Visual information underpinning skilled anticipation: The effect of blur on a coupled and uncoupled in situ anticipatory response

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Coupled interceptive actions are understood to be the result of neural processing—and visual information—which is distinct from that used for uncoupled perceptual responses. To examine the visual information used for action and perception, skilled cricket batters anticipated the direction of balls bowled toward them using a *coupled* movement (an interceptive action that preserved the natural coupling between perception and action) or an *uncoupled* (verbal) response, in each of four different visual blur conditions (plano, +1.00, +2.00, +3.00). Coupled responses were found to be better than uncoupled ones, with the blurring of vision found to result in different effects for the coupled and uncoupled response conditions. Low levels of visual blur did not affect coupled anticipation, a finding consistent with the comparatively poorer visual information on which online interceptive actions are proposed to rely. In contrast, some evidence was found to suggest that low levels of blur may enhance the uncoupled verbal perception of movement.

The accurate anticipation of event outcomes based on the observation of early portions of an action sequence is an important element of expertise in many interceptive tasks, yet traditional means of assessing anticipatory skill may rely on neural mechanisms different from those used in the natural setting. Existing evidence (e.g., Abernethy & Russell, 1987) indicates that skilled athletes are better able than less skilled performers to predict the movement outcomes of opposition players based on the availability of *advance* visual information (i.e., movement pattern information that occurs prior to the availability of unambiguous confirmatory information, such as ball flight). Skilled tennis players, for example, are able to predict characteristics of the serve (such as ball direction and spin) at better-than-chance levels, based on observation of the precontact movement pattern of the opposing player. Likewise, skilled soccer goalkeepers are able to predict the direction of a penalty kick at better-than-chance levels before the opposition player actually kicks the ball (e.g., Savelsbergh, van der Kamp, Williams, & Ward, 2005). Skilled athletes can make predictions of an event outcome earlier in the progression of the action sequence than can

novice observers (Abernethy, 1990; Goulet, Bard, & Fleury, 1989), with these predictions made on the basis of additional sources of kinematic information different from those used by nonexperts (Abernethy, Gill, Parks, & Packer, 2001; Müller, Abernethy, & Farrow, 2006). The accurate perception of advance information facilitates enhanced interceptive performance in skilled athletes by allowing the athlete's own interceptive movements to be initiated earlier (Shim, Carlton, Chow, & Chae, 2005) and/ or at the most appropriate moment (Ranganathan & Carlton, 2007). This allows for the apparently unhurried movements that characterize expert performance (cf. Bartlett, 1947) and, importantly, for outcomes compatible with the goal of the task (Mann, Abernethy, & Farrow, 2010; Renshaw, Oldham, Davids, & Golds, 2007).

Although a substantial body of knowledge has been developed to better understand skilled anticipation, a considerable proportion of this evidence is based on tasks that require athletes to make highly perceptual predictions of an event outcome rather than examining the movement requirements and constraints that coexist within the natural performance environment. As a result, rather than more

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appropriately examining tasks that engage visual processing via the dorsal (vision-for-action) pathway, some authors (e.g., van der Kamp, Rivas, van Doorn, & Savelsbergh, 2008) have proposed that the majority of the literature examining anticipation has been based on assessments of the ventral (vision-for-perception) pathway. The dorsal pathway is believed to be specifically responsible for the online control of interceptive actions (see Milner & Goodale, 1995), like those that occur in the natural setting for most interceptive sports.

It has been hypothesized for some time (e.g., Abernethy, Thomas, & Thomas, 1993) that the expert advantage on anticipatory tasks will be enhanced as the response requirements of an experimental task can more closely mirror those performed in situ, but experimental confirmation of this contention has been limited. Farrow and Abernethy (2003) manipulated the degree of perception–action coupling required of participants anticipating the direction of a tennis serve; they showed that anticipatory accuracy for coupled responses (in which the task was to attempt to hit a return stroke) was superior to that for uncoupled responses (in which the task was simply to verbally report the oncoming service direction), although this superiority was observed only when ball-flight information was available to participants when they were making their response. Stronger coupling between perception and action did not result in enhanced anticipation when responses were based solely on pre-ball-flight information. Farrow and Abernethy proposed that the coupled and uncoupled responses were underpinned by different perceptual processors and noted that their findings were consistent with a dissociation of responses produced by the dorsal and ventral pathways (Milner & Goodale, 1995). In a model ascribing the relative contributions of the two streams in visual anticipation, van der Kamp et al. (2008) proposed that anticipation based on pre-ball-flight information is predominantly a result of processing by the ventral visual pathway, but that anticipation *also* relies on contributions from the dorsal visual stream (van der Kamp et al. also went on to propose that the dorsal stream provides the predominant contribution to the interceptive action *following* ball release). In contrast to the results of Farrow and Abernethy (2003), Mann, Abernethy, and Farrow (in press) found that enhanced perception–action coupling resulted in superior anticipation for skilled cricket batters anticipating ball direction in situ, even when the anticipation was based on pre-ball-flight information. For those judgments based on pre-ball-flight information, a simplified movement response enhanced the anticipation of skilled batters over a verbal prediction. Furthermore, a more complex movement response requiring an attempt at interception (reasoned to be most likely to engage the dorsal visual system) produced a further improvement in anticipation above and beyond that achieved by a simplified movement. These findings were interpreted to support the integrative model put forward by van der Kamp et al., with what was reasoned to be a dorsally based coupled response facilitating enhanced performance when based on pre-ball-flight information, compared to performance for an uncoupled verbal response (produced predominantly by the ventral visual pathway).

The dorsal and ventral neural pathways thought to underpin coupled and uncoupled anticipatory responses may have evolved to process rather different types of visual information. Visual output from the retina is primarily communicated to the brain along two parallel pathways: The *magnocellular* pathway conveys information processed in a rapid manner and is highly sensitive to movement and contrast; the *parvocellular* pathway is responsible for information very detailed (of fine visual acuity) and rich in color (Livingstone & Hubel, 1988; Milner & Goodale, 1995). The dorsal visual pathway produces the online visual guidance of interceptive movements, relying only on visual input from the magnocellular stream. The ventral pathway produces conscious perceptual interpretations of the world; this pathway is believed to have evolved relatively late in the evolutionary pathway, and—in contrast to the dorsal stream—is based on shared magnocellular and parvocellular input (Goodale, Milner, Jakobson, & Carey, 1991; Milner & Goodale, 1995). As a result, the dorsal visual stream produces actions based on information highly sensitive to movement and contrast, but the input is relatively blurred and colorless when compared with the normal (ventral) interpretation of our surrounds (and what we experience phenomenologically as *vision*). Although the ventral stream has the capacity for sensitivity to movement and contrast, the clear and more colorful information is thought to dominate processing. The disparate visual information supplying the two visual pathways offers a potential means to differentially affect their respective visual input. For example, the ventral (but not the dorsal) visual stream is reliant on clear visual information; hence, the introduction of visual blur may be expected to have a much greater effect on the ventral than on the dorsal pathway.

Visual blur (simulated by either spectacle or contact lenses) has been shown to adversely affect performance in a variety of *perceptual* tasks; however, the impact of blur on *motor* skills appears to be less severe. In an examination of driving performance, Higgins, Wood, and Tait (1998) found that the introduction of blur resulted in an immediate decrease in contextually relevant perceptual judgments such as road sign recognition, road hazard avoidance, and total driving time; yet the blur had no effect on the ability of participants to drive through targets. Norman (2002) interpreted these findings to be a result of visual blur limiting the performance of ventrally dependent perceptual tasks but not that of dorsally dependent motor tasks. Jackson, Abernethy, and Wernhart (2009) recently investigated the effect of visual blur on the anticipation of skilled tennis players. They manipulated video footage of a series of tennis serves using three levels of Gaussian blur (0%, 20%, 40%).[1] It was reported that 20% blur reduced the verbal anticipation of serve direction to levels achievable by chance guessing when predictions were based on pre-ball-flight information. This provides an example of visual blur affecting a task that is, in all probability, ventrally based. Most peculiarly, though, the 40% blur condition resulted in a significant *increase* in anticipation. It was reasoned that this increase might reflect a change in strategy on the part of participants, with better judgments in the 40% blur condition proposed to be a result of the interpretive strategy switching from a prediction

based on featural information (relying on fine acuity) to one based on figural information (relying on coarse acuity).

In contrast to the perceptual tasks that appear to rely on fine visual acuity, motor tasks have tended to demonstrate some degree of resilience to visual blur. This has been shown by the maintenance of performance despite high levels of blur in tasks such as the basketball free throw (Applegate & Applegate, 1992) and golf putting (Bulson, Ciuffreda, & Hung, 2008). Although these particular tasks would not be considered to be visually onerous, this resilience to blur has been replicated in an interceptive striking task (cricket batting) which is much more likely to require fine online visual–motor manipulations (Mann, Abernethy, & Farrow, 2010b; Mann, Ho, De Souza, Watson, & Taylor, 2007). Collectively, these results are consistent with Norman's (2002) conceptualization of visual clarity being a limitation to ventrally based but not dorsally based tasks. As a result, it appears reasonable to propose that if visual clarity is a limitation to perceptual performance, low levels of blur may be expected to adversely affect a ventrally based task but not a dorsally based one. In the case of an examination of anticipation, it may be reasonable to expect an interaction between blur and perception–action coupling, such that there would be an immediate decrease in the performance of an uncoupled prediction of movement outcome, but not a coupled prediction of outcome.

In a recent examination of interceptive performance in cricket batting, Mann, Abernethy, and Farrow (2010b) demonstrated that the effect of blur on interceptive skill was dependent on target velocity, with increased ball velocity resulting in decreased performance with a lesser amount of blur. Although this association was attributed to the differences in ball velocity, there is reason to expect that this relationship may extend to the observation of pre-ball-flight information. For instance, tests of dynamic visual acuity seek to address the ability of observers to resolve meaningful detail in a moving target (Ludvigh & Miller, 1958). For clear resolution, results suggest that larger target sizes are required as the velocity of the target is increased (Hoffman, Rouse, & Ryan, 1981). This effect becomes particularly pronounced for observation times of less than 600 msec (Long & May, 1992). If one considers two objects of similar size but different movement velocities, it is reasonable to extrapolate that better acuity will be required for the adequate resolution of the faster moving target. As a result, it seems fair to expect that, as the level of visual blur is progressively increased, resolution of the faster moving target should be adversely affected earlier than it would be for a slower moving target. When considering skilled anticipation, if faster ball velocities are demonstrated to be the result of faster movement action sequences (that is, fast ball velocity is most likely a result of faster arm movement by the bowler/pitcher), one may reasonably expect anticipation based on faster pre-ball-flight movements to be affected by a lower level of visual blur than that level found to affect the anticipation of slower movements.

The present study set out to address two specific aims. The first was to examine the interaction between visual blur and the degree of perception–action coupling in the response used to test anticipatory performance. We asked participants to predict the direction of cricket balls bowled toward them using two different types of response that differed in the degree of coupling between perception and action: (1) an *uncoupled* response condition, in which participants simply made a verbal prediction of ball direction; and (2) a *coupled* response condition, in which participants were required to make an interceptive movement in order to hit the ball as it approached (as they would in a typical match situation). It was hypothesized—consistent with the findings of Mann et al. (in press)—that performance for coupled responses would be greater than for uncoupled responses when decisions were based on pre-ball-flight information in normal viewing conditions (no visual blur; Hypothesis 1.1). Given the proposition that coupled and uncoupled responses are sourced by different types of visual information, we expected to find that visual blur would have a different effect, depending on the degree of perception–action coupling used in the anticipatory response (an interaction effect; Hypothesis 1.2). Consistent with the predictions of Norman (2002) that visual clarity would not limit the performance of a dorsally based task, it was hypothesized that the coupled response would demonstrate some degree of resilience to blur (Hypothesis 1.3). In contrast, it was expected that performance in the uncoupled condition would immediately and progressively decrease as the level of visual blur increased (Hypothesis 1.4).

The second aim of the present study was to examine the mediating effect of increased movement velocity on the relationship between visual blur and perception–action coupling. We predicted that there would be an interaction between movement velocity and visual blur, such that trials necessitating anticipation based on faster movement velocities would be adversely affected by a lower level of blur (Hypothesis 2.1). More specifically, it was expected that this relationship would hold for both the coupled (Hypothesis 2.2) and the uncoupled (Hypothesis 2.3) response conditions.

METHOD

Participants

A total of 10 skilled male cricket batters (mean age 22.5 ± 4.9 years) voluntarily took part in the study. All participants had played in the local regional first-grade competition within the previous 12 months, with the majority (8) representing their state at a junior and/or senior level. Participants reported an average of 9.1 ± 3.6 years of junior and 7.3 ± 4.5 years of senior cricket-playing experience. All gave written informed consent according to the relevant institutional guidelines prior to taking part in the study.

Experimental Task

A two-choice prediction task was designed with the goal being for participants to predict the impending direction of an approaching ball projected by an opposing actor (*bowler*). The direction of the ball was judged to be either toward the *off* (away from the batter's legs) or *leg* (toward the batter's legs) side of a center stump, in front of which the participants were standing. The task represented an important element of expertise in cricket batting, in which the direction of the ball must be judged quickly and accurately to facilitate the most favorable bat–ball interception.

Three actors were recruited to assist in the study, bowling balls toward participants in situ. All actors had played as bowlers in the local regional first-grade competition within the previous 12 months (and, as a result, were of a skill level comparable to that of the partic-

ipants). One of these actors was classified as a bowler of fast-paced bowling velocity (ball speeds: 120–130 kph), with the remaining 2 actors classified as bowlers of medium-paced bowling velocity (ball speeds: 90–110 kph). All 10 participants faced 3 bowlers, though only 7 of the participants faced the fast-paced bowler, due to logistical constraints with testing. Any bowler who was unavailable was replaced by a substitute bowler of medium-paced bowling speed. As a result, all participants faced 3 bowlers: 7 participants facing 2 medium- and 1 fast-paced bowler, the remaining 3 participants facing 3 medium-paced bowlers.

All bowlers followed scripts of intended ball direction for each trial to ensure an equal distribution of trials to the off and leg side [actual direction = 49.1% vs. 47.1%, respectively; $t(9) = 0.98$; $p = .35$]. Bowlers correctly delivered 86% of trials, as specified to the off or leg side of the center stump. A speed radar (Stalker ATS sports radar, Plano, TX) was used to monitor ball velocity for each trial to ensure consistency across conditions. The classification of bowlers by ball velocity was confirmed by a significant difference in ball velocity between the two groups [fast pace vs. medium pace = 120.8 vs. 104.2 kph; $t(6) = 13.22$, $p < .001$]. A skilled cricket batter is able to anticipate ball-flight characteristics of a cricket delivery on the basis of the information available in a key kinematic event that occurs prior to ball release. More specifically, this kinematic event takes place from the moment of the bowler's final back-foot contact with the ground prior to ball release through to the moment of ball release (Müller et al., 2006). Examination of high-speed video footage revealed that the time taken for this kinematic event was shorter for the fast-paced bowler than it was for the medium-paced bowlers (fast pace vs. medium pace = 309 vs. 367 msec). As a result, anticipation of the faster paced bowler in this study required perception of a faster action sequence than when observing the medium-paced bowlers.

Liquid crystal occlusion goggles worn by participants (PLATO Model P-1, Translucent Technologies Inc., Toronto, ON) facilitated the occlusion of vision at desired points in the approach sequence of the bowlers. To examine anticipation skill, participants observed the approach of the bowler with either (1) vision occluded at (or immediately prior to) the point that the ball was released from the bowler's hand (*ball-release* condition), or (2) no occlusion (*no-occlusion* condition). This ensured that judgments of ball direction made in the ball-release condition were based purely on prerelease kinematic information, and in the no-occlusion condition with the addition of all possible ball-flight information. The occlusion goggles were triggered by a bowler-specific signal delay initiated by registration of a reliably occurring point in the bowling event sequence (see Mann, Abernethy, Farrow, Davis, & Spratford, 2010). Skilled bowlers have a consistent time delay from the penultimate foot strike prior to ball release through to the point of ball release, providing a trigger point for the accurate occlusion of vision in situ. Surface-embedded force plates sampling at 250 Hz (Kistler 9287BA, Kistler Instrumente AG, Winterthur, Switzerland) registered the penultimate foot strike prior to ball release, with a bowler-specific computer-delayed signal used

on chosen trials to occlude vision immediately prior to ball release. This method of occlusion has been demonstrated to facilitate occlusion windows within 50 msec of the desired time point, affording a greater level of precision than in previous studies of occlusion in situ (300-msec time windows; Farrow & Abernethy, 2003; Müller & Abernethy, 2006). A second signal was sent, parallel with that for occlusion, to an LED to facilitate post hoc examination of test footage to confirm the trials where occlusion took place.

Testing was conducted in an indoor facility, with the surface replicating an artificial cricket pitch, and with markings reproducing the dimensions of a pitch used for official play. Participants stood at their batting position ≈17.7 m from where actors delivered the ball (replicating the distance that a batter would stand from a bowler in a match). To prevent the ball from hitting the batter, a small net was suspended 0.8 m in front of participants. The top of the net was 1.4 m above the ground, ensuring that the view of the bowler in his approach was unobstructed from the stance of the batter. The positioning and suspension of the net ensured that bat–ball interception was still possible, with participants able to hit the ball through the net. Participants wore all standard protective equipment, and faced a softer ball (Kookaburra Supa Soft with factory-lowered seam, Kookaburra Sport Pty. Ltd., Australia) specifically designed to maintain the appearance and properties of a cricket ball. Video footage of all testing was recorded (Sony HDR-FX1E digital video camera) from an elevated position behind the bowler.

A vision screening was performed prior to testing to fit contact lenses to participants. Habitual visual acuity (VA) was assessed in addition to a full refraction so that soft contact lenses could be fitted to simulate four refractive conditions relative to habitual vision: plano, +1.00, +2.00, and +3.00 (see Figure 1). In the plano condition, participants took part with habitual vision, wearing either no correction or soft contact lenses if they usually batted with visual correction in a game. All participants wore contact lenses for the +1.00, +2.00, and +3.00 conditions. Mean habitual VA for all participants was 6/5.3 equivalent (range, 6/4.5–6/6), with mean VA for the three remaining blur conditions (+1.00, +2.00, and +3.00) found to be 6/11 (range, 6/6–6/19), 6/20 (range, 6/10–6/33), and 6/49 (range, 6/25–6/80), respectively. Participants with habitual VA worse than 6/6, or those who could not adapt to contact lenses, were omitted from the study.

Procedure and Design

The prediction of event outcome was examined in each of two response conditions that differed according to the degree of coupling between perception and action: (1) a *coupled* condition, in which participants were required to hit the approaching ball with a cricket bat (as would occur in a match), and (2) an *uncoupled* condition, in which participants verbalized the anticipated direction of the ball as either toward the off or leg side (with no concurrent movement). The coupled and uncoupled conditions were respectively selected as being the responses most representative of the dorsal and ventral pathways (see Mann et al., in press; van der Kamp et al., 2008).
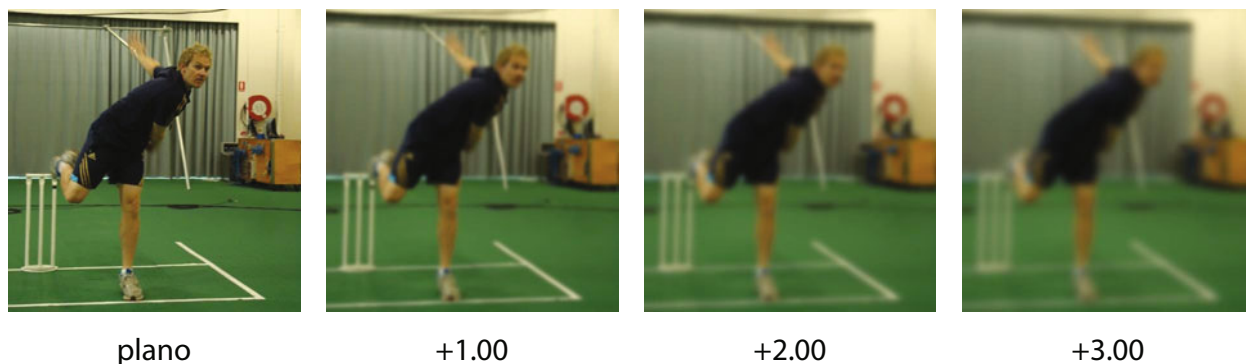

| plano | +1.00 | +2.00 | +3.00 |

Figure 1. Simulation of the four refractive blur conditions experienced by the participants.

Participants were instructed that responses in both conditions were to be made prior to the ball hitting the net.

A 2 (coupling: coupled, uncoupled) × 4 (blur: plano, +1.00, +2.00, +3.00) × 2 (movement velocity: fast, medium) within-participants design was used to examine for changes in coupling-based anticipation across increasing levels of refractive blur. The order of presentation for blur condition was balanced across participants, with the order of coupling conditions held constant within participants but counterbalanced across all participants. Each participant faced a total of 144 experimental trials: 72 trials to test the coupled response (an 18-trial set for each of the four blur conditions) and 72 trials to test the uncoupled response (a further 18-trial set for each of the four blur conditions). Each 18-trial set comprised a 6-trial block from each of the 3 bowlers. Six practice trials (2 trials from each bowler) preceded each 18-trial set. Following a randomized schedule, two thirds of all trials were occluded at ball release, with 4 of the 6 practice trials and 12 of the 18 experimental trials for each set randomly occluded at ball release and no occlusion scheduled for the remainder of the trials. All testing took approximately 2 h to complete.

Data Analysis

Task performance was assessed by a measure of response accuracy (RA), calculated as the percentage of trials where the predicted direction matched the actual direction of the ball. All verbal responses (either "off" or "leg") were recorded by a research assistant at the time of testing, with the response in the coupled condition and the actual ball direction for all trials judged by a trained observer (blind to the blur condition) viewing video footage post hoc. Participant responses for the coupled trials were judged according to whether the plane of motion of the bat swing was directed toward the off or leg side of the center stump. Ball direction was judged according to the direction of the ball relative to the center stump, with those trials where the ball was judged to have been directed at the center stump (rather than to either side) being excluded from all analyses.

The trials where no occlusion took place were included in the experiment so that batters would participate in trials where bat–ball interception was likely to occur, engaging the visual–motor pathway responsible for online interception. We were concerned that if occlusion were to occur at ball release for *all* trials, the minimal chance of successful bat–ball interception in these trials might result in participants engaging the vision-for-perception pathway rather than the vision-for-action pathway. Because the trials without occlusion were irrelevant to our

primary aim of examining anticipation, they were excluded from all analyses. Accurate occlusion proved to be difficult for 1 of the bowlers recruited in the study (5 bowlers in total, including replacements), since his penultimate foot strike prior to ball release frequently missed the force plate, resulting in occlusion not taking place for the majority of trials. In particular, this resulted in an uneven distribution of trials for this bowler across conditions within participants. As a result, all trials from this bowler were excluded from analyses.

All data for RA underwent an arcsine transformation prior to being subjected to statistical analysis. To investigate the first set of hypotheses related to the relationship between blur and coupling, a 2 (coupling) × 4 (blur) × 2 (movement velocity) ANOVA with repeated measures on all factors was performed. To investigate the second set of hypotheses related to the influence of movement velocity (and because there were different participant numbers across the two movement velocity conditions), separate 2 (coupling) × 4 (blur) ANOVAs were conducted for the fast-paced (7 participants) and medium-paced (10 participants) trials. Successive contrasts were used to examine for within-group changes in RA across increasing levels of blur, with *t* tests performed to determine whether mean responses were significantly different from the 50% level achievable by chance guessing. Alpha was set at .05 for all testing. Partial eta squared (η_p^2) was calculated to determine the proportion of total variability accounted for by an effect or combination of effects.

RESULTS

Response Accuracy Across All Trials

The 2 (coupling) × 4 (blur) × 2 (movement velocity) ANOVA for the 7 participants who experienced both fast and medium-paced trials failed to demonstrate significant main effects for coupling [$F(1,6) = 0.56$, $p = .48$, $\eta_p^2 = .09$] or blur [$F(3,18) = 2.36$, $p = .11$, $\eta_p^2 = .28$], or for movement velocity [$F(1,6) = 1.37$, $p = .29$, $\eta_p^2 = .19$]; it did, however, reveal a significant interaction between coupling and blur [$F(3,18) = 3.70$, $p < .05$, $\eta_p^2 = .38$] (Figure 2) in the absence of any other interactions [movement velocity × coupling, $F(1,6) = 0.71$, $p = .80$,
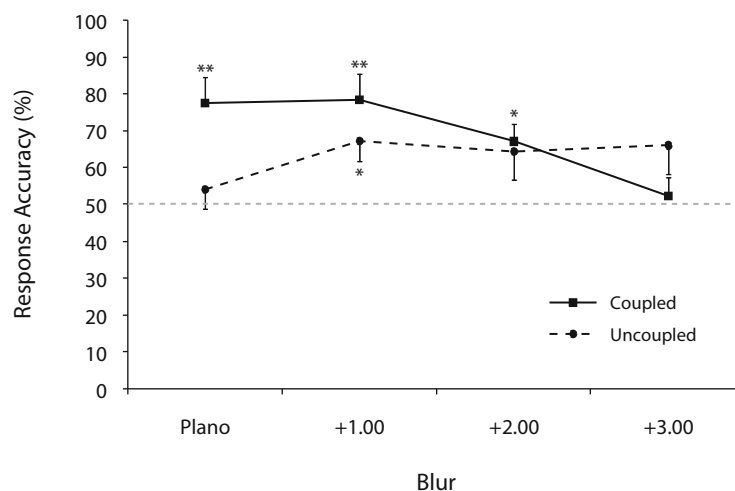

Figure 2. Coupled and uncoupled response accuracy as a function of refractive blur, averaged across both fast and medium-paced movement velocity trials. Response accuracy is indicated for those mean data points significantly greater than the 50% level achievable by chance through guessing (*$p < .05$, **$p < .01$). Data are displayed with standard error bars.

$\eta_p^2 = .01$; movement velocity × blur, $F(3,18) = 2.32$, $p = .11$, $\eta_p^2 = .28$; movement velocity × coupling × blur, $F(3,18) = 0.38$, $p = .77$, $\eta_p^2 = .06$]. Coupled anticipation was found to demonstrate a degree of resilience to blur, with RA at levels significantly greater than 50% for the plano ($p < .01$), +1.00 ($p < .01$), and +2.00 ($p < .05$) blur conditions. RA was not different from chance guessing levels for the +3.00 blur condition. On the other hand, uncoupled anticipation improved with a low level of blur, with RA being significantly greater than 50% in the +1.00 ($p < .05$) but in no other blur condition.

Response Accuracy by Movement Velocity

When examining the two movement velocity conditions separately, the ANOVA for the 7 participants who faced fast-paced movement velocity trials demonstrated a main effect for blur [$F(3,18) = 3.59$, $p < .05$, $\eta_p^2 = .37$] (Figure 3A), due to an increase in performance from the plano to +1.00 blur condition ($p < .05$) and a subsequent decrease from the +1.00 to +2.00 condition ($p < .05$). No significant effects were found for coupling [$F(1,6) = 0.49$, $p = .51$, $\eta_p^2 = .08$] or for the interaction between blur and coupling [$F(3,18) = 1.29$, $p = .31$, $\eta_p^2 = .18$]. RA was found to be significantly greater than the level achievable by chance/guessing for the plano and +1.00 coupled conditions, and for the +1.00 uncoupled condition (all ps $< .05$).

The ANOVA for all 10 participants against medium-paced trials failed to demonstrate effects for coupling [$F(1,9) = 0.41$, $p = .54$, $\eta_p^2 = .04$] or blur [$F(3,27) = 1.18$, $p = .34$, $\eta_p^2 = .16$], or for the interaction between coupling and blur [$F(3,27) = 1.77$, $p = .18$, $\eta_p^2 = .16$] (Figure 3B). RA was found to be significantly greater than the 50% chance guessing levels for the plano ($p < .05$), +1.00 ($p < .05$), and +2.00 ($p < .01$) coupled conditions, and for the +2.00 uncoupled condition ($p < .05$).
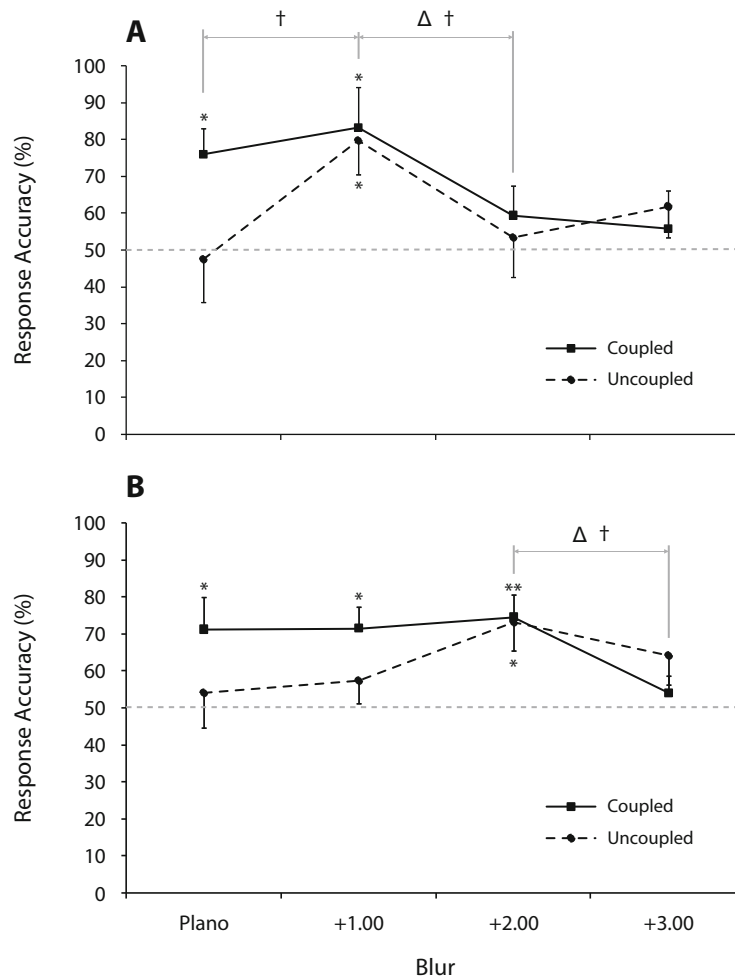

Figure 3. Coupled and uncoupled response accuracy as a function of refractive blur for fast-paced (A) and medium-paced (B) movement velocity trials. Response accuracy for those mean data points significantly greater than the 50% chance level is indicated (*$p < .05$, **$p < .01$), along with significant changes in performance across successive blur conditions for the coupled condition ($\Delta p < .05$), and collapsed across both coupling conditions ($\dagger p < .05$). Data are displayed with standard error bars.

DISCUSSION

This study was performed with two specific aims in mind. The first was to examine the relationship between visual blur and the degree of coupling in an anticipatory response. Hypothesis 1.1 predicted that coupled anticipation would be better than the uncoupled equivalent when pre-ball-flight information was viewed with clear vision. Hypothesis 1.2 predicted a significant interaction between visual blur and perception–action coupling, with Hypothesis 1.3 more specifically expecting the coupled response to demonstrate some resilience to visual blur; Hypothesis 1.4, however, predicted that uncoupled anticipation would be more sensitive to blur. The second aim of the present study was to examine whether the relationship between visual blur and coupling was mediated by the speed of the movement being observed. Hypothesis 2.1 foresaw a significant interaction between movement velocity and visual blur, with an expectation that higher movement velocity trials would be more susceptible to blur. It was predicted that the greater blur susceptibility for higher movement velocity trials would hold true for both coupled (Hypothesis 2.2) and uncoupled (Hypothesis 2.3) trials.

Visual Blur and Perception–Action Coupling

Coupled but not uncoupled anticipation (based on pre-ball-flight information) was shown to be at a level significantly greater than chance for the plano visual condition, a finding consistent with the prediction of Hypothesis 1.1. This supports the results reported by Mann et al. (in press), giving weight to the case for a coupling-facilitated improvement in performance, since the task more closely replicates the real-world conditions (Farrow & Abernethy, 2003). This is in contrast to the alternate view that stronger coupling may result in *decreased* performance as a result of increased task complexity or of requiring participants to make an earlier response (Ranganathan & Carlton, 2007). Most interestingly, the support for coupling-enhanced anticipation in the absence of confirmatory ball-flight information supports the role of movement in facilitating anticipation, and is consistent with the van der Kamp et al. (2008) model, according to which the dorsal visual stream makes critical contributions to anticipation even when decisions are based purely on pre-ball-flight information.

Testing revealed—consistent with Hypothesis 1.2—a significant interaction between visual blur and coupling. As was predicted by Hypothesis 1.3, the coupled response condition demonstrated a degree of resilience to blur, with +3.00D required to reduce RA to the 50% level achievable by guessing (Figure 2). This finding suggests that visual clarity is not critical for coupled anticipation and is consistent with the expectation that a low level of blur would not adversely affect functions produced via the dorsal visual stream (which relies on a relatively poor quality of visual acuity; Brown, Halpert, & Goodale, 2005; Livingstone & Hubel, 1988; Norman, 2002). In contrast to the response for coupled anticipation, even with clear (habitual) vision, uncoupled anticipation was not different from chance guessing levels; rather curiously, however, (and in contrast to Hypothesis 1.4), performance tended to *increase* with the introduction of blur (Figure 2). Verbal predictions of ball direction were significantly greater than chance guessing levels with the +1.00D lenses, and remained at comparable levels with the addition of further blur. This is a most intriguing finding, and it will be revisited shortly. Collectively, these contrasting responses to visual blur support the proposal that the different forms of anticipatory response (based on differences in perception–action coupling) are underpinned by different neural pathways that source different types of visual input.

The Effect of Movement Velocity on the Interaction Between Visual Blur and Perception–Action Coupling

The experimental findings did not strictly support Hypothesis 2.1, which predicted that there would be a significant interaction between movement velocity and visual blur. This statistical finding (in terms of p value) suggests that visual blur is not more likely to adversely affect faster movement velocities than it is to affect slower velocities, although the magnitude of the effect size reported ($\eta_p^2 = .28$), in conjunction with the low statistical power available, suggests that this could be a consequence of the relatively low number of participants (only 7 participants were able to face both the medium- and fast-paced bowlers). In contrast, the outcomes from the separate ANOVAs performed for the fast- and medium-paced bowlers did provide some support for Hypothesis 2.1 (although a larger number of participants is clearly still required to provide a more definitive conclusion). Figure 3 reveals that RA decreased significantly with +2.00D of blur for the fast-paced movement velocity trials and with +3.00D of blur for the medium-paced trials. This is consistent with Hypothesis 2.1 that faster movement velocities would be adversely affected by lower levels of visual blur and supports the results from work on dynamic visual acuity, which has previously established that visual resolution is more difficult at faster movement velocities (Hoffman et al., 1981; Long & May, 1992).

Consistent with Hypothesis 2.2, coupled anticipation for fast-paced movement velocity trials was affected by a lower level of blur than for the medium-paced trials (supported by the magnitude of the effect size reported for the coupling × blur interaction). The results for the uncoupled condition were somewhat different. Once again, RA for the uncoupled trials with clear vision was not different from levels achievable by chance guessing; this result makes it difficult to evaluate whether the introduction of even a low level of blur would adversely affect ventral processing (Hypothesis 2.3). Most surprisingly, some evidence was found to suggest that—specific to the movement velocity of the bowler—a particular level of blur *enhanced* the verbal prediction of ball direction. Uncoupled anticipation was found to be significantly greater than 50% in the +1.00 blur condition when facing the fast-paced trials, and in the +2.00 condition when facing the medium-paced trials. These levels of blur directly correspond to the highest levels tolerated prior to decreases in *coupled* anticipation (Figure 3). Further increases in blur result in commensurate decreases in both the coupled and uncoupled conditions. If these findings are indeed re-

producible ones, the responses demonstrated in Figure 3 are consistent with the uncoupled response defaulting to the performance level of the coupled response at a level of blur specific to the movement velocity of the bowler. We speculate that this outcome could be rationalized by at least one of two particular explanations. The first is that the dorsal stream may provide a relatively greater contribution (even in perceptual tasks) when the ventral stream is operating suboptimally. Milner and Goodale (2008) have outlined that no single task is likely to be purely perceptual or purely visual–motor; rather, all tasks are likely to be a result of simultaneous contributions from each of the ventral and dorsal streams. In this case, blur may have resulted in a relatively greater contribution from the dorsal stream, since the ventral system is forced to operate in a less favorable manner (the converse has been shown to take place when dorsal processing is disturbed; see Hu, Eagleson, & Goodale, 1999). The second possible interpretation is that blur may have forced the ventral stream to rely on visual information more similar to that used by the dorsal stream, and that this information may be more favorable for the perception of relative motion.

Evidence for Improved Ventral Processing With Visual Blur?

The evidence in this study suggesting that certain levels of visual blur may enhance uncoupled anticipation are, although tentative, consistent with the findings of Jackson et al. (2009), who reported that a particular level of Gaussian blur (40%) enhanced the verbal anticipation of tennis serves. They attributed this effect to observers altering their focus from fine featural to more course figural information. Considering that the only two known studies to examine the effect of blur on verbal (and hence ventrally based) anticipation have found similar results, this is worthy of further consideration in the context of the wider body of literature addressing visual perception.

A small number of studies have reported enhanced task performance with the introduction of visual blur, and they may provide important insights into this apparent phenomenon. Harmon (1973) used computer simulations to blur images of human faces and found that the removal of high-spatial-frequency information (necessitating fine VA) had very little effect on the ability to recognize a face. Even with levels of blur so extreme that facial features were entirely indistinguishable, the remaining low-frequency information, which permitted some identification of head shape (plus neck and shoulder geometry), was sufficient for a good degree of facial recognition. In extending this work, Harmon produced block facial portraits, in which the image was divided into squares of uniform size, with the brightness for each square averaged across all the points in that square. He found that blurring significantly enhanced the recognition of the faces depicted in these block images, since it removed the higher spatial-frequency information that acted as noise interfering with facial recognition. By way of explanation, an image (much like sound) can be considered to be a combination of simple component frequencies; in Harmon's studies, the blur was considered to act like a low-pass filter, removing high- but not low-

frequency visual information. Interestingly, this distinction has been used to explain the curious smile evident in the Leonardo da Vinci masterpiece the *Mona Lisa* (Kontesevich & Tyler, 2004). Commentators have often remarked that the subject in this painting has a distinct smile most evident when the observer focuses anywhere *but* on the mouth; when we look at her mouth, the smile seems to disappear. This phenomenon has been explained by spatial frequency: Low-spatial-frequency images of the painting (of the type that might be resolved by peripheral vision) reveal a broad smile hidden by higher spatial-frequency "noise" (of the type that dominates central vision); that is to say, the relatively blurred image produced by peripheral vision reveals the lower spatial-frequency information (in this case, the woman's broad smile) hidden by the high-spatial-frequency information, which is seen by central vision. The capacity for visual blur to remove these higher spatial frequencies may hold an important implication for the interpretation of the results found in the present study as well as in other studies.

Visual blur has been identified as a potential facilitator of two particular advantages in the perception of fast-moving visual information. The first is based on the work of Luria and Newacheck (1992), who found that the introduction of visual blur improved the ability of participants to discern the temporal order of two flashing lights. Luria and Newacheck examined the amount of time required to elapse between the presentation of two spatially close stimuli for those lights to be perceived as flashing one before the other, rather than being perceived to flash simultaneously (a task considered to be important in naval navigation). They performed this examination using five different levels of visual blur (plano, +1.00, +2.00, +3.00, and +4.00) and found that for the discrimination of temporal order, the time needed to elapse between the presentations *decreased* as the blur increased from plano to +2.00, and remained constant with further increases in blur. This represented an improvement in visual function with the addition of visual blur in that participants with blur were better able to distinguish lag times between the two lights. The second possible way that blur may enhance the perception of temporally related visual information is based on examinations of *visual persistence*, which refers to the perceptual phenomenon that a brief visual stimulus will remain perceptible as a photograph-like representation of that image for a short period of time after it has disappeared. Visual persistence is thought to be associated with the time required for cognitive processing, with longer visual persistence related to a longer period of visual processing (Di Lollo, 1977, 1980). Di Lollo and Woods (1981) reported that progressive increases in visual blur produce corresponding *reductions* in the duration of visual persistence. For each of these phenomena, it has been proposed that the findings could be explained by blur reducing the perceptual contribution of high- but not low-spatial-frequency information in order to favor visual mechanisms that are more sensitive to movement. Low-spatial-frequency information is known to possess a greater capacity for the discrimination of temporal frequency, has shorter visual persistence, and is processed with shorter response latencies. Blurring may force the visual system to

rely on this lower frequency information, which is likely to have been processed in the habitual situation but is made redundant as preference is generally allocated to clearer, higher spatial-frequency input (Di Lollo & Woods, 1981, p. 769). This would be consistent with the findings demonstrated in Figure 3, where at particular points of blur the uncoupled response accuracy begins to mirror the coupled response. It is as if the blur had caused the uncoupled response (proposed to be ventral in nature) to rely on the same visual information that the coupled response (supposed to be dorsal) relies on.

At this point, it is worth revisiting the results of Jackson et al. (2009), who found that verbal anticipation of the ball direction for a tennis serve was initially decreased, then increased, with the progression of image blur. They reasoned that this later increase in performance with blur was the result of participants shifting focus from featural to figural display information. Perhaps an alternate explanation for their (and the present) findings may be that the removal of higher spatial-frequency information has been advantageous in forcing the ventral visual pathway to make decisions based on the lower spatial-frequency information that the dorsal system would usually rely on. It appears that this lower spatial frequency information—which may typically be considered redundant by the ventral visual system—may afford temporal advantages to aid conscious movement detection. Indeed, it is possible that this is the *most useful* form of information for movement detection and discrimination; otherwise, one might have expected the improved visual quality of the ventral pathway to have been adopted through evolutionary processes by the dorsal pathway. Additional work is, of course, required to replicate and further test this proposition. Future research should examine whether particular bands of spatial frequency are most favorable for movement perception and, if these bands are found to exist, whether they are specific to the velocity of the movement being observed. If verified, these findings could hold important implications for tasks of conscious movement perception such as those involved in driving, flying, air traffic control, the military, and various sports.

The Neural Basis for Superior Anticipatory Performance With Increased Perception–Action Coupling

Improvements in anticipation found as a result of greater coupling between perception and action are assumed to be the result of enhanced ecological validity, producing an experimental design that is more likely to effectively examine the neural pathways and connections relied on in the natural setting (Farrow & Abernethy, 2003; van der Kamp et al., 2008). In this sense, the ability to obtain functional information from movement (e.g., Oudejans, Michaels, Bakker, & Dolné, 1996; Oudejans, Michaels, van Dort, & Frissen, 1996) and to couple these movements to the invariants specific to environmental properties has been seen to facilitate improved decision-making (e.g., Michaels, 2000). Indeed, anticipation has been associated with common coding theory (Abernethy, Zawi, & Jackson, 2008) and has been shown to share a neural basis with the mirror neuron network (Wright, Bishop, Jackson, & Abernethy, 2010; Wright

& Jackson, 2007), providing further evidence that anticipation maintains a strong interactive relationship with movement production. There is little reason to doubt that it is the incorporation of movement that elicits enhanced anticipation with improvements in perception–action coupling, yet the results of this study raise an alternate (or at least adjunct) explanation worthy of consideration. It is possible that it is the quality of the visual information used, rather than the actual coupling per se, that provides the functional reason for improved performance with perception–action coupling. The results of the present study (particularly as presented in Figure 3) suggest that, at some point, the addition of blur causes the performance of uncoupled responses to mirror those found for coupled ones. This could be explained by the type of visual information the two different types of response rely on. If the uncoupled and coupled responses are considered to be the outcome of ventral and dorsal processing respectively, there is, therefore, likely to be a difference in the comparative quality of the visual information the two streams rely on. If one accepts that the dorsal pathway is dependent on relatively impoverished visual information (when compared with the ventral pathway), then, with experience, it has learned to converge on the most meaningful visual information using this comparatively *poorer* visual information; that is, if, for example, skilled tennis players have learned (using the dorsal visual system) to couple their movements to the advance precontact information from their opponents' bodies, they have done so on the basis of an image of poor visual quality (compared with our normal phenomenological experience of "vision"). The ventral stream relies on a clearer visual image pertaining to information of higher spatial frequency that may act as noise when an attempt is made to detect the important visual information the dorsal stream has learned to rely on. This comparatively poorer image is the most functionally meaningful visual information for the brain when context-specific events are anticipated. It is possible that the improvement in anticipation (found as a result of enhanced perception–action coupling) is a result of the response being produced via processing of the most functionally meaningful visual information available (of lower spatial frequency but higher temporal sensitivity), rather than simply by the incorporation of movement into the participant's response.

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NOTE

1. Gaussian blur applies a mathematical function to reduce image noise and detail in a video display. This study provided no indication of what the levels of Gaussian blur would equate to in terms of visual acuity or dioptric blur.