An Action-Incongruent Secondary Task Modulates Prediction Accuracy in Experienced Performers: Evidence for Motor Simulation

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Abstract

We provide behavioural evidence that the human motor system is involved in the perceptual decision processes of skilled performers, directly linking prediction accuracy to the (in)ability of the motor system to activate in a response specific way. Experienced and Non-Experienced darts players were asked to predict, from temporally occluded video sequences, the landing position of a dart thrown previously by themselves (Self) or another (Other). This prediction task was performed whilst additionally performing; (a) an action incongruent secondary motor task (right arm force-production), (b) a congruent secondary motor task (mimicking) or (c) an attention-matched task (tone-monitoring). Non-Experienced dart players were not affected by any of the secondary task manipulations, relative to control conditions, yet prediction accuracy decreased for the Experienced players when additionally performing the force production, motor task. This interference effect was present for 'Self' as well as 'Other' decisions, reducing the accuracy of Experienced participants to a novice level. The mimicking (congruent) secondary task condition did not interfere with (or facilitate) prediction accuracy for either group. We conclude that visual-motor experience moderates the process of decision making, such that a seemingly visual-cognitive prediction task relies on activation of the motor system for Experienced performers. This fits with a motor simulation account of action prediction in sports and other tasks, and alerts to the specificity of these simulative processes.

Introduction

In many sports and games, one of the hallmarks of a skilled performer is his or her ability to predict action outcomes quickly, arguably homing in on the key components of the action that are most predictive of success. Much has been written about the perceptual-cognitive skills of athletes in sport, particularly those related to decision processes that enable prediction of an unfolding outcome (see Abernethy et al. 2012; Mann et al. 2007; Yarrow et al. 2009). Until recently, the perceptual skills exhibited by visual-motor experts in sports were presumed to be based on the acquisition of a large repertoire of visual experiences that allow for fast associations between certain cues, a memory of these stored experiences and appropriate responses (e.g., Abernethy et al. 2012; Williams and Davids 1998; Williams and Ward 2003, 2007). These ideas were based primarily on the study of cognitive tasks, such as chess (e.g., Ericsson and Kintsch 1995; Gobet 1998; Gobet and Jackson 2002), rather than motor tasks. Although for sports skills, the 'motor' component of visual-motor expertise was considered important in the development of these relevant perceptual events (e.g., Williams and Davids 1995), the emphasis was still on the acquisition of visual experiences and visual recognition processes leading to the retrieval of the appropriate action response through stored, if-then type associations (e.g., Anderson 1982; Starkes 1987). In several recent studies, this visual emphasis has shifted to one on motor experiences and the suggestion that prediction accuracy is related to a motor simulation of an observed action (e.g., Aglioti et al. 2008; Ikegami and Ganesh, 2014; Tomeo et al. 2012; Urgesi et al. 2012).

During action observation, it is thought that the observer's motor system is covertly activated, such that it 'resonates' with the observed stimuli, through simulation mechanisms that generate a visual understanding of the observed action (e.g., Blakemore and Decety 2001;

Gallese and Goldman 1998; Hommel et al. 2001; Jeannerod 2001; Knoblich and Flach 2001; Schubotz 2007; Wilson and Knoblich 2005). Accordingly, perceptual codes linked to the motor command that generated the same action are activated in the observer (Blakemore and Frith 2005; Hommel et al. 2001; Wolpert et al. 2003), arguably in real time (Springer et al. 2013a, b). Perception and action are thought to exist in a common representational domain and exert bi-directional effects on each other (Prinz 1997; Prinz and Hommel 2002). Support for the idea that action and perception are subserved by common pathways comes from behavioural research showing both facilitation and interference effects during the concurrent execution and observation of congruent or incongruent movements (Brass et al. 2001; Craighero et al. 2002; Hamilton et al. 2004; Kilner et al. 2003; Miall et al. 2006; Wohlschläger 2000; for reviews see: Blakemore and Frith 2005; Schütz-Bosbach and Prinz 2007). Moreover, these effects are dependent on the observer's motor experience with the observed action (Capa et al. 2011).

There is considerable neurophysiological evidence to support the idea that action observation involves a type of motor simulation in the observer, primarily based on activation of parietal (Fogassi et al. 2005; Iacoboni et al. 1999), frontal (Pobric and Hamilton 2006), and temporal (Mukamel et al. 2010; Saygin 2007) regions of the brain during both action execution and action observation, also known as the Mirror-Neuron System or Action-Observation Network (e.g., Caspers et al. 2010; Decety et al. 1994; Gazzola and Keysers 2009; Grafton 2009; Grossman and Blake 2001 ; Iacoboni et al. 2005; Rizzolatti and Craighero 2004; Rizzolatti et al. 2001). Importantly, this activation is specific to the action experiences of the observer, rather than their visual experiences (Calvo-Merino et al. 2005, 2006; Cross et al. 2006; Reithler et al. 2007).

Research examining the effects of visual-motor experience on the perception of action has shown that visual-motor ‘experts’ are better than novices at recognising actions that they have had more experience performing (Hohmann et al. 2011; Wilson and Knoblich 2005). Because observers are better able to recognise their own actions in comparison to the actions of others, this has been taken as further evidence that it is motor experience per se, and not visual experience, that plays the primary role in action recognition and understanding, as one would have little visual experience of their own action (Knoblich and Flach 2001; Loula et al. 2005; Repp and Knoblich 2004). Indeed, participants have improved their visual recognition performance after training on a motor task in the absence of vision (Casile and Giese 2006; Hecht et al. 2001; Reithler et al. 2007).

In several recent studies, suggestions have been made that action-simulation is not only implicated in action *recognition*, but is also the mechanism underlying the *prediction* of action outcomes (Aglioti et al. 2008; Knoblich and Flach 2001; Urgesi et al. 2012). These conclusions have been based on four lines of evidence. First, that the expert perceptual advantage in making these predictive decisions is limited to those who have acquired significant motor experiences, such as sport’s performers, and not just visual experiences (e.g., fans; Aglioti et al. 2008, Urgesi et al. 2012; Williams and Davids 1995). Second, during action prediction, externally-evoked activation of the motor cortex was shown to lead to an increase in the amplitude of muscles involved in the observed action relative to baseline (Aglioti et al. 2008; Tomeo et al. 2012). Third, areas of the brain known to be part of the Action Observation Network also differentiated across novice and experts (in tennis) during prediction of action outcomes (Balser et al. 2014). Fourth, action predictions also improved following training without vision on a dart-throwing task (Mulligan and Hodges 2013).

In summary, evidence from several research streams supports the idea that motor experience plays a role in action recognition and prediction of action outcomes. However, direct evidence that activation of the motor system is involved in action prediction is still lacking. As noted above, researchers have shown muscle-specific changes following electrical stimulation of areas of the motor cortex associated with the observed action during prediction of basketball free-throw shots (Aglioti et al. 2008) and shot direction in soccer penalty kicks (Tomeo et al. 2012), but it is still unclear if this increased activity impacts the decision process. This is further clouded by the fact that in the study by Aglioti et al. (2008) both "motor" experts and "visual" experts (coaches and writers) showed modulation of the muscles implicated in the action of shooting a basketball (i.e., wrist and hand muscles), making it difficult to attribute the superior predictive performance of the motor experts to effector-specific, motor system activation. Tomeo et al. (2012) showed a negative relationship between response accuracy and motor facilitation among kickers in a soccer penalty prediction task, but this was only for artificial, biomechanically "impossible" actions, where the body kinematics and ball were incongruent. There was no positive relationship between amplitude of MEPs (motor evoked potentials) and response accuracy for decisions made when watching congruent (normal penalty kick) actions. Similarly, using repetitive TMS (Transcranial Magnetic Stimulation) to the PMd (dorsal Premotor Cortex), some of the same group of researchers showed a decrease in prediction accuracy about the outcome of these impossible actions, but again, motor interference did not affect prediction accuracy for the congruent 'real' actions (Makris and Urgesi 2014). In addition to some potential issues with inferring predictive responses from artificially constructed "fooling" actions (see Mann et al. 2013), it is also possible that with this type of dyad task (where a mirrored responder acting as a goal-keeper has to decide kick direction from an approaching soccer player), that any general technique which serves to disrupt or activate a specific cortical area would also interfere with the anticipated response (i.e., to move left or right) in addition to any potential simulative processes involved in watching the kickers.

Another relatively simple technique, which might help determine if motor simulation is responsible for prediction accuracy, would involve using a secondary motor task to selectively interfere with motor components of the action during prediction. The advantage of such a technique is that it is possible to determine direct costs in accuracy associated with the secondary motor task. Similar motor interference paradigms have been used in studies probing motor-system influences on stimulus detection (e.g., Paulus et al. 2009; Witt and Proffitt 2008; Witt et al. 2010). In these studies it has generally been shown that performing a secondary motor task (e.g., ball squeezing) while viewing a stimulus, results in the modulation of perceptual estimations concerning the stimulus (Witt and Proffitt 2008).

In the current study, we adopted a dart-prediction task as our primary task, where no physical (reactive) response was required in the observer (just a judgement as to where the dart would land). Participants were required to engage in two different types of motor secondary tasks during action observation, that were either congruent to the action, what we refer to as action mimicking, or incongruent to the action, pressing against a force gauge. The latter task was designed to prevent or at least interfere with the participants' ability to simulate the observed action, as the effector involved in the action would be tasked with pushing (causing immobilization of the right arm), whereas the primary dart throwing task required extension and flexion of the elbow and wrist.

Non-experienced and experienced darts players were required to judge the final location of a thrown dart from video clips that were occluded at different time points early in the throwing motion. Participants completed the prediction task (the primary task), by itself, and while performing each of three secondary-task conditions: a force-production task, a tone-monitoring task, and a mimicry task. We expected the Experienced group to make more accurate decisions than the Non-Experienced group. Consistent with the simulation hypothesis, we predicted that the force-production task, which required an action incongruent to the one being watched, would interfere with prediction accuracy of experienced performers (directly impacting the quality of predictions). Non-experienced participants, who would have no motor experience with the task, and hence be theoretically unable to simulate the observed action, were hypothesised to show no, or minimal, interference from the force-production secondary task (Capa et al. 2011). The mimicry secondary task was not expected to produce interference for either group due to the compatible nature of the action (Christensen et al. 2011; Schütz-Bosbach and Prinz 2007; Springer et al. 2011). A lack of interference from the mimicry task would also allow for conclusions about motor-system-specific effects associated with action simulation, rather than suggesting general motor system interference. Although there has been evidence that incongruent tasks lead to more interference in the primary task than congruent tasks, it is possible that the mimicry task could interfere. For congruent actions, the action plans for both the prediction task and the secondary task are the same. Because the action and observation of the action are thought to be served by a similar common code (Hommel et al. 2001), the mimicry task could potentially render the action-code associated with the same action unavailable for perception (e.g, Hamilton et al. 2004; Wuhr and Müsseler 2001). However, based on a recent review of the perception-action literature and potential for interference effects of action on perception, Zwickel and Prinz (2012) suggest that for concurrently produced actions, where the actions are functionally related (e.g., concurrent mimicry), congruent actions are unlikely to interfere with perception. In this case, perception-action links are thought to be strengthened because the movement features become linked to the perceptual representation of the stimulus.

Evidence suggests that action recognition and prediction accuracy improve when watching oneself versus someone else perform. This is said to come about because the action being simulated in the observer is the same as that being observed (Bischoff et al. 2012; Knoblich and Flach 2001; Loula et al. 2005; Repp and Knoblich 2004). With this in mind, we used both ‘self’ and ‘other’ stimuli in the prediction tasks. We expected participants, particularly the experienced players, to show better prediction accuracy when viewing their own throws, and a corresponding increase in interference in the force-production condition due to greater motor system activation in this condition. Based on a control experiment (see below) involving visual-spatial decisions (i.e., matching a rotated pattern), we were able to show that the force-production and tone-monitoring tasks were approximately matched with respect to attentional demands and general difficulty, suggesting that any interference from the force-production task would be due to the motor-specific nature of the task.

We also asked participants to report confidence in their predictions as a secondary measure of anticipation accuracy (see Jackson et al. 2009; Jackson et al. 2006; Mulligan and Hodges 2013). We expected that confidence would mirror the pattern of results based on prediction accuracy, with experienced participants being more confident, particularly for “Self” versus “Other” video clips. If experienced participants show awareness of the potential interfering effects of the secondary tasks, particularly the force-production task, then confidence should decrease under these conditions relative to the control.

Methods

Participants

Twenty-four volunteer participants, between the ages of 19 and 60 years, with normal or corrected vision, took part in the study. All participants were self-report right-handed. Half of the participants self-reported that they had never had any experience throwing darts. These were termed the Non-Experienced group (n = 12 males) who consisted of University students. The other half reported significant experience at dart playing (4-26 years experience; *M* = 11.6 yr, *SD* = 6.9) and hence these were termed the Experienced group (n=12; n=4 females). Participants in the Experienced group were recruited from adverts placed around the University, local darts' leagues and via snowball sampling. A three-dart pre-test performed on the first day (aiming for the centre of the dart board and based on mean radial error), provided an approximate measure of skill. Due to an error in video recording, it was only possible to calculate radial error for *n* =10 in the Experienced group (*n* =12 in the non-Experienced). The Experienced group was significantly more accurate (*M* = 7.09 cm, *SD* = 3.43; 95% CI = 4.96 – 9.21 cm) than the Non-Experienced group (*M* = 13.15 cm, *SD* = 4.50; 95% CI = 10.61 – 15.70 cm), $t(20) = 3.50$, $p < .01$, $d = 1.53$.

All participants gave signed consent before testing and were blind to the hypotheses of the experiment. Ethics' protocols for human experiments were strictly followed, as laid out by the ethics' board of the University. Participants were paid $10 /hour.

Apparatus and stimuli

The task was modeled on an earlier dart throwing study designed to look at self-other perceptions (Knoblich and Flach 2001; see also Mulligan and Hodges 2013). Participants in the earlier experiment by Knoblich and Flach (2001) were proficient at recognising their own action from a side-on view, even though they had only received visual-motor experience from a first-person perspective. A standard dart board was used and height and distance regulations typically observed in the game of darts were adopted (i.e., the participant stood at a distance of 2.37 m from the dartboard, which was placed at a height of 1.73 m from the floor to the bulls-eye). The board was divided into 3 sections (top, middle and bottom), that were formed by two horizontal lines an equal distance from the top and bottom of the dart board and from each other. Participants were required to make predictive judgements concerning which of the 3 sections they thought the dart would land. Because the model was shown from the side view on the video stimuli, any estimate of the horizontal trajectory of the dart would not be practical from such an angle, and was therefore not included as part of the prediction task. Further, all stimuli used were harvested from throws by the model that landed at the vertical and horizontal centre of each section (see below).

Video clips for the prediction test were created using a Cannon HV20 camera (30 fps, 33ms/frame) showing a moderately skilled actor, after significant practice with the task, throwing a dart at the centre of each of three sections of a dartboard (see Figure 1). The actor was filmed from a side-on perspective from a distance of 3 metres. Three video clips were created for each of the top, middle, and bottom sections, for a total of 9 clips. The actor threw to each section until 9 clips landed in what was subjectively determined to be the centre of each section (both vertically and horizontally). This requirement to aim for the centre of the section reduced any potential kinematic variability associated with differences in horizontal and vertical error within a section. Each of these clips was further edited into 4 temporal lengths termed occlusion points (OP), each length being one frame (33 ms) longer than the previous. Four OPs for 3 clips at 3 different targets resulted in 36 total stimuli. Each clip showed the initial part of the dart throw (i.e., raising the throwing arm) which lasted approximately 2 s (M = 1930 ms, SD = 20). The first OP showed this initial 'setup' phase, plus one more frame (+33 ms, the start of the forward propulsion phase). Each subsequent OP consisted of an additional frame. The dart left the hand at OP4. The last frame of the video remained on the screen for 2 s before a decision was required. Video editing was performed using Sony Vegas and Adobe Premiere video editing software. Clips were shown via a projector on a full length screen (Cineplex Pro, IN, U.S.A), providing an approximate life-size image (~180 cm), as seen by participants from a distance of 4 metres. E-prime 2.0 software was used to present the stimuli and for entering responses (Psychology Software Tools, Inc., PA, USA).

Other than for the control condition, participants performed a secondary task while viewing the dart clips. For the secondary motor task, a force sensor load cell (JR3 Inc, Woodland, CA) was attached to a tall iron post and adjusted to the participant's hand position when they stood adjacent to the post with their hands at their sides. This position enabled the participant to push against the force sensor with the edge of their hand in a fist shape, keeping the rest of their arm and body relatively immobile. The force sensor was connected to a laptop, running Labview software, which allowed real-time monitoring and data collection. Audio files used for the tone monitoring secondary task were created using Audacity Inc. software, v2.0.2 (Boston, MA). These were 5 s files that consisted of a 250 Hz control tone with a randomly interspersed high tone of 440 Hz, played for 100 ms on a third of the trials. We used three different temporal orders, allowing the duration of the control tone to vary from 3 s – 4.8 s before interspersing the 440 Hz tone.

Conditions and Procedures

The study took place over two days (~ one week apart). On the first day, following the 3-dart motor pre-test, participants made predictive decisions about the action-outcomes of the model ("Other"), whereas on the second day decisions were made about their own edited actions

(“Self”). The reason for this ordering was primarily a logistical issue associated with the need to first film participants (and edit videos) in order to make the “Self” stimuli. To avoid an unnecessary third session, we filmed after testing on the first day, immediately after completing the “Other” tests. Because no feedback was provided to participants during the prediction tasks, we did not expect improvements associated with repeated testing. This was confirmed when we compared the prediction accuracy data from the first and second half of testing within each session in two repeated-measures ANOVAs, for both ‘Self’ and ‘Other’ stimuli. There were no significant differences in performance between the first and second block of trials for either ‘Self’, $F(1,22) = 1.16$, $p = .29$, $\eta_p^2 = .05$ or ‘Other’ stimuli, $F<1$, nor any Group x Block interactions for either ‘Self’, $F<1$, or ‘Other’ stimuli, $F(1, 22) = 1.97$, $p = .18$, $\eta_p^2 = .08$.

The prediction test was completed under 4 conditions: no secondary task, force-production task, tone-monitoring task, and mimicry task. The mimicry condition was always completed last in order to avoid potential carry over effects associated with instructions to explicitly copy. Any possible issues associated with running the mimic condition last should be allayed by the results above, showing no practice order effects within the other 3 conditions. All other conditions were counterbalanced for order. For each test condition, 36 video clips were presented in a random order. Via a screen prompt after the video, participants were asked where they thought the dart would have landed (top, middle, bottom) and their confidence in their answer, ranging from 0 - 100 % confident based on a 5 point scale in 25 % increments. Participants stood facing the screen for all conditions, but a 3-5 min seated rest was given between conditions. Participants were presented with 4 practice trials (without prediction accuracy feedback) at the beginning of each condition.

Force-production task

Participants were required to stand with their arms by their side adjacent and to the left of the iron post, facing the projection screen at ~45-60° angle. They could therefore see the action unfold in approximately the same plane as the actor, without having to turn their head (see Figure 2). They were then told to make a fist and to press against the force gauge with the elbow extended and their shoulder and wrist in a neutral position. This procedure was designed to be incompatible with the motion involved in throwing a dart, requiring activation of the same muscle groups involved in the throw, but in a different pattern (i.e., isometric versus dynamic contractions) and for a different function (e.g., the arm muscles are stabilizing and the elevator muscles of the shoulder are providing motive force whereas in the dart throw, shoulder muscles are stabilizing and the triceps are providing motive force).

Participants first completed a maximal force test to calculate a 15 % maximum force for the force-production task. Fifteen percent was considered a low force threshold (based on pilot testing in the control experiment, see below), that was relatively easy to maintain for the duration of a trial and throughout the testing condition. Participants pressed as hard as possible against the force sensor with their dominant right hand for 4 s, three times. From the average of these readings, 15 % average force was calculated. Participants next practised producing 15 % of their maximum force. The experimenter was able to monitor force output relative to the criterion in real time in all trials. During the practice trials only, participants were given feedback when pressing against the load cell during the trial. This was provided intermittently such that they were told when they had reached the criterion and when they varied from the force by more than ~1 Newton. During testing, a screen appeared before each trial prompting the experimenter to press a key to continue testing. The participant also saw this screen and they were instructed to begin pressing against the load cell when this prompt screen appeared (~1s before the video began). They were instructed to maintain the force until the video clip had finished and the video-prompted questions appeared. This was to make sure that they maintained force through the entire clip, but stopped pressing before they had to respond with their answer. During experimental trials, force was monitored by the experimenter and if the participant veered from the required force on a trial, feedback was provided at the end of the trial.

Tone monitoring task

A control tone was presented on every trial, and the participant's task was to determine whether there had been a change in the tone. On 66 % of the trials, participants heard a continuous 250 Hz control tone for a 5s duration. The tone started when the experimenter initiated the trial and ended when the question screen appeared asking the participant about dart location. On the remaining trials, which were administered randomly throughout the condition, a 440 Hz tone was interspersed with the control tone for 100 ms. The tone started to play when the video clip started and stopped when the questions appeared on the screen. An additional question appeared, after the confidence question, asking participants if the tone had changed frequency during the trial.

Mimicry task

Participants were asked to hold a dart as if they were going to throw it. They were instructed to use the dart to 'mimic' the dart throw on the screen in a way that would help them "understand what was happening on the screen". They were advised that, during each trial, they could also view the real dartboard on the wall and could imagine themselves throwing the dart. Participants were not required to try to precisely match the temporal or kinematic aspects of the model's action.

At the end of the first day all participants were videotaped throwing darts so that video clips of their own action could serve as stimuli for the “Self” prediction tests on Day 2. Participants aimed for the centre of each section until three successful throws were obtained for each section (top/middle/bottom). The videos of these throws were subsequently edited, creating twelve clips for each section of the board, corresponding to the 4 occlusion points for each throw (36 clips in total). Participants returned approximately one week later and performed the prediction tasks in the same order, this time viewing stimuli of their own action.

Control experiment using visuospatial rotations

To ensure that the attentional demands of the force-production and tone-monitoring tasks were low and approximately matched, we first compared 12 different participants (9 male), all right-handed, on a visuospatial rotation task. This task was chosen because it required participants to make visual-spatial decisions and to make a decision based on a 3 choice protocol (thereby matching aspects of the main dart-throwing task). Participants viewed a single un-rotated pattern on a screen (made up of intersecting horizontal and vertical bars of different widths), with 3 rotated patterns shown directly below (see Cooper and Podgorny 1976; Shepard and Cooper 1982 for similar tasks). Only one of these patterns was the same as the single, un-rotated pattern. Participants were instructed to match the single pattern with the correctly matched rotated pattern. These decisions were made under either single-task, tone-monitoring or force-production conditions (as detailed above). There were 108 trials in total. With respect to accuracy, there were no significant differences across conditions (Force = 67.59%, *SD* =14.62; Tone = 65.97%, *SD* = 10.47; Control = 62.96%, *SD* = 15.04, F<1), confirming the low attentional requirements of these tasks and a lack of difference between the Force and Tone monitoring conditions.

Data analysis

Prediction accuracy and Confidence

We calculated percentage accuracy scores for each of the four occlusion points (OP) and these were subjected to a 2 Group (Non-Experienced, Experienced) x 4 Condition (Control, Tone, Force, Mimic) x 2 Model (Other, Self) x 4 OP repeated measures (RM) ANOVA. Condition, Model and OP were RM factors. The same analysis was conducted on the % confidence scores. Partial eta squared (η_p^2) values are reported as measures of effect size, and Tukey's HSD post hoc tests were used to compare differences involving more than 2 means ($p<.05$). Where violations to sphericity were encountered, Greenhouse-Geisser corrections were applied.

Secondary task accuracy

Median force, for both the "Other" and "Self" conditions, was calculated as a measure of secondary task accuracy. Median values were chosen due to the fact that data was continually tracked during this condition, which would involve ramping up and ramping down between trials. The median values were compared to the required values (based on 15 % of maximum force). We also ran correlations on the % force output and prediction accuracy for the "Other" and "Self" conditions for the Non-Experienced and Experienced participants to determine any potential trade-offs. For the tone-monitoring secondary task we summed any trials that were identified incorrectly (either tone miss or misidentification of a tone change). This was repeated for "Other" and "Self" conditions and any errors were reported as a percentage of the total number of trials. Correlations were also ran on these data and prediction accuracy.

Results

Action prediction accuracy

Percentage accuracy data are shown in Figure 3a (Other) and b (Self) as a function of condition and skill group. As predicted, Experienced participants were more accurate than the Non-Experienced participants, $F(1,22) = 14.87$, $p = .001$, $\eta_p^2 = .40$. There was a difference across conditions, $F(3,66) = 5.71$, $p = .002$, $\eta_p^2 = .21$, due to a significant decrease in accuracy for the force-production task compared to the other conditions. The condition effect was due primarily to the Experienced performers, as supported by a Group x Condition interaction, $F(3,66) = 7.03$, $p < .001$, $\eta_p^2 = .24$. Post hoc comparisons confirmed that only the Experienced group performed worse in the force-production task in comparison to the other three conditions. The Experienced group also performed significantly more accurately than the Non-Experienced group under all conditions except the force-production task, where their accuracy did not differ from the Non-Experienced group.

Although participants were less accurate when viewing stimuli of the "Other" model versus "Self", $F(1,22) = 5.06$, $p = .035$, $\eta_p^2 = .19$, there were no significant interactions involving Group and Model-type (F values between .03 and 1.45). Prediction accuracy for the 4 test conditions did, however, depend on Model-type, $F(3,66) = 4.00$, $p = .011$, $\eta_p^2 = .15$. For "Self" stimuli, accuracy during the force task was significantly impaired relative to the other three conditions, which did not differ from each other. No differences were seen for the "Other" condition. Participants were more accurate when viewing themselves, compared to the model, under all conditions except the force-production task.

To determine when differences emerged while watching the action, we also looked at the effects of Occlusion Point (OP). There were differences in accuracy as a function of OP, $F(3,66) = 14.76$, $p < .001$, $\eta_p^2 = .40$, as well as a Group x OP interaction, $F(3,66) = 3.16$, $p = .030$, $\eta_p^2 = .13$. As would be expected, accuracy significantly increased from OP1 ($M = 48.67\%$, $SD = 7.96$)

to OP2 (*M* = 53.41% , *SD* = 7.65) and also from OP2 to OP3 (*M* = 57.29% , *SD* = 7.42). The interaction was mostly due to the lack of any change in accuracy for the Non-Experienced group from OP2-4 (OP2 = 51.39%, OP3 = 51.85%, OP4 = 54.28%) in comparison to OP1 (41.90%), whereas the Experienced group showed improvements for OPs 3 (62.73%) and 4 (62.38%) in comparison to OPs1 (55.44%) and 2 (55.54%).

Confidence

Confidence data are shown in Figures 4a (Other) and b (Self) as a function of occlusion point. Despite a trend for higher confidence ratings from the Experienced (M = 68.35%, SD = 11.33) versus Non-Experienced (M = 61.55%, SD = 11.33) groups, this difference was not statistically significant, *F*(1,22) = 1.91, *p* = .18, η_p^2 = .08. Similarly, although there was a trend for "Self" ratings to be higher than "Other" ratings, these too were not statistically different, *F*(1,22) = 3.31, *p* = .083, η_p^2 = .13. Confidence differed as a function of condition, *F*(3,66) = 10.29, *p* <.001, η_p^2 = .32, with confidence significantly higher under the Mimicry condition (*M* = 68.04%; *SD* = 8.19) compared to the other three conditions (control, *M* = 63.43%, *SD* = 8.35; tone, *M* = 64.66%, *SD* = 8.21; force, *M* = 63.67%, *SD* = 8.16), which were not different from each other. However, there were no Group or Model-type interactions with Condition. Confidence generally increased across OPs as more information became available, *F*(1.3,28.5) = 74.93, *p* <.001, η_p^2 = .77, such that confidence significantly increased at each occlusion point (*p*s < .001, see Figure 4). There was also a Group x OP interaction, *F*(3,66) = 3.12, *p* =.032, η_p^2 = .12. The Experienced and Non-Experienced participants were significantly different from each other at all OPs, except OP4, where confidence was above 70% for both groups.

Secondary task accuracy

With respect to the force (motor) task, participants were required to maintain 15 % of their max force during the trial. The Non-Experienced participants achieved a mean of 14.34 % (*SD* = 2.64) and 16.13% (*SD* = 3.46) for the “Other” and “Self” conditions respectively. Experienced participants achieved a mean of 17.04 % (*SD* = 2.46) for the “Other” condition and 14.69 % (*SD* = 1.68) for the “Self” condition. Comparing statistically across the force data for the 2 groups and 2 (Other and Self) model-type conditions, there were no main effects of group or model-type (Fs<1). However, there was a significant interaction, $F(1,22) = 10.19$, $p<.01$, $\eta_p^2 = .32$. The Experienced participants exerted more force (than required) in the “Other” condition compared to the “Self” (wherein the latter they were more accurate). The Non-Experienced group showed the reverse (i.e., more force was exerted in the “Self” condition versus the “Other”). We also ran correlations between prediction accuracy and % force values for the “Self” and “Other” conditions, given the difficulty in interpreting the % force values. Importantly, these yielded low and non-statistically significant correlations, speaking against any force-for-accuracy trade-offs (Experienced: Other, $r = .0003$; Self, $r = -.16$; Non-Experienced: Other, $r = .17$, Self, $r = .15$).

For the tone monitoring task errors overall were low (<3% of trials). The Non-Experienced group made more errors (*M* = 3.94 %, *SD* = 4.66) than the Experienced group (*M* = 2.78 %, *SD* = 3.35) on the “Other” condition. For the “Self” condition there were fewer errors generally (Non-Experienced, *M* = 2.78%, *SD* = 3.35; Experienced, *M* = 2.55%, *SD* = 4.18). An ANOVA conducted on the error data did not yield any statistically significant group-related effects (all Fs<1). As with the force data, correlations were performed between prediction accuracy and % of tone monitoring errors for the “Self” and “Other” conditions. These were generally low and non-statistically significant particularly for the Experienced group (Other, $r = -.09$; Self, $r = -.10$) compared to the Non-Experienced group (Other, $r = -.43$, Self, $r = -.37$).

Discussion

We tested whether the predictive decisions of skilled performers would be directly impaired by a secondary motor task that would prevent or interfere with any potential involvement of the motor system in the prediction process. This manipulation was designed to test the proposal that a simulation-type mechanism is responsible for the prediction of action outcomes in humans, which involves a low-level activation of the motor system in the observer (Blakemore and Decety 2001; Gallese and Goldman 1998; Jeannerod 2001; Schubotz 2007; Wilson and Knoblich 2005). We also tested the specificity of this effect, through manipulation of the action required of the primary effector. Either a congruent (mimicry) or incongruent action (isometric force production) was required whilst watching dart throwing actions performed with the same arm. In support of this action-specific simulation account, while viewing action sequences performed by themselves and another person, skilled darts players were susceptible to motor interference from a force task that used the same effector in an incompatible configuration. This interference effect took the form of a significant reduction in accuracy predicting the landing position of a thrown dart. This effect was not seen in a Non-Experienced group. Indeed, the Experienced group showed superior prediction accuracy under all conditions except the force-production task, where their performance was reduced to the level of the Non-Experienced group.

These results provide evidence for active engagement of the human motor system during the prediction of action outcomes among experienced performers and support the idea that action and perception share a common representational medium (Hommel et al. 2001; Prinz 1997). It appears that motor experience plays a direct role in modulating the prediction of action outcomes, through mechanisms that work in real time to simulate the observed action to aid in prediction of its sensory consequences (Springer et al. 2013a, b).

The mimicry secondary task, which required a congruent action (actively copying the observed dart throw), did not interfere with, nor aid the decisions of the skilled or novice participants, although it was performed with the highest degree of confidence. Previous studies involving the concurrent performance and observation of action have likewise shown no interference effects as a result of performing actions congruent to observed stimuli (e.g., Bouquet et al. 2007; Kilner et al. 2003). The high confidence scores suggest that participants perceived this congruent action as helpful to their decision process, although this did not translate into improved prediction accuracy. Because this condition was always performed last, we questioned if the increased confidence might be a practice effect. However, correct feedback was never provided to participants during testing (and hence there would be no error signal on which to base a change in confidence), such that we have no reason to think that the high(er) confidence levels in the mimicry task were a result of practice. Moreover, when we compared statistically across the other three conditions, there was no evidence of an order effect with respect to confidence ratings ($F < 1$).

According to common-coding principles, individuals may utilize the same motor representations used in performing an action for predicting the outcome of the same action observed in someone else (Hommel et al. 2001; Prinz 1997). This is thought to take place internally via motor simulation processes. However, the requirement to *internally* simulate an observed action may not be necessary while executing a congruent action (i.e. our mimic condition). As such, performing a concurrent action could provide the same real-time representations needed to predict the outcome of the observed action, eliminating the need for an additional internal simulation process (Springer et al. 2011). This may explain the lack of interference for the Experienced participants when they performed the mimic condition. Conversely, for the incongruent condition (i.e. the force condition), because the motor representations used for initiating the (incongruent) action are different from those of the action being observed, these incongruent motor representations are not used (or available) to predict the outcome of the observed action. Instead, internal simulation processes are invoked in this case, but these motor representations are then partially interfered with by the motor representations from the (incongruent) executed (force) action (Springer et al. 2011; Springer et al. 2013).

Several lines of evidence converge in this study to support the suggestion that the predictions of the skilled participants were based on a motor simulation of the dart-throwing action, and that interference from the force production task was due to action-specific motor engagement and not alternative mechanisms (such as increased attention or visual-spatial processing). Participants generally made more accurate predictions when viewing “Self” stimuli versus “Other” stimuli and the interference effects observed for the force production task were more pronounced for the “Self” condition. These results are congruent with the hypothesis that self-stimuli are more likely to promote action simulation than observation of a stranger’s actions (Knoblich and Prinz 2001), which has shown to be true even when participants are unaware that they are watching themselves (Bischoff et al. 2012). There is also evidence that predictions made on the basis of “Self” actions (e.g. Bischoff et al. 2012), lead to increased brain activation in regions of the medial Frontal Cortex, associated with implicit self-processing, as well as areas of the Inferior Parietal Lobe, thought to involve internal models and the processing of self-other kinematics (Lorey et al. 2009; Pilgramm et al. 2009; Ruby and Decety, 2003). The fact that explicit awareness of one's own actions was not needed for simulation to occur in these prior studies, and we did see evidence of simulation with awareness, suggests that awareness is not likely to be a moderator of this process.

Both the force task and the tone task required low-level monitoring of a secondary stimulus during action observation and hence were approximately matched for attentional demands. This was confirmed by: i) a lack of difference in prediction accuracy between these tasks for the Non-Experienced group, even though this group's performance was above chance, and hence there was room for deterioration, ii) a lack of effect associated with these secondary tasks in the control experiment involving a 3 choice decision on a visual-spatial rotation task (akin to the decisions required in the dart prediction task), iii) no detriments in prediction accuracy associated with the secondary tone monitoring task in the main experiment, showing that attention demands for the Experienced participants in the experimental task were not higher than for Non-Experienced and, iv) the mimic task did not interfere with prediction accuracy, even though it was similar in execution (right handed forward motion) to the force-production task. This latter effect associated with the mimic task, further points to an action-specific role of this interference effect, and by extension, of the simulation process.

In the sport expertise literature, considerable emphasis has been placed on the importance of acquiring a repertoire of visual experiences to account for the expert advantage in making fast and accurate predictive decisions. Although the motor system was thought to moderate the effects of visually stored memories (i.e., altering how they were encoded and retrieved), until quite recently, this system was not thought to impact directly on the decision process. With the demonstration that muscles of the arm involved in basketball shooting were moderated when action decisions were required about the fate of a basketball free-throw shot (Aglioti et al. 2008), researchers began considering a more direct role for the motor system in predicting action outcomes. Neuro-physiological changes in motor system activity during action prediction have been demonstrated, but it has not been clear if this activity was directly involved in generating predictions or was a consequence of action observation (Aglioti et al. 2008) or action response (Tomeo et al. 2012). Here we show that the requirements to perform an action-incongruent motor task to that being observed, impairs action prediction, and that this interference is only seen among individuals with acquired motor experience.

In summary, these results lead us to conclude that predicting action outcomes from a video display of another person leads to a motor-based simulation of the observed action in the observer. Although we are unable to say whether motor system activation is essential to accurate prediction across contexts, we have strong evidence that interference with the effector and muscles involved in a discrete and rather simple motor action (involving only one effector) significantly impairs prediction accuracy amongst performers with considerable experience in the observed action. Testing the role of the motor system in more complex actions using this type of methodology is potentially more challenging, due to the difficulty in isolating effector-specific roles. For example, a tennis serve involves movement of the whole body, and there is evidence that predictive decisions are based on various features of the action as it unfolds, such as the hips, shoulders and finally arm and racket position (e.g., Cañal-Bruland et al. 2011; Ward et al. 2002). However, it may be possible to use such an economical and simple paradigm as this secondary task methodology to test how predictive decisions are made when occlusion points are tied to key information sources (such as the hip area ~240-180 ms before ball-racket contact).

In sports that require a response to anticipatory decisions, especially when this response might be opposite to the seen action, it is less clear how (or if) such an incongruent action would interfere with decisions. Perhaps a mechanism exists to inhibit such interference in these types of interactive scenarios. Alternatively, rather than invoking only a motor simulation of the observed action, decisions may, under certain circumstances, come about via a more visual-based process. In line with this notion, it has been suggested that both visual- and motor-based processes are utilized by 'experts' when anticipating the outcomes of observed actions (Tomeo et al. 2012; Urgesi et al. 2012; see also Springer et al., 2013a,b). Accordingly, perceptual experience is said to build internal models that define the motion of objects in the environment, creating visually-based predictive representations of the observed action (Hubbard 2005; Motes et al. 2008; Zago and Lacquaniti 2005). In contrast, motor experience develops predictive internal models, based on acquired motor commands that are thought to be simulated during the observation of similar action sequences (Flach et al. 2004; Ramnani and Miall 2004). The fact that the Non-Experienced group performed at ~50 % accuracy, rather than closer to 33% (chance), suggests that their predictions might have been based on these visual experiences with moving objects. This is underscored by the fact that the secondary motor task failed to degrade performance for the Non-Experienced group. Similarly, motor interference reduced the skilled performers' accuracy to that of the novices (~50 %) rather than to chance levels (33 %). Although there may be reason to think that the more experienced performers should still outperform the novices who have no or little visual experience with darts specifically (cf., Aglioti et al., 2008), it is likely that playing darts does not promote any intentional, visually-driven predictive strategies (based on the association of visual cues to responses). In contrast to sports like basketball and volleyball, in darts, there is no advantage in intentionally learning how to predict where a dart will land. However, it is also possible that the motor incongruent secondary task interfered with the processing of any potentially helpful visual cues acquired through dart's experience.

It has also been suggested that the motor system may be able to re-purpose internal models of particular biological motion to make predictions about other similarly-structured motion (e.g., Grosjean et al. 2009). Indeed, it has been demonstrated that areas within the ventral Pre-motor Cortex, previously thought to only be activated via established motor representations, are active when predicting actions unrelated to one's motor repertoire (Schubotz and von Cramon 2003, 2004; Wolfensteller, Schubotz and von Crammon 2007; for a review see: Zentgraf et al. 2011). Therefore, visual-motor experience with throwing objects in general might have aided prediction. As a result, in addition to producing noisier, less-accurate predictions, these more-generic representations may also have been less susceptible to effector-specific interference effects.

While previous researchers have shown interference effects from motor secondary tasks during action recognition and discrimination (Paulus et al. 2009; Witt and Proffitt 2008; Witt et al. 2010), our results show, for the first time, that the *prediction* of future action outcomes is also subject to interference from a secondary task that either inhibits, or interferes with, in an action-specific way, motor areas that would be implicated in the observed action. As such, these data provide further insights into the role, and specificity, of the motor system in predicting the sensory consequences of others' actions, and the kinds of simulative mechanisms that may facilitate such predictions in real time.

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Figure Headings

Fig. 1 Trial presentation: All video sequences included an initial dart preparation /set-up phase which lasted ~ 2 s. Depending on the condition the participant would then see an additional 1-4 frames (33 ms – 132 ms), corresponding to the 4 temporal occlusion points. The final frame would remain on the screen for 2 s after which point 2 prompt screens would be presented, requesting a predictive decision from the participant (top, middle or bottom) as well as a rating of confidence.

Fig. 2 A view of the task setup for the force-production task. Participants were required to press on the force gauge with their right hand in a fist position while viewing the video stimuli in approximately the same plane as the observed action. Although not shown in the picture, participants could also see the dartboard on the wall to the far right of this picture.

Fig. 3 Percentage accuracy for Other-judgments (A) and Self-judgments (B) as a function of group and condition. Error-bars show between-subject SDs

Fig. 4 Percentage confidence for Other-judgments (A) and Self-judgments (B) as a function of group and occlusion point. Error-bars show between-subject SDs

Figure 1

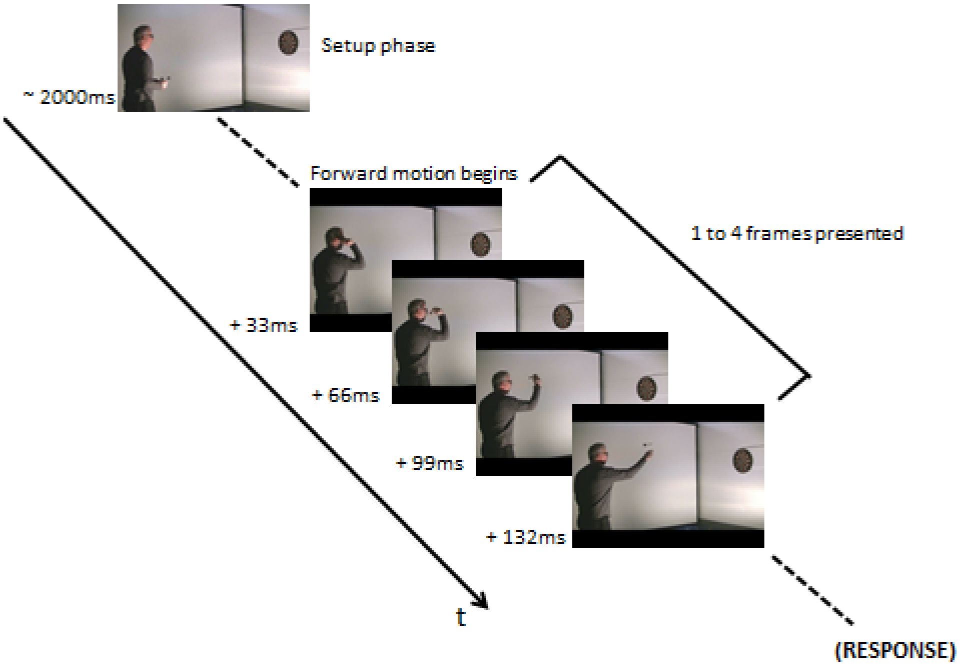

Setup phase
~ 2000ms
Forward motion begins
1 to 4 frames presented
+ 33ms
+ 66ms
+ 99ms
+ 132ms
t
(RESPONSE)

Figure 2

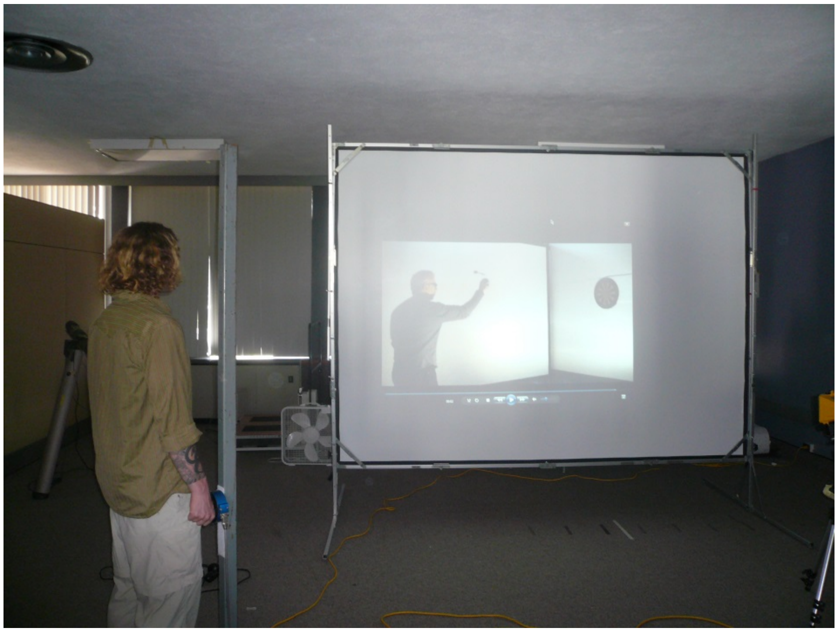


Figure 3

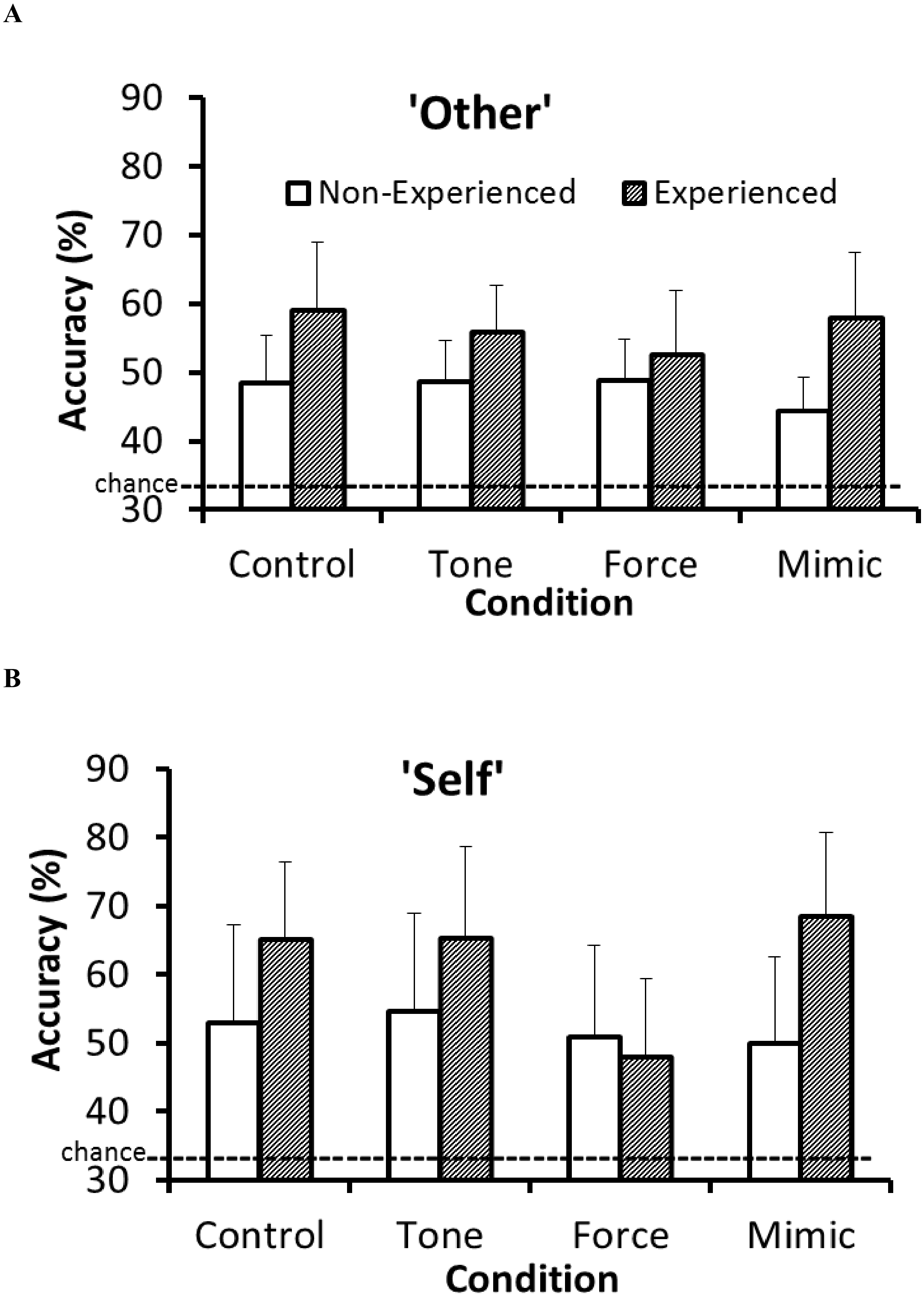
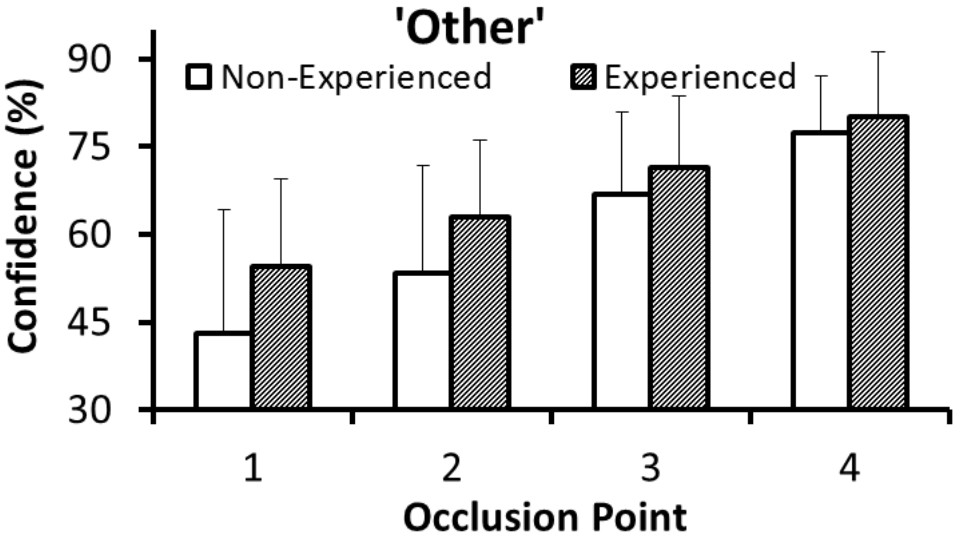
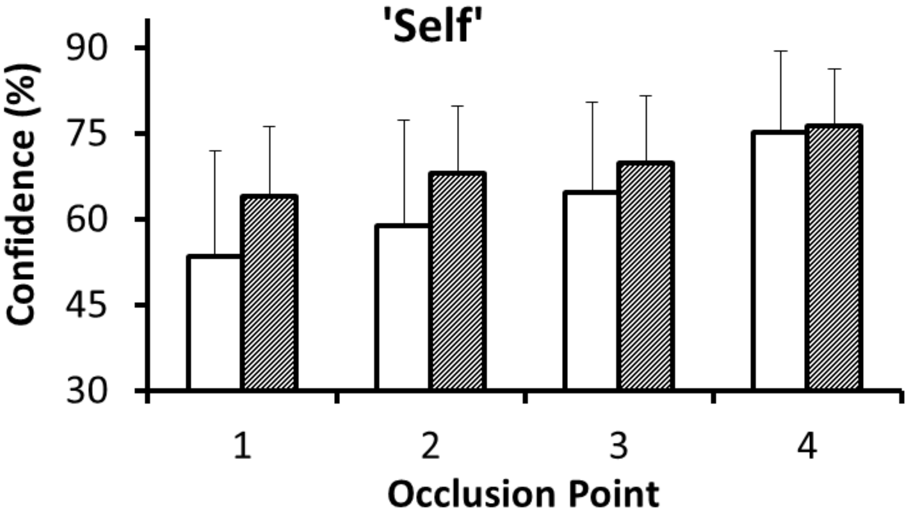

A
'Other'
☐ Non-Experienced
▨ Experienced
Accuracy (%)
90
80
70
60
50
40
30
chance
Control
Tone
Force
Mimic
Condition
B
'Self'
Accuracy (%)
90
80
70
60
50
40
30
chance
Control
Tone
Force
Mimic
Condition

Figure 4

A


'Other'
☐ Non-Experienced
▨ Experienced
Confidence (%)
90
75
60
45
30
1
2
3
4
Occlusion Point

B


'Self'
Confidence (%)
90
75
60
45
30
1
2
3
4
Occlusion Point