1   Temporal and Spatial Occlusion of Advanced Visual Information Constrains

2   Movement (Re) organization in One-Handed Catching Behaviors

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1 **Abstract**
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3 Dynamic interceptive actions are performed under severe spatial and temporal

4 constraints. Here, behavioral processes underpinning anticipation in one-handed

5 catching were examined using novel technology to implement a spatial and temporal

6 occlusion design. Video footage of an actor throwing a ball was manipulated to create

7 four temporal and five spatial occlusion conditions. Data from twelve participants'

8 hand kinematics and gaze behaviors were recorded while attempting to catch a

9 projected ball synchronized with the video footage. Catching performance decreased

10 with earlier occlusion of the footage. Movement onset of the catching hand and

11 initiation of visual ball tracking emerged earlier when footage of the thrower was

12 occluded at a later time point in the throwing action. Spatial occlusion did not affect

13 catching success, although movement onset emerged later when increased visual

14 information of the actor was occluded. Later movement onset was countered by

15 greater maximum velocity of the catching hand. Final stages of action (e.g., grasping

16 action of the hand) remained unchanged across both spatial and temporal conditions

17 suggesting that later phases of the action were organized using ball flight information.

18 Findings highlighted the importance of maintaining information-movement coupling

19 during performance of interceptive actions, since movement behaviors were

20 continuously (re)organized using kinematic information from a thrower's actions and

21 ball flight information.

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23 *Keywords:* Perception-action coupling; Informational constraints; Interceptive timing;

24 Gaze; adaptive behaviors; Anticipation.

Introduction

Dynamic interceptive actions, such as catching a moving object, are performed under severe spatial and temporal constraints with a margin of error for interception during catching of only $\pm$ 15 ms even at a moderate speed of 10 m/s (Alderson, Sully, & Sully, 1974). A critical factor in countering these demands is the ability to anticipate event outcome, since waiting for information available after a projectile has been hit, struck or kicked results in insufficient time to successfully perform the interceptive action (van der Kamp & Renshaw, 2015). Evidence supporting this proposal has come from experiments using occlusion paradigms, which require participants to anticipate while viewing video footage that has been edited to occlude actions at different time points (temporal occlusion) or different features within the display (spatial occlusion) (Abernethy & Russell, 1987; Jackson, Warren, & Abernethy, 2006; Müller, Abernethy, & Farrow, 2006; Shim, Carlton, Chow & Chae, 2005; Starkes, Edwards, Dissanayake, & Dunn, 1995).

Despite the considerable body of research investigating pre-ball release behaviors, researchers employing occlusion paradigms have typically overlooked the role of movement organization in interceptive actions. Instead the preferred focus has been on *perceptual judgments* of the predicted direction in which a participant *might have moved* or where a ball *might land*, or on reactive *micro-movements* (very simplified responses such as stepping or pointing in a specific direction). The spatio-temporal (re)organization of coordination patterns, however, appears to be an important factor in anticipation timing as skilled performance differences become more pronounced when actual dynamic interceptive actions are performed in comparison to reactive micro-movements (Travassos, Davids, Araújo & Esteves, 2013).

The theoretical approach of ecological psychology, highlights the importance of studying animal-environment relations and emphasizes the fundamentality of the reciprocal relationship between perception and action (Gibson, 1979; Michaels & Carello, 1981; Warren, 2006). Seminal work in ecological psychology has highlighted the need to design experimental conditions that sample representative information from an organism's environment, and which involve research designs that allow participants to organize functional movement behaviors (i.e., predicated on information-movement coupling; see Brunswik, 1956; Gibson, 1979; Warren, 2006). One attempt to support information-movement coupling in research designs employing occlusion paradigms has been the use of micro-movements or simulated responses to occluded video footage of opponents. However, evidence from behavioral neuroscience has demonstrated that simulated (micro) movements engage different neural processes compared to performing actual interceptive actions. For example, in their study, Króliczak, Heard, Goodale, and Gregory (2006) suggested that merely introducing any type of movement may not be sufficient to engage the dorsal stream compared to when individuals need to physically intercept a moving object. Using a hollow-face illusion in their study, participants had to either point at a marker on the face or intercept the face by flicking the marker off it. Results showed that participants were able to direct rapid movements (i.e. flicking) to the real, not illusory positions of the targets. However, when participants were asked to perform the "slow" pointing movement toward the target, they pointed to the perceived, not the real position of the targets. These results suggested that the ventral stream of the visual cortex was engaged when the hand was pointed at a marker, and, only when participants had to organize a movement to intercept the marker, was the dorsal visual system engaged. In a follow-up study with using fMRI, Króliczak, Cavina-Pratesi,

Goodman, and Culham (2007) showed that that organization of an actual interceptive action and performance of a shadowed one were mediated by activity in different areas of the brain (anterior intra-parietal area vs. right parietal cortex respectively). This evidence suggests that different neural processes underpin the organization of simulated and actual interceptions. Therefore, studies examining coordination behaviors with simplified responses that do not require interception may fail to fully capture the role of the dorsal visual pathway in regulating action.

A challenge for researchers examining the nature of movement (re)organization processes is to allow representative interceptive actions to emerge while controlling the information sources available to participants. To address this issue, Stone et al. (2013) developed an integrated video and ball projection machine enabling rigorous control of pre-ball release visual information while supporting a fully coupled interceptive action that was representative of actual performance. Integrated video and ball projection technology allowed participants access to the kinematic information from a thrower's action (enhancing functionality) and to also organize a physical catching action to intercept a ball projected through a hole cut into a screen (synchronized in time and space with the thrower's action; enhancing fidelity) (see Stone et al., 2013 for a detailed description).

Using this integrated video and ball projection machine, the importance of both advanced visual information from the kinematics of a throwing action and ball flight characteristics in supporting successful catching performance has been reported (Panchuk, Davids, Sakadjian, MacMahon, & Parrington, 2013; Stone, et al., 2014a). When advanced visual information from a thrower's kinematics and ball flight information were combined, catching performance was more successful, movement initiation began earlier, and ball flight was visually tracked from an earlier point and

for a longer time compared to when only ball flight information was available. Stone et al. (2014a) also included a condition in which participants were presented with visual information from an image of a thrower's kinematics, but no ball was projected and participants were asked to simulate a catching action. The organization of the simulated catching actions differed greatly compared to when balls were physically intercepted, with analyses of hand kinematics revealing that movements were initiated later with greater maximum and minimum grip apertures under the former task constraints.

Using the same apparatus, Stone et al. (2014b) examined how advance visual information regulated catching actions by synchronizing and de-synchronizing its relationship with ball trajectory characteristics. When participants viewed footage of slower throws, paired with faster ball projection speeds, these task constraints led to a decrease in catching performance. In early phases of the catching action, timing was organized to match the advance visual information presented in the video images. However, in later phases of catching, like the grasp component, ball flight informational constraints were clearly functional in adapting and regulating behaviors. Together, these findings demonstrated the importance of coupling advanced visual information and ball flight in regulating emergent movement patterns.

Both advanced visual information prior to ball release and subsequent ball flight information have been demonstrated as critical for the (re)organization of catching behaviors using the integrated video and ball projection technology (Panchuk et al., 2013; Stone et al., 2014a; 2014b). Currently, however, there have been no attempts to use integrated technology that provides rigorous control of advanced visual information, which can be spatially and temporally occluded, facilitating the (re)organization of actions for catching a ball, compared to a reactive

micro-movement. This type of occlusion paradigm has typically been used in the past to only investigate "when" advanced perceptual information is used and to identify "what" the key sources of information are for performers to use in predicting and initiating movement responses (e.g. Muller et al., 2006).

In the present study, therefore, we sought to examine how temporal and spatial occlusion of video images of a person throwing a ball shaped movement organization and gaze behaviors during one-handed catching. Based on previous research by Stone et al. (2014a), we hypothesized that tracking latency and time of movement onset would be scaled to visual information available, emerging later when temporal occlusion occurred earlier. These informational constraints were expected to result in participants tracking less of the ball flight and producing higher maximum velocity of the hand to ensure it was in the correct location at the point of ball impact. In turn, as a consequence of these behavioral changes, we expected that catching performance would be less successful when visual information was occluded at an earlier time point, compared to when video images of the full throwing action were available. We also predicted that maximum and minimum grip aperture of the catching hand would be unaffected by temporal occlusion conditions as this action component, occurring later in the catching action, would be adapted to *ball flight* rather than *video image* information. Under spatial occlusion task constraints, we predicted that when larger portions of information from the video image were occluded (e.g. the whole upper body), time of movement onset and tracking latency would emerge later, resulting in a greater maximum hand velocity, and reduced time spent visually tracking the ball. In line with the hypotheses for temporal occlusion conditions, these adaptive movement behaviors were also expected to result in decreased catching performance. However, it was expected that maximum and minimum grip apertures in the grasp phase would

be adapted to ball flight information and would remain the same across the different spatial occlusion conditions.

Method

Participants

Twelve (10 men, 2 women; mean age 24.3 ± 4 years, stature 1.76 ± 0.06 m and body mass 79.8 ± 10.7 kg) right-handed, skilled catchers volunteered to participate in the study. Participants were defined as skilled because they had at least 5 years' experience in sports requiring catching projectiles such as cricket, handball or Australian Rules football (reported via a sport participation questionnaire). Additionally, during a pre-test, participants had to catch at least 16 out of 20 balls (Mean = 18.1 ± 1) projected at 13.9 m/s, standing 7 meters from the ball projection machine. Skill level was confirmed by the high overall catching success level of participants across all experimental conditions (Mean = 92.0 ± 2.6 %). Institutional ethical approval was granted by a University Research Ethics Committee and all participants provided informed consent.

Apparatus

A custom-built apparatus integrated a ball projection machine (Spinfire Pro 2, Spinfiresport, Tennis Warehouse, Victoria, Australia) with a PC (Windows XP, Microsoft, USA), video projector (BenqMP776s, Benq, Australia) and a freestanding projection screen (Grandview, Grandview Crystal Screen, Canada) with a 15-cm hole cut into the screen (see Stone et al., 2013 for a detailed description). The integrated technology allowed video images of an actor throwing a ball to be projected onto a screen and synchronized with balls being projected through the hole cut into the screen. Video images of an actor throwing a ball from the participants' perspective

were recorded with ball speeds measured using a radar gun. Throwing accuracy of the video images was ensured by only including film of trials when the thrown ball hit a 1m x 1m target at a speed of 13.9 ± 0.5 m/s. This speed value corresponded to a ball speed setting on the projection machine of 14 ± 0.2 m/s. Ten video clips (5 for temporal, 5 for spatial occlusion conditions) were selected to ensure video presentation of consistent kinematics of the thrower's action. Final Cut Pro software (Apple, California, USA) was used to edit footage so that time to ball release was recorded and aligned to ensure accurate synchronization of the image of the thrower's release and the projection of a ball (mid-pressed tennis balls, 66mm diameter) from the machine (for details see Stone et al., 2013). Final Cut Pro was then used to edit the videos to create four temporal and five spatial occlusion conditions.

The four temporal occlusion conditions were edited so that video information was removed and replaced by a blank screen at the point of occlusion. These time points were selected by adapting Seroyer et al.'s. (2010) kinetic chain of overhand pitching. Condition T1 was occluded at the point when the ball was below the waist (start of arm movement) representing the point of movement initiation. The next stage condition T2, was defined as the step/early 'cocking' phase of the throwing action, with the video occluded after the point of front foot contact with the floor. The acceleration phase of the throw was split into two components. Condition T3 was defined as the late cocking phase with occlusion occurring at the point of maximal external rotation of the throwing shoulder (arm in front of torso) (Seroyer et al., 2010). The second acceleration phase, condition T4 was defined as the point of ball release (see Figure 1). The video image and ball projection were synchronized so that the ball was projected at the time point at which the video-recorded thrower would have released the ball.
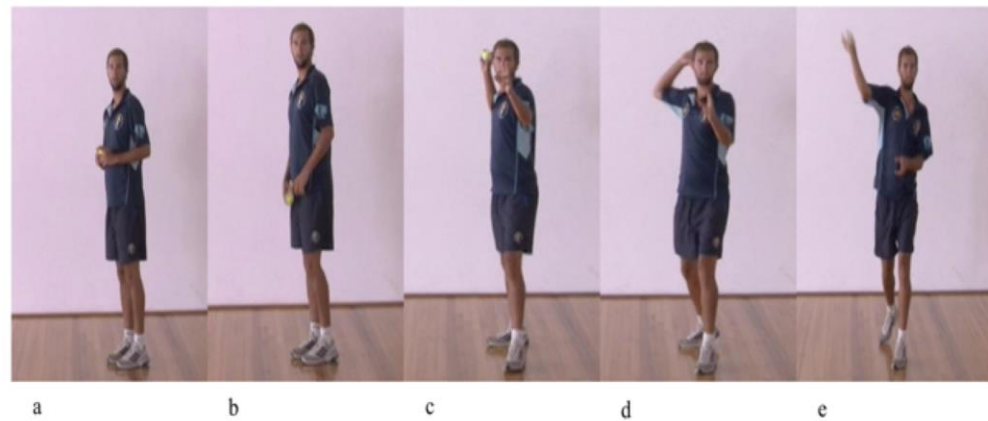
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Figure 1. Screenshots of the final frame before temporal occlusion a) Start of video, b) T1- start of throw/ball below waist, c) T2 front foot contact, d) T3- early cocking/acceleration, e) T4- last acceleration/ release of ball.

The five spatial occlusion conditions removed aspects of the thrower and included: (i) a no-occlusion control condition; (ii) occluded lower body; (iii) occluded upper body-head; (iv) occluded upper body; and (v), occluded throwing arm (see Figure 2). These locations were selected to alter the amount of specifying information available, based on previous research which has highlighted that people use the upper body, head and throwing arm as the most specifying information (see Stone et al., 2014a; 2014b) in catching tasks.
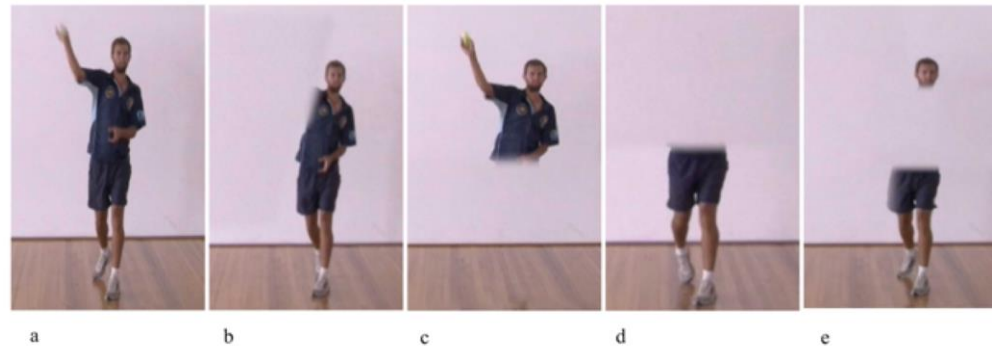
Figure 2. Screenshots of the five spatial occlusion conditions. a) No-Occlusion, b) Occluded throwing arm, c) Occluded lower body, d) Occluded upper body-head, e) Occluded upper torso/trunk.

Kinematic data from participants' movements were collected using a VICON MX System consisting of 10 MX-T-40S cameras recording data at 500 Hz. Markers were placed using a kinematic gait model and marker set (Plug-In-Gait, VICON, Peak, Oxford, UK), with two additional markers placed on the end of the right distal phalanges of the index finger and thumb of each participant. A Mobile Eye tracking device (Mobile Eye, Applied Sciences Laboratories, Bedford, MA) sampling at 30Hz was worn by each participant to record gaze behaviors during performance.

Procedure

Participants were first given an overview of the apparatus and completed the sport participation questionnaire. Using ball flight only (with no video images), three familiarization trials at a ball velocity of 13.9 m/s were performed, followed by a 20-trial pre-test of participant catching skill. After confirming catching skill, reflective markers were attached to the selected landmarks of participants using double-sided tape and the Mobile Eye was fitted and calibrated using 5 points projected on the video screen. Ten further catching trials were performed at ball speeds of 13.9 m/s

with video images of a thrower's actions available to enable participant familiarization with the equipment. Participants stood 7 m from the screen in a relaxed position, hand by their sides, feet shoulder width apart, and were asked to catch the ball with their right hand. Apart from asking participants to catch the ball, no other instructions were prescribed regarding how to organise gaze or movement behaviors to allow analysis of emergent behaviors. The 40 temporally occluded trials and 50 spatially occluded trials were presented in a random order but kept consistent across all participants. Half of the participants completed the temporal occlusion condition first, half the spatial occlusion condition. Two researchers independently recorded catching performance outcomes for each trial with a 100% agreement. No discomfort or impediment was reported when catching the ball using the equipment, with acoustic information from the apparatus being removed by participants wearing earplugs.

Data Processing

A total of 1,080 trials were captured across all participants, of which 76 trials (7 % spatial, 7 % temporal) were removed due to technical faults. One participant's gaze data were removed due to loss of calibration. Each trial's performance outcome was recorded as a catch or drop, with catching success rate expressed as a percentage of total number of trials. Kinematic data were recorded and analyzed off-line using VICON Nexus software and MS Excel. Kinematic data were smoothed using a Butterworth filter (set to 8Hz). The hand marker was used to calculate time of movement onset and defined from the time of ball release until a change of velocity of 5 m/s or greater (in line with Stone et al., 2014b). Ball release was identified as time 0 with negative values indicating movement onset prior to ball release and positive values occurring after release. Maximum velocity and time to maximum velocity

were calculated after being temporally realigned to movement onset and the resulting time. Maximum grip aperture (MaxGA) was defined as the maximal distance between the thumb and finger markers relative to movement onset. Minimum grip aperture (MinGA) was the minimal distance between the thumb and finger markers measured after maximal grip aperture, which represents the point the ball was caught. Time to MaxGA (TMaxGA) and MinGA (TMinGA) were calculated relative to movement onset. Time from Ball Release to MinGA was calculated by subtracting TMinGA from time of ball release. Total movement time was the time from movement onset to MinGA.

Gaze data were coded frame-by-frame with fixations and tracking behavior recorded when the gaze cursor remained within 3^0 of visual angle on a location or a moving object for a minimum of three frames (100ms; Vickers, 2007). Seven gaze locations were identified for all conditions: head, upper body, lower body, throwing arm/hand, release point (ball projection machine hole), ball, and other (based on previous research by Panchuk et al., 2013; Stone et al., 2014a; 2014b). Fixation frequency was the total number of fixations made during each trial divided by total trial time. Tracking latency was determined by calculating the duration between time of ball release and time of onset of ball tracking, with tracking duration expressed as the percentage of total ball flight tracked (total time ball tracked ÷ total ball flight x 100). Intra-coder reliability of gaze behaviors was determined using 20 randomly selected trials with an intraclass correlation coefficient of $r = .97$.

Statistical Analysis

Separate repeated measures ANOVAs were performed for temporal occlusion conditions (4 temporal occlusion conditions) and spatial occlusion conditions (5 spatial occlusion conditions) on data including: catching success, movement onset,

maximum velocity, time to maximum velocity, MaxGA, MinGA, Time to MaxGA, Time to MinGA, tracking latency, tracking duration and fixation frequency. A Two-way repeated measures ANOVA was used to analyze percentage viewing time in both the temporal and spatial occlusion conditions (occlusion condition x viewing location). A Greenhouse Geisser correction was applied (all estimates were below 0.75) to any violations of the sphericity assumption and post-hoc testing was conducted using a Bonferroni procedure. Means and SD's are presented in descriptive statistical analyses. Omega Squared (ω^2) (calculated using formulas based on Olejnik & Algina, 2003) were used for effect size estimations of main effects and interactions on ANOVAs. Cohen's d is presented, when appropriate, for t-tests and post-hoc analyses involving comparison of two means.

Results

Temporal Occlusion

Catching Performance

Temporal occlusion constrained catching performance, $F (3, 33) = 3.60$, $p < .05$, $\omega^2 = 0.05$. Post-Hoc testing, however, revealed no significant differences in outcomes ($p > .05$), yet a trend was observed with performance decreasing at earlier occlusion points; T1 (86.7 ± 17.7 %) was most different to T4 (95.8 ± 7.6 %, $p = .118$ $d = 0.69$) (see Table 1).

Hand kinematics

Movement onset of the catching hand was shaped by temporal occlusion, $F (3, 33) = 7.38$, $p < .001$, $\omega^2 = 0.14$. Post-hoc testing showed that movement onset during T4 (-127 ± 166 ms) began earlier than T1 (33 ± 170 ms) ($p < .05$, $d = 0.99$) and T2 (24 ± 163 ms) ($p < .05$, $d = 0.92$). Total movement time was also affected by temporal condition $F (3, 33) = 6.84$, $p < .01$, $\omega^2 = 0.38$. Post-hoc testing showed that T4 ($728 \pm$

14

152 ms) had longer movement times than T1 (601 ± 135 ms) ($p < .05$, $d = 0.88$) and T2 (577 ± 170 ms) ($p < .05$, $d = 0.93$).

Maximum velocity of the catching hand was influenced by temporal occlusion, $F(3, 33) = 5.03$, $p < .05$, $\omega^2 = 0.03$. Post-hoc testing showed condition T1 (2.42 ± 0.7 m/s) resulted in a quicker velocity than T3 (2.09 ± 0.7 m/s) ($p < .05$, $d = 0.49$). Effect size data suggested a trend for T1 having a quicker velocity than T4 (2.13 ± 0.7 m/s) ($p = .107$, $d = 0.45$). However, time to maximum velocity of the catching hand was not affected by temporal occlusion condition, $F(1.67, 18.42) = 2.35$, $p > .05$, $\omega^2 = 0.05$.

Table 1. Catching performance and hand kinematics for the four temporal occlusion conditions (Mean ± SD).

	T1	T2	T3	T4
Catching Performance (%)	86.7 ± 17.7	92.5 ± 9.7	91.7 ± 12.8	95.8 ± 7.6
Movement Onset (ms)	33 ± 170	24 ± 163	-75 ± 132	-127 ± 166
Total Movement Time (ms)	601 ± 135	577 ± 170	677 ± 121	728 ± 152
Max Velocity (m/s)	2.42 ± 0.7	2.35 ± .83	2.09 ± 0.7	2.13 ± 0.7
Time to Maximum Velocity (ms)	218 ± 97	175 ± 55	187 ± 52	170 ± 24
Time to MaxGA (ms)	376 ± 142	439 ± 125	375 ± 159	427 ± 114
Time MinGA from Ball release (ms)	634 ± 90	601 ± 52	602 ± 66	601 ± 73
MaxGA (cm)	10.1 ± 1.4	9.9 ± 1.4	10 ± 1.4	10 ± 1.4
MinGA (cm)	4.9 ± 1.0	5.1 ± 1.0	4.7 ± 2.4	4.7 ± 1.0

MaxGA was not constrained by temporal occlusion, $F (3, 33) = .30$, $p > .05$, $\omega^2 = 0.001$. Time to MaxGA was also unaffected by temporal occlusion, $F (3, 33) = 1.10$, $p > .05$, $\omega^2 = 0.05$. MinGA was not shaped by temporal occlusion, $F (3, 33) = 2.71$, $p > .05$, $\omega^2 = 0.03$ with Ball Release to MinGA also not affected by temporal occlusion, $F (1.52, 16.67) = .76$, $p > .05$, $\omega^2 = 0.001$.

Eye Tracking Data

Tracking latency of ball flight was affected by temporal occlusion, $F (1.58, 15.75) = 7.45$, $p < .01$, $\omega^2 = 0.07$. Post-hoc testing revealed tracking latency was later during condition T1 (161 ± 49 ms) compared to T3 (134 ± 52 ms) ($p < .05$, $d = 0.55$) and differed, approaching statistical significance, with T4 (124 ± 45) ($p = .06$, $d = 0.83$). Tracking latency for T2 (149 ± 52 ms) was also later than T4 ($p < .05$, $d = 0.55$). The relationship between tracking latency, catching performance and movement onset is displayed in Figure 3.
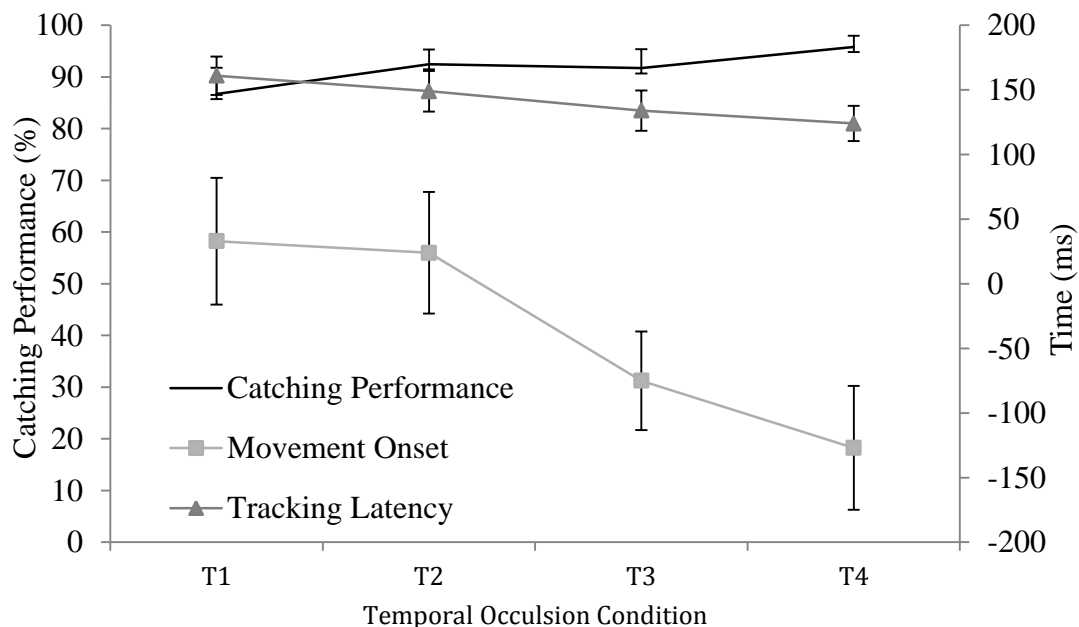

Figure 3. The relationship between catching performance, movement onset and tracking latency in the temporal occlusion conditions (Mean $\pm$ SEM). Time 0 represents the point of ball release.

Time spent visually tracking ball flight was shaped by temporal occlusion condition, $F(3, 30) = 7.73$, $p < .001$, $\omega^2 = 0.07$. Post-hoc testing showed that, during condition T1 (252 ± 56 ms), ball flight was tracked for less time than T3 (289 ± 53 ms) ($p < .05$, $d = 0.69$), and with a similar trend that approached statistical significance for T4 (291 ± 52 ms) ($p = .07$, $d = 0.74$). Percentage of ball flight tracked was also affected by temporal occlusion condition, $F(3, 30) = 8.22$, $p > .001$, $\omega^2 = 0.09$. Post-hoc testing showed that percentage of ball flight tracked was lower in T1 (47.1 ± 10.1 %) than T3 (53.5 ± 9.7 %) ($p < .05$, $d = 0.68$) and T4 (55.1 ± 9.0 %) ($p = .05$, $d = 0.88$). Percentage of ball flight tracked was also lower in T2 (49.9 ± 10.1 %) than T4 (55.1 ± 9.0 %) ($p < .05$, $d = 0.56$). Fixation frequency was not affected by temporal occlusion condition $F(3, 30) = 1.97$, $p > .05$, $\omega^2 = 0.01$. (see Table 2).

Table 2. Gaze behaviors for the four temporal occlusion conditions (Mean $\pm$ SD).

	T1	T2	T3	T4
Tracking Latency (ms)	161 ± 49	149 ± 52	134 ± 52	124 ± 45
Tracking Abs (ms)	252 ± 56	267 ± 60	289 ± 53	291 ± 52
Tracking Percentage (%)	47.1 ± 10.1	49.9 ± 10.1	53.5 ± 9.7	55.1 ± 9.0
Fixations Frequency	1.44 ± 0.3	1.54 ± 0.4	1.45 ± 0.3	1.46 ± 0.4

Spatial Occlusion

Catching Performance

Catching performance was not affected by spatial occlusion, $F(2.07, 22.75) = .40$, $p > .05$, $\omega^2 = 0.001$ (see Table 3).

Hand Kinematics

Movement onset of the catching hand was constrained by spatial occlusion condition, F (4, 44) = 3.48, $p < .05$, $\omega^2 = 0.03$. However, post-hoc comparisons revealed no significant differences (see Table 3). Effect size calculations showed a trend for movement onset to begin earlier with no-occlusion (-35 ±149 ms) than in the occluded upper body-head condition (24 ± 114 ms) ($p = .15$, $d = 0.69$). There was also a trend for movement onset to occur earlier when the throwing arm (-35 ± 170 ms) was occluded, compared to during the occluded upper body- head condition (24 ± 114 ms) ($p = .20$, $d = 0.40$).

Total movement time was shaped by spatial occlusion, F (1.97, 21.68) = 4.93, $p < .05$, $\omega^2 = 0.03$. Post-hoc testing showed that the occluded upper body-head condition (578 ± 180 ms) resulted in a reduced total movement time, compared to no-occlusion (663 ± 214 ms) ($p < .05$, $d = 0.43$) and occluded throwing arm (671 ± 228 ms) ($p < .05$, $d = 0.45$) conditions. There were also trends within the data for faster movement times in the occluded upper body (567 ± 187 ms) condition compared to the occluded throwing arm (671 ± 228 ms) ($p = .06$, $d = 0.50$) and no-occlusion (663 ± 214 ms) ($p = .07$, $d = 0.48$) conditions.

Maximum velocity of the catching hand was constrained by spatial occlusion, F (2.29, 25.23) = 4.57, $p < .05$, $\omega^2 = 0.02$. Post-hoc testing revealed that maximum velocity of the catching hand was slower when the throwing arm (1.95 ± 0.7 m/s) was occluded in comparison to the occluded upper body (2.21 ± 0.7 m/s) ($p < .001$, $d = 0.37$) and occluded upper body-head (2.18 ± 0.6 m/s) ($p = .05$, $d = 0.35$) conditions. There was also a trend for the maximum velocity of the catching hand to be slower in the no-occlusion condition (2.04 ± 0.6 m/s) than when the upper body-head (2.18 ±

0.6 m/s) was occluded ($p = .06$, $d = 0.23$). Spatial occlusion did not shape the time to maximum velocity, $F (4, 44) = 2.05$, $p = .10$, $\omega^2 = 0.04$.

MaxGA was not affected by spatial occlusion, $F (1.45, 15.98) = 1.02$, $p > .05$ $\omega^2 = 0.001$. Time to MaxGA was also not affected by spatial occlusion, $F(2.04, 22.46) = 1.34$, $p > .05$, $\omega^2 = 0.01$. MinGA was not affected by spatial occlusion, $F (4, 44) = 1.41$, $p > .05$, $\omega^2 = 0.005$. Ball release to Time to MinGA was also not affected by spatial occlusion, $F (1.89, 20.80) = 2.55$, $p > .05$, $\omega^2 = 0.03$.

Table 3. Catching performance and Hand Kinematics for the five spatial occlusion conditions (Mean ± SD).

	No occlusion	Occluded lower body	Occluded throwing arm	Occluded upper body	Occluded upper body-head
Catching Performance (%)	92.5 ± 8.6	94.2 ± 9.0	93.3 ± 14.9	90.8 ± 18.4	90.8 ± 17.6
Movement Onset (ms)	-35 ± 149	-29 ± 173	-35 ± 170	35 ± 121	24 ± 114
Total Movement Time (ms)	663 ± 214	618 ± 215	671 ± 228	567 ± 187	578 ± 180
Maximum Velocity (m/s)	2.04 ± 0.6	2.13 ± 0.7	1.95 ± 0.7	2.21± 0.7	2.18 ± 0.6
Time MaxVel (ms)	178 ± 24	200 ± 59	172 ± 28	170 ± 24	180 ±49
MaxGA (cm)	102 ± 10.7	99 ± 12.8	100 ± 11.1	103 ± 11.1	101 ± 11.4
Time MaxGA (ms)	475 ± 80	457 ± 118	483 ± 80	430 ± 69	447 ± 90
Time MinGA from Ball Release (ms)	627 ± 87	588 ± 83	636 ± 94	602 ± 90	603 ± 83
MinGA (cm)	5.1 ± 1.0	4.8 ± 1.0	5.1 ± 1.0	4.9 ± 0.7	4.8 ± 1.0

Eye Tracking

Tracking latency of ball flight was constrained by spatial occlusion, F (4, 40) = 4.91, $p < .05$, $\omega^2 = 0.07$. Although post-hoc testing revealed no significant differences, effect sizes showed a trend for tracking latency to emerge later in the occluded upper body-head (156 ± 52 ms) than in the occluded lower body (115 ± 45 ms) condition ($p = .06$, $d = 0.89$). The relationship between tracking latency, catching performance and movement onset is displayed in Figure 4.
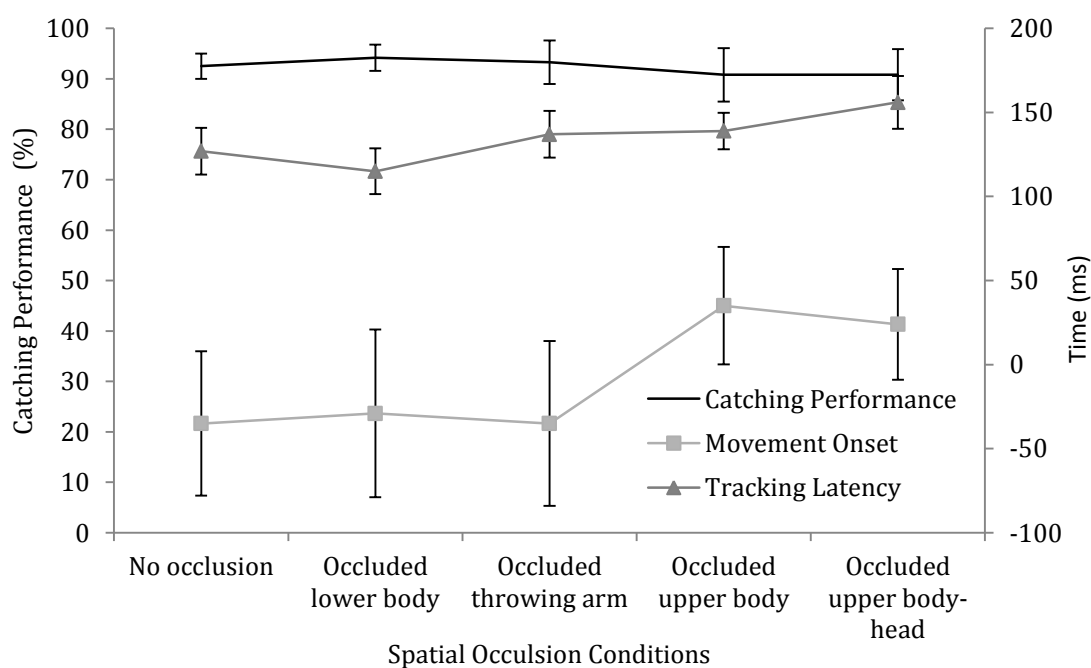

Figure 4. The relationship between catching performance, movement onset and tracking latency in the spatial occlusion conditions (Mean ± SEM). Time 0 represents the point of ball release.

Fixation frequency was affected by spatial occlusion, F (4, 40) = 8.27, $p < .001$, $\omega^2 = 0.14$. A higher frequency was observed in the occluded lower body (1.62 ± 0.3) than in the occluded upper body-head (1.31 ± 0.3) ($p < .05$, $d = 0.98$), no occlusion (1.30 ± 0.3) ($p < .01$, $d = 1.03$) and occluded upper body (1.28 ± 0.3) ($p < .05$, $d = 1.09$) conditions (see Table 4).

Table 4. Gaze behaviors for the five spatial occlusion conditions (Mean ± SD).

	No occlusion	Occluded lower body	Occluded throwing arm	Occluded upper body	Occluded upper body-head
Tracking Latency (ms)	127 ± 46	115 ± 45	137 ± 46	139 ± 36	156 ± 52
Tracking Abs (ms)	289 ± 46	295 ± 52	291 ± 53	287 ± 46	256 ± 59
Tracking Percentage (%)	54.6 ± 8.5	55.6 ± 8.3	54.3 ± 8.3	54.4 ± 7.6	48.6 ± 10.0
Fixation Frequency	1.30 ± 0.3	1.62 ± 0.3	1.48 ± 0.30	1.28 ± 0.3	1.31 ± 0.3

Visual tracking time of ball flight was influenced by spatial occlusion, $F (4, 40) = 6.07$, $p < .01$, $\omega^2 = 0.06$. Participants spent less time tracking the ball during the occluded upper body-head (257 ± 56 ms) than in the occluded lower body condition (295 ± 52 ms) ($p < .05$, $d = 0.73$). There was also a trend for less time to be spent tracking the ball in the occluded upper body-head (256 ± 59 ms) than in the no-occlusion condition (289 ± 46 ms) ($p = .06$, $d = 0.63$). Percentage of ball flight tracked was also shaped by spatial occlusion, $F (4, 40) = 5.50$, $p < .01$, $\omega^2 = 0.07$. Post-hoc testing showed a reduction in the percentage of ball flight tracked during the occluded upper body-head (48.6 ± 10.0 %) than in the occluded lower body (55.6 ± 8.3 %) ($p < .05$, $d = 0.77$) and no-occlusion (54.6 ± 8.5 %) ($p < .05$, $d = 0.66$) conditions.

Discussion

In this study we investigated how temporal and spatial occlusion of advanced kinematic information from a thrower's action constrained movement(re) organization, evidenced by analysis of hand kinematics and visual search strategies

during performance of a one-handed catching task. Findings from both experimental manipulations demonstrated the emergent nature of information-movement coupling during organization of interceptive actions. As predicted, temporal occlusion affected catching performance with a reduction in catching success at earlier occlusion points and the greatest difference being between T1 and T4. Catching performance was not affected by spatial occlusion of the thrower prior to ball release.

The findings from the temporal conditions suggest the importance of seeing visual information of the actor close to time of ball release. Movement onset of the catching hand emerged earlier when more perceptual information was available (i.e., at later occlusion points). During temporal occlusion conditions T1 and T2, movement onset did not occur until after ball release. In comparison, during conditions T3 and T4, movement onset of the catching hand occurred prior to ball release. López-Moliner et al. (2010) argued that seeing the thrower's hand during early stages of the throwing action (e.g. T1 and T2) is less effective than seeing it just before or at release (e.g. T4). They suggest that it is important to see the release of the ball because the time and place at which the ball can be caught is sensitive to the precise moment at which the ball is released (López-Moliner et al., 2010). Visual tracking latency of the ball was delayed during the earliest occlusion condition (T1) compared to the latest two occlusion points (T3 and T4), which suggests that having access to perceptual information from a thrower close to ball release (i.e., during T3 and T4) allowed participants to accurately anticipate ball release and initiate tracking of the ball earlier. Earlier tracking latency in T3 and T4 in turn enabled participants to track total ball flight for longer and could be a critical reason for the increase in catching performance.

22

Results of this study support those reported by López-Moliner et al. (2010) suggesting that, if visual information of a thrower's action is still available closer to ball release, the earlier movement onset can be initiated. When visual information of the thrower was occluded earlier, participants were constrained to rely on information after ball release to adapt their actions. This finding was demonstrated when movement onset emerged later and the catching action was performed with increased maximum velocity in T1, compared to T3 and T4. As participants were constrained to regulate their actions on the basis of ball flight, rather than advance kinematic information, it resulted in later movement initiation, which in turn meant participants had to move the hand more rapidly to ensure it was in the correct position to make the catch. Increasing velocity in T1 and T2 resulted in the total movement time from ball release to MinGA being similar across the four temporal occlusion conditions. The observed findings support the suggestions of Faisal and Wolpert (2009) who argued that the longer an individual perceives information, the lower the sensory variability regarding an object's location, but this results in increased motor variability because the remaining time for movement decreases. The findings propose that, for a successful catch, participants will give themselves enough time to predict ball location, but also leave enough time to successfully perform the action (Faisal & Wolpert 2009). The findings here, provide evidence that participants can functionally adapt between focusing on perceptual information to predict ball location (both from pre-release and ball flight information) and initiating movement organization (Faisal & Wolpert 2009). The data support findings of previous research demonstrating how movements can be continuously re-adjusted based on updated sensory information (Smeets & Brenner 1995; Brenner & Smeets 2009).

Values of variables from analyses of the later phases of the catching movement, such as the grasping action of the hand (i.e., MaxGA, Time to MaxGA, MinGA), remained the same across the four temporal occlusion conditions. With consistent later phases of the catching action, it was the early emergence of hand movements that resulted in a longer total movement time (i.e., movement onset to MinGA) in T4 compared to T1 and T2. This slower and more controlled movement, along with increased visual tracking of the ball, is proposed to underpin increased success in catching performance.

These findings could be interpreted in light of results from previous studies of performance of dynamic interceptive actions like hitting (e.g., Hubbard & Seng, 1954; Ranganathan & Carlton, 2007). Those data suggested that pre-ball flight kinematic information is essential for gross body orientation in performance of time-stressed, interceptive tasks, with ball flight information needed for fine adjustments for subsequent interception of the target (Montagne, 2005). During catching performance, it is proposed that the gross movement of the initial arm and hand movements at an appropriate velocity to the correct location to intercept a ball is based on advanced pre-ball flight information. This suggestion is supported by our evidence of earlier movement initiation times, at a slower velocity, when participants had access to more advanced visual information. Subsequent finer actions, such as the size and timing of grip aperture, were not affected by temporal occlusion and, hence, appear to be regulated by ball flight information. It is proposed, as the time constraints on the performer increase (i.e. quicker ball speed), then the importance of the visual information prior to ball flight will increase (see Stone et al., 2014b).

In contrast to the temporal occlusion manipulation, no differences in catching performance were observed across spatial occlusion conditions. However, changes in

hand kinematics and gaze behaviors emerged, suggesting adaptive behaviors are dependent on pre-ball release visual information available. These findings support the idea that ongoing perception of information in a performance environment constrains the emergence of adaptive, functional behaviors to achieve a performance goal. Here, movement kinematics were adapted to the emergent task constraints, facilitating successful catching performance (Warren, 2006; Davids et al., 2013). As informational constraints were manipulated by occluding sections of the thrower's body, movement onset of the catching hand adapted. Movement initiation began earlier and prior to ball release during conditions of no-occlusion, occluded throwing arm, and occluded lower body. When larger proportions of the thrower's body were occluded (i.e. occluded upper body-head and occluded upper body), participants initiated movement later, waiting for ball release. This observation adds support to the results from the temporal occlusion manipulation revealing that certain information sources from the thrower (i.e. upper body) allow participants to predict ball release and initiate earlier movement onset. Earlier movement onset seems to be constrained by the amount of visual information available to participants, enabling them to predict ball release (Panchuk et al., 2013; Stone et al., 2014a).

These findings from the spatial occlusion manipulation question previous research which has attempted to find the most critical information to predict actions on the assumption there is an *a priori* "optimal" decision or perceptual strategy (e.g., Williams, Ward & Chapman, 2003). Many studies examining perceptual-motor skill in sport have sought to identify critical information which is localized to specific parts of the body (e.g., Diaz et al., 2012). However, recent findings suggest performers process perceptual information more globally rather than utilizing localized information sources when anticipating the outcome of another person's action (Huys

et al., 2009; Huys et al., 2008; Smeeton & Huys, 2010). The results appear to show that, even when certain aspects of the movement are occluded (i.e. throwing arm), as long as the global movement pattern can be perceived (i.e. the throwing action) participants can predict the point of ball release. However, when a larger area is occluded (i.e. upper body) coherence of the global movement pattern is lost and results in participants adapting to use information that emerges after ball release. During conditions in which more perceptual information was removed (i.e., occluded upper body and occluded upper body-head), movement onset occurred later and was countered by greater maximum velocity of the hand compared to the no-occlusion condition. The functional, adaptive behaviors of our sample of skilled catchers were also highlighted in the gaze behavior data. Contrary to previous research examining spatial occlusion with a coupled response (Panchuk & Vickers, 2009), the data we have presented show that, by manipulating the visual information available, (i.e., removing information such as the throwing arm) participants adapted their gaze to use other information (i.e., upper body). However, when a substantial portion of the thrower's actions was removed (i.e. occluded upper body-head) the result was not only later movement initiation, but also less time spent tracking the ball. These findings are aligned with growing appreciation for the possible contributions of information sources contained in dynamic patterns of movement that are distributed across the body. Although we have not specifically examined the role of global and local perceptual information, the results suggest there is not one optimal local source of information that is relevant for performance of an interceptive action, but rather that information is distributed in the kinematics of a performer (in our study the thrower) that can guide and control actions (Huys et al., 2009; Huys et al., 2008; Smeeton & Huys, 2010; Williams et al., 2009).

Later phases of the catching action (i.e., MaxGA, Time to MaxGA, MinGA) showed no changes as a function of both temporal and spatial occlusion manipulations, suggesting these actions were closely adapted to ball flight information. As a result of later movement onset in the occluded body and body-head conditions, (re)organization of hand movements to ball flight information resulted in a reduction in total movement time compared to the no-occlusion and occluded-throwing arm conditions. Observations of a longer time period from movement initiation to time of ball contact, when more perceptual information was available, supports the proposal that access to relevant advanced visual information affords the performer greater movement time, which can be a critical factor in effective interception under complex and temporally demanding performance constraints. The findings also highlight that, even with changes to time of movement onset, actions can still be flexibly adapted during later stages to allow precision in interception. Hence, experimental protocols that neglect fully coupled actions, in favour of micro-movements, tend to ignore this crucial aspect of skilled action and considerably reduce the generality of the experimental findings (Araújo, Davids, & Passos, 2007).

Conclusion

We have provided evidence which demonstrates that advance visual information of an actor's actions guides the emergence of dynamic interceptive behaviors. When information was temporally occluded during early stages of an actor's action, catching performance was negatively affected. Movement onset of the catching hand and maximum velocity were constrained by temporal occlusion, with a later onset and greater velocity emerging at earlier occlusion points. Not all components of the interceptive catching action were constrained in the same way; the

grasping phase, for example, was not affected by temporal occlusion but was instead adapted to ball flight information. When perceptual information was spatially occluded, both gaze behaviors and movement initiation were constrained by advanced information available. However, the skilled catchers were able to co-adapt their actions to the removal of these visual information sources by altering both gaze and movement behaviors. These behavioral adaptations have important implications for research that assesses interceptive skills based solely on pre-ball flight information. The data we have presented here suggest the need to ensure that perception-action coupling is maintained in experimental work on movement coordination. Our findings suggest that interceptive actions, such as catching, are continuously (re)organized and adapted as information becomes available, first by using kinematic information of a thrower's actions, and subsequently adapting performance on the basis of ball flight information.

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