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Research Progress on the Application of Occlusion Paradigms in Sports Action Prediction

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Abstract

In high-speed interceptive sports, athletes are required to judge ball trajectories and execute motor actions within extremely short time windows due to inherent physiological delays. This paper reviews the application and primary findings of temporal and spatial occlusion paradigms in the research of sport action prediction. Temporal occlusion studies reveal that expert athletes demonstrate superior capability in utilizing early kinematic cues for anticipation compared to novices, and this perceptual-cognitive skill can be significantly improved through specific training interventions. Spatial occlusion research supports the "proximal-to-distal" information pickup hypothesis, indicating that experts rely more on proximal cues (such as the trunk and hips) and global movement patterns rather than isolated distal features, which enables them to effectively detect deceptive movements. Furthermore, combined spatiotemporal occlusion paradigms highlight the strict temporal sequencing of visual cue extraction and the adaptive mechanisms of perception-action coupling. Future research directions should integrate virtual reality (VR) and neuroimaging technologies to investigate the underlying neural mechanisms within more ecologically valid and open competitive environments.

Keywords

Action Prediction; Temporal Occlusion; Spatial Occlusion.

1. Introduction

In high-speed interceptive sports such as tennis, cricket, and baseball, athletes are required to judge ball trajectories and execute motor actions within extremely short time windows. Müller et al. reported that the flight time of a fast cricket delivery typically lasts only 500–700 ms [1]. However, human visuomotor responses are subject to inherent physiological delays. Research by Land and McLeod demonstrated that the latency from visual stimulus onset to the initiation of muscle contraction is approximately 200 ms; when movement planning and execution time are included, the total duration often approaches or even exceeds the ball's flight time [2].

Given these severe temporal constraints, elite athletes cannot rely solely on late ball-flight information after release. A meta-analysis encompassing 42 studies confirmed that the core difference between expert and novice athletes lies in superior perceptual–cognitive skills, particularly action anticipation ability [3]. North et al. defined action anticipation as the ability to predict the outcome of an opponent's action based on early kinematic cues before critical environmental information (e.g., ball trajectory) becomes fully available [4]. Neuroimaging studies further reveal that experts can activate mirror neuron systems within their motor cortex by observing opponents' movements, enabling rapid simulation and recognition of action intentions [5].

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To quantify anticipatory ability and isolate key visual information sources, the occlusion paradigm has been established as a primary methodological approach in this field. Farrow and Abernethy elaborated on the logic of this paradigm in tennis serve research: by artificially removing (occluding) specific temporal segments or spatial regions of visual stimuli, researchers can assess how information loss affects prediction accuracy and thereby determine the causal contribution of specific information sources [6].

This approach effectively overcomes limitations inherent in eye-tracking techniques. Eye-tracking data reflect only overt attention, whereas expert athletes frequently employ covert attention to extract information from peripheral vision or use gaze-anchor strategies (fixating on empty space between relevant locations to monitor multiple cues). Consequently, fixation location alone cannot confirm whether information is processed. In contrast, the occlusion paradigm physically removes information input, allowing direct verification of the functional role of specific visual cues in action prediction [7].

Specifically, temporal occlusion involves cutting off video footage at different time points in an action sequence to identify critical temporal windows for prediction, whereas spatial occlusion involves masking specific anatomical structures (e.g., arms, racket, lower limbs) to identify body regions that provide key kinematic information.

2. Application of the Temporal Occlusion Paradigm in Sport Action Prediction

The temporal occlusion paradigm is one of the most important experimental tools for studying sport action prediction. By truncating visual information during action presentation, observers are limited to early action cues, allowing assessment of their ability to predict future outcomes.

2.1. Temporal Occlusion Reveals Experts' Predictive Advantage

A growing body of research indicates that when performing temporal occlusion tasks, expert athletes demonstrate significantly higher prediction accuracy and faster decision-making than non-experts. A large-scale three-level meta-analysis showed a robust expert advantage in action prediction measured via temporal occlusion tasks, consistent across multiple sports [8].

Numerous studies have employed temporal occlusion paradigms to examine goalkeepers' prediction of penalty kicks and pass directions in soccer. Results indicate that under various occlusion timings, elite goalkeepers outperform lower-level counterparts in predicting shot direction and force, suggesting that experts extract and utilize early kinematic cues from shooters' movements [9]. Temporal occlusion experiments in tennis serving have shown that expert players can accurately judge serve direction before racket–ball contact, a capacity crucial for return performance. Further experiments comparing fixed occlusion points and moving occlusion windows support the notion that experts are more efficient in exploiting advance information [6].

In striking sports such as baseball and cricket, temporal occlusion paradigms are widely used to assess batters' prediction of pitch trajectories. By cutting video footage at different moments before ball release, studies reveal that skilled batters can identify pitch type and direction based on early body movement information from the pitcher, even at very early occlusion points—an ability critical for successful hitting [10] [11].

2.2. Application of the Temporal Occlusion Paradigm in Training and Intervention Studies

Beyond skill assessment, the temporal occlusion paradigm has been systematically applied in training research. A meta-analysis demonstrated that video-based temporal occlusion training significantly improves athletes' visual anticipation abilities. These improvements not only

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appear in laboratory-based video tasks but also transfer to on-field performance, such as small-sided games or decision-making tasks.

Training interventions typically adopt progressively earlier occlusion points, forcing participants to rely on increasingly early information and thereby enhancing sensitivity to action unfolding. Intervention studies in tennis, cricket, and basketball employing pre–post designs have shown that training groups exhibit improvements in decision time and prediction accuracy compared to control groups [12].

Overall, the temporal occlusion paradigm demonstrates high methodological robustness and applied value in sport action prediction research. Extensive empirical evidence and recent meta-analyses confirm that it effectively distinguishes athletes of different skill levels, supports training interventions, and facilitates decision-making analysis in complex contexts. With the integration of video technology and virtual reality, the application of temporal occlusion paradigms in action prediction research is expected to continue expanding.

3. Advances in the Application of the Spatial Occlusion Paradigm in Sport Action Prediction

Unlike temporal occlusion, which manipulates "when information is visible," the spatial occlusion paradigm manipulates "what information is visible" by masking specific spatial regions or body parts within action displays. Through video editing or real-time masking techniques, researchers systematically occlude certain body parts (e.g., upper limbs, lower limbs, trunk), moving objects (e.g., the ball), or background areas to examine changes in prediction performance.

The core research question of spatial occlusion concerns which body parts or spatial information are most critical for action prediction. Accordingly, this paradigm is widely used to examine whether prediction relies on local body cues, global body coordination, or relational information between athletes and the environment.

3.1. Proximal Information Pickup Strategies in Athletes

In whole-body sports involving throwing, striking, and kicking, empirical studies using spatial occlusion strongly support the proximal-to-distal information pickup hypothesis. According to biomechanical kinetic chain theory, movement energy is transferred sequentially from proximal large muscle groups (trunk, pelvis) to distal effectors (arms, implements). Consequently, proximal kinematic features often contain earlier and more stable information about action intent.

Abernethy and Zawi found in badminton that occluding the racket arm and racket (distal cues) did not significantly reduce experts' prediction accuracy, indicating effective compensation via proximal cues such as trunk rotation and shoulder displacement. In contrast, novices exhibited a dramatic performance collapse when distal effectors were occluded, reflecting overreliance on end-effector cues [13]. Similar findings have been reported across sports. Using point-light display (PLD) techniques, Huys et al. demonstrated that experts are more sensitive to relative motion between shoulders and hips in tennis serves [14]. Loffing et al. further identified trunk orientation as a key spatial cue for predicting spike direction in volleyball [15].

Collectively, these studies indicate that expert perceptual systems adapt to biomechanical regularities, forming a strategy that prioritizes information from the origin of the kinetic chain.

3.2. Application of the Spatial Occlusion Paradigm in Detecting Deceptive Actions

In high-contact sports such as soccer, rugby, and basketball, deceptive actions exploit exaggerated movements of non-essential body parts to create visual noise. Spatial occlusion

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studies reveal stark differences between experts and novices in visual attention allocation during deception detection: experts focus on "honest signals," whereas novices are misled by "deceptive signals."

Brault et al. demonstrated in rugby sidestepping tasks that selectively occluding information revealed the body center-of-mass region (e.g., pelvis and lower trunk) as the critical cue for experts judging true running direction. Because center-of-mass displacement cannot be easily faked in short timeframes, it provides high cue validity. In contrast, head and upper-limb movements, which possess greater degrees of freedom and are easier to manipulate, often mislead novices [16]. Jackson et al. further proposed that expert rugby players possess heightened sensitivity to biomechanically "honest" versus deceptive cues and can dynamically suppress processing of misleading spatial information based on task demands [17].

3.3. Integration of Global Perception and Local Features

Beyond attention to specific anatomical regions, spatial occlusion research also reveals the global nature of expert information processing. Using PLD and principal component analysis (PCA), Diaz, Fajen, and Phillips found that in soccer penalty kicks, predictive information was not localized to a single joint but was distributed globally across the evolution of the kicker's posture. Expert goalkeepers could detect this global variable by perceiving coordination among trunk and limb segments [18]. A handball study similarly showed that experts maintained high prediction accuracy under PLD conditions [19], confirming their heightened sensitivity to spatiotemporal relationships among body segments and reflecting a cognitive shift from local feature extraction to holistic pattern recognition.

In summary, the spatial occlusion paradigm provides direct evidence regarding the key visual cues underlying action prediction by systematically manipulating available spatial information. Extensive research indicates that action prediction is not based on a single body part or isolated cue but rather on integrated processing of multiple spatial information sources. Compared with temporal occlusion, spatial occlusion holds unique advantages in addressing the question of "which information prediction relies on," laying a foundation for combined spatiotemporal occlusion paradigms.

4. Advances in Combined Temporal–Spatial Occlusion Paradigms in Sport Action Prediction

By manipulating the visibility of specific spatial information within defined temporal windows, combined temporal–spatial occlusion paradigms overcome the limitations of single-dimension approaches and allow more precise analysis of experts' spatiotemporal information pickup mechanisms, pattern recognition strategies, and perception–action coupling in dynamic environments.

4.1. Temporal Sequencing of Visual Cue Pickup in Experts

Combined paradigms confirm that experts exhibit high temporal sensitivity when extracting biological motion information. In cricket, experts' utilization of bowling-arm information (BHBA) is concentrated within specific windows characterized by maximal kinematic change, and this extraction must follow the natural biomechanical sequence; disrupting cue order eliminates expert advantages [20]. Similarly, Causer et al. found in soccer penalty tasks that the informational value of different body parts evolves over time: hip information predicts direction early, whereas height prediction requires later visual cues [21].

4.2. Cue Selection and Trade-Offs

Predictive strategies are highly dependent on task complexity. Ivosevic and Stöckel found in complex soccer corner-kick scenarios that skilled players prioritized global running patterns of

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attacking players over local movement details of the kicker. Blurring global patterns impaired prediction more severely than blurring local cues [22], indicating that in complex multi-player environments, experts shift attention from local biomechanics to global tactical pattern recognition to cope with information overload.

4.3. Perception–Action Adaptive Compensation under Visual Constraints

Combined paradigms incorporating motion-capture techniques reveal how visual information loss dynamically reshapes movement organization. Stone et al. found in one-handed catching tasks that when critical visual information was occluded early, participants compensated by delaying movement initiation and increasing peak hand velocity rather than failing the task [23]. This finding demonstrates the high plasticity of the perception–action system, which dynamically adjusts execution parameters based on “what can be seen and when,” enabling adaptive transitions from gross orientation to fine motor control.

5. Conclusions and Future Directions

In summary, combined spatiotemporal occlusion paradigms provide profound insights into the mechanisms underlying sport action prediction. Empirical evidence indicates that expert advantages are built upon heightened sensitivity to specific biomechanical cues (e.g., bowling arm, hips) and their natural temporal sequencing. In complex multi-player contexts, experts tend to shift from local feature reliance toward global pattern recognition to overcome informational bottlenecks.

Embodied research further demonstrates that the spatiotemporal integrity of visual information directly constrains movement organization strategies, forcing the motor system to adapt by adjusting temporal and velocity parameters, thereby reflecting tight perception–action coupling.

Despite significant progress, existing research remains limited by the low ecological validity of screen-based tasks, lack of real physical interaction and competitive pressure, and relatively small sample sizes in some studies. Accordingly, future research should focus on three key directions: Employ immersive technologies such as virtual reality (VR) to create environments involving real physical interception and opposition, thereby more accurately simulating competitive performance. Combine eye-tracking with neuroimaging techniques (e.g., fNIRS, EEG) to elucidate neural processing mechanisms underlying expert handling of complex cues and deceptive actions. Shift from standardized closed skills to more uncertain, open competitive contexts to refine theoretical frameworks of perception–action coupling.

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