(De)synchronization of advanced visual information and ball flight characteristics constrains emergent information–movement couplings during one-handed catching

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Published version

STONE, Joseph, MAYNARD, Ian, NORTH, J.S, PANCHUK, D and DAVIDS, K (2015) (De)Synchronisation of advanced visual information and ball flight characteristics constrains emergent information-movement couplings during one-handed catching. Experimental Brain Research.

(De)Synchronisation of Advanced Visual Information and Ball Flight Characteristics Constrains Emergent Information-Movement Couplings during One-Handed Catching.

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Abstract

Advance visual information of a projection action and ball flight information is important for organizing dynamic interceptive actions like catching. However, how the central nervous system (CNS) manages the relationship between advance visual information and emerging ball flight information in regulating behaviour is less well understood. Here, we sought to examine the extent that advance visual information to the CNS constrains regulation of catching actions by synchronizing and de-synchronizing its relationship with ball trajectory characteristics. Novel technology was used to present video footage of an actor throwing a ball at three different speeds, integrated with information from a real ball projected by a machine set to the three speeds. The technology enabled three synchronized and six desynchronized conditions between advance visual information and subsequent ball flight trajectories. Catching performance, kinematic data from the catching hand and gaze behaviors were recorded. Findings revealed that de-synchronization of video images of ball projection shaped emergent catching behaviors. Footage of slower throws, paired with faster ball projection speeds, caused catching performance decrements. Timing in early phases of action was organized by the CNS to match the advance visual information presented. In later phases, like the grasp, ball flight information constraints adapted and regulated behaviors. Gaze behaviors showed increased ball projection speed resulted in participants tracking the ball for a smaller percentage of ball flight. Findings highlighted the role of the two visual systems in perception and action, implicating the importance of coupling advanced visual information and ball flight to regulate emergent movement coordination tendencies during interceptive behaviors.

Key Words: Two-visual systems; Perception; Dynamic interceptive actions; Eye movements; Ball projection machine

Introduction

Dynamic interceptive actions have frequently been used as task vehicles to enhance understanding of perception and action in human movement (e.g., Davids et al. 2008; Renshaw et al. 2007; Tijtgat et al. 2012) because they require the central nervous system (CNS) to establish and maintain a specific spatiotemporal relationship between a moving object (e.g., a ball) and responding effector(s) (e.g., a catching arm and hand). The putatively simple act of intercepting a ball with the hand requires accurate anticipation of a ball's trajectory followed by a precise fine-tuning of hand closure for grasping, even under the time constraints of slow projectile velocities (Montagne et al. 1993). For example, Alderson et al. (1974) demonstrated that, at moderate projection speeds (10 ms^{-1}), with fixed spatial orientation of the hand, organisation of the grasping action had a margin of error of ±15 ms.

It has been proposed that visual anticipation, which is needed when catching a ball, is not regulated by a unitary perceptual process, but rather by two independent, yet interacting, cortical visual systems (for detailed arguments, see van der Kamp et al. 2008). van der Kamp et al. (2008) proposed that two visual pathways in the brain operate along a continuum, with both systems remaining active during movement, and their influence being dependent on the specific task constraints of performance. The ventral system is responsible for perceptual recognition of objects, relationships with other objects in the performance environment (e.g. location, trajectory) and perceiving information about an individual or machine that is projecting an object to be intercepted (“vision for perception”). While performing an interceptive action, the dorsal stream becomes influential in the on-going regulation of movement (“vision for action”), picking up information to regulate and refine a movement response with respect to a moving object identified for interception. This description of the role of the two visual systems is predicated on Gibson’s (1979) proposal that perception and action are interdependent and mutually constraining systems. Designing experimental task protocols that fail to recognize their deep integration will not support a full understanding of performance of dynamic interceptive actions, and research attempting to explain performance of interceptive actions must ensure that information-movement coupling is retained in task design.

One proposed source of advanced visual information that the ventral cortical stream can utilize to enable accurate anticipation of ball trajectory is the kinematic information sources emerging from the actions of an individual projecting an object to be intercepted (for example, an individual throwing or hitting a ball to be caught). van der Kamp et al. (2008) suggested that individuals attend to action images (e.g., an actor throwing a ball) to constrain behaviors by using allocentric information that specifies the relationship between the individual and the speed, direction and location of a 'to-be-intercepted' object (i.e., in Gibsonian (1979) terms: *affordances*). Evidence from video-based visual occlusion paradigms has consistently supported the assertion that skilled participants in sport use advanced kinematic information from an opponent's actions to anticipate direction and velocity of ball trajectory (e.g., Abernethy and Russell 1987; Mann et al. 2007; Müller et al. 2006; Starkes et al. 1995). However, these video-based paradigms have failed to adequately consider the action component of task design, commonly using reductionist response methods (e.g., button pressing, pen and paper responses, verbal answers). By using reductionist and non-representative actions as responses, van der Kamp et al. (2008) argued that most existing studies of perceptual-motor expertise have inadvertently implemented task constraints which have over-emphasized the role of the ventral cortical pathway, limiting understanding of the role of the dorsal pathway, which is believed to refine an ongoing movement response. As a result the task constraints of such studies may have failed to capture the tightly integrated and emergent coupling of perception and action systems which underpins successful performance of dynamic interceptive actions (see Withagen and van der Kamp 2010; Pinder et al. 2011).

Research that has required a representative action response from participants during studies of dynamic interceptive actions has typically failed to include advanced perceptual information from the actions of an individual projecting (e.g., throwing) a ball, with participants required to catch balls launched from a ball projection machine (e.g., Tijtgat et al. 2010, 2011). Although such experimental designs are implemented to allow rigorous control of ball trajectory, they fail to recognize the coupling of perception and action, limiting the involvement of the integrated visual-system, forcing participants to rely exclusively on information from the dorsal cortical pathway to regulate actions. As Gibson (1979) proposed, perception informs movement and movement informs perception in a cyclical, integrated way, so the inadvertent separation of these complementary cortical systems by task design limits understanding of how the CNS might precisely coordinate behaviors in performance environments.

To overcome the limitations of removing advanced visual information or ball flight, whilst retaining strict experimental control and allowing representative actions, Stone et al. (2013) developed novel integrated technology that allowed advanced visual information of a thrower's actions to be synchronized with ball projection from a machine. Stone et al. (2014) demonstrated how both advanced visual information from the kinematics of throwing actions *and* ball flight characteristics were functional in supporting successful performance. For example, these sources of information constrained the precise nature of hand kinematics and visual search strategies when participants completed catching actions. Indeed, catching performance was more successful, movement initiation began earlier, with ball flight being visually tracked earlier, and for a longer time, when advanced visual information from thrower kinematics and ball flight properties were perceived in combination, compared to when only ball flight information was available from a ball projection machine (Stone et al. 2014). In another condition, Stone et al. (2014) presented participants with advanced visual information only from images of a throwing action (no ball was projected), requiring them to simulate a catching action. It was observed that participants were unable to effectively simulate a catching action when ball flight information was removed, since they displayed significantly different hand kinematics to other conditions when a ball was projected, organizing later hand movements with greater maximum and minimum grip apertures. These findings shed some insights on how both advanced visual information from a thrower's actions prior to ball flight, and information from ball flight trajectory, might be important for regulating interceptive actions. Other recent work in interceptive actions has also shown that the removal of advanced visual information or ball flight informational constraints results in adaptations to participants' movement initiation and kinematic movement patterns (Pinder et al. 2009, 2011; Shim et al. 2005; Vignais et al. 2010). Collectively these findings highlight the importance of coupling perception and action during performance of interceptive actions (Davids et al. 2002; Panchuk et al. 2013; Stone et al. 2013). The clear implication is that experimental task designs should allow the cyclical relationship between perception and action to emerge during performance (Araújo et al. 2007; Gibson 1979).

Despite this body of research, there is limited understanding of the precise nature of the relationship between the two information sources during regulation of interceptive behaviors. For example, it is not well determined whether there is a point where having access to advanced visual information is no longer advantageous for the CNS in regulating interceptive performance (e.g., under constraints of low ball speed values). Understanding how advance kinematic information to the CNS influences resulting action behaviors will provide evidence relevant to the debate in the psychology literature regarding whether humans prospectively control interceptive actions based on continuous perceptual information or utilize predictive control, based on prior knowledge (e.g. Katsumta and Russell 2012; Zago et al. 2009).

Panchuk et al. (2013) attempted to examine these issues by systematically manipulating availability of advanced visual information (video images of an actor throwing a ball) and actual ball projection speed during performance. They investigated catching performance when actual ball projection speed either matched that displayed in video footage of an actor throwing a ball or was different to projection speeds shown in a video of a one-handed throwing action. With participants being unaware of mismatches between ball projection speeds and video images of the throwing action, it was predicted that movement behaviors would be similar until the point of ball release from the projection machine, with movement adaptations only emerging once changes to ball flight speed were perceived. Results supported this prediction since hand kinematics were scaled to actual ball speed, irrespective of video image speed. These data indicated that the dorsal cortical pathway was most influential during performance, enabling perception of metrically precise, egocentric information to scale interceptive actions to the specific informational constraints of the task. This observation provided evidence that, as long as the desynchronization of advanced information from resulting ball projection was not consciously perceived by participants, anticipatory behaviors would not change. However, an interaction between video images and ball projection speed on movement initiation time was observed in their study, with movement initiation emerging earlier during video images of slower throws compared to images of quicker throws. Participants also unexpectedly increased catching performance as throwing speeds in video images increased. These results challenged Panchuk et al.'s (2013) hypotheses. With the proposal that participants could not consciously perceive differences, no clear theoretical interpretation for these findings was apparent. One further limitation with Panchuk et al.'s (2013) study concerned the skill level of participants, which was not clearly defined, with catching success rate ranging between 55-68% across all speeds (in comparison to a mean catching accuracy level of 91% in the study by Stone et al., 2014). Given that previous research has suggested advanced kinematic information is likely to be most beneficial to skilled participants, it may have been possible that participants in the study of Panchuk et al. (2013) were not skilled enough in catching to fully exploit the kinematic information being presented (effectively using the ventral cortical stream) and were relying more on ball flight information to scale their actions (over-relying on the dorsal cortical stream).

Given the limited and ambiguous research findings to date, further work is required to gain greater understanding of how such task constraint manipulations might constrain participant movement behaviors. To examine the precise nature of the ventral and dorsal stream functions, and to ascertain whether control strategies in the CNS are predictive or prospective, further task constraint manipulations are required in which participants can actually perceive differences in available advance kinematic information. These advances will help clarify the nature of the relationship between advance kinematic information, tracking latency/duration, hand kinematics and performance of interceptive actions, and might begin to determine whether there is a point where advance visual information no longer benefits performance and vice versa. As van der Kamp et al. (2008) suggested, visual search behaviors and use of advance visual information during performance of interceptive actions is likely to depend on the level of anticipation needed. Hence it seems that as ball speed increases, the potential performance benefits of advanced visual information would be greater (Pinder et al. 2011).

The aim of this study, therefore, was to investigate the effect of greater desynchronization between advance perceptual information and associated ball projection information during one-handed catching performance in skilled individuals. Based on previous research (e.g., van der Kamp et al. 2008; Panchuk et al. 2013), it was hypothesized, that, as ball projection speed increased, catching performance would decrease. It was also expected that the timing of movement onset would be linked to advanced perceptual information available from video images of a throwing action, rather than ball flight information, as ball speed was increased. This prediction was made because of the assumption that the ventral cortical stream would regulate movement before participants switched to dorsal stream control. With expected later movement initiations during video images of a slower throwing action, it was also predicted that the CNS would organize greater arm velocity values during higher ball projection speeds to ensure the hand arrived in the correct spatial location at the appropriate time for ball interception. It was also expected that the grasping action would be linked to ball speed rather than video image speed during desynchronised trials, since the dorsal cortical stream would be most influential during visual perception at this point. Finally, we predicted that eye movement tracking latency would change dependent on the mismatch, with later tracking movements organized by the CNS during the higher ball projection speeds.

Method

Participants

Twelve (10 Male, 2 Female; mean age 24.3 ± 4) skilled, right-handed 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 (via a sport participation questionnaire). Additionally, during a pre-test, participants had to catch at least 16 out of 20 balls (M = 18.1 ± 1) projected at 50 km/h from the ball projection machine. Skill level was confirmed by overall catching success rate across all experimental conditions (M = 85.6 ± 3.2 %). Institutional ethical approval was granted by a Research Ethics Committee and all participants provided informed consent.

Apparatus

A custom-built apparatus (see Stone et al. (2013) for a detailed description) integrated a ball projection machine (Spinefire 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. This integrated technology enabled video images of a throwing action to be projected onto the screen and synchronized with ball projection. Three speeds with a larger range compared to those used by Panchuk et al. (2013) (51.5, 55.7, 59.7 km/h) were selected to increase the likelihood of participants perceiving the mismatches. The three speeds were: (i) 40 km/h as this was the lowest speed level on the ball projection machine; (ii) 60 km/h as this was the highest speed at which it was considered still safe for participants to perform; and (iii) the mid-point between these two values, 50 km/h.

Video images of an actor throwing a ball from the participants' perspective were recorded with ball speed 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. Five video clips of the actor throwing the ball at speeds of 40 km/h ± 1, 50 km/h ± 1 and 60 km/h ± 1 were selected and defined as, Videos of thrower speed-40, Videos of thrower speed-50 and Videos of thrower speed-60. These speeds corresponded to the ball speed increments of the projection machine: 39.8 km/h ± 0.7, 50.5 km/h ± 0.8 and 59.7 km/h ± 1.3. They were defined as, ball projection speed-40, ball projection speed-50 and ball projection speed-60. Using the three video clip speeds and three ball projection speeds, 9 conditions with 10 trials in each, giving a total of 90 experimental trials, were created. 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 of the ball and the projection of a ball (mid-pressed tennis balls, 66mm diameter) from the machine (for details see Stone et al. 2014).

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) 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. Without synchronized video images of thrower speed, three practice trials at a ball velocity of 50 km/h were performed, followed by a 20-trial pre-test of participant catching skill. Reflective markers were attached to the selected landmarks of participants using double sided tape and the Mobile Eye fitted and calibrated using 5 points projected on the video screen. Ten further catching trials were performed at ball speeds of 50 km/h with video images of a thrower's actions available to enable participant familiarization with 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 specifying instructions were given in relation to gaze or movement behaviors to allow analysis of emergent behaviors. The 90 trials were presented in a random order but kept consistent across all participants. Two researchers independently recorded catching performance outcomes for each trial. 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 32 trials (2.9 %) were removed due to technical faults. Each attempt was recorded as a catch or drop, with success rate expressed as a percentage. Kinematic data was recorded and analysed off-line using VICON Nexus software and MS Excel. Kinematic data was 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 5m/s or greater. Maximum velocity and time to maximum velocity was calculated after being temporally realigned to movement onset and the resulting time. Maximum grip aperture (MaxGA) was 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 Max (TMaxGA) and Min (TMinGA) grip aperture were calculated relative to movement onset. Time from Ball Release to MinGA was calculated by subtracting TMinGA from time of ball release.

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). Six gaze locations were identified for all conditions: head, 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. 2014). Fixations per second were 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.

Statistical Analysis

Separate, 2 way repeated measures ANOVAs were performed (3 ball speeds x 3 video images of thrower speeds) on data including: catching performance, movement onset, maximum velocity, time to maximum velocity, MaxGA, Time to MaxGA, MinGA, Time to MinGA, Time from Ball Release to MinGA, fixations per second, tracking latency and Percentage of Ball Flight Tracked from Ball Release to Interception. Simple main effects were used to examine any significant interactions between independent variables. A Greenhouse Geisser correction was applied (all estimates were below 0.75) to any violations of the sphericity assumption and post-hoc testing occurred by a Bonferroni procedure. Partial Eta Squared (ηp^2) is presented for effect size estimations of main effects on ANOVAs, with Cohen's *d* presented when appropriate for post-hoc analyses. Means and SEs are presented in descriptive statistical analyses.

Results

Catching Performance

Ball projection speed affected catching performance $F(2, 22) = 15.96$, $p < .000$, $\eta p^2 = .592$. Post-Hoc tests revealed that, as ball projection speed increased, catching performance decreased, with ball projection speed-40 (97.5 ± 0.7 %) resulting in more successful catches than ball projection speed-60 (74.2 ± 5.2 %, $p < .05$, $d = 1.78$). Catching accuracy at ball projection speed-50 was also greater than ball projection speed-60 ($p < .05$, $d = .88$). Although not statistically significant ($p = .06$), there was a strong trend for more successful catches at ball projection speed-40 than ball projection speed-50, which showed a large effect size ($d = 1.01$). Video images of thrower speed also affected catching performance $F(2, 22) = 11.37$, $p < .000$, $\eta p^2 = .508$. Post-Hoc tests showed reduced catching performance associated with video images of thrower speed-40 (81.7 ± 4.0%), than video images of thrower speed-50 (90.6 ± 2.3%)($p < .05$, $d = .79$) and of thrower speed-60 (87.5 ± 2.8%, $p < .05$, $d = .49$). Finally, a ball projection speed x video images of thrower speed interaction was present $F(2, 22) = 2.67$, $p < .05$, $\eta p^2 = .195$ (See Figure 1). The interaction analyses show that desynchronzations at ball projection speed-40 and the video images of thrower speed did not affect catching performance. Ball projection speeds 50 and 60 were associated with a decrease in catching success, although not as great as the reduction during video images of thrower speed-40.

Hand Kinematics

Movement Onset of the Catching Hand

Kinematic data are summarised in Table 1. Video images of thrower speed affected movement onset $F(2, 22) = 5.24$, $p < .05$, $\eta p^2 = .323$. Post-Hoc tests showed a later movement onset during videos of thrower speed-40 (-25 ± 23 ms), than in videos of thrower speed-60 (-84 ± 32 ms) ($p < .05$, $d = .61$). (De) synchronization of ball projection speed did not affect movement onset $F(2, 22) = 1.00$, $p > .05$, $\eta p^2 = .083$ and no video images of thrower speed x ball projection speed interaction was present in the data $F(2, 22) = 1.48$, $p > .05$, $\eta p^2 = .119$.

Maximum Velocity of the Catching Hand

Video images of thrower speed affected maximum velocity values $F(1.24, 13.62) = 16.99$, $p < .01$, $\eta p^2 = .607$. Post-Hoc tests showed maximum velocity was different across all performance conditions, increasing as throwing speed in video images increased. Maximum velocity emerging during video images of thrower speed-40 (2.00 ± .15 m/s) was slower than values observed with video images of thrower speed-50 (2.12 ± .17 m/s) and of thrower speed-60 (2.29 ± .18 m/s, both $p < .05$, $d = .21$, $d = .53$ respectively). Video images of thrower speed-50 was also associated with lower maximum velocity values than video images of thrower speed-60 ($p < .05$, $d = 0.29$). Ball projection speed also affected maximum velocity $F(2, 22) = 6.08$, $p < .05$, $\eta p^2 = .356$. Post-Hoc tests showed that, at ball projection speed-40 (2.03 ± .15), maximum velocity of the hand was lower than at ball projection speed-60 (2.27 ± .19) ($p < .05$, $d = .40$). However, no ball projection speed x video images of thrower speed interaction was present, $F(3.15, 34.65) = 1.35$, $p > .05$, $\eta p^2 = .109$.

Time to Maximum Velocity of the Catching Hand

Video images of thrower speed affected time to maximum velocity $F(2, 22) = 10.82$, $p < .001$, $\eta p^2 = .496$. Post-hoc tests showed maximum velocity occurred later during video images of thrower speed-40 (206 ± 9 ms), than with video images of thrower speed-50 (185 ± 9 ms) and of thrower speed-60 (185 ± 8 ms) (both $p < .05$, $d = .67$, $d = .71$, respectively). The (de)synchronization of ball projection speed had no effect on time to maximum velocity of the hand, $F(1.12, 12.27) = 1.99$, $p > .05$, $\eta p^2 = .154$. There was also no ball projection speed x video images of thrower speed interaction $F(4, 44) = 1.15$, $p > .05$, $\eta p^2 = .094$.

MaxGA

Ball projection speed affected MaxGA values, $F(1.09, 12.04) = 7.41$, $p < .05$, $\eta p^2 = .402$. Post-Hoc testing revealed that during ball projection speed-60 (10.5 ± 0.3 cm) maximum grip aperture was greater than in ball projection speed-50 (10.3 ± 0.3 cm) ($p < .05$, $d = .19$) and ball projection speed-40 (10.1 ± 0.3)($p > .05$, $d = .38$). The (de)synchronization of video images of thrower speed prior to ball release had no effect on MaxGA $F(2, 22) = 2.88$, $p > .05$, $\eta p^2 = .207$. There was also no ball projection speed x video images of thrower speed interaction $F(4, 44)$, = .855, $p > .05$ $\eta p^2 = .072$.

Time to MaxGA

Ball projection speed constrained time to MaxGA $F(2, 22) = 55.31$, $p < .000$, $\eta p^2 = .834$. Post-Hoc testing showed that, as ball projection speed increased, time to MaxGA emerged earlier. Values of MaxGA emerged later with ball projection speed-40 (607 ± 23 ms) than with ball projection speed-50 (436 ± 31 ms $p < .001$, $d = 1.81$) and ball projection speed-60 (395 ± 34 ms, $p < .000$, $d = 1.7$). In contrast, (de)synchronization of the video images of thrower speed had no effect on time to MaxGA $F(2, 22) = 3.19$, $p > .05$, $\eta p^2 = .225$. There was also no ball projection speed x video images of thrower speed interaction $F(2.15, 23.64) = 1.39$, $p > .05$ $\eta p^2 = .112$

MinGA

Ball projection speed affected MinGA $F(2, 22) = 3.78$, $p < .05$, $\eta p^2 = .256$. Post-Hoc tests showed that values of MinGA seemed to decrease during ball projection speed-60 (4.5 ± 0.2 cm), compared to ball projection speed-50 (4.8 ± 0.2 cm) and ball projection speed-40 (4.9 ± 0.2 cm) although these changes were not statistically significant ($p = .082$, $d = .43$ $p = .069$, $d = .58$ respectively). (De)synchronization of video images of thrower speed had no effect on MinGA $F(2, 22) = .83$, $p > .05$, $\eta p^2 = .07$. There was also no ball projection speed x video images of thrower speed interaction $F(4, 44)$, = 1.15, $p > .05$, $\eta p^2 = .094$.

Time to MinGA

Ball projection speed affected time to MinGA $F(2, 22) = 84.40$, $p < .000$, $\eta p^2 =.885$. As ball projection speed increased the time to MinGA decreased. Values of MinGA were lower with ball projection speed-40 (805

± 16 ms) than ball projection speed-50 (621 ± 20 ms) and ball projection speed-60 (569 ± 19 ms) (both $p < .000$, $d = 2.9$, $d = 3.8$ respectively). Time to MinGA also emerged earlier during ball projection speed-50 than ball projection speed-60 ($p < .05$, $d = .77$). The (de)synchronization of video images of thrower speed also had a main effect on time to MinGA $F(2, 22) = 7.36$, $p < .05$, $\eta p^2 = .401$. As video images of thrower speed increased, time to MinGA decreased, with video images of thrower speed-40 (692 ± 20 ms) producing lower values than video images of thrower speed-50 (657 ± 16 ms, $p < .05$, $d = .56$) and thrower speed-60 (645 ± 14 ms, p < .05, $d = .78$). Time to MinGA was earlier during video images of thrower speed-50 than video images of thrower speed-60 ($p < .05$, $d = .23$). There was no ball projection speed x video images of thrower speed interaction $F(4, 44) = 1.84$, $p > .05$, $\eta p^2 = .144$.

Time from Ball Release to MinGA

Ball projection speed influenced the time from ball release to emergence of MinGA $F(2, 22) = 32.58$, $p < .000$, $\eta p^2 = .748$. Post-Hoc tests showed that, as ball projection speed increased, time from ball release to emergence of MinGA decreased with values at ball projection speed-40 (735 ± 38 ms) being greater than at ball projection speed-50 (587 ± 19 ms) ($p < .05$, $d = 1.42$) and ball projection speed-60 (497 ± 12 ms) ($p < .000$, $d = 2.43$). Time from ball release to emergence of MinGA during ball projection speed-50 was also lower than for ball projection speed-60 ($p <.05$, $d = 1.63$). (De)synchronization of video images of thrower speed also affected time from ball release to MinGA $F(2, 22) = 12.51$, $p < .000$, $\eta p^2 = .532$. Time between these two events decreased as inferred ball speed of the throwing action increased, with video images of thrower speed-40 (672 ± 17 ms) resulting in greater temporal values than with video images of thrower speed-50 (587 ± 27 ms) ($p < .05$, $d = 1.08$) and of thrower speed-60 (561 ± 25 ms) ($p < .05$, $d = 1.14$). There was no interaction between ball projection speed x video images of thrower speed $F(4, 44) = .924$, p > .05, $\eta p^2 = .077$.

Gaze Behaviors

Fixations per Second

Ball projection speed affected the number of fixations per second used by participants during catching performance, $F(2, 22) = 5.55$, $p < .05$, $\eta p^2 = .335$. Post-Hoc testing, however, showed no significant differences in fixations per second at ball projection speed-40 (1.63 ± .09), ball projection speed-50 (1.71 ± .12) and ball projection speed-60 (1.78 ± .13). Video images of thrower speed had no effect on the number of fixations per second $F(2, 22) = 1.25$, $p > .05$, $\eta p^2 = .102$. There was also no ball projection speed x video images of thrower speed interaction $F(4, 44) = 1.97$, $p > .05$, $\eta p^2 = .152$.

Tracking Latency

Ball projection speed affected tracking latency values $F(2, 22) = 23.51$, $p < .000$, $\eta p^2 = .681$. Participants started tracking the ball later, as ball projection speed decreased, with ball projection speed-40 (184 ± 8 ms) inducing later ball tracking than ball projection speed-50 (152 ± 8 ms) and ball projection speed-60 (145 ± 7 ms) (both $p < .05$, $d = 1.15$, $d = 1.49$ respectively).Video images of thrower speeds (de)synchronization also affected tracking latency $F(2, 22) = 3.64$, $p < .05$, $\eta p^2 = .249$. Yet post-hoc tests revealed no significant effects between video images of thrower speed-40 (158 ± 6 ms), thrower speed-50 (154 ± 7 ms) and thrower speed-60 (169 ± 10 ms) ($p >.05$). There was also a ball projection speed x videos of thrower speed interaction $F(4, 44) = 2.58$, $p = .05$, $\eta p^2 =.190$ (see Figure 2). The interaction suggested that tracking latency was dependent on video images of thrower speedduring ball projection speed-40, with tracking latency less dependent on video images of thrower speed as ball projection speed increased.

Percentage of Ball Flight Tracked from Ball Release to Interception

Ball projection speed affected the percentage of ball flight tracked by each participant $F(2, 22) = 96.26$, $p < .000$, $\eta p^2 = .897$. Post-hoc tests revealed that, as ball projection speed increased, there was a reduction in time spent tracking the ball. At ball projection speed-40 (58.9 ± 1.3 %), tracking time was greater than at ball projection speed-50 (49.7 ± 2.3 %, $p < .000$, $d = 1.42$) and ball projection speed-60 (41.1 ± 2.2 %, $p < .000$, $d = 2.85$). Percentage of ball flight tracked was also longer during ball projection speed-50 compared to ball projection speed-60 ($p < .000$, $d = 1.10$). Video images of thrower speed did not affect percentage of ball flight tracked $F(2, 22) = 2.91$, $p > .05$, $\eta p^2 = .209$, and there was no ball projection speed x video images of thrower interaction, $F(4, 44) = .57$, $p > .05$, $\eta p^2 = .049$.

Discussion

In this study we examined how synchronization and desynchronization of advanced kinematic information of a thrower's actions and subsequent ball flight information from a projected ball constrained emergent one-handed catching performance and associated hand coordination patterns and visual search strategies. As predicted, catching performance was negatively affected by an increase in ball speed. In line with our hypotheses, catching performance was affected by the advance visual information available prior to ball release, with a decrease in performance observed during video images of thrower-40 (slowest speed), compared to images of thrower speeds 50 and 60. These two findings supported Gibson's (1979) proposal that perception and action are interdependent, with perception informing movement and movement informing perception in a cyclical manner.

The interactive effects of the inferred speed of a filmed throwing action and actual ball projection speed on catching performance outcomes showed that perceptual information enabled a greater catching success rate when the ball was projected at the middle and top speeds. This finding supports the argument that utilising kinematic information from a thrower's action to catch a ball is dependent on the degree of anticipation required (van der Kamp et al. 2008; Pinder et al. 2011). Results suggested that under desynchronised conditions, when participants anticipated a lower ball projection speed (video images of thrower speed-40 conditions), yet the ball was actually projected at a higher speed, they could not always react quickly enough to perform a successful catch. This outcome supports the proposal by Panchuk et al. (2013), that performance of an interceptive action is not primarily linked to object trajectory at high ball speeds (as previously suggested by Arzamarski et al. 2007; Montagne et al. 1999). Rather our data propose that a closer synchronization of advance information of throwing actions, with ball flight information, will support more successful performance. At lower ball speeds, it seems that the potential benefit of advance visual information sources may reduce, because these specific task constraints allow participants to use ball flight information to constrain their actions. This explanation is supported by observations that participants tracked the ball for a greater percentage of time, as ball speed reduced. Hence, although participants may have anticipated a quicker ball speed (videos of thrower speed-60), the greater ball flight duration, and increased tracking time, enabled movement adaptations for successful interception.

Kinematic analysis of movement patterns during performance provided insights into the possible causes for changes in catching performance. A reduction in time to MinGA (time from ball release to catching the ball) as video images of thrower speed and ball projection speeds increased, demonstrates how the emergent catching behavior is constrained by both advanced visual information and ball flight constraints. The point of movement initiation is of particular interest, with respect to the visual systems model proposed by van der Kamp et al. (2008), since it is suggested to be the point when complementary control of activity may switch from pre-dominant ventral to dorsal system regulation. Movement onset occurred prior to ball release in all conditions, suggesting that the CNS relied on anticipatory processes prior to ball release, regulating performance with the advance visual information of a thrower's actions, in line with previous findings (e.g., Panchuk et al. 2013; Stone et al. 2014). A key indicator for changes in catching performance may be the observation of earlier time of movement onset when participants watched video images of the quicker throwing action (videos of thrower speed-60), compared to the two slower throwing actions (videos of thrower speed 40, 50). With no changes in movement onset across ball projection speeds, our data suggest that the dorsal stream is most influential at this point in the action, demonstrating how the CNS might have used information from the video images of the throw to activate movement onset.

After movement onset, the CNS might have relied on information from both video images, and ball flight information, to regulate maximum velocity of the catching hand. Effector velocity increased as participants watched video images of throwing actions for faster projection speeds and caught balls projected at quicker speeds. This finding indicates that maximum velocity of the catching hand may be predicated on advance visual information available, yet continuously adapted with ball flight information. This observation provides support for a prospective control strategy during catching with individuals modulating limb acceleration with available optical information to achieve and maintain the required velocity. This performance strategy enables the CNS to move a catching limb to the right place at the right time to intercept a ball (e.g., current hand velocity at a given instant can be increased or decreased for the hand to move at the required velocity needed to catch a ball) (Peper, et al. 1994). During the final grasping action, the data suggested that the dorsal cortical stream became more influential in action regulation, with maximum grip aperture only constrained by ball speed. Maximum aperture values were greater at the higher ball speeds, with time to maximum aperture emerging earlier as ball speed increased, providing further evidence for a strategy of continuous movement regulation during the catching action.

Overall the kinematic data highlight the importance of both advanced visual information and the related ball projection information in providing critical informational constraints for the CNS to regulate catching behaviors. Participants tended to start moving later and more slowly when watching the slowest video image speed of a filmed throwing action. Yet when balls were projected at a faster speed, despite attempting to increase hand velocity using prospective control, the CNS was not always capable of organizing a functional movement pattern, resulting in poorer catching performance.

An unexpected finding was tracking latency being affected by ball projection speed, with the ball being tracked from a later time point as ball speed decreased. It seems intuitive that at a lower ball speed it would be easier to visually locate and track the ball. However, it is possible that under more severe time constraints, the task constraints dictated that participants had to locate the ball more quickly to enable enough time to track the ball. As the ball was moving too quickly to track for a long period of time (supported by the reduction in the percentage of ball flight time tracked as ball speed increased), it may be that participants had to locate the ball early to predict its location and speed before they lost sight of the ball, as evidenced by the reduced tracking time as ball projection speeds increased. In contrast, when the ball was projected at slower speeds, participants were placed under less-strict time constraints. Consequently, participants were afforded more time to locate the ball and began tracking the ball at a later time. However, participants still tracked the ball for a greater proportion of ball flight when the ball was projected at lower speeds and most likely used the latter portion of ball flight information to adapt and modify their actions. This observation provides evidence that a participant's behaviors (i.e., gaze behavior, anticipatory postural adjustments) and actions (i.e., catching action, postural control) emerge from, and are adapted to, specific emergent environmental and task constraints.

In summary, the data reported here provide support for the two-visual systems explanation for visual control of actions, with an apparent continuum for the amount of control on action exerted by the dorsal and ventral streams, dependent on the stage of the action. Early phases of the catching action, such as at movement onset, were organised with advance informational constraints and were likely regulated by vision in the ventral pathway. Later movement phases, however, like the grasping action, were likely regulated by using ball flight informational constraints and vision from the dorsal cortical pathway. Desynchronizing the relationship between advance visual information and related ball flight information resulted in the CNS adapting movement behaviors, indicative of a prospective control strategy during catching performance in skilled individuals. The impact of desynchronization became more critical as ball speed values increased. As desynchronisation effects became greater, catching performance significantly decreased. This finding highlights the importance of the relationship between advance visual information from a thrower's actions and subsequent ball flight information when participants are performing under high time constraints, such as in fast ball sports like baseball or cricket.

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Table 1. Summary of Hand Kinematics during the three video speeds and Ball speeds

	Video Speed			Ball Speed		
	Video Speed 40	Video Speed 50	Video Speed 60	Ball Speed 40	Ball Speed 50	Ball Speed 60
Movement Onset (ms)	⬆ **-25 ± 23**	-70 ± 36	⬇ **-84 ± 32**	-69 ± 40	-39 ± 31	-71 ± 24
Maximum Velocity (m/s)	⬇ **2.00 ± .15**	⬆ **2.12 ± .17**	⬆ **2.29 ± .18**	⬇ **2.03 ± .15**	2.12 ± .17	⬆ **2.27 ± .19**
Time to Maximum Velocity (ms)	⬆ **206 ± 9**	⬇ **185 ± 9**	⬇ **185 ± 8**	191 ± 7	183 ± 8	202 ± 13
MaxGA (cm)	10.3 ± .28	10.2 ± .30	10.4 ± .32	⬇ **10.1 ± .32**	⬇ **10.3 ± .30**	⬆ **10.5 ± .29**
Time to MaxGA (ms)	498 ± 26	483 ± 31	459 ± 28	⬆ **608 ± 23**	⬇ **437 ± 31**	⬇ **395 ± 34**
MinGA (cm)	4.7 ± **.2**	4.8 ± .2	4.7 ± .2	4.9 ± .2	4.8 ± .2	4.7 ± .2
Time to MinGA (ms)	⬇ **692 ± 20**	⬆ **657 ± 16**	⬆ **645 ± 14**	⬆ **805 ± 16**	⬇ **621 ± 20**	⬇ **569 ± 19**
Time from Ball Release to MinGA (ms)	⬆ **673 ± 17**	⬇ **587 ± 27**	⬇ **561 ± 25**	⬆ **736 ± 39**	⬇⬆ **587 ± 19**	⬇ **498 ± 12**

⬆ Highlights an increase value in comparison to the values highlight by ⬇

⬆⬇Highlights a difference from two groups, one value is higher, one value is lower.

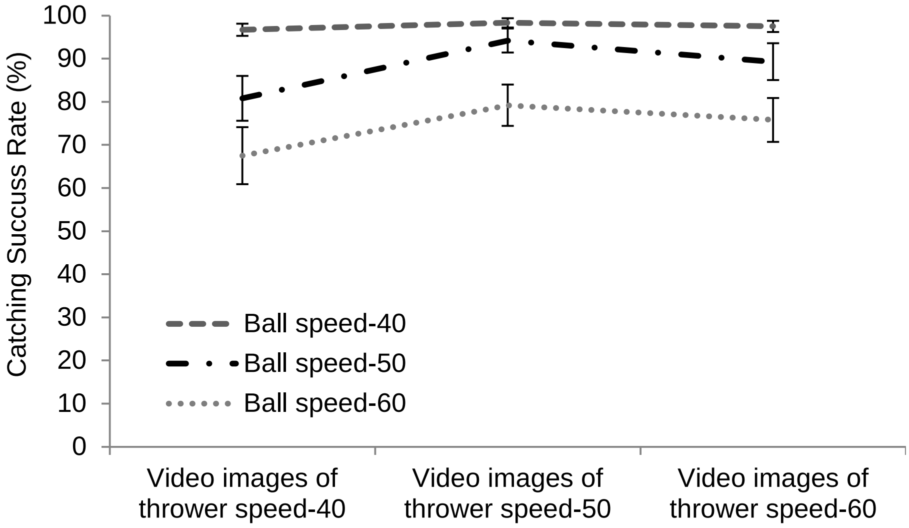

Figure 1. Interaction between video images of thrower speed and ball projection speed on catching performance (Mean ± SE).

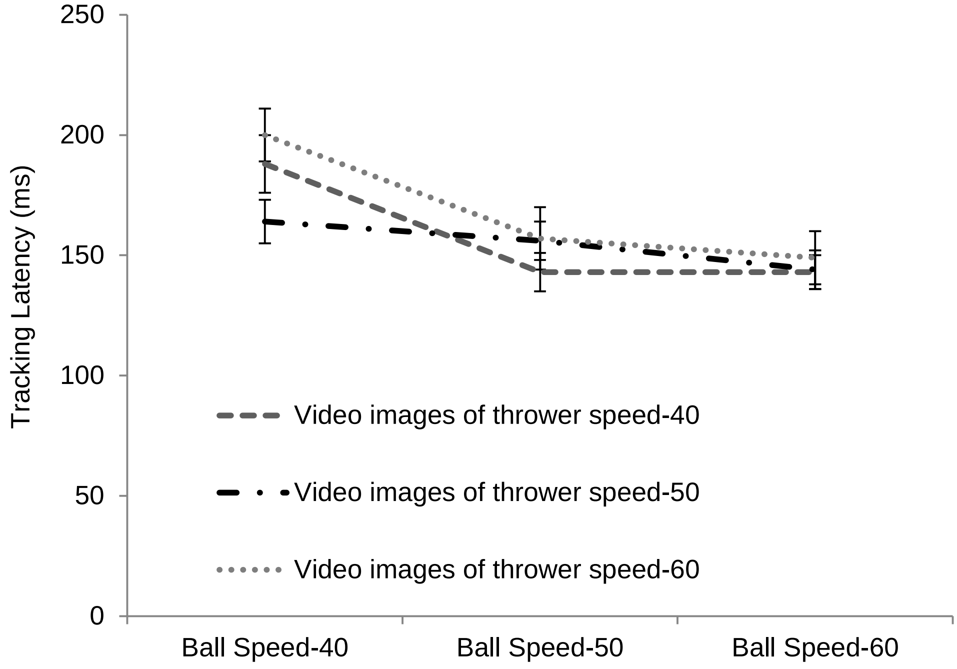

Figure 2. Interaction between video image speed and ball speed for tracking latency.