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The Use of Anticipatory Visual Cues by Highly Skilled Tennis Players

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ABSTRACT. The authors examined 13 skilled and 12 novice tennis performers' ability to use visual information of an opponent's movement pattern to anticipate and respond. In Experiment 1, skilled and novice players anticipated the type of stroke and the direction in which the ball was hit in a highly coupled perception–action environment. Both groups of players correctly anticipated at greater than chance levels. Skilled players were significantly more accurate than novices with live and video displays but not with point-light displays. In Experiment 2, the reaction latencies of 10 expert performers were significantly faster when they returned balls hit by a live opponent than when they returned balls projected from a cloaked ball machine. The findings indicate that experts are able to use movement-pattern information to determine shot selection and to use that information to significantly reduce their response delay times. The findings are discussed in terms of perception–action coupling in time-stress activities.

Key words: anticipation, delay time, point-light display, response, tennis, visual cues

Our perception of the environment and our responsive actions are more directly and intricately related in sports activities than in many other activities of daily living. Temporally constrained situations in many sports demand that players extract the most valuable sources of visual information and use that information to quickly anticipate the opponent's action. A recently published list of the 10 hardest things to do in sports ("Sportsline," 2003) included three sports in which task performance relies on that anticipation. Highly skilled athletes are believed to possess the ability to perceive visual information from an opponent's motion pattern and use that information to anticipate subsequent events. A number of investigators have been interested in that conspicuous ability of expert players and have examined anticipation in activities such as tennis (e.g., Jones & Miles, 1978), hockey (Salmela & Fiorito, 1979), badminton (Abernethy & Russell, 1987), squash (e.g., Abernethy, 1990a), and soccer (e.g., Savelsbergh, Williams, Van der Kamp, & Ward, 2002).

Investigators have used a variety of strategies to examine anticipation in activities that have a tight perception–action coupling and require rapid reactions. In one common approach, experimenters have presented to an observer visual displays of an opponent's action and have manipulated the amount of the action the observer sees by temporally occluding movement phases or spatially occluding movement segments. In temporal occlusions, the typical approach is to use video or film representations to show observers the movements of an opponent and to stop the visual display at various times before or slightly after some critical event, such as ball–racquet contact in tennis (e.g., Jones & Miles, 1978) or foot–ball contact in soccer (e.g., Williams & Burwitz, 1993). The observer then predicts the outcome of the movement, such as the direction in which the ball was hit. In spatial occlusions, particular body segments of an opponent are occluded (e.g., Abernethy & Russell, 1987). Observers watch a film or video display that has been edited or screened so that certain parts of the body cannot be seen and then predict the outcome of the action on the basis of the partial information available. A significant decrease in prediction accuracy with the removal of a body segment indicates that the removed segment was important for the perception of the event (for a recent review, see Williams, Davids, & Williams, 1999).

A second approach has been to examine where skilled performers look while watching a video display of an opponent's

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action (e.g., Singer, Cauraugh, Chen, Steinberg, & Frehlich, 1996). In the visual search pattern approach, the performer is required to wear an eye-movement recording device that allows the investigator to determine where the eyes are pointed (direction of gaze). The assumption underlying that research is that the object at which the eyes are pointed during periods of stable eye position (visual fixations), the length of the fixations, and the pattern of search between fixations indicate the visual information important for the activity. The focus in much of that research has been on racquet sports and soccer, although studies of a number of sport tasks have been completed (for reviews, see Cauraugh & Janelle, 2002; Williams et al., 1999). Differences between experts and novices are often examined in both occlusion and visual search pattern studies.

The results of several temporal occlusion studies have indicated that skilled coaches or players are able to use precontact visual cues better than novice performers can. Jones and Miles (1978), for example, had expert coaches, other coaches, and novices look at film clips of an opponent hitting a serve. Just before ball contact and 126 ms or 336 ms after ball–racquet contact, the film was stopped, and participants were asked to write down whether the serve went to the forehand, middle, or backhand side. The results showed that expert coaches were better than novices, but even the expert coaches were correct on only 40% of the trials. That percentage was marginally better than the 33.3% expected by chance. Some (e.g., Abernethy, 1990b, squash; Abernethy & Russell, 1987, badminton; Williams & Burwitz, 1993, soccer), but not all (e.g., Goulet, Bard, & Fleury, 1989, tennis; McLeod, 1987, bowling in cricket), studies have shown expert–novice differences in anticipating outcome from an opponent's movement patterns.

The perception of patterns of action has been studied extensively under the rubric of perception of biological motion. Johansson (1973) argued that the kinematic pattern of an action is more informative than are other types of information (e.g., the actual shape of a moving animal) in specifying movement to an observer. To display only movement kinematics, Johansson used a point-light technique by placing reflective markers on each major joint of the human body. Using that technique, Johansson and others have demonstrated that observers can perceive the activity being performed (e.g., Johansson), the gender of a walker (e.g., Kozlowski & Cutting, 1977), and the amount of weight being lifted (e.g., Shim & Carlton, 1997). It has been argued that a point-light representation provides the essential information for perceiving the relative motion pattern of the actor and specifies the pattern of coordination (Newell, 1985) and also the response kinetics (Bingham, 1987). Investigators have used point-light techniques to study anticipation in sport contexts, and the results have been mixed. Experimenters have shown that both experts and novices are able to anticipate movement outcomes from point-light displays (Abernethy, Gill, Parks, & Packer, 2001; Abernethy & Packer, 1989; Ward, Williams, & Bennett, 2002). In some studies, experts were found to anticipate more accurately than novices (Abernethy et al.; Abernethy & Packer), and standard video displays were found to allow more accurate anticipation than did point-light displays. In other studies (Ward et al.), no effect of expertise or visual display on anticipation accuracy was found.

Although significant advances have been made in our understanding of anticipation in sport activities, much of the research has been criticized because the experimental method used led to a reduction of the natural setting in which the observer's action normally occurs. Several problems have been identified. One significant concern relates to the use of a two-dimensional (2D) screen or a monitor; a 2D display is considered to be deficient in what people naturally perceive in dimension and, in many experiments, size. The use of real-life settings has been difficult to achieve experimentally and also brings with it a certain loss of experimental control (Williams, Davids, Burwitz, & Williams, 1992). A second problem relates to the nature of the responses used by the observers in the experiments. In general, the importance of the interrelationship between perception and action has been ignored. Participants in those experiments typically respond to the visual scene by pushing buttons, controlling a joystick, verbally reporting, or writing. The responses do not coincide with the actual responses that are produced while they engage in the activity. As a result, the experiments may not have provided an accurate reflection of the anticipatory behavior normally exhibited in those activities, especially for experts.

As noted previously, the focus in much of the work on anticipation has been on telling rather than acting. In recent experiments, investigators have attempted to incorporate a more natural setting by using large video projection systems rather than small video monitors (e.g. Savelsbergh et al., 2002; Ward et al., 2002) and by having performers generate some motor action, although, with the exception of Abernethy et al. (2001, Experiment 2), typically not the action normally associated with the activity. As a result, the studies may be providing information about identification rather than action (Milner & Goodale, 1995).

In the present study, we examined anticipation in a tennis activity. The tennis volley requires reactions with minimal temporal delays because of the speed of the ball and the closeness of the opponent. The ability to "read" the opponent's movement patterns would reduce the time stress and potentially improve performance. In Experiment 1, we examined the influence of the type of visual display on anticipation of skilled and novice performers; in Experiment 2, we examined how the availability of visual cues before ball contact influences reaction latencies of skilled players.

EXPERIMENT 1

Previous results have demonstrated that players of racquet sports are able to anticipate ball direction at better than chance levels from observing the motion pattern of their opponent in both standard video and point-light displays.

However, the effect of expertise and display type is unclear. Standard video displays resulted in greater prediction accuracy than did point-light displays in some (Abernethy et al., 2001; Abernethy & Packer, 1989) but not all (Ward et al., 2002) studies. Also, it is not known if the use of 2D displays results in poorer anticipation than does the use of live 3D viewing conditions normally experienced by performers.

In Experiment 1, we examined how the nature of the display influences anticipation accuracy in a perception–action coupled task. Skilled and novice performers observed tennis ground strokes being produced on a tennis court while viewing a point-light display, a full-sized 2D video display, or a 3D live action. The two video displays were matched in size to the live action presentation. Observers were asked to produce time-coupled actions specific to the shot hit by the opponent. The actions were those normally produced during play. We expected that differences between experts and novices would be magnified in simulated playing conditions because experts have been exposed to that environment from their past experience and have developed a strong perception–action couple.

Method

Participants

Thirteen skilled and 12 novice tennis players participated in Experiment 1. One of the 13 skilled players served as the player hitting the ball (hitter). The remainder served as the receivers. Skilled male tennis players (ages 18–35 years) and 2 female and 10 male novice players (aged 20–34 years) participated. The skilled tennis players were current or former collegiate players and had ratings above 5.5 according to the national tennis rating system. In that system, developed by the United States Tennis Association, beginning players are rated at 1.0 and professional players at 7.0. Players rated 5.0 are described as being able to make good shot anticipation. The novice players had never participated regularly in tennis.

Apparatus

An S-VHS (Panasonic AG-455, 60 Hz) and a VHS video camera were used. The S-VHS camera recorded the movement patterns of the hitter producing the strokes, and the VHS camera recorded the movement patterns of the receivers. We used a microphone placed immediately behind the hitter to determine the instant when the hitter's racquet made ball contact. The microphone output was amplified and rectified before being input to a bipolar comparator. The threshold for the bipolar comparator was set just above room noise. The sound from the ball–racquet impact activated a 5-V signal from the bipolar comparator. We aligned a single-dimension accelerometer attached to the receivers' racquet so that it would provide acceleration perpendicular to the long axis of the racquet; we used it to determine the instant the receivers initiated movement. A personal computer sampled the output from the accelerometer and the bipolar comparator at 200 Hz.

The receivers wore a pair of PLATO S-2 goggles (Translucent Technologies, Inc., Toronto, Ontario, Canada) that could change from clear to opaque; we used the goggles to occlude the receivers' vision after the hitter made ball contact. Receivers wore earphones so that they would hear no auditory information about ball contact and ball landing. A headband with an integrated Plexiglas shield protected the receivers' face and provided protection during the live condition. A ball machine (Apollo Wizard) tossed the ball to the hitter. A projector (Sharp Model XG-E1200U) and a projection screen (3.5 m diagonal; Da-Lite Model C) displayed the recorded movements from the S-VHS camera for the point-light and 2D display conditions. To generate point-light displays, we attached pieces of retroreflective tape (3M) to the ball, racquet, and hitter's body. We used a 1,000-W spotlight to generate reflections from the pieces of tape in the point-light display condition. All testing occurred on a standard singles tennis court set up in a large research gymnasium. The general layout of the court is provided in Figure 1.

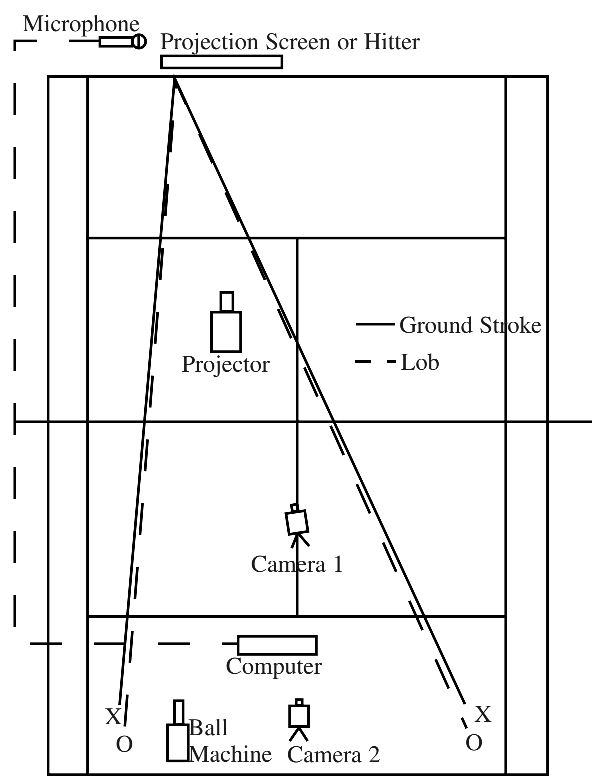

FIGURE 1. The court layout for Experiment 1. The hitter hit the ball by using two stroke types (ground stroke and lob) and two stroke directions (left and right). The Xs represent the mean landing locations of the ground strokes and the Os represent the landing locations for the lobs. The recording camera used to generate the two-dimensional and point-light displays (Camera 1) and the receivers' location on the court were the same.

Recording Procedure

Before the start of data collection, we recorded the hitter's movements to generate the 2D and point-light displays. For the 2D display, the hitter wore conventional tennis attire. The S-VHS camera was positioned midway between the net and the service line on the receivers' side of the court at a height of 1.75 m, the approximate eye height of the receivers.

For the point-light display, we attached 13 pieces of reflective tape to the head (i.e., above the ear) and to the left and the right sides of the greater tubercle of the humerus, lateral supracondylar ridge, ulnar notch, greater trochanter, lateral epicondyle of the femur, and the lateral malleolus. The hitter wore dark clothing so that only the markers were visible. Small pieces of retroreflective tape were also attached around the ball and the racquet. The S-VHS camera was positioned at the same location used for the 2D display, and the 1,000-W spotlight was positioned just below the camera. The movements of the hitter were recorded in a dimly lit environment, with the spotlight pointed directly at the hitter.

For the recording of both 2D and point-light displays, the trial started when the ball was projected to the hitter from the ball machine. The hitter stood in ready position on the tennis court, behind the baseline and near the center mark, with his feet shoulder-width apart, hips and knees slightly flexed, and heels off the ground. When the ball was projected, the hitter struck the ball by using one of four strokes. Those included forehand drives (high velocity shots with a low trajectory, sometime referred to as *passing shots*) and topspin lobs (high shots hit over the receivers' head) that were hit to the recording camera's left (down-the-line) or right (cross-court). The hitter was told in advance of each trial which stroke to hit and was highly accurate in hitting the stroke. Five trials of each of the four strokes were recorded for the 2D and point-light displays. We selected the point-light display trials from a number of attempts on the basis of the visual clarity of the markers. Each selected trial was representative of that stroke type. As a result, twenty 2D and 20 point-light trials were recorded.

Experimental Procedure

We used the following general procedures for all conditions. Each receiver wore the goggles, face shield, and earphones during all trials. Using a Velcro belt, we attached cables from the goggles and racquet accelerometer to the receivers' back at the waist. The cables did not interfere with the receivers' motion. Receivers stood in ready position, 3.2 m behind the net, facing the hitter or the hitter's projected image in the 2D or the point-light display conditions (see Figure 1). The receivers observed the ball coming to the hitter and the hitter's swing. Immediately after the hitter made ball–racquet contact, the transparent goggles turned opaque. Therefore, no visual information was available to receivers after ball–racquet contact. We verified the elimination of visual information by videotaping several strokes through the lens of the goggles. In each case, the ball had not left the racquet strings before the goggles turned opaque. After ball contact, the receivers' task was to anticipate the outcome of the ball by initiating a movement to hit a forehand (cross-court) or backhand (down-the-line) volley or to hit an overhead from the forehand or backhand side as quickly as possible. Because the goggles turned opaque at ball–racquet contact, receivers performed only the initial movement and did not try to return the ball. After each trial, the experimenter recorded the stroke type and ball direction the receivers anticipated.

Receivers observed the hitter's movements in three types of displays: live, 2D, and point-light. In the live display, the receivers observed the hitter's movement live in real time. The ball was projected to the hitter from the ball machine. The hitter was informed before each trial which stroke to hit for that trial, and the order of trials was randomized. At ball–racquet contact, the receivers' goggles turned opaque and they immediately moved in the direction of the anticipated shot. In the 2D and point-light displays, the experimenter projected the trials previously recorded from the S-VHS camera onto the screen positioned just behind the baseline by using the LCD projector (Figure 1). Because the image was recorded on the same court and from the same position as the receivers, the 2D projected image matched the background of the court. In the point-light display, the pieces of reflective tape that were attached to the hitter, ball, and racquet appeared as small dots or lines on an otherwise dark background. The LCD projector was positioned near the service line on the hitter's side of the court. From that location, the size of the hitter displayed on the screen was the same as the size of the hitter in the live condition. The microphone was moved next to the projector, and we used the moment of ball–racquet contact to turn the goggles opaque, as in the live condition.

Receivers each viewed all three types of display in a random order. For each type of display, receivers viewed 20 strokes, five trials of each type of shot (down-the-line and cross-court ground strokes and lobs) in a random order before viewing the next type of display. Thus, the receivers each viewed 60 strokes.

Data Analysis

The experimenter initially and independently evaluated anticipation accuracy during data collection by using the video recordings of the receivers' actions. We determined the receivers' shot selection on the basis of the racquet motion and the direction of the receivers' step pattern. A forehand passing shot was indicated if receivers stepped to their right, either laterally or forward, and moved the racquet laterally. A forehand lob was identified if receivers stepped backward to the right and brought the racquet up over their right shoulder to prepare for hitting the shot. Backhand shots and movements made to the receivers' left were identified in a similar manner. The data were converted to percentages that represented stroke anticipation accuracy. Fewer than 5%

of anticipations were identified differently from the live observation and the video recordings, and those data were excluded from data analysis.

We performed statistical analysis on stroke anticipation accuracy. We transformed correct anticipation percentages to arcsine values to satisfy the normal distribution assumption. We analyzed data by using a 2 (skill level) × 3 (display: live, 2D, point-light) two-way mixed-design analysis of variance (ANOVA) with repeated measures on display. We performed one sample *t* test to determine if the players anticipated at levels greater than chance.

Results and Discussion

Stroke anticipation accuracy was statistically greater than chance (25%) for both novices (43.7%) and experts (63.1%), ts(1, 11) = 5.69 and 10.11, respectively, ps < .001. Those results indicate that experts and novices were able to use visual information from the hitter's movement to correctly anticipate his shot. The Skill × Display ANOVA for stroke anticipation accuracy revealed that skilled players were significantly more accurate than novice players, $F(1, 22) = 18.93$, $p < .05$. No significant effect was found for display, but there was a significant interaction between skill and display, $F(2, 44) = 6.22$, $p < .05$ (Figure 2). Increasing the information in the display had opposite effects on novices and skilled performers. The novice players' anticipation accuracy decreased as more information was presented, whereas the accuracy of skilled performers increased. Paired contrasts revealed expert–novice differences for the live and 2D displays ($p < .05$), but differences between novices and skilled players for the point-light display were not significant ($p > .10$).

Skilled performers may be able to extract contextual information from video and live displays in addition to the relative motion pattern information provided in the point-light display. The added information in the live and video displays may not be beneficial to novices because the additional information may be distracting or may cause an information overload.

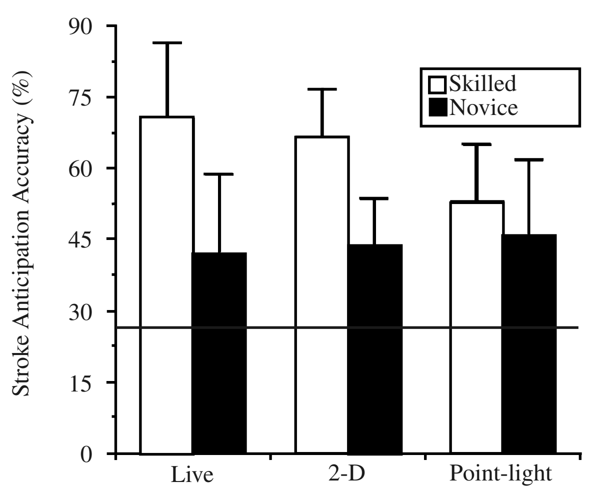

FIGURE 2. Stroke anticipation accuracy of skilled and novice players when viewing the three displays. The horizontal line (25%) represents chance behavior, and the error bars represent one standard deviation.

EXPERIMENT 2

The findings from Experiment 1 indicated that receivers could predict the shot hit by their opponent (the hitter) at greater than chance levels when visual information was eliminated before ball flight occurred. In addition, experts were significantly more accurate than novices. It has not been established, however, that the ability to predict outcomes on the basis of observation of an opponent's movement pattern translates into an actual performance advantage. Howarth, Walsh, Abernethy, and Snyder (1984) have provided some preliminary data indicating short response latencies for skilled squash players in competitive conditions. It is not clear, however, whether the short latencies were a function of information obtained from observation of the opponent's movement pattern or of situational information (e.g., where the opponent was standing on the court or the opponent's tendencies). In Experiment 2, we addressed the question of whether expert tennis players are able to use visual information from their opponent's movement pattern to respond quickly. If players can do so, then their response delay times should be shorter when that information is available than when no precontact movement pattern information is provided.

Skilled tennis players volleyed balls hit by a live "opponent" or projected from a tennis ball projection machine. Response delay times were measured as the time between when the ball was hit by the opponent or projected from the ball machine and when the players initiated racquet motion.

Method

Participants

Ten highly skilled tennis players from a top-ranked collegiate tennis team participated in Experiment 2. Eight players had a rating of 7.0, and 2 players had a rating of 6.0. One of the 2 players with a rating of 6.0 served as the player hitting the ball (hitter), and the remaining 9 players served as receivers.

Apparatus

The experiment was conducted on the same tennis court as in Experiment 1. The ball machine used in Experiment 1 was attached to a plywood platform and placed just behind the baseline of the tennis court. The plywood platform was attached to the court surface at one corner so that the platform could be rotated. That set-up allowed the experimenter to quickly and accurately change the direction of the ball between trials. A screen made of plywood was placed in front of the ball machine (Figure 3). The screen, approximately 1.3 m high and 1 m wide, had an opening in the center for the ball to pass through. Attached to the screen was a

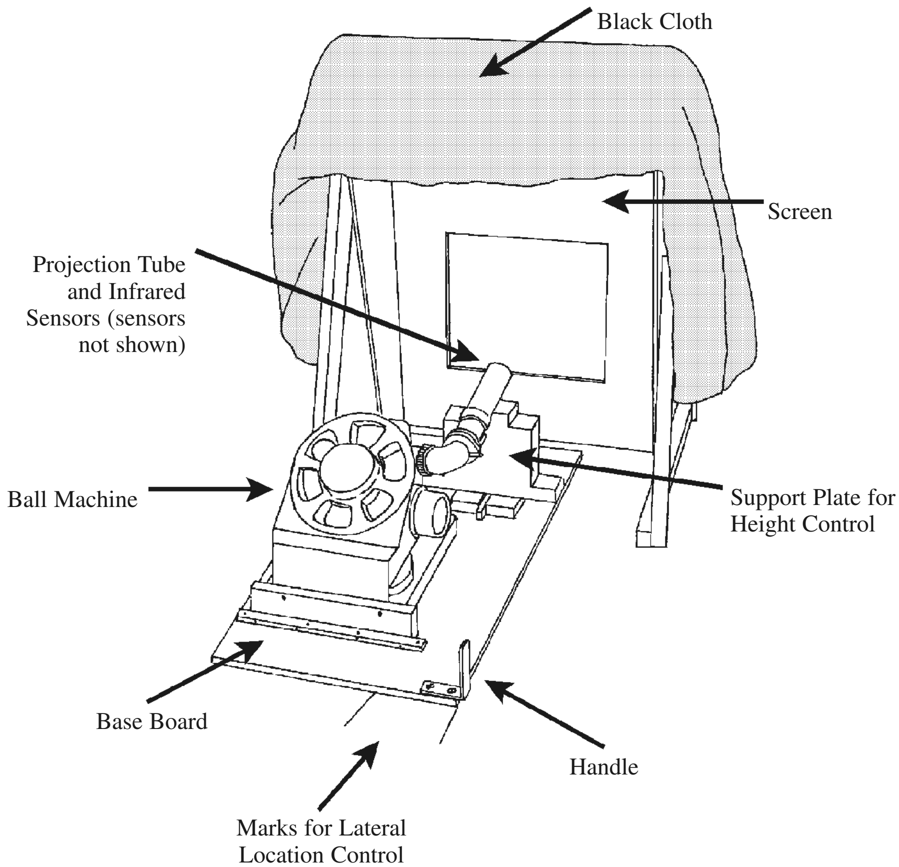

FIGURE 3. The ball machine assembly and screen. The ball machine was dark blue in color; the rest of the assembly was painted black.

black cloth that was draped over the ball machine. The cloth prevented light from entering the enclosure. In addition, the ball machine was dark blue in color; thus, receivers were unable to tell in which direction the ball would be projected.

To determine when the ball was projected from the tennis ball machine, we constructed an infrared photo assembly and placed it at the end of the tennis ball projection tube. When the ball exited the tube, the infrared light beam was broken, and a logic circuit was activated. The logic circuit controlled a voltage sent to the data-collection computer used for this experiment. The change in voltage took less than 1 ms, and the computer sampled data at a rate of 1000 Hz. To determine when the live player contacted the ball, we used a microphone and bipolar comparator, as in Experiment 1. The output from the bipolar comparator was also sampled at 1000 Hz.

To determine when the receivers started to initiate a volley, we placed a 3D accelerometer on the throat of the racket held by the receivers. We positioned the accelerometer so that the x dimension measured acceleration perpendicular to the racquet face. From the normal ready position, it measured left and right (horizontal) motion of the racquet. The y dimension measured acceleration perpendicular to both the longitudinal axis of the racquet and the x dimension. From the ready position, it measured up and down (vertical) motion of the racquet. The z dimension measured acceleration along the shaft of the racquet; that is, movement along a line from the handle to the head of the racquet. The racquet (Prince 850) had a throat opening that was wide enough to give some protection to the accelerometer. The accelerometer was further protected by a tennis ball, cut in half and placed over the accelerometer assembly. With the accelerometer, mounting hardware, and protective covering, the racquet weighed less than 0.5 kg.

Procedure

Each receiver completed 30 trials with both the live hitter and the tennis ball machine. The order of conditions was randomly determined. The specific procedures for each condition are outlined next.

Ball machine (no preprojection visual cues). Receivers stood in a normal volleying position, midway between the net and the service line, with their feet approximately shoulder-width apart. They used the racquet with the accelerometer attached and were instructed to hit normal volleys as they would in a tennis match. The only exception was that receivers were asked to keep the racquet reasonably still just before the ball was projected to them so that we could readily detect the initiation of racquet motion. Three small-diameter cables carrying the output signals from the 3D accelerometer were attached by Velcro straps to the receivers at the wrist, upper arm, and waist.

The ball machine projected tennis balls at a speed of 23.7 m/s (53 mph) with a standard deviation (*SD*) of 0.5 m/s. The balls were projected to a location 1.35 m to the left or right of the center service line at a height of 1.5 m as it crossed the net. The variation of spatial locations was small (range < 0.6 m). We randomly determined whether the ball was projected to the receivers left or right on any trial, with the constraint that there be 15 trials to each side.

At the start of the trial, the ball was held up in the air by the person feeding the ball machine so that the receivers could clearly see the ball. The ball was then placed directly into the ball projector. The time between ball injection in the machine and ball exit was approximately 1.5 s. During that delay, air pressure increased inside the ball machine. The sound produced during that process allowed the receivers to know when the ball would be released. A cover was placed over the opening in the plywood screen until just before the ball was projected (approximately 0.5 s). That procedure further reduced the receivers' ability to determine the ball direction before it was projected. When the ball was released, the receivers attempted to hit a normal volley aiming for a location deep in the center of the court. There were approximately 30 s between trials.

Live hitter. The procedures used with the live hitter were the same as those used with the ball machine, with the following exceptions. The hitter produced forehand ground strokes from the center of the court at the baseline. Before the start of data collection, the hitter was trained to hit balls at the same speed as the balls projected from the ball machine. An electronic circuit was developed for that purpose; it allowed the experimenter to measure the time between ball–racquet contact and when the ball arrived at the receivers. Feedback was given to the hitter after each attempt during practice until the hitter could consistently hit the ball within 25 ms of the ball flight time from the ball machine (*M* = 652 ms).

In the live-hitter condition, each trial started with the ball's being projected by the ball machine at a low speed from the receivers' side of the court. The ball bounced in the center of the court near the intersection of the center service and service lines. The ball was approximately waist high when the hitter struck the ball. Before each trial, the hitter was informed about which side of the court he should place his shot. The hitter aimed for the location balls were projected to by the ball machine (1.35 m from the center service line and 1.5 m high). The accuracy of the hitter's shots was measured during training. The distribution of the hitter's shots resulted in a 4-m *SD*. The receivers' task was the same as it was in the ball machine condition.

Data Analysis

Response delay times specific to the condition being tested were calculated. For the ball machine, response delay time was measured from the time of deactivation of the infrared photocell when the ball left the ball machine projection tube to the initiation of racquet movement. For the live hitter, response delays were calculated as the time between the hitter's contacting the ball with the racquet, as measured by the sound picked up from the microphone, and the initiation of racquet movement.

We obtained the time of racquet movement by calculating the resultant racquet acceleration from the three orthogonal components of the 3D accelerometer. We then differentiated the resultant acceleration by using the central difference technique over 2-ms samples to obtain the resultant jerk. Using that time series data, we calculated the time of racquet movement as the first time after ball release (ball machine condition) or ball contact (live-hitter condition) that the jerk was equal to or greater than a threshold value specified for that receiver. The typical value used was 25 m/s^3. For 2 participants, the threshold was 37.5 m/s^3. Following that procedure, we checked each trial by hand for accuracy. Occasionally the threshold was adjusted for a trial. That adjustment occurred on less than 20% of the trials and with the same frequency for ball machine and live-hitter trials. We analyzed the response delay times by using a paired *t* test to compare delay times between the ball machine and live-hitter conditions.

Results and Discussion

Example data from a typical live-hitter trial are shown in Figure 4. The figure shows the change in voltage associated with the activation of the microphone–bipolar comparator assembly when the ball was hit, the patterns for each dimension of the 3D accelerometer, the resultant acceleration, and the resultant jerk. In this example, the time between the hitter's ball–racquet contact and the receiver's racquet movement initiation was 127 ms. An example trial for the ball machine condition is shown in Figure 5. The information in the figure is similar to that for the live-hitter condition, with the exception that the top trace represents the output of the infrared photocell. In this example, the time between the ball's leaving the projection tube and the start of racquet movement by the receiver was 197 ms. An analysis of the response delay times revealed a significant difference between the live-hitter (M = 129 ms, SD = 11) and ball machine (M = 179 ms, SD = 12) conditions, $t(1, 8) = 9.53$, $p < .01$. That finding indicates that skilled players are able to make use of visual information preceding ball contact to significantly reduce their response delay times.

The difference in response delay time was dramatic. Performers were more than 25% faster when they could see the movement pattern of the hitter. The 50-ms time savings means that skilled players have an additional 50 ms to move, which would allow players to increase their court coverage by as much as 1.2 m (0.6 m on both the forehand and backhand sides). The observed temporal delays are similar to the most rapid estimates of visual process times (e.g., Carlton, 1981; Elliott & Allard, 1985; Zelaznik, Hawkins,

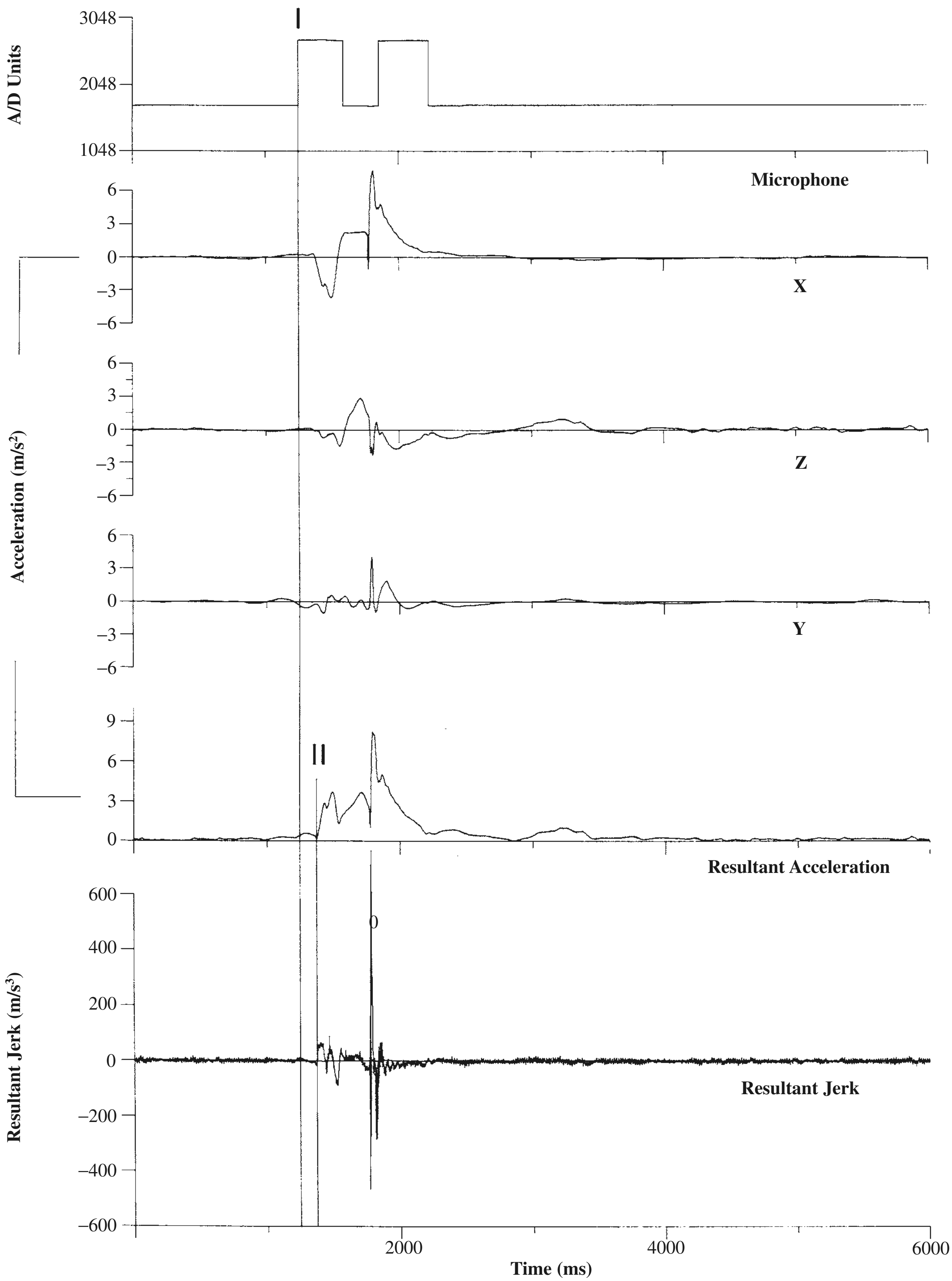

FIGURE 4. An example trial from the live-hitter condition. The top trace shows the microphone output obtained from the analog/digital (A/D) converter. The next three traces are from the accelerometer. The bottom two traces are the resultant acceleration and jerk patterns. The single (|) and double (||) vertical lines represent, respectively, the time of ball contact and the time of movement initiation.

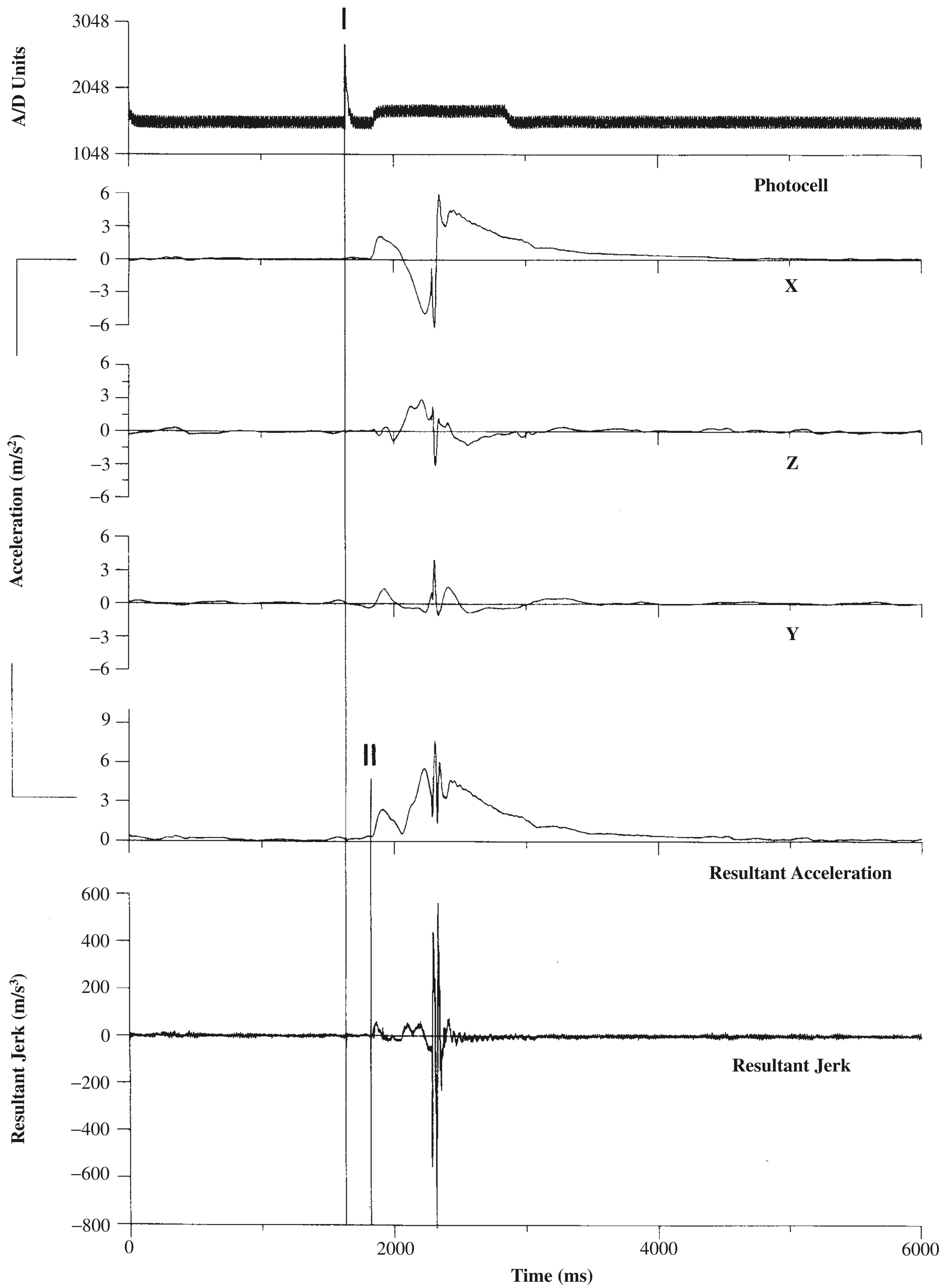

FIGURE 5. An example trial from the ball machine condition. The top trace shows the photocell output obtained from the analog/digital (A/D) converter. The next three traces are from the accelerometer. The bottom two traces are the resultant acceleration and jerk patterns. The single (|) and (||) double vertical lines represent, respectively, the time of ball projection and the time of movement initiation.

& Kisselburgh, 1983). Although the standard deviations were small, response delay times on some live-hitter trials were as short as 90 ms. Latencies were short, considering that the task required the selection of one of two fundamentally different responses. Latencies are generally thought to increase as the number of response alternatives increases (see Keele, 1986, for a review). In previous research (Gibson & Adams, 1989) comparing balls pitched by performers and machines in cricket, differences have been found in the timing of critical events of the batsman's swing. Some events (foot movements) occurred earlier for balls thrown by the machine, and some events (backswing) occurred earlier for balls thrown by the pitcher. Gibson and Adams concluded that the batsman had more information from the machine than from the pitcher because the batsman could see the changes in machine position between trials. In the present experiment, the aim points of the ball machine and the hitter were not available before ball release, and the data indicated that players had more information from the hitter than from the machine.

GENERAL DISCUSSION

The findings from the present experiments support the results of a growing body of literature showing that expert performers can anticipate future events on the basis of their opponent's movement pattern. That outcome has been obtained in a number of activities in which verbal or written responses from projected images were used. Using a perception–action approach in which performers were required to produce task-appropriate actions both spatially and temporally, we demonstrated in Experiment 1 that both novice and skilled players can anticipate tennis groundstrokes from precontact visual information at much higher than chance levels and that skilled players are significantly more accurate than novices. The results of Experiment 2 demonstrated that experts are able to take advantage of the precontact visual information under playing conditions by reacting significantly faster when that information is available.

A more detailed visual display was helpful for skilled but not for novice players. The ability of skilled players to obtain additional information in the live-hitter but not from the two projected visual conditions (video and point-light) suggests that the information needed to perceive subtle visual cues during an action may not be available from point-light or video displays. That finding is consistent with the argument of Bruno and Cutting (1988) that when more visual information is made available, it is used in an additive fashion, but that appears to hold true only if observers have experience with the task. Skilled players were marginally, and not significantly, more accurate than novices in the point-light condition, and that finding is consistent with the results of Ward et al. (2002). Practice is an alternative explanation for the superior performance of experts with a live hitter. On the one hand, skilled players have had millions of trials reacting to a live player returning a ball, but they have had no experience observing point-light displays. Novices, on the other hand, have had little practice at any of the display conditions. The practice hypothesis corresponds to the experimental findings; novices had similar anticipation success for each of the displays, and skilled players and novices anticipated similarly with the novel point-light display. The greater anticipation accuracy for novices with the point-light display than with the live and video displays, although small, suggests that that type of display may be effective for providing movement coordination information to learners (Scully & Carnegie, 1998).

The experimental results provide partial support for the findings of a number of previous studies that have demonstrated that individuals can perceive motor actions accurately with limited visual information and without the benefit of figural information (e.g., Barclay, Cutting, & Kozlowski, 1978; Bingham, 1993; Cutting, 1978; Johansson, 1973; Kozlowski & Cutting, 1977; Runeson & Frykholm, 1983). Johansson was the first to suggest that the kinematic patterns provided by point-light displays allow observers access to the invariant features of a motion, enabling them to perceive it unambiguously. That suggestion is consistent with the performance of novice players, but skilled players were able to obtain additional information from video and live displays. The ability to extract additional information from a live or video display may be related to the type of action being examined. In most of the experiments in which point-light displays have been found to be effective, motions that were mostly planar, such as locomotion and lifting a weight, were used. The rotational motions produced in the tennis stroke may result in ambiguous visual information when viewed from a point-light display. Abernethy and colleagues (Abernethy et al., 2001; Abernethy & Packer, 1989) have also demonstrated reduced perceptual accuracy with point-light displays in sport tasks.

In an actual tennis match, players appear to anticipate infrequently; rarely do they anticipate incorrectly, and when they do anticipate, it is because their opponent is very close and the players' combined reaction and movement time is too long to allow them to reach the ball. Instead, it appears that players wait until they have sufficient information about the ball's direction before moving. That strategy was evident in Experiment 2. Of the 480 trials (8 participants $\times$ 2 conditions $\times$ 30 trials), there appeared to be no false alarms. That is, participants did not move before the hitter contacted the ball, and they did not move the racquet in one direction, realize their error, and move back in the direction of the ball. The lack of anticipation errors is remarkable, considering the short response latencies observed.

The data from Experiment 2 are consistent with the notion that response latencies decrease when the nature of the response or amendment is known or is highly probable. Investigators have typically examined visual amendment latencies by using discrete aiming movements of the hand to a target (see Carlton, 1992, for a review). In aiming tasks, participants generally produce an initial submovement that ends short of the target in 2D aiming and short of and above the target in 3D aiming (e.g., Carlton, 1981; Chua & Elliott, 1993; Elliott et al., 1999). The initial undershooting of the target leads to movement adjustments that are highly predictable, resulting in short, visually based, amendment latencies. Players appear to use kinematic information from their opponent's movement pattern in much the same way. Information from the swing kinematics increased the predictability of the direction of the shot and reduced the players' reaction latency.

The short latencies observed in Experiment 2 are also consistent with the position of Milner and Goodale (1995) that there are two separate visual streams, one for perception (ventral system) and one for the visual guidance of motor behavior (dorsal system). Speed is one of the primary distinctions between those two systems. The dorsal system is characterized by shorter latencies (see Norman, 2003, for a review). Tight coupling between perceptual and motor components, along with a considerable amount of experience and practice, would lead to dorsal system functioning and short temporal delays. It has been argued that typical reaction time tasks in which standard key press or joystick responses are used are perceptual decision tasks (Michaels, 2000) and therefore are controlled by the ventral system. Thus, short temporal delays for the guidance of movement, such as those seen in Experiment 2, are consistent with the two visual streams account of the use of visual information for perception or action (Michaels; Milner & Goodale; Norman). It is interesting to speculate whether visual input from point-light displays is processed by the ventral stream and provides for perception or is processed by the dorsal stream in support of action. In the present experiments, however, we did not directly address that issue.

It is interesting that skilled players showed a good deal of individual differences in anticipation accuracy in Experiment 1 but fairly high consistency in latencies in Experiment 2. The greater performance consistency in Experiment 2 may have resulted from the higher level of skill of those participants. Because different players were used in the two experiments, it is not possible to determine if the players who were most accurate in anticipation also had the shortest response latencies. Differences in anticipation accuracy may be related to conscious strategies used by players. In conversations with the players, some indicated that they concentrated on shoulder turn and some indicated they focused on the legs. The players in Experiment 2 did not report using any specific strategy, just returning the shots as in a normal competitive situation. Manipulation of the visual information presented either by masking portions of the display or by using animations may be useful for determining the nature of the visual information used in this task.

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