Anticipation From Biological Motion: The Goalkeeper Problem

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CITATION
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People can often anticipate the outcome of another person’s actions based on visual information available in the movements of the other person’s body. We investigated this problem by studying how goalkeepers anticipate the direction of a penalty kick in soccer. The specific aim was to determine whether the information used to anticipate kick direction is best characterized as local to a particular body segment or distributed across multiple segments. In Experiment 1, we recorded the movements of soccer players as they kicked balls into a net. Using a novel method for analyzing motion capture data, we identified sources of local and distributed information that were reliable indicators of kick direction. In Experiments 2 and 3, subjects were presented with animations of kickers’ movements prior to foot-to-ball contact and instructed to judge kick direction. Judgments were consistent with the use of distributed information, with a possible small contribution of local information.

Keywords: biological motion, anticipation, prediction, motion analysis

In 1973, Gunnar Johansson (1973) pioneered a method for isolating the motion of a human from structural information. Actors dressed in black outfits with reflective markers affixed to their joints were filmed while walking in a darkened environment, such that only the joint markers were visible. Although static frames of such point-light (PL) stimuli may be interpreted by observers as a random constellation of dots, Johansson found that moving PL stimuli created a compelling impression of a walking human, even when such stimuli were viewed for a brief period.

Human sensitivity to biological motion has been thoroughly investigated in the decades since Johansson’s discovery. The ability to identify biological motion is remarkably robust to the introduction of various forms of masking noise (Bertenthal & Pinto, 1994; Cutting, Moore, & Morrison, 1988; Ikeda, Blake, & Wattanabe, 2005; Mather, Radford, & West, 1992; Neri, Morrone, & Burr, 1998), leading some to suggest that it provides a means for the rapid detection of potential predators in naturally cluttered environments (Johnson, 2006; Troje & Westhoff, 2006). Because humans are also adept at perceiving more complex qualities such as the identity of the actor (Loula, Prasad, Harber, & Shiffrar, 2005; Troje, Westhoff, & Lavrov, 2005), the activity in which the actor is engaged (Dittrich, 1993; Mass, Johansson, Janson, & Runeson, 1971; Norman, Payton, Long, & Hawkes, 2004), and the actor’s emotional state (Clarke, Ward, & Jones, 1999; Dittrich, Troscianko, Lea, & Morgan, 1996; Walk & Homan, 1984), it has also been suggested that biological motion perception plays an important role in social interaction (Blake, Turner, Smoski, Pozdol, & Stone, 2003; Chawarska, Klin, & Volkmar, 2008; Klin, Lin, Gorrindo, Ramsay, & Jones, 2009). Based on findings that observers can accurately perceive the magnitude of forces exerted by an actor (Bingham, 1993; Runeson & Frykholm, 1983; Shim, Carlton, & Kim, 2004), even if the person is deliberately attempting to deceive the observer (Runeson & Frykholm, 1983), others have suggested biological motion perception plays a role in action understanding.

This study focuses on one of the many possible roles of biological motion perception—the ability to anticipate the actions of others. Anticipation from biological motion is perhaps most commonly observed on the sports field, where athletes often try to gain a competitive edge by predicting their opponent’s next move (Yarrow, Brown, & Krakauer, 2009). Studies of athletes demonstrate the ability to anticipate the direction of a penalty kick in soccer (Savelsbergh, Van der Kamp, Williams, & Ward, 2005; Savelsbergh, Williams, Van der Kamp, & Ward, 2002; Williams & Burwitz, 1993), a serve in tennis (Farrow & Abernethy, 2003; Jackson & Mogan, 2007; Shim, Carlton, Chow, & Chae, 2005; Shim, Carlton, & Kwon, 2006; Ward, Williams, & Bennett, 2002), a bowled ball in cricket (Müller, Abernethy, & Farrow, 2006), a stroke in badminton (Abernethy & Zawi, 2007) or squash (Abernethy, 1990a, 1990b), and a pitch in baseball (Ranganathan & Carlton, 2007).

The ability to anticipate an opponent’s next move might benefit from knowledge of the opponent’s preferences (Chiappori, Levitt, & Groseclose, 2002) and the game situation (Gray, 2002). However, such factors are not always good predictors of the opponent’s next move. Furthermore, although there are many sources of visual information about the direction, speed, and time-to-contact of a moving ball (Regan, 1997), such information is only available after the ball is moving, by which time it is often too late to execute an appropriate response. In a soccer penalty kick situation, for example, the ball reaches the mouth of the goal about 600 ms after it is kicked, which is less time than it takes to initiate and complete the sort of whole body movement necessary to block a well-placed shot (Franks & Harvey, 1997). This means that goalkeepers must...
rely on visual information from the movement of the kicker’s body before the ball is kicked. Indeed, goalkeepers who are shown films of penalty kicks can anticipate the area of the goal in which the ball will arrive at levels above chance before foot-to-ball contact (Savelsbergh et al., 2005; Savelsbergh et al., 2002; Williams & Burwitz, 1993). In Williams and Burwitz (1993), the visual scene was occluded at 120 ms before contact, 40 ms before contact, at contact, or 40 ms after contact. Although experts were more accurate than novices when reporting the corner to which the ball would travel in all conditions, both groups were consistently performed above chance, and performed at approximately 80% accuracy when the clip ended at foot-to-ball contact. The videos used in Savelsbergh et al. (2002) included a short duration of the ball’s flight, however, both experts and novices began moving a joystick to provide a response well before foot-to-ball contact. Experts correctly anticipated the side of the goal at which the kick would arrive with 83.8% accuracy, with a mean response initiation time of 296 ms before contact. In contrast, novices initiated their response 480 ms before contact and anticipated side with 71.4% accuracy. In Savelsbergh et al. (2005), experts were separated into two subgroups—one relatively skilled at anticipating kick direction and one not. Successful experts initiated their response 230 ms before contact and anticipated side with 93.3% accuracy, while relatively poorly performing experts initiated their response 359 ms prior to contact with 68.9% accuracy. Interestingly, their performance was no better than those of the novice group. Novices initiated their responses 479 ms before contact and correctly anticipated side on 71.4% of trials.

Some research suggests that experts’ advantage may be tied to motor familiarity with the observed action. In one study, subjects were instructed to watch videos of basketball players shooting free throws, and asked to judge whether each shot was successful (Aglioti, Cesari, Romani, & Urgesi, 2008). Expert basketball players who had extensive experience shooting free throws made more accurate judgments than subjects who spent a lot of time watching basketball but had much less experience shooting basketballs. Because the experts and watchers shared a roughly equivalent amount of experience watching basketball, the experts’ advantage was attributed to their extensive experience taking basketball shots. Consistent with this account, the experts’ advantage did not generalize to the anticipation of soccer kicks, an action for which the two groups had a roughly equivalent amount of motor experience.

Information in Biological Motion for Anticipation

The ability to anticipate the outcome of another person’s action is impressive given the complex structure of the human body, its many possible configurations and movements, and the variation across individuals in body type and movement style. What visual information exists in the movement of another person’s body that allows observers to accurately anticipate the outcome of an action?

Local Information

In an attempt to characterize the reliability of various sources of information, Franks and Harvey (1997) conducted a film analysis of 132 penalty kicks taken in the 1982–1994 World Cup. They found that kick direction is accurately foreshadowed by the point of ball contact and the orientation of the knee of the kicking leg. However, these cues are only available in the latter portion of the kick, and do not leave the keeper enough time to react. The only source of information that was found to be both reliable (above 80%) and that provided enough time for the keeper to react was the angle of the nonkicking foot during the kick. Among the cues found to be unreliable were the kickers’ starting position, the angle of approach to the ball, and the forward or backward lean of the trunk.

Although these findings suggest that the angle of the nonkicking foot is the most reliable indicator of kick direction, self-reports suggest that expert goalkeepers do not consciously attend to the nonkicking foot, but rather to the angle of approach to the ball, the trunk position at contact, and the position of the kicking foot on contact (Kuhn, 1988). These findings are in agreement with the self-reports of expert goalkeepers collected by McMorris and colleagues (McMorris & Colenso, 1996, McMorris, Copeman, Corcoran, Saunders, & Potter, 1993). Similarly, Williams and Burwitz (1993) found that expert keepers believe the best information to be the arc of the kicking leg, the angle of the kicking foot, and the angle of the hips. Information concerning the height of the ball’s arrival point was reportedly most prevalent in the lean of the trunk.

More recently, researchers have adopted eye-tracking technology as a less subjective means of investigating the visual information underlying professional goalkeepers’ judgments of kick direction. When anticipating the outcome of video clips that end on foot-to-ball-contact, the high-performing professional goalkeepers, who blocked a relatively high percentage of penalty kicks within the Bundesliga (the most competitive German league) from 1963–1997, were found to spend a large proportion of time fixating on the ball and the kicker’s nonkicking leg. In contrast, the less successful of the expert goalkeepers were no better than novices, and shared with novices a tendency to fixate the kicker’s head early in the trial (Savelsbergh et al., 2005; Savelsbergh et al., 2002). In addition, novices spent more time fixating on the kicker’s trunk, arm, and hips. What is interesting is that both experts and novices spent a significant amount of time fixating on areas near to, but off of the foot and ball region, suggesting that motion information is likely also extracted through peripheral vision.

In summary, self-reports suggest that high-performing professional keepers believe the nonkicking foot to be the best indicator of kick direction. Furthermore, eye-tracking studies show that fixations of high-performing experts are consistent with this belief. However, because these fixations represent only a small portion of total fixation duration, and because motion information may be picked up in the periphery, one should be cautious about concluding that experts’ anticipatory judgments are based only on information in the nonkicking foot (Savelsbergh et al., 2005; Savelsbergh et al., 2002).

Distributed Information

The vast majority of studies on anticipation in sports seek to identify information that is localized to a specific part of the body. However, complex skills such as kicking a soccer ball involve coordinated patterns of movement that span the entire body, reflecting the formation of motor synergies involving multiple body segments (Bernstein, 1967). For example, generating a powerful
kick while maintaining stability requires the participation of the arms, legs, torso, and head (Shan & Westerhoff, 2005). Thus, the components of a kicking motion that are invariant across all kicks to the right (or left) may be distributed across the body rather than localized to a particular limb segment. Likewise, the information used to anticipate the outcome of another person’s action may be distributed rather than local.

To better illustrate the concept of distributed information, consider the hypothetical case of the deceptive kicker. If both kickers and goalkeepers believe that kick direction is forecasted by the orientation of the nonkicking foot, the kicker may try to deceive the goalkeeper by kicking the ball in the direction opposite that to which the nonkicking foot is pointed. However, such a deceptive movement may affect the stability of the kicker and therefore the strength or accuracy of the kick. To maintain stability, the kicker may compensate by altering the movement of another part of the body—perhaps his or her arms. Considered this way, the orientation of the nonkicking foot alone is not a reliable indicator of kick direction—it is only useful when considered in conjunction with information from the motion of the arms, as a single distributed source of information.

Principal component analysis (PCA) has emerged as a method to identify distributed patterns of movement coordination, or modes, in motion data (Daffertshofer, Lamoth, Meijer, & Beek, 2004; Huys et al., 2009; Huys, Smeeton, Hodges, Beek, & Williams, 2008; Troje, 2002). To best understand how to produce complex whole-body movements, it is best to first consider the effects of modulating a single mode returned by PCA. A single mode identified by PCA describes a weighted linear relationship between the positions of multiple joints or markers, and their movement along the three spatial dimensions. By changing an associated control signal at a constant rate, one can cause each marker to move along a linear trajectory and at a constant speed, both of which may be unique from those of other markers. For each marker, the amplitude of movement is proportional to the product of the control signal and the weightings for the marker’s movement along the x, y, and z directions that are defined by the mode. Increasing the same control signal by a greater rate would cause the same markers to move along the same trajectories, albeit at greater constant velocities. To produce curvilinear marker trajectories, one must modulate the control signals of several modes at once, bringing about complex changes in marker velocities along multiple dimensions at different times. In this manner, one may reproduce arbitrarily complex motions, such as a walking motion or a penalty kick in soccer.

Huys et al. (2008) used PCA to explore anticipation of a shot in tennis. PCA was applied to the motion capture data of professional tennis players taking cross-court and inside-out shots. Subjects were subsequently presented with these stimuli or artificial stimuli created using a subset of modes. Based on the observation that including or excluding information from specific modes affected subjects’ ability to anticipate kick direction, Huys et al. concluded that subjects are sensitive to the low-dimensional structures similar to the modes extracted using PCA. However, the possibility remains that subjects were making decisions on the basis of a local component of motion contained within a mode. In fact, previous studies have implicated motion local to the arm, racket, shoulder, hips, trunk, and legs in judgments about shots in various racquet sports (Abernethy, 1990a, 1990b; Abernethy & Russell, 1987; Williams, Ward, Knowles, & Smeeton, 2002). Using similar methods, two additional studies investigated the possibility that judgments were based on local rather than on distributed information. Huys et al. (2009) presented subjects with artificial PL stimuli in which information local to specific regions had been rendered ambiguous by averaging across cross-court and inside-out shots. Similarly, Williams, Huys, Cauhal-Bruland, and Hagemann (2009) traded the dynamics of local limb segments with those of a shot to the opposite direction. Both found performance degradations for experts when the manipulation occurred at any one of multiple regions, such as the arm and racket, trunk, or legs. Novices, however, were affected only when the arm and racket were perturbed. Based on the finding, the authors concluded that experts were able to use information from various parts of the players’ body, and thus were sensitive to distributed patterns of movement information.

In the present study, we investigated the reliability of various sources of information as indicators of the outcome of a penalty kick in soccer. Our aim was to provide a fair test of both local sources of information, such as the orientation of the nonkicking foot and sources of information distributed across the kicker’s body. In Experiment 1, we characterized the reliability of spatially local and spatially distributed sources of information as indicators of a kick’s outcome. Whereas Experiment 1 focused on the reliability of information, Experiment 2 focused on the information used by subjects as they anticipated kick outcome. Subjects were presented with stimuli depicting a PL penalty kicker approaching and kicking a ball. The stimulus ended on foot-to-ball contact, ensuring that judgments of kick direction were based only on information in the motion of the kicker during his approach to the ball. Subsequently, a classification procedure was used to measure information use—a measure of the ability for an information source to account for subject’s judgments of kick direction. Finally, in Experiment 3, trained subjects were presented with a randomly intermixed subset of artificial stimuli in which potential sources of local and distributed information were made unreliable. Degradation in performance on these artificial stimuli was interpreted as evidence that subjects relied on the information source that was made unreliable.

**Experiment 1**

Experiment 1 was designed to characterize the reliability of several potential sources of information about the direction of a penalty kick. To this end, a motion capture system was used to record penalty kicks to the right or the left side of a soccer goal from three college-level soccer players. Subsequently, the data were subjected to an analysis intended to characterize the reliability of multiple sources of movement information as indicators of kick direction. To be clear, Experiment 1 concerned only the reliability of movement information contained in the stimulus and did not involve psychophysical judgments. Each kick included a single approach step with the right foot, a planting of the left (nonkicking) foot, and a kick to a predetermined side of the soccer goal using the right foot. The data were temporally cropped to begin with the initiation of the first approach step and to end at foot-to-ball contact. The data were then spatially and temporally normalized to enable comparisons across kicks. Mathematical methods were used to measure the continuously changing state of
27 potential sources of information. The analysis included sources of local information, such as hip angle, and distributed information extracted using PCA. Finally, the reliability of each potential source of information was calculated at each frame of the kicking motion, producing a time-series representation of reliability over the course of the kicking motion.

**Method**

**Subjects.** Three male soccer players, ages 23, 25, and 25, volunteered to provide movement data. All kickers were previously experts at the college level, and all preferred to kick with their right foot.

**Procedure.** Each kicker’s movements were recorded using a 14-camera Vicon infrared motion-capture system at 240 Hz. Kickers wore tight-fitting black clothing to which 45 reflective motion-capture markers were affixed. Using Vicon IQ software (version 2.5), the 45 reflective marker locations were used to recover the x, y, and z locations of 18 locations on the kicker’s body throughout the kicking motions (see Figure 1). Although these locations lie primarily on the joints, locations also include those that are salient throughout the kicking motion (e.g., the head). Due to the limited size of the motion-capture volume, the speed of the ball in flight could not be recorded.

Regulation size 5 soccer balls were kicked into a 2.43-m wide canvas that was hanging at a distance of 3.66 m from the ball. This distance-to-width ratio was the same that is specified for a penalty kick situation by Fédération Internationale de Football Association regulation. Two target regions, each 2.13 m high and 0.91 m wide, were clearly outlined with black marker. The inside edges of the left and the right target regions were located 0.91 m from the vertical center of the canvas. The ground behind the ball was marked with an approach 45 degree from the hanging canvas. This line was used to designate the angle along which kickers were to approach the ball.

The kicker was instructed to practice several kicks prior to the start of the recording process. Subjects were told to kick the ball with force typical of a real-world penalty kick situation. This practice period was also used as an opportunity to settle on a comfortable distance from which to approach the ball. The starting location was marked by the experimenter and used throughout the session.

At the beginning of each trial, the kicker stood with each foot parallel to and equidistant from the designated approach path, with hands comfortably at his side and with his body oriented toward the placed ball. The experimenter informed the kicker of the side of the goal to which the ball should be kicked, initiated the motion capture, and gave a “go” command. During a kick, the kicker took a step toward the ball with the right foot, planted the left foot next to the ball, and then kicked the ball using the right foot. Once the ball was kicked, the experimenter replaced the ball in preparation for the next kick. Trials in which the kicked ball missed the target or in which the kicker clearly failed to conform to the constraints were repeated. A total of approximately 60 kicks were recorded for each kicker. Each session lasted approximately two hours.

**Data analysis: Normalization.** To reduce spatial differences in data due to differences in the kickers’ body sizes (188, 170, 175 cm), each kicker’s data were scaled to the mean height of the three kickers (177.7 cm). In addition, temporal normalization was necessary to ensure that across-kick analyses compared marker locations at the same stage of the kicking movement. Motion data were temporally cropped to begin at the initiation of the first step with the right foot and to end on foot-to-ball contact. Normalization occurred within three separate motion segments, separated by the start and end of the kick, and by the following temporal events within the kicking motion: the initiation of the second step by the left foot and the backward lift of the right foot prior to the forward kicking motion. Events were identified quantitatively, first by finding local minima in foot velocity, and then by identifying the first frame in which the foot exceeded a vertical velocity of 0.5 mm per frame.

One unavoidable consequence of temporal normalization is that marker velocity and acceleration patterns, which have previously been found to aid in the detection of PL walkers embedded in noise (Chang & Troje, 2009; Westhoff & Troje, 2007), are distorted. To minimize the temporal distortion caused by the normalization process, trials with the largest deviations from the average segment duration were excluded from further analysis until there were 42 trials per kicker. Future efforts might further reduce the temporal distortion by forcing kickers to adopt more rhythmically constrained movement patterns, perhaps through the use of an audible timing mechanism.

Prior to temporal normalization, the first segment of the kicking motion had a standard deviation of 85.4 ms from the mean duration of 469 ms. The second segment had a standard deviation of 136 ms from the mean duration of 317 ms, and the final segment had a standard deviation of 31.7 ms (7.2%) from the mean duration of 371 ms. Cubic-spline interpolation was used to normalize each trial to the global average of that segment’s duration. Rounding to the nearest frame produced segment durations of 470.83, 316.67, and 360.83 ms, and a total trial duration of 1,158.3 ms.

**Data analysis: Identification of local and distributed information.** Local information was measured in terms of the yaw and pitch angles of relevant body segments, where yaw represents...
the segment’s rotation about the vertical world axis, and pitch is the angle of declination of the relevant limb segment relative to the horizontal plane. The local sources of information were chosen on the basis of the published studies of the soccer penalty kick situation summarized on page 2 of the Introduction and included: the yaw and pitch between the midpoint of the soccer ball and the point of foot-to-ball contact (hereafter referred to as contact yaw and contact pitch), the orientation (i.e., yaw and pitch) of the upper portion of the kicking leg, the orientation of the kicking shank, the orientation of the kicking foot, the orientation of the nonkicking foot, and the orientation of the hips.

PCA was used to extract independent and distributed patterns of linearly related marker translation (e.g., modes). Prior to analysis, several steps were taken to ensure that movement information was not diluted by motion due to the kickers’ translation through the environment. First, the location of each marker was defined by its position relative to the marker located at the base of the kicker’s spine, producing 54 vectors \( \vec{q}(t) \) in which each column is the time series of a joint’s location along a single spatial dimension \( (N = 18 \text{ [joint locations]} \times 3 \text{ [spatial dimensions]} = 54 \text{ [time series]}) \). To facilitate the comparison of multiple kicks, we concatenated the \( \vec{q}(t) \) from all 126 kicks to form matrix \( \tilde{\vec{q}}(t) \) that retained the width of 54, but was extended to a length of 126 kicks \( (kicks) \times L \) (normalized trial length). Finally, data were transformed into \( z \) scores, ensuring that early modes were not biased to include markers at proximal body locations, which are associated with greater marker translation.

PCA operates on the covariance matrix of \( \tilde{\vec{q}}(t) \) to choose a set of \( M \) linearly independent eigenvectors \( \vec{v} \), also known as modes. Modes of a PCA are rank ordered on the basis of their eigenvalues, which reflect the proportion of variance in the original dataset that is accounted for by each mode (e.g., mode \( j \) refers to the mode that accounted for the \( j \)-th-most variance). In the present study, we used the first 15 modes; that is, the original 54-dimensional data set was approximated in a new reduced 15-dimensional space created by the first 15 modes. The location of the original data when projected into this new space is defined as \( \xi_j(t) \). We refer to these projections as control signals. One may approximate the original dataset \( \tilde{\vec{q}}(t) \) by multiplying the control signals \( \xi_j(t) \) with their associated modes \( \vec{v} \).

\[
\vec{q}(t) = \sum_{j=1}^{M < N} \xi_j(t) \vec{v}^j \tag{1}
\]

where \( M \) equals 15.

To summarize, the main goal of PCA is to calculate a set of modes \( \vec{v} \) and control signals \( \xi_j(t) \) that, when multiplied, minimize the least square error with the original dataset \( \tilde{\vec{q}}(t) \):

\[
\text{Error}^M = \frac{1}{T} \int_0^T \left[ \tilde{\vec{q}}(t) - \sum_{j=1}^{M < N} \xi_j(t) \vec{v}^j \right]^2 dt = \min \tag{2}
\]

**Data analysis: Classification of kick direction.** Logistic regression was applied at each frame to test how reliably each possible source of information foreshadowed the kick’s true outcome. When applied to local sources of information, the regression was applied directly to the pitch or yaw angle. When applied to a distributed source of information, the regression was applied to the control signal associated with each individual mode. An example of the classification procedure for a single information source at a single frame is represented in Figure 2. True kick direction is represented as a probability that the kick will go left, which in this case is either 0 or 1. Predicted kick direction is determined by the logistic function (the solid line in Figure 2). All \( p \) values greater than .50 correspond to kicks to the left side of the goal and all \( p \) values less than .50 correspond to kicks to the right side of the goal. Our measure of the reliability of a given source of information was the percentage of correctly classified kicks.

Because a logarithmic function is monotonic, use of a logistic classifier assumes that the relation between information and the actual kick direction is also monotonic. For example, in the analysis of hip yaw in Figure 2, the hypothesis that is being tested is that the likelihood that the kick is to the left increases monotonically with hip yaw. The analogous plot for each source of information was visually inspected prior to classification to confirm that the assumption of monotonicity was not violated. Although more complex classification methods might yield higher reliabilities, allowing arbitrarily complex classifiers would make it possible to classify just about any possible variable. Therefore, we opted to use the logistic classifier, which is the more conservative approach.

**Results and Discussion**

Reliability scores for several information sources are shown in Figure 3. For clarity, only those information sources with peak reliability greater than 75% are shown. Of those sources of information, both local and distributed information are most informative in the third and final phase of kicker’s approach, as the right foot is lifted from the ground and undergoes the terminal kicking motion.
Consistent with Franks and Harvey’s (1997) video-based study of information reliability, the yaw angle of the nonkicking foot was the earliest reliable source of information, with a peak reliability of 77.9% at 250 ms before foot-to-ball contact. Many other sources of local information were found to be reliable later in the kicking motion. Consistent with intuition, contact yaw was the most reliable source, with 98.4% reliability. The finding that the pitch of the shank on the kicking leg was 76.1% reliable at 8.3 ms before contact and that the yaw of the kicking shank was 80.7% reliable 54.1 ms before contact resembles Franks and Harvey’s (1997) suggestion that the kicking knee is a reliable indicator of kick direction. We also identified several reliable local sources of information that were not identified by Franks and Harvey. The yaw angle of the kicking foot peaked at 84.9% accuracy as the foot made contact with the ball, and the angle of the hips were of increasing reliability during the final portion of the terminal kicking motion, eventually peaking at 83.3% reliability on foot-to-ball contact.

The three distributed sources of information whose peak reliability exceeded 75% were Modes 12, 13, and 15 (see Figure 3b). Mode 12 reached a peak reliability of 85.9% at 16 ms before contact, Mode 13 peaked at 75% reliability 87 ms before contact, and Mode 15 peaked at 79.7% reliability 137.5 ms before contact.

One might wonder whether these modes are genuinely distributed and not simply a mathematical repackaging of one of the previously identified local sources of information, such as the orientation of the nonkicking foot. If this were the case, then changes in the control signal for a given mode would result in disproportionately large marker displacements for a single marker location. Figure 4 shows the magnitude of marker displacement per unit change in control signal for Modes 12, 13, and 15. Note that the contribution of Mode 12 to changes at the location of the nonkicking foot is relatively small when compared to changes at the location of the kicking foot and hands. Mode 15 is more evenly distributed across the arms, hands, and legs, and feet located at both sides of the body. Mode 13 accounts for motion of mostly the left forearm, but also the left and right feet and the right forearm, albeit to a lesser degree. The point is that changes in the control signals for each mode resulted in marker displacements for more than one marker, which confirms that the modes were distributed rather than local.

To summarize, in Experiment 1 we introduced a novel method to quantify the reliability of various sources of information. The results were in agreement with previous findings that the angle of the nonkicking foot is the earliest local form of information. In addition, we identified two sources of distributed information (Modes 12 and 15) that were equally reliable more than 200 ms before foot-to-ball contact, and additional sources of information that were reliable later in the trial, including a distributed source of information (Mode 13), and information local to the hips, foot-to-ball contact, and the shank and foot of the kicking leg.
Experiment 2

In Experiment 1, we measured the reliability of both local and distributed sources of information as indicators of kick direction. In Experiment 2, we focused on the use of information by observers who made judgments of kick direction. Subjects were presented with animations of penalty kicks based on the motion capture data collected in Experiment 1 and were asked to make judgments of the side of the goal (left or right) to which the ball was kicked. We then tested the degree to which each candidate source of information predicted subjects’ judgments of kick direction. Sources of information that could be used to correctly classify judgments were considered more likely to underlie subjects’ judgments of kick direction.

Method

Subjects. Thirty-one undergraduates with normal or corrected-to-normal vision participated in Experiment 2. To ensure that subjects were uniformly inexperienced, sign-up instructions clearly stated “You must not have participated on a soccer team of any skill level, or played soccer regularly (four or more times a month), within the past five years.” This was verbally confirmed prior to participation.

Stimuli and apparatus. Motion capture data from Experiment 1 were rendered into visual stimuli using Matlab R2009a in conjunction with the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). The stimuli were presented as PL displays on a Macintosh G5 running Mac OS 10.6.5. Subjects viewed the stimuli on a 19-in. monitor from a distance of approximately 1 m using unrestricted binocular vision of the monocular display. A sample stimulus frame is shown in Figure 5. Marker locations were represented as constant-size points, and the ball was marked as a large green disk and the ground plane as a grid texture. The camera was placed at a viewpoint located at the center of the goal and oriented toward the ball’s starting position at a height of 1.77 m. Subjects specified the judged side of passage using the left or right shift keys on a keyboard.

Procedure. On each trial, subjects were presented with PL stimuli of a penalty kick, as viewed from the keeper’s perspective.
A single trial began with a 500-ms presentation of the first frame of the stimulus with red markers depicting the kicker in a standing pose oriented toward the soccer ball. This presentation was immediately followed by the continuation of the stimulus with markers depicted in white. The screen was blanked on foot-to-ball contact, before ball-flight information was available, and remained blank for 500 ms, during which time the subject was expected to choose the direction in which the ball was kicked by pressing either the left or right shift key on the keyboard.

To facilitate learning, the response window was followed by feedback about the correctness of the response at the end of most but not all trials. Specifically, although each of the 126 stimuli was presented once, only 84 trials were associated with feedback. The remaining 42 trials were never associated with feedback and will hereafter be referred to as no-feedback trials. Of note, the stimuli used for feedback and no-feedback trials remained the same across blocks and across subjects so that stimuli used on no-feedback trials were never associated with feedback about correctness. Because feedback and no-feedback trials were randomly intermixed, subjects were unaware of the specific trial type until feedback had been received. This helped to ensure that subjects would use the same strategy on both feedback and no-feedback trials. If subjects had learned a simple mapping from individual stimuli to posttrial feedback, then they should perform at chance levels on no-feedback trials. On the other hand, if subjects learned to rely on some reliable source of information that generalizes to stimuli used for feedback and no-feedback trials, performance on feedback and no-feedback trials should be comparable.

If no response was registered within the allotted time on either feedback or no-feedback trials, the trial was returned to a random location in the queue and the subject was presented with a message stating that his or her response was too slow. Late responses occurred infrequently—on just 2.6, 3.2, 2.9, 2.0, and 2.4% of trials in Blocks 1–5.

The decision to allow subjects to respond up to 500 ms after foot-to-ball contact was motivated by the results of pilot studies in which subjects performed at near-chance levels when they were required to respond before foot-to-ball contact. The analysis of reliability in Experiment 1 indicated that the inability for subjects to make accurate judgments of kick direction before foot-to-ball contact could not be attributed to a lack of reliable information. Both the angle of the nonkicking foot and Modes 12 and 15 reached 77% reliability more than 220 ms before foot-to-ball contact. The explanation is likely to be the use of inexperienced soccer players. Indeed, in a study by Savelsbergh et al. (2002), amateur and semiprofessional goalkeepers were able to judge kick direction before contact 71.4% and 83.8% of the time, respectively, while novices performed at near chance levels.

One might also wonder why we limited the response window to 500 ms rather than allowing subjects to respond at any time. The 500-ms time limit was imposed to encourage subjects to respond based on the available information without contamination by cognitive factors. Had we not imposed a time limit, subjects may have adopted different strategies, with some responding quickly based on the available information and others responding later after thinking about the stimulus. Because we were more interested in responses of subjects who adopted the information-based strategy, we imposed the 500-ms response time limit. The time limit also helped to minimize the duration of the experiment, which was important for avoiding fatigue.

**Results and Discussion**

The mean percentage of correct responses for both feedback and no-feedback trials for each block is shown in Figure 6. A two-way repeated-measures analysis of variance (ANOVA) with an alpha level of .05 and Greenhouse-Geisser corrections for violations of sphericity indicated significant main effects of trial type (feedback or no-feedback), $F(1, 30) = 4.25, p < .05$, and block, $F(2.81, 84.32) = 11.52, p < .001$, with no significant interaction. The main effect of trial type indicated that subjects performed better on trials with feedback than on trials without feedback.

However, performance on no-feedback trials was above chance in all five blocks and was only slightly below performance on feedback trials. In addition, performance improved across blocks at a rate that was similar to that on feedback trials. Although this provides strong evidence against a rote association between feedback and stimuli, it does not explain the discrepancy in performance. One possible explanation is that the trials associated with feedback happened to be easier to anticipate than those on no-feedback trials. Alternatively, subjects may have learned an association between a stimulus and a feedback on a subset of feedback trials.
trials, perhaps because specific stimuli had a particularly memo-
rable characteristic (e.g., an arm that was swung in an odd way).

The results shown in Figure 6 along with the significant main
effect of block indicate that performance steadily improved with
practice. Further insight into the learning process can be gleaned
through an analysis of response time (see Figure 7). This analysis
reveals a consistent performance advantage for subjects who
waited longer to respond. Subjects with accuracy above 70% on at least one block, /H11003/H11005subjects who never
performed above 70%.

To highlight the trend toward a late-response strategy, successful subjects (> 70% accuracy on any block, N = 16) are represented as circles throughout Figure 7. This group appears to gravitate toward later responses throughout the experiment, suggesting that, once a subject adopted a late-response strategy, he or she was unlikely to revert back to an early-response strategy. This is most likely due to the fact that the most reliable information does not become available until the last 300 ms before foot-to-ball contact.

As might be expected, the learning trend for these late-
responding, successful subjects (Figure 8a) is distinct from the
learning trend for early responding, unsuccessful subjects (see
Figure 8b). Whereas performance steadily improved throughout
the experiment for successful subjects, $F(4,60) = 25.115$, $p < .001$, performance for unsuccessful subjects did not change across blocks, $F < 1.0$. In addition, the percentage of correct responses for unsuccessful subjects differed significantly from chance (50%) in just two conditions—on feedback trials in Block 2, $t(14) = 2.84, p < .05, r = .37$, and no-feedback trials in Block 5, $t(14) = 2.17, p < .05, r = .29$.

**Analysis of information use.** Can improvement in performance by successful subjects be explained in terms of convergence on more reliable information? To investigate this question, we assessed the likelihood that each candidate source of information was used through an analysis similar to that introduced in Experi-
ment 1. Just as information reliability was quantified in Experi-
ment 1 by classifying stimuli according to actual kick direction,
information use was quantified in Experiment 2 by classifying stimuli according to perceived kick direction. For each subject and on each frame of the kicking motion, a measure of classification rate was generated for each information source using a logistic classifier.

Table 1 presents peak information use for successful subjects. Four sources of information stood out in terms of both the number of subjects whose responses were correctly classified and the overall classification rate: (a) the yaw angle of the hips, (b) contact yaw, (c) Mode 12, and (d) Mode 15. Of note, these sources were all rated highly on information reliability in Experiment 1, suggesting that successful subjects performed well because they learned to use one of the reliable sources of information.

By comparison, it proved difficult to identify sources of infor-
mation used by unsuccessful subjects. Of the 15 unsuccessful
subjects, only five subjects returned information sources that
scored above 70% on information use. Closer inspection revealed that these five subjects exhibited a strong bias to respond either left or right well over 50% of the time. Specifically, left responses for these five subjects were made on 91, 73, 70, 10, and 2% of all trials. If the magnitude of bias is greater than an information source’s score on information use, the classification method will reflect the magnitude of bias. Note, however, that this was not the case for successful subjects, whose bias never exceeded the re-
ported values of information use.

Why did the analysis fail to reveal sources of information that
were used by unsuccessful subjects? One possibility is that unsuccess-
sful subjects relied on some source of information that was not among those were considered. Alternatively, the analysis of un-
successful subjects could reflect frequent switching between in-
formation sources within blocks. A third possibility is that subjects
relied on a single source of information, but frequently switched the criterion that maps the state of information (e.g., hip angle) to a decision on kick direction. Similar conclusions might be made about the performance of Subject 1, the only successful performer for whom information use could not be traced.

In summary, 16 of 31 subjects were able to anticipate the outcome a penalty kick at well above chance levels. Successful performance was characterized by later responses—between 200 and 300 ms after foot-to-ball contact. Analysis of information use suggests that successful subjects used one of four potential sources of information (the yaw angle of the hips, the horizontal point of foot-to-ball contact, Mode 12, or Mode 15), all of which were

![Figure 7](image-url)  
*Figure 7.* Percentage correct for each subject in Experiment 2 plotted as a function of average response time in each block. Feedback and no-feedback trials were combined for this analysis. ○ = subjects who performed above 70% on at least one block, × = subjects who never performed above 70%.
among the more reliable sources of information identified in Experiment 1. The finding that successful subjects may have relied on the horizontal point of foot-to-ball contact is consistent with several self-report studies of information use (Kuhn, 1988; McMorris & Colenso, 1996; McMorris et al., 1993; Savelbergh et al., 2005; Williams & Burwitz, 1993). Similarly, the possible use of hip information echoes the findings of Williams and Burwitz’s (1993) self-report study. However, the fact that judgments were also predicted by Modes 12 and 15 means that subjects may have relied on distributed rather than local information.

Experiment 3

In Experiment 2, we adopted a post hoc approach to narrow the initial pool of 27 candidate sources of movement information down to four potential sources of information that predict the judgments of high-performing subjects. Experiment 3 was designed to provide a more direct test of the use of these four sources of information. Subjects began the task by judging kick direction based on the same stimuli used in Experiment 2 for four blocks. To encourage convergence on a single source of information, performance feedback was provided on all trials in Blocks 1–4. In Blocks 5 and 6, the normal stimuli used in Experiment 2 were randomly mixed with artificial stimuli in which one or more of the information sources that scored high on information use in Experiment 2 were decorrelated with kick direction and thus made uninformative. Feedback was withheld on trials with artificial stimuli, to minimize their influence on subjects’ information use. If, after several blocks of training on normal stimuli, subjects had learned to use one of these information sources, the removal of that information source should be accompanied by a noticeable drop in performance.

In one type of artificial stimulus, which we refer to as hip-only stimuli, information related to the location of foot-to-ball contact as well as distributed sources of information were made unreliable, leaving the hip markers as the only reliable indicator of kick direction. In the second type of stimuli, labeled ball-unreliable stimuli, information related to the location of foot-to-ball contact was made unreliable, leaving only distributed sources of information and hip information. In blocks with artificial stimuli (i.e., 5 and 6), feedback was provided on trials with normal stimuli but not on trials with hip-only or ball-unreliable stimuli.

The various sources of information available in each stimulus type are summarized in Table 2. By measuring anticipation accu-

Table 1

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<tr>
<th>Subject</th>
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<th>Upper leg yaw (k)</th>
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<th>Shank pitch (k)</th>
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<th>Mode 12</th>
<th>Mode 13</th>
<th>Mode 14</th>
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Note. Modes extracted using principal component analysis. Only those sources of information with at least one peak greater than 75% were included. Count reflects the number of subjects with peak information use above 75%. k = kicking foot, nk = nonkicking foot.

Figure 8. Percentage of correct responses for successful (a) and unsuccessful (b) subjects in Experiment 2.
racy on both normal and artificial stimuli, we were able to test for use of each information source. Because information about the contact yaw is available only in normal stimuli, if kick direction is perceived based on this source of information, subjects should perform well on normal stimuli but not on hip-only or ball-unreliable stimuli. If subjects rely on the yaw angle of the hip, they should perform well on all three types of stimuli. Finally, if subjects rely on one of the distributed sources of information, then they should perform well on normal and ball-unreliable stimuli but not on hip-only stimuli.

Method

Subjects. Seventeen undergraduate students with normal or corrected-to-normal vision participated in Experiment 3. To ensure that subjects were uniformly inexperienced, sign-up instructions clearly stated "You must not have participated on a soccer team of any skill level, or played soccer regularly (four or more times a month), within the past five years." This was verbally confirmed prior to participation.

Stimuli. Ninety of the 126 kicks recorded in Experiment 1 were used to create normal stimuli. Because these stimuli were used without modification, information reliability for normal stimuli was the same as that depicted in Figure 3. The remaining 36 stimuli were used to create 18 hip-only stimuli and 18 ball-unreliable stimuli. This was achieved by systematically manipulating particular joint locations to alter the reliability of specific information sources. Ball-unreliable stimuli, in which information related to the point of foot-to-ball contact was made unreliable, were created by shifting the screen coordinates of the PL kicker so that the midpoint of the kicker’s foot hit the horizontal center of the ball on foot-to-ball contact. For hip-only stimuli, the motions of all markers other than the two hip markers (location 8 in Figure 1) were identical. This was achieved by first creating a base stimulus, which was obtained by averaging joint positions across all 126 trials recorded in Experiment 1. Specifically, the position of joint j on frame i of the base stimulus was determined by calculating the mean position of joint j on frame i across all 126 stimuli from Experiment 1. Next, the locations of the hip markers from the 18 trials used to create hip-only stimuli were spliced onto the base stimuli. To ensure that the global translation of the hip markers through the 3-dimensional environment was consistent with that of the base stimulus, hip marker locations were converted from global position to position relative to the marker located at the base of the spine prior to the splicing process. Information related to the point of foot-to-ball contact was also made unreliable using the same methods used to create ball-unreliable stimuli.

Procedure. The design of Experiment 3 closely followed that of Experiment 2, with some exceptions. Experiment 3 narrowed the response window to the 500 ms immediately after foot-to-ball contact. This differed from Experiment 2, in which responses could be made at any point prior to 500 ms after foot-to-ball contact, including during stimulus presentation. This change was motivated by the observation that the 16 “successful” subjects in Experiment 2 responded an average of 230 ms after foot-to-ball contact (SD = 90.1), while the 15 unsuccessful subjects responded an average of 7 ms before contact (SD = 231). Therefore, forcing subjects to respond later might improve performance. Subjects were verbally informed of the response widow before the start of the task. If a response was not received within the allotted response window, the response window was immediately followed by the on-screen message, “No response received.”

During each of the first four blocks of Experiment 3, subjects were presented with 90 normal stimuli in random order with posttrial feedback indicating whether the response was correct, incorrect, or too slow. Based on the results of Experiment 2, it was expected that subjects would converge on one of the reliable sources of information during Blocks 1–4. On Blocks 5 and 6, the 18 ball-unreliable and 18 hip-only stimuli were randomly interspersed with the 90 normal stimuli. Feedback was provided on trials with normal stimuli, but not on trials with ball-unreliable or hip-only stimuli.

Results and Discussion

One of the 17 subjects was excluded from analysis because she responded “left” on all 612 trials. Figure 9 presents the percentage of correct responses as a function of response timing for each

![Figure 9](image-url)

Figure 9. Percentage of correct responses by response timing for subjects in Experiment 3. ○ = subjects who performed above 70% on any block, X = subjects who never performed above 70%.
block. For Blocks 5 and 6, these averages reflect response timing on all trial types. Based on the criterion used in Experiment 2, 13 of the 16 subjects were successful performers, having reached performance levels above 70% on any block. These successful subjects responded within the allotted response window on all but 3.7 trials per block ($SD = 1.8$). Furthermore, successful subjects responded later than unsuccessful subjects, as is implied by the slope of a linear regression ($\beta = 0.14, r^2 = .53$). The percentage of successful subjects in Experiment 3 (81%) was considerably higher than it was in Experiment 2 (52%). One possible explanation for the improvement in Experiment 3 is that feedback was available on every trial during the first four blocks compared to two thirds of all trials in Experiment 2. However, the number of feedback trials per block (84 in Experiment 2 vs. 90 in Experiment 3) was approximately the same. Therefore, we attribute the improvement in Experiment 3 to the fact that subjects were forced to respond after foot-to-ball contact. In both experiments, there was a consistent relation between response timing and performance—that is, subjects who responded later performed better. Even at the within-subjects level, performance improved across blocks as subjects learned to respond later. Therefore, the requirement to respond after foot-to-ball contact better accounts for the improvement in performance in Experiment 3.

Changes in performance on normal trials across blocks were investigated with a one-way repeated-measures ANOVA. Using Greenhouse-Geisser methods to correct for a violation of sphericity, the ANOVA revealed a main effect of block, $F(2.95, 35.43) = 24.88, p < .001$, which verifies that performance improved with practice.

The main focus of Experiment 3 was on performance on normal, hip-only, and ball-unreliable stimuli in Blocks 5 and 6. Figure 10 shows the performance level of the 13 successful subjects across blocks. Because there were no systematic differences in the percentage of correct responses on normal trials in Blocks 5 and 6, it was assumed that performance reached a plateau and that the data from Blocks 5 and 6 could be pooled.

Figure 10 shows good performance on both normal and ball-unreliable stimuli, and poorer performance on hip-only stimuli. Indeed, if one considers that random selection would produce a chance performance of 50% accuracy, then the percentage of correct responses on Blocks 5 and 6 (combined) was significantly greater than chance on both normal and ball-unreliable stimuli, $t(12) = 24.83, p < .001, r = .99; t(12) = 9.67, p < .001, r = .941$, but not on hip-only stimuli, $t(12) = 0.79, p < .790, r = .222$. Poor performance on hip-only stimuli is inconsistent with the hypothesis that kick direction was judged on the basis of the yaw angle of the hips. Likewise, good performance on ball-unreliable stimuli is inconsistent with the use of information related to the point of foot-to-ball contact (i.e., contact yaw). The results are, however, consistent with reliance on one of the distributed sources of information, which was available on normal and ball-unreliable stimuli but not on hip-only stimuli.

Although response accuracy was significantly better than chance for both normal and ball-unreliable stimuli, subjects did perform significantly better on normal stimuli, $F(1, 12) = 19.92, p < .01$. One possible explanation for the difference between normal and ball-unreliable stimuli is that there was something unrelated to the position of the foot at contact that made the 18 trials that were randomly selected for ball-unreliable stimuli more difficult than the 90 trials that were used for normal stimuli. This account was ruled out using the data from successful subjects in Experiment 2 by comparing response accuracy on the same 18 stimuli used for ball-unreliable stimuli with the 90 used for normal stimuli. Performance was actually slightly better on stimuli used to create ball-unreliable stimuli (74.3% on the stimuli later used to create ball-unreliable stimuli vs. 68.9% for all other stimuli).

Another possible explanation for the difference between normal and ball-unreliable stimuli is that subjects relied on some source of local information that was not considered in Experiment 3. To test this assumption, we ran the same analysis of information use that was run in Experiment 2 on the data from normal trials in Blocks 5 and 6 in Experiment 3. The results for Block 6 are shown in Table 3. (The results for Block 5 were very similar.) For clarity, information sources that exceeded the 75% threshold for fewer than three subjects were omitted from Table 3. Scores on information use resemble those from Experiment 2, with high scores on the yaw angle of the hips, contact yaw, and Modes 12 and 15. However, the yaw angle of the kicking foot, which did not score high in Experiment 2, exceeded 75% for seven of the 13 successful subjects in Experiment 3.

If, in fact, some subjects used kicking foot yaw angle in Experiment 3, one might wonder whether this could explain the small drop in performance on ball-unreliable stimuli. By shifting the kicker’s location relative to the ball on ball-unreliable stimuli, occlusion of the kicking foot by the ball occurred slightly earlier on ball-unreliable stimuli compared to normal stimuli. Thus, the yaw angle of the kicking foot may have been more difficult to detect on ball-unreliable stimuli, which would account for the drop in performance. However, the ball does not occlude the foot until the last frame of the stimulus, which is well after the reliability of foot yaw reaches its peak. Furthermore, if the performance drop on ball-unreliable stimuli was due to the use of kicking foot yaw angle, then the difference in performance between normal and ball-unreliable stimuli should be greatest for the seven subjects who scored highest on kicking foot yaw angle. This was not the case, because the drop in performance for these seven subjects did not differ significantly from the drop in performance for the other subjects, $t(10.98) = 0.126, p > .05$. Therefore, the difference between normal and ball-unreliable stimuli does not appear to reflect the use of kicking foot yaw angle in Experiment 3.

![Figure 10. Percentage of correct responses by block for normal, hip-only, and ball-unreliable stimuli in Experiment 3. Data are from successful subjects only.](image-url)
A third possible explanation for the small difference in performance between normal and ball-unreliable stimuli is that subjects relied on a combination of distributed information and contact yaw. According to this account, performance dropped on ball-unreliable stimuli because contact yaw information was made unreliable. However, the availability of distributed information on such trials allowed subjects to perform well above chance. Thus, although we cannot conclude that subjects relied entirely on distributed information, the findings suggest that the task can be performed well above chance based on distributed information alone.

In summary, subjects in Experiment 3 who were able to judge kick direction on normal trials were also able to judge kick direction on trials on which normal information was made unreliable, but unable to judge kick direction on trials in which reliable hip information was available. These findings provide strong evidence against the use of hip information and information related to the location of foot-to-ball contact. Instead, the findings support the conclusion that judgments were based on distributed information, possibly in conjunction with a reliable source of local information.

### General Discussion

In this study, we investigated the ability to anticipate the outcome of another person’s action based on the movements of his or her body. In Experiment 1, we introduced a novel method to quantify the reliability of various sources of information about kick direction. In agreement with data from previous studies, we found that kick direction is forecasted by several local sources of information. We also identified three new sources of distributed information, two of which reached 77% reliability 200 ms before foot-to-ball contact. To our knowledge, this is the first study of anticipation in sports to characterize changes in the reliability of candidate sources of information throughout the duration of the movement.

In Experiment 2, we used the motion data from Experiment 1 to create animations of a person approaching and kicking a ball. These animations were then presented to subjects, who were instructed to judge the side of the goal to which the ball was kicked. Applying the same method introduced in Experiment 1 to subjects’ judgments of kick direction, we narrowed the list of sources of information used by subjects down to four: the yaw angle of the hips, contact yaw, and two sources of distributed information (Modes 12 and 15).

In Experiment 3, we further investigated the contributions of these four sources of information by testing performance on artificial stimuli in which one or more possible sources of information were removed. Subjects performed at chance when hip yaw was the only reliable source of information, ruling out hip yaw as the source of information used by subjects. On the other hand, subjects were able to judge kick direction (albeit slightly less accurately) even in the absence of information about contact yaw, suggesting that they relied on some other source of information. Taken together, the findings were most consistent with the hypothesis that kick direction was perceived on the basis of distributed information, possibly in conjunction with a reliable source of local information (i.e., contact yaw).

Of course, caution must be exercised when generalizing these findings beyond the laboratory. Although the task performed by subjects in the present study in many ways resembles to the task performed by goalkeepers in an actual penalty kick situation, there are also important differences. As previously mentioned, goalkeepers have less time than subjects in the present study to decide which direction to move. In addition, kickers in real soccer matches typically attempt to deceive the goalkeeper and may alter the intended kick direction based on the behavior of the goalkeeper. Kuhn (1988) suggested that three quarters of kickers use strategies that are reactive to movements of the keeper. Although these keeper-dependent strategies may increase the odds that the kick arrives at the opposite side of the goal as the keeper, the accuracy of kicks toward the empty side of the net may be affected by fixation of the keeper (Wood & Wilson, 2010) and late alterations of the kicking movement (Van der Kamp, 2006). These

### Information Use by Subject in Experiment 3

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<tr>
<th>Subject</th>
<th>Foot yaw (k)</th>
<th>Foot yaw (nk)</th>
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<th>Shank yaw (k)</th>
<th>Shank yaw (nk)</th>
<th>Contact yaw</th>
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Note. Modes extracted using principal component analysis. Only those sources of information with at least one peak greater than 75% were included.
results suggest the movements of the keeper and kicker evolve in a parallel and interdependent fashion that is not well understood.

Although subjects’ judgments were accurately classified by Modes 12 and 15, one may wonder about the perceptual detectability of such high-numbered modes. Recall that the modes of a PCA are ordered on the basis of their eigenvalues, which reflect the proportion of variance in the original dataset that is accounted for by each mode. Thus, Modes 12 and 15 accounted for a smaller proportion of variance than lower-numbered modes. If PCA was applied to the dataset of the Cartesian coordinates of markers translating through 3-dimensional space, then the movements associated with higher-numbered modes would be very subtle—arguably too subtle to detect. In the present study, however, we adopted a recommendation of Daffertshofer et al. (2004), who advocated normalizing joint locations to units of standard deviations (z scores) prior to performing PCA. The reason for normalizing (or “whitening”) the data is to guard against a bias that associates the first modes with markers that exhibit the greatest amount of translation through Cartesian space, which in the case of a penalty kick would be the legs. The decision to run PCA on whitened data means that the eigenvalues reflect the amount of variance explained in units of standard deviation; that is, eigenvalues do not reflect the amount of movement in Cartesian space. This means that higher-numbered modes could be just as perceptually detectable as lower-numbered modes.

Because motion data were whitened prior to the application of PCA, the possibility remains that one of the untested higher-numbered modes is an even better predictor of subjects’ responses than Modes 12 or 15. This would be troubling if the aim of this study was to identify the single most reliable mode or the single mode used by human observers. However, because the aim was to compare the reliability and use of both local and distributed information sources, the more important contribution is the finding that there exist distributed sources of information that are as reliable as local sources of information and that people may actually rely on such information to anticipate the actions of another person. Therefore, although we cannot make any strong claims about the contribution of Modes 12 and 15 to judgments of kick direction, the data suggest that distributed information is reliable and may be used by human observers for the purposes of anticipation.

Applications for Training

As researchers gain a clearer picture of the relevant sources of information, coaches can begin to integrate these findings into their training regimes to improve anticipation skills. Attempts to design more effective training regimes may benefit from more research on the reliability and use of local versus distributed information. Some evidence suggests that coaches may be able to explicitly guide their players toward more reliable local sources of information using verbal or visual illustrations of information (Daffertshofer et al., 2004; Hagemann, Strauss, & Cañal-Bruland, 2006; Poultier, Jackson, Wann, & Berry, 2005; for a review, see Williams, 2000). However, researchers have found the effects of explicit training to be less robust than implicit methods (Farrow & Abernethy, 2002) and the advantage from explicit training methods to diminish in high-pressure situations (Liao & Masters, 2001; Masters & Maxwell, 2004; Masters, 1992; Masters, Maxwell, & Eves, 2009; Smeeton, Williams, Hodges, & Ward, 2005). Furthermore, to the degree that successful athletes rely on distributed sources of information—a concept difficult to verbalize and illustrate—implicit training methods might be more effective. For example, one might develop a perceptual training regime in which subjects practice judging kick direction using artificial stimuli in which less reliable sources of information are made completely unreliable, and more reliable sources of information are exaggerated. By providing feedback consistent with the use of the most reliable sources of information, it might be possible to guide the observer’s attention toward the most reliable sources of information.

It is also worth pointing out that the approach introduced in this study is generic in that the same methods for measuring reliability can be applied to tasks other than blocking a penalty kick in soccer, including anticipating the direction of a shot in tennis and the type of pitch in baseball.

Theoretical and Methodological Contributions

There is a long history of basic research on perception and action in the context of sports. Just as previous studies of outfielders (McBeath, Shaffer, & Kaiser, 1995; McLeod, Reed, & Dienes, 2006; Michaels & Oudejans, 1992), cricket batsmen (Land & McLeod, 2000), and table tennis players (Bootma & van Wieringen, 1990; van Soest, et al., 2010) have implications that extend beyond the playing field, so does the present study and other recent studies on anticipation in soccer, tennis, and other sports. In this section, we highlight the theoretical and methodological contributions of the present study.

Traditionally, studies of biological motion perception have focused on judgments of properties such as sex, identity, and movement direction based on the movements of an actor who is engaged in a relatively simple, unskilled action (e.g., walking). The number of articles on anticipation from biological motion published in the last few years suggests a growing interest in the detection of information in more complex, skilled movements that involve the coordination of many biomechanical degrees of freedom. Accompanying the emerging focus on complex, skilled movements is a growing appreciation for the possible contribution of information contained in dynamic patterns of movement that are distributed across the body and the development of methods to identify such information (Huys et al., 2009; Huys et al., 2008; Mantovani, Ravaschio, Piaggi, & Landi, 2010; Smeeton & Huys, 2010; Williams et al., 2009). Although the degree to which anticipation is based on distributed rather than local information remains an open question, the findings of the present study add to the growing body of evidence supporting a role for distributed information.

PCA was used to identify distributed information in both the present study and in recent work by Huys et al. (2008). However, the way in which PCA was applied differs in the two studies. The analysis introduced by Huys et al. searches for differences in shot direction in terms of different modes. Recall that each mode of a PCA has an associated eigenvector, which is an array of coefficients that reflects the contribution of each joint in the x, y, and z directions. Huys et al. arranged their data prior to running PCA so to obtain a set of eigenvector coefficients for each trial in the inside-out condition and another set of eigenvector coefficients for each trial in the cross-court condition. This allowed them to look
for differences between inside-out and cross-court shots by testing for statistically significant differences in eigenvector coefficients. Furthermore, because each eigenvector coefficient reflects the contribution of a single joint in a single dimension, their analysis tests for differences between shot directions at each joint. In contrast, our analysis assumes that kicks to the right and kicks to the left share the same modes, and looks for differences in kick direction in terms of differences in the control signals associated with certain modes at particular points in time. This was achieved by concatenating the data from all subjects and all trials prior to running PCA as described in the Method section.

There are advantages to both approaches. The method adopted by Huys et al. (2008) allowed them to identify locations (e.g., marker locations or joints) where significant differences between shot directions were found. By comparison, the method used in the present study allowed us to measure the reliability of each mode at each point in time between the first approach step and foot-to-ball contact. Thus, we view these two approaches as complementary rather than competing. Future research on this topic is likely to reveal other ways of applying PCA and similar methods to identify global patterns of movement.

Conclusion

The results of this study suggest that, when anticipating the outcome of another person’s movement, observers are sensitive to sources of information that are distributed across the body of the actor. This conclusion is largely based on results obtained using a novel method for identifying and measuring the reliability of local and distributed sources of information. A natural extension of this study would be to repurpose the method for the development of a perceptual training regime with artificial stimuli. In addition, our method might be used to investigate a variety of psychological questions related to reliability of movement information across large populations and of different levels of expertise.

References


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