavioral task associated with interpreting the static image (Flevaris and Robertson, 2016; Liu and Luo, 2019). Our preparatory period did not have an associated behavioral task, which may have resulted in more passive stimulus observation while waiting for the stimulus to begin moving.

Investigations using visual blur during anticipation have generally not compared performance outcomes between skilled and less skilled athletes, with previous work only highlighting that experts are largely resilient to blur (Krabben et al., 2021; Limballe et al., 2022). Our findings corroborate the notion that skilled athletes are better at anticipating under blur than less skilled athletes (Mann et al., 2010a, 2010b), but blur had a negative impact on anticipation of combined kick height and direction in both skill groups. One study by Ryu and colleagues (Ryu et al., 2015) compared skilled and less skilled individuals in a basketball decision-making task under visual blur. Performance was preserved under mild to moderate blur in skilled players, whereas performance suffered depending on the location of blur (central or peripheral vision) in less skilled individuals (Ryu et al., 2015). The task used by Ryu et al. is markedly different from our soccer task; Ryu's study featured third-person video footage and required tracking player positions, while our study entailed observing a single opponent's movements in first-person. Thus, our results present novel comparisons for anticipation performance under visual blur between skill levels, showing that successful anticipation for both skill groups likely depends on some local information, which blur degrades.

It is possible that the skilled group would have demonstrated more distinct behavioral and neural results from the less skilled group if all skilled players were goalkeepers. Supporting this notion, behavioral results from the work by Causser and colleagues using the same footage produced larger performance differences between skill-levels with a skilled sample of purely goalkeepers (Causser et al., 2017). However, Causser's task was not computer-based (participants physically moved to respond), and their study had significantly less trials than our study (96 trials versus 276; Causser et al., 2017). Nevertheless, the skilled group still demonstrated superior performance to the less skilled group in our study, which demonstrates that their perceptual experience acquired in other playing positions contributed to their ability to accurately anticipate the movements of penalty kickers.

It is also possible that the neural activity in the hips-only condition was due to there being less overall motion information available to predict action outcomes, which in turn increased uncertainty about the stimulus and required more vigilance and bottom-up processing to

process motion (Pagnotta et al., 2020, 2022). However, the distinction between global and local motion processing inherently implies that more information is being used for global than local processing. That is, global processing involves synthesizing motion information across multiple body segments, while local processing involves using single kinematic cues. While the hips-only condition affected neural activity in both skill groups, skilled performers were most affected by the hips-only condition (i.e., significantly less parietal alpha and beta power compared to other conditions), suggesting that they were potentially using more information from other body segments in the control and blurred conditions than less skilled players. In future, researchers should investigate the amount of motion information used during global and local motion processing.

5. Conclusions

Scientists have conjectured that experience facilitates global processing, and our findings lend some support to this notion (Chang and Troje, 2009b; Troje and Chang, 2023). Skilled soccer players' neural activity during motion processing was particularly disrupted when global motion information was removed, suggesting that they may predominantly process motion more globally. However, our results did not align neatly with commonly used brain correlates of global or local processing of static images, and our discussion of results primarily draws upon inferences from effects of visual conditions (i.e., blur, hips-only). Further investigation is necessary to elucidate skill-related mechanisms of motion processing. Given that beta power has been much less investigated than alpha power alongside attention, this study provides groundwork for researchers to investigate parietal alpha-beta power relationships when viewing more ecologically valid motion stimuli.

CRediT authorship contribution statement

B.S. DeCouto: Conceptualization, Methodology, Software, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Formal analysis. **N.J. Smeeton:** Conceptualization, Writing – review & editing. **A.M. Williams:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Data availability

Data and code for this manuscript are publicly available at <https://github.com/bradydecouto/GlobalLocalSoccer>.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.neuropsychologia.2023.108718>.

References

- Agnew, H.C., Phillips, L.H., Pilz, K.S., 2016. Global form and motion processing in healthy ageing. *Acta Psychol.* 166, 12–20. <https://doi.org/10.1016/j.actpsy.2016.03.005>.
- Agnew, H.C., Phillips, L.H., Pilz, K.S., 2020. Visual attention, biological motion perception, and healthy ageing. *Psychol. Res.* 84 (3), 625–642. <https://doi.org/10.1007/s00426-018-1068-6/TABLES/6>.
- Antzoulatos, E.G., Miller, E.K., 2014. Increases in functional connectivity between prefrontal cortex and striatum during category learning. *Neuron* 83 (1), 216–225. <https://doi.org/10.1016/j.neuron.2014.05.005>.
- Arif, Y., Spooner, R.K., Wiesman, A.I., Embury, C.M., Proskovec, A.L., Wilson, T.W., 2020. Modulation of attention networks serving reorientation in healthy aging. *Aging (Albany NY)* 12 (13), 12582. <https://doi.org/10.18632/aging.103515>.
- Balsler, N., Lorey, B., Pilgramm, S., Naumann, T., Kindermann, S., Stark, R., Zentgraf, K., Williams, A.M., Munzert, J., 2014. The influence of expertise on brain activation of the action observation network during anticipation of tennis and volleyball serves. *Front. Hum. Neurosci.* 8, 568. <https://doi.org/10.3389/fnhum.2014.00568>.
- Barclay, C.D., Cutting, J.E., Kozlowski, L.T., 1978. Temporal and spatial factors in gait perception that influence gender recognition. *Percept. Psychophys.* 23 (2), 145–152. <https://doi.org/10.3758/BF03208295>.

- Barton, K., 2022. Package "MuMin".
- Battaglini, L., Ghiani, A., Casco, C., Ronconi, L., 2020. Parietal TACS at beta frequency improves vision in a crowding regime. *Neuroimage* 208, 116451. <https://doi.org/10.1016/j.neuroimage.2019.116451>.
- Baumeister, J., Reinecke, K., Liesen, H., Weiss, M., 2008. Cortical activity of skilled performance in a complex sports related motor task. *Eur. J. Appl. Physiol.* 104 (4), 625–631. <https://doi.org/10.1007/s00421-008-0811-x>.
- Benedek, M., Schickel, R.J., Jauk, E., Fink, A., Neubauer, A.C., 2014. Alpha power increases in right parietal cortex reflects focused internal attention. *Neuropsychologia* 56 (1), 393–400. <https://doi.org/10.1016/j.neuropsychologia.2014.02.010>.
- Bidet-Ildes, C., Kitromilides, E., Orliaguet, J.P., Pavlova, M., Gentaz, E., 2014. Preference for point-light human biological motion in newborns: contribution of translational displacement. *Dev. Psychol.* 50 (1), 113–120. <https://doi.org/10.1037/a0032956>.
- Boisgontier, M.P., Cheval, B., 2016. The anova to mixed model transition. *Neurosci. Biobehav. Rev.* 68, 1004–1005. <https://doi.org/10.1016/j.neubiorev.2016.05.034>.
- Breslin, G., Hodges, N.J., Williams, A.M., 2009. Effect of information load and time on observational learning. *Res. Q. Exerc. Sport* 80 (3), 480–490. <https://doi.org/10.1080/02701367.2009.10599586>.
- Causier, J., Smeeton, N.J., Williams, A.M., 2017. Expertise differences in anticipatory judgements during a temporally and spatially occluded task. *PLoS One* 12 (2), e0171330. <https://doi.org/10.1371/journal.pone.0171330>.
- Causier, J., Williams, A.M., 2015. The use of patterns to disguise environmental cues during an anticipatory judgment task. *J. Sport Exerc. Psychol.* 37 (1), 74–82. <https://doi.org/10.1123/jsep.2014.0200>.
- Chamberlain, R., van der Hallen, R., Huygelier, H., van de Cruys, S., Wagemans, J., 2017. Local-global processing bias is not a unitary individual difference in visual processing. *Vis. Res.* 141, 247–257. <https://doi.org/10.1016/j.visres.2017.01.008>.
- Chang, D.H.F., Troje, N.F., 2009a. Acceleration carries the local inversion effect in biological motion perception. *J. Vis.* 9 (1), 1–17. <https://doi.org/10.1167/9.1.19>.
- Chang, D.H.F., Troje, N.F., 2009b. Characterizing global and local mechanisms in biological motion perception. *J. Vis.* 9 (5) <https://doi.org/10.1167/9.5.8>, 8–8.
- Corbetta, M., Patel, G., Shulman, G.L., 2008. The reorienting system of the human brain: from environment to theory of mind. *Neuron* 58 (3), 306–324.
- Dale, G., Arnell, K.M., 2013. Investigating the stability of and relationships among global/local processing measures. *Atten. Percept. Psychophys.* 75 (3), 394–406. <https://doi.org/10.3758/S13414-012-0416-7/TABLES/4>.
- Deeny, S.P., Haufler, A.J., Saffer, M., Hatfield, B.D., 2009. Electroencephalographic coherence during visuomotor performance: a comparison of cortico-cortical communication in experts and novices) electroencephalographic coherence during visuomotor performance: a comparison of cortico-cortical communication in experts. *J. Mot. Behav.* 41 (2), 106–116. <https://doi.org/10.3200/JMBR.41.2.106-116>.
- Delis, D.C., Robertson, L.C., Efron, R., 1986. Hemispheric specialization of memory for visual hierarchical stimuli. *Neuropsychologia* 24 (2), 205–214. [https://doi.org/10.1016/0028-3932\(86\)90053-9](https://doi.org/10.1016/0028-3932(86)90053-9).
- Denis, D., Rowe, R., Williams, A.M., Milne, E., 2017. The role of cortical sensorimotor oscillations in action anticipation. *Neuroimage* 146, 1102–1114. <https://doi.org/10.1016/j.neuroimage.2016.10.022>.
- Fink, G.R., Halligan, P.W., Marshall, J.C., Frith, C.D., Frackowiak, R.S.J., Dolan, R.J., 1997. Neural mechanisms involved in the processing of global and local aspects of hierarchically organized visual stimuli. *Brain* 120 (10), 1779–1791. <https://doi.org/10.1093/brain/120.10.1779>.
- Flevaris, A.V., Bentin, S., Robertson, L.C., 2011. Attentional selection of relative SF mediates global versus local processing: evidence from EEG. *J. Vis.* 11 (7) <https://doi.org/10.1167/11.7.11>.
- Flevaris, A.V., Robertson, L.C., 2016. Spatial frequency selection and integration of global and local information in visual processing: a selective review and tribute to Shlomo Bentin. *Neuropsychologia* 83, 192–200. <https://doi.org/10.1016/j.neuropsychologia.2015.10.024>.
- Fox, R., McDaniel, C., 1982. The perception of biological motion by human infants. *Science* 218 (4571), 486–487. <https://doi.org/10.1126/science.7123249>.
- Hayes, S.J., Hodges, N.J., Huys, R., Williams, A.M., 2007. End-point focus manipulations to determine what information is used during observational learning. *Acta Psychol.* 126 (2), 120–137. <https://doi.org/10.1016/j.actpsy.2006.11.003>.
- Hirai, M., Senju, A., 2020. The two-process theory of biological motion processing. *Neurosci. Biobehav. Rev.* 111, 114–124. <https://doi.org/10.1016/j.neubiorev.2020.01.010>.
- Hodges, N.J., Williams, A.M., Hayes, S.J., Breslin, G., 2007. What is modelled during observational learning? *J. Sports Sci.* 25 (5), 531–545. <https://doi.org/10.1080/02640410600946860>.
- Hong, X., Sun, J., Bengson, J.J., Mangun, G.R., Tong, S., 2015. Normal aging selectively diminishes alpha lateralization in visual spatial attention. *Neuroimage* 106, 353–363. <https://doi.org/10.1016/j.neuroimage.2014.11.019>.
- Hunt, A.R., Halper, F., 2008. Disorganizing biological motion. *J. Vis.* 8 (9), 1–5. <https://doi.org/10.1167/8.9.12>.
- Huys, R., Cañal-Bruland, R., Hagemann, N., Beek, P.J., Smeeton, N.J., Williams, A.M., 2009. Global information pickup underpins anticipation of tennis shot direction. *J. Mot. Behav.* 41 (2), 158–171. <https://doi.org/10.3200/JMBR.41.2.158-171>.
- Jacobs, A., Pinto, J., Shiffrar, M., 2004. Experience, context, and the visual perception of human movement. *J. Exp. Psychol. Hum. Percept. Perform.* 30 (5), 822–835. <https://doi.org/10.1037/0096-1523.30.5.822>.
- Jaeger, B.C., Edwards, L.J., Das, K., Sen, P.K., 2017. An R2 statistic for fixed effects in the generalized linear mixed model. *J. Appl. Stat.* 44 (6), 1086–1105. <https://doi.org/10.1080/02664763.2016.1193725>.
- Jasper, H., 1958. The ten twenty electrode system of the international federation. *Electroencephalogr. Clin. Neurophysiol.* 10, 371–375.
- Jensen, O., Mazaheri, A., 2010. Shaping functional architecture by oscillatory alpha activity: gating by inhibition. *Front. Hum. Neurosci.* 4, 186. <https://doi.org/10.3389/FNHUM.2010.00186/BIBTEX>.
- Kauffmann, L., Ramanoël, S., Peyrin, C., 2014. The neural bases of spatial frequency processing during scene perception. *Front. Integr. Neurosci.* 8 (MAY), 37. <https://doi.org/10.3389/fnint.2014.00037>.
- Kayser, J., Tenke, C.E., 2015. Issues and considerations for using the scalp surface Laplacian in EEG/ERP research: a tutorial review. *Int. J. Psychophysiol.* 97 (3), 189–209. <https://doi.org/10.1016/j.ijpsycho.2015.04.012>.
- Kerr-Gaffney, J.E., Hunt, A.R., Pilz, K.S., 2016. Local form interference in biological motion perception. *Atten. Percept. Psychophys.* 78 (5), 1434–1443. <https://doi.org/10.3758/s13414-016-1092-9>.
- Kloosterman, N.A., Meindertsma, T., Hillebrand, A., van Dijk, B.W., Lamme, V.A.F., Donner, T.H., 2015. Top-down modulation in human visual cortex predicts the stability of a perceptual illusion. *J. Neurophysiol.* 113 (4), 1063–1076. <https://doi.org/10.1152/jn.00338.2014>.
- Krabben, K., Mann, D.L., van Helden, A., Kalisvaart, Y., Fortin-Guichard, D., van der Kamp, J., Savelsbergh, G.J.P., 2021. Getting a grip on the resilience to blur: the impact of simulated vision loss on a visually guided combat sports interaction. *Psychol. Sport Exerc.* 55, 101941. <https://doi.org/10.1016/j.psychsport.2021.101941>.
- Kristensen, M., Hansen, T., 2004. Statistical analyses of repeated measures in physiological research: a tutorial. *Am. J. Physiol. - Adv. Physiol. Educ.* 28, 2–14. <https://doi.org/10.1152/ADVAN.00042.2003/ASSET/IMAGES/LARGE/ZU10010401990006.JPEG>.
- Lamb, M.R., Robertson, L.C., Knight, R.T., 1990. Component mechanisms underlying the processing of hierarchically organized patterns: inferences from patients with unilateral cortical lesions. *J. Exp. Psychol. Learn. Mem. Cognit.* 16 (3), 471–483. <https://doi.org/10.1037/0278-7393.16.3.471>.
- Lange, J., Georg, K., Lappe, M., 2006. Visual perception of biological motion by form: a template-matching analysis. *J. Vis.* 6 (8), 836–849. <https://doi.org/10.1167/6.8.6>.
- Lappe, M., Wittinghofer, K., de Lussanet, M.H.E., 2015. Perception of biological motion from size-invariant body representations. *Front. Integr. Neurosci.* 9 (MAR), 24. <https://doi.org/10.3389/FNINT.2015.00024/BIBTEX>.
- Lee, H., Kim, J., 2017. Facilitating effects of emotion on the perception of biological motion: evidence for a happiness superiority effect. *Perception* 46 (6), 679–697. <https://doi.org/10.1177/0301006616681809>.
- Leiker, A.M., Pathania, A., Miller, M.W., Lohse, K.R., 2019. Exploring the neurophysiological effects of self-controlled practice in motor skill learning. *J. Mot. Learn. Dev.* 7 (1), 13–34. <https://doi.org/10.1123/JMLD.2017-0051>.
- Lieberman, L.M., 1984. Visual perception versus visual function. *J. Learn. Disabil.* 17, 182–185.
- Limballe, A., Kulpa, R., Bennett, S., 2022. Using blur for perceptual investigation and training in sport? A clear picture of the evidence and implications for future research. *Front. Psychol.* 12:752582. doi: 10.3389/fpsyg.2021.752582.
- Liu, L., Luo, H., 2019. Behavioral oscillation in global/local processing: global alpha oscillations mediate global precedence effect. *J. Vis.* 19 (5), 1–12. <https://doi.org/10.1167/19.5.12>.
- Loffing, F., Hagemann, N., 2014. Skill differences in visual anticipation of type of throw in team-handball penalties. *Psychol. Sport Exerc.* 15 (3), 260–267. <https://doi.org/10.1016/j.psychsport.2014.01.006>.
- Lüdtke, D., 2019. Package "sjstats".
- MacLean, M.H., Arnell, K.M., Cote, K.A., 2012. Resting EEG in alpha and beta bands predicts individual differences in attentional blink magnitude. *Brain Cognit.* 78 (3), 218–229. <https://doi.org/10.1016/j.bandc.2011.12.010>.
- Mann, D.L., Abernethy, B., Farrow, D., 2010a. The resilience of natural interceptive actions to reflective blur. *Hum. Mov. Sci.* 29 (3), 386–400. <https://doi.org/10.1016/j.humov.2010.02.007>.
- Mann, D.L., Abernethy, B., Farrow, D., 2010b. Visual information underpinning skilled anticipation: the effect of blur on a coupled and uncoupled in situ anticipatory response. *Atten. Percept. Psychophys.* 72 (5), 1317–1326. <https://doi.org/10.3758/APP.72.5.1317>.
- Mann, D.L., Ho, N.Y., De Souza, N.J., Watson, D.R., Taylor, S.J., 2007. Is optimal vision required for the successful execution of an interceptive task? *Hum. Mov. Sci.* 26 (3), 343–356.
- Metzen, D., Genc, E., Getzmann, S., Larra, M., Wascher, E., Ocklenburg, S., 2021. Frontal and parietal EEG alpha asymmetry: a large-scale investigation of short-term reliability on distinct EEG systems. *Research Square*. <https://doi.org/10.21203/RS.3.RS.323548.V1>.
- Navon, D., 1977. Forest before trees: the precedence of global features in visual perception. *Cognit. Psychol.* 9 (3), 353–383. [https://doi.org/10.1016/0010-0285\(77\)90012-3](https://doi.org/10.1016/0010-0285(77)90012-3).
- Nurislamova, Y.M., Novikov, N.A., Zhodzikhshvili, N.A., Chernyshev, B.v., 2019. Enhanced theta-band coherence between midfrontal and posterior parietal areas reflects post-feedback adjustments in the state of outcome uncertainty. *Front. Integr. Neurosci.* 0, 14. <https://doi.org/10.3389/FNINT.2019.00014>.
- Packheiser, J., Schmitz, J., Arning, L., Beste, C., Güntürkün, O., Ocklenburg, S., 2020. A large-scale estimate on the relationship between language and motor lateralization. *Sci. Rep.* 10 (1), 1–10. <https://doi.org/10.1038/s41598-020-70057-3>, 2020 10:1.
- Pagnotta, M.F., Pascucci, D., Plomp, G., 2020. Nested oscillations and brain connectivity during sequential stages of feature-based attention. *Neuroimage* 223, 117354. <https://doi.org/10.1016/J.NEUROIMAGE.2020.117354>.

- Pagnotta, M.F., Pascucci, D., Plomp, G., 2022. Selective attention involves a feature-specific sequential release from inhibitory gating. *Neuroimage* 246, 118782. <https://doi.org/10.1016/j.neuroimage.2021.118782>.
- Palacios-García, I., Silva, J., Villena-González, M., Campos-Arteaga, G., Artigas-Vergara, C., Luarte, N., Rodríguez, E., Bosman, C.A., 2021. Increase in beta power reflects attentional top-down modulation after psychosocial stress induction. *Front. Hum. Neurosci.* 15, 142. <https://doi.org/10.3389/FNHUM.2021.630813/REFERENCE>.
- Pang, C., Qi, M., Gao, H., 2020. Influence of global precedence on spatial Stroop effect. *Acta Psychol.* 208, 103116. <https://doi.org/10.1016/j.actpsy.2020.103116>.
- Peirce, J., Gray, J.R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., Lindeløv, J.K., 2019. PsychoPy2: experiments in behavior made easy. *Behav. Res. Methods* 51 (1), 195–203. <https://doi.org/10.3758/S13428-018-01193-Y>, 2019 51:1.
- Pitchford, B., Arnell, K.M., 2019. Resting EEG in alpha and beta bands predicts individual differences in attentional breadth. *Conscious. Cognit.* 75, 102803. <https://doi.org/10.1016/j.concog.2019.102803>.
- Pratt, C.C., 1950. The role of past experience in visual perception. *J. Psychol.* 30 (1), 85–107. <https://doi.org/10.1080/00223980.1950.9916054>.
- Riddle, J., Hwang, K., Cellier, D., Dhanani, S., D'esposito, M., 2019. Causal evidence for the role of neuronal oscillations in top-down and bottom-up attention. *J. Cognit. Neurosci.* 31 (5), 768. <https://doi.org/10.1162/JOCN.A.01376>.
- Robertson, L.C., Lamb, M.R., Knight, R.T., 1988. Effects of lesions of temporal-parietal junction on perceptual and attentional processing in humans. *J. Neurosci.* 8 (10), 3757–3769. <https://doi.org/10.1523/jneurosci.08-10-03757.1988>.
- Romei, V., Driver, J., Schyns, P.G., Thut, G., 2011. Rhythmic TMS over parietal cortex links distinct brain frequencies to global versus local visual processing. *Curr. Biol.* 21 (4), 334–337. <https://doi.org/10.1016/j.cub.2011.01.035>.
- Romei, V., Thut, G., Mok, R.M., Schyns, P.G., Driver, J., 2012. Causal implication by rhythmic transcranial magnetic stimulation of alpha frequency in feature-based local vs. global attention. *Eur. J. Neurosci.* 35 (6), 968–974. <https://doi.org/10.1111/j.1460-9568.2012.08020.x>.
- Ryu, D., Abernethy, B., Mann, D.L., Poolton, J.M., 2015. The contributions of central and peripheral vision to expertise in basketball: how blur helps to provide a clearer picture. *J. Exp. Psychol. Hum. Percept. Perform.* 41 (1), 167–185. <https://psycnet.apa.org/buy/2014-54056-001>.
- Ryu, D., Abernethy, B., Park, S.H., Mann, D.L., 2018. The perception of deceptive information can be enhanced by training that removes superficial visual information. *Front. Psychol.* 9 (AUG), 1132. <https://doi.org/10.3389/fpsyg.2018.01132>.
- Samaha, J., Gosseries, O., Postle, B.R., 2017. Distinct oscillatory frequencies underlie excitability of human occipital and parietal cortex. *J. Neurosci.* 37 (11), 2824–2833. <https://doi.org/10.1523/JNEUROSCI.3413-16.2017>.
- Scheeringa, R., Fries, P., Petersson, K.M., Oostenveld, R., Grothe, I., Norris, D.G., Hagoort, P., Bastiaansen, M.C.M., 2011. Neuronal dynamics underlying high- and low-frequency EEG oscillations contribute independently to the human BOLD signal. *Neuron* 69 (3), 572–583. <https://doi.org/10.1016/j.neuron.2010.11.044>.
- Schielzeth, H., Dingemans, N.J., Nakagawa, S., Westneat, D.F., Allogue, H., Teplitsky, C., Réale, D., Dochtermann, N.A., Garamszegi, L.Z., Araya-Ajoy, Y.G., 2020. Robustness of linear mixed-effects models to violations of distributional assumptions. *Methods Ecol. Evol.* 11 (9), 1141–1152. <https://doi.org/10.1111/2041-210X.13434>.
- Shulman, G.L., Wilson, J., 1987. Spatial frequency and selective attention to local and global information. *Perception* 16 (1), 89–101. <https://doi.org/10.1068/p160089>.
- Simion, F., Regolin, L., Bulf, H., 2008. A predisposition for biological motion in the newborn baby. In: *Proceedings of the National Academy of Sciences of the United States of America*, vol. 105, pp. 809–813. <https://doi.org/10.1073/pnas.0707021105>, 2.
- Smeeton, N.J., Hüttermann, S., Williams, A.M., 2019. Postural cues, biological motion perception, and anticipation in sport. In: *Anticipation and Decision Making in Sport*, first ed. Routledge, pp. 16–18.
- Song, Y., Hakoda, Y., 2012. The interference of local over global information processing in children with attention deficit hyperactivity disorder of the inattentive type. *Brain Dev.* 34 (4), 308–317. <https://doi.org/10.1016/j.braindev.2011.07.010>.
- Spitzer, B., Haegens, S., 2017. Beyond the status quo: a role for beta oscillations in endogenous content (re)activation. *ENeuro* 4 (4). <https://doi.org/10.1523/ENEURO.0170-17.2017>.
- Theusner, S., de Lussanet, M., Lappe, M., 2014. Action recognition by motion detection in posture space. *J. Neurosci.* 34 (3), 909–921. <https://doi.org/10.1523/JNEUROSCI.2900-13.2014>.
- Thirkettle, M., Benton, C.P., Scott-Samuel, N.E., 2009. Contributions of form, motion and task to biological motion perception. *J. Vis.* 9 (3). <https://doi.org/10.1167/9.3.28>, 28–28.
- Troje, N.F., Chang, D.H.F., 2023. Life detection from biological motion. *Curr. Dir. Psychol. Sci.* 32 (1), 26–32. https://doi.org/10.1177/09637214221128252/ASSET/IMAGES/LARGE/10.1177_09637214221128252-FIG1.JPEG.
- Troje, N.F., Westhoff, C., 2006. The inversion effect in biological motion perception: evidence for a “life detector”. *Curr. Biol.* 16 (8), 821–824. <https://doi.org/10.1016/j.cub.2006.03.022>.
- Tzagarakis, C., Ince, N.F., Leuthold, A.C., Pellizzer, G., 2010. Beta-band activity during motor planning reflects response uncertainty. *J. Neurosci.* 30 (34), 11270–11277. <https://doi.org/10.1523/JNEUROSCI.6026-09.2010>.
- Tzagarakis, C., West, S., Pellizzer, G., 2015. Brain oscillatory activity during motor preparation: effect of directional uncertainty on beta, but not alpha, frequency band. *Front. Neurosci.* 9 (JUN), 246. <https://doi.org/10.3389/FNINS.2015.00246/BIBTEX>.
- Ueda, H., Yamamoto, K., Watanabe, K., 2018. Contribution of global and local biological motion information to speed perception and discrimination. *J. Vis.* 18 (3), 1–11. <https://doi.org/10.1167/18.3.2>.
- van Helvert, M.J.L., Wijdenes, L.O., Geerlings, L., Medendorp, W.P., 2021. Cortical beta-band power modulates with uncertainty in effector selection during motor planning. *J. Neurophysiol.* 126 (6), 1891–1902. https://doi.org/10.1152/JN.00198.2021/ASSET/IMAGES/LARGE/JN.00198.2021_F005.JPEG.
- Volberg, G., Kliegl, K., Hanslmayr, S., Greenlee, M.W., 2009. EEG alpha oscillations in the preparation for global and local processing predict behavioral performance. *Hum. Brain Mapp.* 30 (7), 2173–2183. <https://doi.org/10.1002/hbm.20659>.
- Voytek, B., Kramer, M.A., Case, J., Lepage, K.Q., Tempsta, Z.R., Knight, R.T., Gazzaley, A., 2015. Age-related changes in 1/f neural electrophysiological noise. *J. Neurosci.* 35 (38), 13257–13265. <https://doi.org/10.1523/JNEUROSCI.2332-14.2015>.
- Weissman, D.H., Woldorff, M.G., 2005. Hemispheric asymmetries for different components of global/local attention occur in distinct temporo-parietal loci. *Cerebr. Cortex* 15 (6), 870–876. <https://doi.org/10.1093/cercor/bhh187>.
- Wickham, H., 2016. *ggplot 2: Elegant Plots for Data Analysis*.
- Wickham, H., Grommunt, G., 2020. *Tidyverse*. <https://www.tidyverse.org/>.
- Williams, A.M., Davids, K., 1998. Visual search strategy, selective attention, and expertise in soccer. *Res. Q. Exerc. Sport* 69 (2), 111–128. <https://doi.org/10.1080/02701367.1998.10607677>.
- Williams, A.M., Huys, R., Cañal-Bruland, R., Hagemann, N., 2009. The dynamical information underpinning anticipation skill. *Hum. Mov. Sci.* 28 (3), 362–370. <https://doi.org/10.1016/j.humov.2008.10.006>.
- Wittinghofer, K., de Lussanet, M.H.E., Lappe, M., 2012. Local-to-global form interference in biological motion perception. *Atten. Percept. Psychophys.* 74 (4), 730–738. <https://doi.org/10.3758/s13414-011-0262-z>.
- Zaretskaya, N., Bartels, A., 2015. Gestalt perception is associated with reduced parietal beta oscillations. *Neuroimage* 112, 61–69. <https://doi.org/10.1016/j.neuroimage.2015.02.049>.