Perception–Action Coupling and Anticipatory Performance in Baseball Batting

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ABSTRACT. The authors examined 10 expert and 10 novice baseball batters’ ability to distinguish between a fastball and a change-up in a virtual environment. They used 2 different response modes: (a) an uncoupled response in which the batters verbally predicted the type of pitch and (b) a coupled response in which the batters swung a baseball bat to try and hit the virtual ball. The authors manipulated visual information from the pitcher and ball in 6 visual conditions. The batters were more accurate in predicting the type of pitch when the response was uncoupled. In coupled responses, experts were better able to use the first 100 ms of ball flight independently of the pitcher’s kinematics. In addition, the skilled batters’ stepping patterns were related to the pitcher’s kinematics, whereas their swing time was related to ball speed. Those findings suggest that specific task requirements determine whether a highly coupled perception–action environment improves anticipatory performance. The authors also highlight the need for research on interceptive actions to be conducted in the performer’s natural environment.

Keywords: animations, anticipation, virtual reality, visual processing

In many activities of daily living, humans must perceive and use relevant information from the environment to guide their actions. That ability becomes even more critical in sports that require interception of fast-moving objects. In such sports, performers have to organize motor actions to respond to rapidly changing visual information. Consider the case of a baseball batter trying to hit a ball pitched at 160 km/h. In that situation, the batter has to produce a spatially and temporally accurate bat swing in as little as 400 ms from the time the ball is released. To alleviate such severe temporal constraints, skilled performers are believed to use visual information on the movement pattern of the opponent to anticipate subsequent events. A number of researchers have investigated that ability in a variety of sports, such as badminton (Abernethy & Russell, 1987), baseball (Paul & Glencross, 1997), cricket (Abernethy & Russell, 1984), hockey (Salmela & Fiorito, 1979), soccer (Savelbergh, Williams, van der Kamp, & Ward, 2002; Williams & Burwitz, 1993), and tennis (Goulet, Bard, & Fleury, 1989; Jones & Miles, 1978). In general, experts have been found to be capable of using the visual information from an opponent to predict movement outcome (for a detailed review, see William, Davids, & Williams, 1999).

One limitation of much of the cited work is that the observers in those studies predicted the outcome of the movement by using verbal, written, or button-pressing responses instead of the actual responses that are required when one is normally engaged in those tasks. The separation of perception and action in those studies has been criticized on the basis that the investigators ignored the mutual dependence between perception and action. Gibson (1979) emphasized that coupling by saying that “we perceive in order to move but we must also move in order to perceive” (p. 223). Therefore, attempting to study one aspect while neglecting the other may fail to reveal aspects of either (Turvey, 1977). Ecological psychologists have argued that control of action on the basis of visual information is governed by lawful relations between the information in the environment and the movement that is produced. From that perspective, button-pressing or verbally reporting responses, for example, are uncoupled because parameters such as the direction, scale, or speed of those responses do not relate to the information in the environment (Michaels, 2001). In contrast, the parameters of a natural action would
be influenced by environmental information and would therefore be coupled.

There is also neurophysiological evidence suggesting that those two categories of responses may be different (Milner & Goodale, 1995). On the basis of evidence from clinical studies with neurological patients and studies of the effect of visual illusion on perceptual judgments and actions in normal populations, Milner and Goodale proposed that there are two separate neurophysiological streams involved in visuomotor responding: (a) a ventral stream that is responsible for the identification and classification of the visual stimuli and (b) a dorsal stream that is responsible for the control of motor actions on the basis of the visual stimuli. Thus, the use of uncoupled responses to predict the outcome of a movement may be more indicative of stimulus identification, which primarily involves the ventral stream, than is a coupled response, which primarily involves the dorsal stream.

In a direct examination of the influence of coupled and uncoupled perception–action environments, Farrow and Abernethy (2003) had tennis players predict the direction of tennis serves. The results indicated that coupled responses were significantly more accurate than uncoupled responses, but only if ball flight information was available. On the basis of those results, Farrow and Abernethy suggested that there may be specialized neural circuits for processing ball flight information but not the movement kinematics of the opponent.

We need to raise two issues in the context of those findings. First, if the relative accuracy of coupled and uncoupled responses depends on the source of information used, then the selection of the source of information may be related to specific task demands, including factors such as the complexity of the motor response and the time available to make the response. For example, if the ball is traveling sufficiently slowly and the motor response is fairly simple, then, because ball flight information is more reliable, performers may choose to rely more on that information than on kinematic cues from the opponent. Second, with respect to the effect of movement kinematics of the opponent, Farrow and Abernethy (2003) analyzed only the outcome of the movement response (i.e., the final direction in which the players moved so that they could return the serve). If the control of action is dictated by online changes in visual information, then it seems plausible that anticipatory actions based on the kinematics of the opponent would be reflected mostly in the earlier stages of the motor response. For example, the baseball batter may have to initiate movements such as stepping when very little or no ball flight information is available. Hubbard and Seng (1954) showed that even those preparatory movements were not preprogrammed but were influenced by online visual information. They found that the instant of step initiation correlated with the instant of ball release and that the step duration was correlated with ball speed. Thus, we wanted to investigate the evolution of the entire motor response over time to examine the effect of visual information of the opponent’s kinematics (Savelsbergh et al., 2002).

A methodological concern when one uses a tightly coupled perception–action environment is how to achieve a balance between the degree of coupling and the degree of experimental control. The use of real players in on-field settings provides a maximally coupled environment (e.g., Farrow & Abernethy, 2003; Hubbard & Seng, 1954), but there is a certain loss of control over the kinematics of the opponent because of the inherent trial-to-trial variability in the movements produced. Moreover, to examine the influence of different sources of visual information, one must be able to independently manipulate those factors while keeping the rest of the information intact. For example, to test if the observer is picking up ball flight information, one may have to manipulate the ball flight trajectory independently of the opponent’s kinematics. Such manipulations are difficult to undertake in real environments.

The development of virtual environments has provided an alternative approach. Immersive virtual environments can provide realistic visual information while still allowing researchers the flexibility to independently manipulate objects in the display. Some researchers who have used virtual environments to study catching (Dessing, Peper, & Beek, 2004; Zaal & Michaels, 2003) have focused only on the ball trajectory. To investigate whether visual information of the pitcher provides reliable cues to the batter, we modeled both the ball trajectory and the kinematics of the pitcher. Although there is a certain loss of detail in a virtual environment, previous investigators have shown that the essential information for perceiving biological motion is still preserved in point-light displays (Cutting & Kozlowski, 1977; Johansson, 1973) and animations (Pollick, Fidopiastis, & Braden, 2001).

In the present study, we examined baseball batters’ anticipation abilities to distinguish between fastballs and change-ups in a virtual environment. A fastball is a pitch thrown by the pitcher at maximum speed, and it shows very little lateral deviation from its trajectory. A change-up is a pitch thrown by the pitcher with a reduced ball speed of about 16–24 km/h compared with that of the fastball. The pitcher tries to generate a motion pattern similar to that of the fastball, and the reduction in ball speed results primarily from a change in the grip on the ball. However, significant whole-body kinematic differences between fastballs and change-ups in college-level pitchers have been reported (Escamilla, Fleisig, Barrentine, Zheng, & Andrews, 1998). In the present study, expert and novice batters watched an animation of a pitcher throwing a series of fastballs and change-ups in a virtual environment and responded in two different modes: (a) an uncoupled response mode in which the batters verbally reported the type of pitch thrown and (b) a coupled response mode in which the batters swung a bat to try and intercept the virtual ball. To investigate how batters used the motion pattern of the pitcher and the flight of the ball to regulate their swings, we manipulated
the sources of visual information available to the batter. We used an occlusion technique in combination with dissociation of the pitcher’s and the ball’s motions.

We designed the experiment to test the hypothesis that prediction accuracy is greater for coupled than for uncoupled responses, but only when ball flight is available. Related to that issue, we examined whether greater prediction accuracy is a function of the skill level of the observer. We also tested the hypothesis that coupled responses depend on ball flight information, as suggested by Farrow and Abernethy (2003). We manipulated ball flight and pitching action independently, allowing us to clearly separate dependence on the pitcher’s movement information and dependence on the ball’s flight.

**Method**

The experiment consisted of two phases. In the first phase, we captured the motion of a pitcher throwing fastballs and change-ups and transferred the data into a virtual-reality environment. In the second phase, we presented to the batters the pitches that were produced in Phase 1.

**Phase 1: Motion Capture of Pitcher and Generation of the Animation**

**Participant**

The participant was a male right-handed pitcher on a university baseball team. He had considerable experience in pitching both fastballs and change-ups. The Institutional Review Board of the University of Illinois at Urbana-Champaign approved all protocols.

**Apparatus**

The pitchers stood on an indoor pitching mound of dimensions 2.74 m × 1.22 m × 0.25 m when throwing. We placed a standard size portable home plate 18.44 m (60 ft 6 in.) away from the back of the pitching rubber. We placed a 2.44-m × 2.13-m plywood barrier covered with a soft mat just behind the home plate to stop the thrown ball. We used standard baseballs 9 in. (0.2286 m) in circumference and 5 oz (0.142 kg) in weight in the experiment.

We used a 10-camera motion-analysis system (Motion Analysis Corp., Santa Rosa, CA) to capture the kinematics of the pitcher from the wind-up until his follow through. The sampling frequency was 120 Hz. The pitcher wore a tight-fitting full-body suit that had Velcro strips stitched to it. We then attached lightweight retroreflective markers (diameter = 1.9 cm) to the following 33 sites: the top of the head, the C7 process, the sternal notch, the left scapula, the left posterior superior iliac spine, the L1 process, and the sacrum; and bilaterally at the mastoid process, the acromion process, the belly of the biceps femoris, the olecranon process, midway on the dorsal surface of the wrist between the radial and ulnar styloids, the distal end of the first metacarpal, the distal end of the fifth metacarpal, the greater trochanter, the belly of the rectus femoris, the patella, the lateral malleolus, midway on the lateral side of the fifth metatarsal, and the distal end of the third metatarsal.

We used two standard video cameras (Sony Model DCR-TRV520 and Canon Model DM-G1) to record ball flight. We positioned those cameras on the side at a distance of approximately 20 m from the line joining the pitching mound and home plate. We amplified, rectified, and integrated over a 20-ms window the microphone output from a third camera (Sony Model DCR-TRV520) placed near home plate. We then compared that signal with a criterion sound level set just above room noise by using a bipolar comparator (Coulbourn Instruments, Lehigh Valley, PA). A computer with an analog-digital (A/D) board (National Instruments, Austin, TX) sampled the output from the comparator at 1000 Hz. A schematic of the experimental setup is shown in Figure 1.

**Procedure**

After obtaining informed consent, we attached the reflective markers and allowed the pitcher to go through his usual warm-up drills. The pitcher threw 16 fastballs and 16 change-ups. We simultaneously triggered the motion-analysis system and the A/D board to capture motion and analog data starting from just before the pitcher started his wind-up until he completed his follow-through.

![FIGURE 1. Schematic of experimental setup for capturing the movements of the pitcher.](image-url)
Creating the animation. We selected a total of eight fastballs and eight change-ups for display in the experiment. We selected the trials on the basis of pitch speed. We chose the fastest fastballs and the slowest change-ups. The average time of flight for the fastballs was 522 ms ± 8.4 ms (average speed = 127 km/h), and the average time for the change-ups was 628 ms ± 22.5 ms (average speed = 104 km/h). We modeled the body segments of the pitcher as ellipsoids whose lengths were proportional to the length of the corresponding body segment (Figure 2). We modeled the ball as a white sphere of the same radius as a standard baseball, and no seams or rotations were displayed. The ball was displayed only after the instant of ball release.

Generating ball flight trajectories. To generate the ball flight trajectories, we first determined the time of ball flight. We defined the instant of ball release as the first frame in which the wrist marker of the throwing arm went past the elbow marker in the direction toward home plate (Barrentine, Matsuo, Escamilla, Fleisig, & Andrews, 1998), and we determined the instant of the ball crossing home plate from the microphone signal that resulted from the ball hitting the plywood barrier. We then simulated ball flight trajectories by using equations of projectile motion with the additional assumption that the ball experienced aerodynamic drag in the direction toward home plate throughout its flight. The drag force on the ball is given by $F_d = 0.5 C_d \rho A v^2$, where $F_d$ is the drag force, $C_d$ is the drag coefficient, $\rho$ is the density of air, $A$ is the area of the ball, and $v$ is the velocity of the ball in the horizontal direction. We assumed that the value of the drag coefficient was 0.3 for the given range of ball speeds (Alaways, Mish, & Hubbard, 2001). We iteratively adjusted the initial horizontal velocity until the time of flight matched the actual time of flight. We validated those simulations by comparing them with trajectories we had computed with the direct linear transform (DLT) method (Abdel-Aziz & Karara, 1971). We found the trajectories to be similar on the basis of the criterion that the maximum deviation between the two trajectories was less than 30 cm.

We introduced a white square-shaped flash at the bottom left corner of the display at two instants of time: (a) the instant of ball release and (b) the instant at which the ball got to home plate. The flashes provided the time link between events in the display and the actions of the batter in Phase 2. The participant could not see the flash.

Phase 2: Response of Batters in the Virtual Environment

Participants

The participants in the experiment were 10 male expert baseball batters and 10 novice baseball batters. The experts were batters from a university baseball team. The average age of the experts was 20.2 ± 1.0 years. The participants in the novice group were individuals who were familiar with the game of baseball but had not played baseball at the high school level or higher. The average age of the novice group was 23.3 ± 3.6 years. All participants had normal or corrected-to-normal eyesight, and none of them had any injuries that interfered with their ability to swing a bat. Right- and left-handed batters performed right- and left-handed swings, respectively.
Apparatus

We used a three-sided virtual environment. The projection screens were 2.95 m × 2.03 m (Stewart Filmscreen Corp., Torrance, CA, Model T&G). Two video projectors (EPSON, Long Beach, CA, Power Lite 730 C) rear-projected images on the center screen to the left and right eyes. The two images were polarized 90° out of phase. Batters wore lightweight polarized goggles. The left and right lenses were polarized 90° out of phase so that each eye saw only its corresponding image. That manipulation created the stereoscopic effect for the observer. The images were displayed at a rate of 60 Hz at a resolution of 1024 × 768 pixels.

We placed a photocell near the lower left corner on the projector side of the center rear-projection screen, exactly in line with the location where the flash in the animation occurred. We used a switch mat (Lafayette Instruments, Lafayette, IN) to record the timing of the batter’s step. We placed it on the ground directly under the lead foot of the batter and oriented it along the line of the step that the batter usually took when hitting a ball. To record the instant at which the bat crossed home plate, we used a switch consisting of a laser pointer and a photocell. The photocell was positioned at home plate, pointing upward, at a height of 15 cm. The laser pointer was positioned pointing downward in a vertical line over the photocell at a height of 180 cm. When the bat was swung across home plate, the laser beam was interrupted, causing a voltage change in the photocell. We attached a three-dimensional (3D) accelerometer (Entran Devices, Fairfield, NJ) to the bat at a distance of 65 cm from the handle. For the uncoupled response mode, we used a voice-activated switch to record the time of the batter’s response. A schematic of the experimental setup is shown in Figure 3.

Procedure

We produced six visual conditions by manipulating the visual information available to the batter. The conditions ranged from visual availability of only 100 ms of ball flight (B100) to availability of full visual information, including the pitcher’s motion and complete ball flight (FULL). A complete description of the conditions is provided in Table 1.

![Figure 3. Schematic of experimental setup in Phase 2 for the coupled response mode. 3D = three dimensional.](image)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Time that the pitcher was visible</th>
<th>Time that the ball was visible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball 100 (B100)</td>
<td>Not visible</td>
<td>From release until 100 ms after ball release</td>
</tr>
<tr>
<td>Release (REL)</td>
<td>From wind-up until ball release</td>
<td>Not visible</td>
</tr>
<tr>
<td>Pitcher 100 (P100)</td>
<td>From wind-up until 100 ms after ball release</td>
<td>Not visible</td>
</tr>
<tr>
<td>Pitcher and ball 100 (PB100)</td>
<td>From wind-up until 100 ms after ball release</td>
<td>From release until 100 ms after ball release</td>
</tr>
<tr>
<td>Conflicting 100 (PCB100)</td>
<td>From wind-up until 100 ms after ball release</td>
<td>From release until 100 ms after ball release; ball flight was opposite to the pitch type movement pattern</td>
</tr>
<tr>
<td>Full vision (FULL)</td>
<td>From wind-up until the instant that the ball crossed home plate</td>
<td>From ball release until the ball crossed home plate</td>
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For the B100 condition, we initially displayed the ball in red at the release position. After 3 s, the ball changed color to white and followed the specified trajectory for 100 ms. We used the color change to inform the batter about the instant of ball release. In the PCB100 condition (i.e., the condition with a conflicting throwing motion and ball trajectory), we paired fastball throwing patterns with change-up ball trajectories, and we similarly paired change-up pitches with fastball trajectories. We chose the specific pairing on the basis of ball speed: We combined the movement pattern of the fastest fastball with a ball trajectory from the fastest change-up, and we paired the slowest change-up with the ball trajectory for the slowest fastball.

The batter saw the pitcher from the same perspective as he would have if he had been in a normal batter’s stance. The batter stood at a distance of 3.0 m from the front screen, and the height of the pitcher on the screen was 0.3 m. In that positioning, the visual angle (6°) that is normally experienced in baseball is maintained. To create the effect of the ball coming toward the batter, we adjusted the projected size of the ball so that it corresponded to the same visual angle as an actual approaching ball.

After providing informed consent, the batter stepped inside the virtual environment. We showed the batter examples of one fastball and one change-up in the FULL condition to familiarize him with the virtual environment. We also provided a verbal description of the difference between the two pitches to inform the batter about each type of pitch. We then verbally explained to the batter five of the visual conditions and displayed an example of each condition. Because the batter was not supposed to be aware of the PCB100 condition, however, we neither explained nor displayed that condition to him. We selected the examples for the release (REL; the pitcher was visible from wind-up until ball release), the P100 (the pitcher was visible from wind-up until 100 ms after ball release), and the B100 (the ball was visible from ball release until 100 ms after ball release) conditions from change-ups, whereas we selected the examples for the PB100 (vision of the pitcher from wind-up until 100 ms after ball release, and vision of the ball from release until 100 ms after ball release) and the FULL conditions from fastballs.

There were 8 trials in each of the six visual conditions—4 fastballs and 4 change-ups—in both the coupled and the uncoupled response modes. We randomly selected the trials from a collection of 8 fastball and 8 change-up animation trials. We randomized the order of visual conditions and pitch type for each participant. We blocked the 48 trials in each of the two response modes, but we split them into two blocks of 24 trials. We randomized the order of those four blocks, with the restriction that no two blocks of the same response mode could occur consecutively. We counterbalanced the block order across participants.

In the uncoupled response mode, the batter responded verbally and indicated the type of pitch by saying either “fastball” or “change-up.” We encouraged the batter to make his decision as quickly as possible. In the coupled response mode, we asked him to swing the bat in an attempt to hit the virtual ball and to use a full swing of the bat to maximize bat speed as much as possible. Even in conditions in which we occluded the ball, we asked the batter to time his swing on the basis of whatever information was available. No feedback was provided on whether the batter actually intercepted the ball.

Data Analysis

Pitch prediction. We measured pitch prediction separately for the coupled and uncoupled response modes. For the uncoupled mode, we calculated prediction accuracy as the percentage of responses in which the verbal classification matched the actual pitch type. To allow us to directly compare the uncoupled and coupled response modes, we also classified each swing in the coupled response mode as a fastball or a change-up on the basis of the time between ball release and the time when the bat crossed home plate (crossing time). We tended to classify trials in which the bat crossed the plate earlier in time as fastballs, and swings later in time as change-ups. The algorithm we used to determine swing classification is provided in Appendix A. Because not all the trials within each pitch type were thrown at the same speed, the algorithm adjusted the crossing times to correct for variations in ball flight time within the same pitch type. For the PCB100 condition, we determined the pitch type on the basis of ball speed, not movement pattern. The prediction algorithm makes the swing predictions comparable with the verbal predictions because, in both cases, each response is classified as either a fastball or a change-up. Moreover, just as the verbal prediction can be considered a final outcome of many decision processes, the end result of the action (i.e., the crossing time to classify the swings) is also used in the algorithm.

We used constant timing error to assess the timing accuracy of swings in the coupled response mode. We calculated the constant timing error for each swing by subtracting the instant at which the ball crossed home plate from the instant when the bat crossed home plate. We termed the absolute value of that error absolute timing error. We used the absolute timing error to calculate whether to classify a swing as being appropriate to that type of pitch. We labeled swings with absolute timing errors less than 42 ms as appropriate swings. We calculated the percentage of appropriate swings. We selected the 42-ms threshold by dividing the time difference between the slowest fastball (534 ms) and the fastest change-up (618 ms) by 2. In essence, that criterion was the minimum time that allowed the resolution of whether swings were too late for the fastball or too early for the change-up.

Pitch–swing coupling. We assessed the coupling between the pitch and the swing characteristics of the batter from characteristics of the batter’s step and the swing time. We defined the start of step as the instant at which the lead foot of the batter stepped off the ground. The initiation of step was identified from the change in voltage from the switch.
mat. We expressed the start with reference to the instant of ball release: A positive value indicated that the initiation of the step occurred after ball release. We defined step duration as the time between the start of step and the instant when the lead foot landed back on the ground as recorded by the switch mat.

We defined swing time as the time between the start of the swing and the instant when the bat crossed home plate. The start of the swing was identified from the resultant acceleration obtained from the 3D accelerometer on the bat. Using a double-pass second-order Butterworth filter, we low-pass filtered acceleration data at a cutoff frequency of 15 Hz. We calculated swing time as the time elapsed between the start of the swing (the instant when the resultant acceleration was 5% of maximum acceleration) and the instant when the bat crossed home plate.

Statistical Analysis

We initially used all six visual conditions in the analyses of variance (ANOVAs). Because we found the B100 condition to be qualitatively different (see the first paragraph in the Results section), we dropped that condition from all analyses, which reduced the number of visual conditions to five. We used a $2 \times 2 \times 5$ mixed design ANOVA to analyze prediction accuracy. The between-participant factor was skill (expert, novice), and the within-participant factors were response mode (coupled, uncoupled) and visual condition (Table 1). We used a $2 \times 5$ mixed design ANOVA to analyze the percentage of appropriate swings. The between-participant factor in that analysis was skill, and the within-participant factor was visual condition. Using a $2 \times 2 \times 5$ mixed design ANOVA, we analyzed constant timing error, swing time, start of step, and step duration. The between-participant factor was skill, and the within-participants factors were pitch (fastball, changeup) and visual condition. We conducted Mauchly’s test of sphericity to determine whether there was a violation of the sphericity assumption. When there was a violation, we used the Greenhouse–Geisser correction to adjust the degrees of freedom. We have reported all results that were significant ($p < .05$) and those that tended toward significance ($p < .1$). We conducted post hoc comparisons with Fisher’s protected least significant difference (LSD) procedure. We report partial eta squared ($\eta^2_p$) values for all main effects and interactions as measures of effect size.

Results

Initial examination of the results for all dependent variables revealed qualitative differences in performance for the B100 condition and for all other visual conditions. Pitch prediction was no better than chance; less than 5% of the trials were labeled as appropriate swings, and the start of the step occurred 300 ms later for the B100 condition than for any other one. It is clear that the attempt to cue the batter as to when the ball would appear was not successful. We therefore removed that visual condition from all statistical analyses.

Pitch Prediction

Prediction Accuracy

There was a significant main effect of response mode, $F(1, 18) = 5.48$, $p = .03$, $\eta^2_p = .233$. Accuracy was higher in the uncoupled response mode ($M = 59\% \pm 18\%$) than in the coupled response mode ($M = 53\% \pm 20\%$). The mean delay between the release of the ball by the pitcher and the batter’s verbal response was 814 ms. Having visual information of the entire pitch and ball flight resulted in higher prediction accuracy than did having any sources in which information was missing. A significant main effect of visual condition, $F(4, 72) = 4.61$, $p = .002$, $\eta^2_p = .204$, confirmed that finding. Post hoc comparisons showed that the main effect resulted from (a) the higher prediction accuracy in the FULL condition than in all other conditions except the PCB100 condition and (b) the higher accuracy for the PCB100 condition than for the REL condition ($p < .05$; Figure 4A). The effect of skill and all interactions were not significant.

Constant Timing Error

The analysis of constant timing error also indicated that having more visual information improved pitch prediction. There was a significant main effect of visual condition, $F(2.84, 51.24) = 5.19$, $p = .004$, $\eta^2_p = .224$ (Figure 4B). Pairwise comparisons indicated that constant timing errors were significantly smaller in the FULL condition than in all other conditions except the PB100 condition, and errors were smaller in the PB100 condition than in the REL condition ($p < .05$). As is evident in Figure 4B, experts systematically reduced their constant timing error as more information was provided. In the FULL condition, both experts and novices had the smallest error, indicating that the batters used ball flight information after the first 100 ms to regulate their swing. There was a significant main effect of pitch, $F(1, 18) = 86.54$, $p < .001$, $\eta^2_p = .828$. Timing errors were larger for fastballs ($M = 121 \text{ ms} \pm 88 \text{ ms}$) than for change-ups ($M = 35 \text{ ms} \pm 95 \text{ ms}$). Although skilled performers’ constant timing errors were consistently smaller than those of novices (Figure 4B), the differences were not statistically significant. There were no significant interactions.

Percentage of Appropriate Swings

The analysis of the percentage of appropriate swings indicated no significant main effects, but there was a significant Visual Condition $\times$ Skill interaction, $F(4, 72) = 3.00$, $p = .024$, $\eta^2_p = .143$ (Figure 4C). Post hoc analysis of the interaction indicated that whereas experts generally had a higher percentage of appropriate swings than novices, the effect was significant only in the PCB100 condition ($p < .05$). That finding suggests that experts were able to perceive and use the first 100 ms of ball flight independently of the pitcher’s movement pattern. That result, along with the low percentage of appropriate swings in the B100 condition we noted earlier, suggests that experts can use early ball
flight information—but only when they know the instant of ball release. No other interactions were significant.

**Pitch–Swing Coupling**

The variables we analyzed to investigate the pitch–swing coupling were the start of step, step duration, and swing time. For the start of the step and the step duration variables, we had to exclude the data for 1 expert and 1 novice because they did not step on more than half of the trials when batting. Therefore, the data reported for those two variables are from 9 experts and 9 novices.

**Start of Step**

The analysis indicated a coupling between the movement pattern used by the pitcher and the start of the step. There was a main effect of skill because the experts ($M = -129$ ms $\pm 135$ ms) stepped earlier than the novices did ($M = 63$ ms $\pm 180$ ms), $F(1, 16) = 7.35$, $p = .015$, $\eta^2_p = .315$. There was also a significant Pitch $\times$ Visual Condition interaction, $F(4, 64) = 5.46$, $p = .001$, $\eta^2_p = .255$, and a significant Pitch $\times$ Visual Condition $\times$ Skill interaction, $F(4, 64) = 2.93$, $p = .027$, $\eta^2_p = .155$. Figure 5 shows that experts were consistent in when they stepped. Negative values indicate that the batters started stepping before ball release. Experts stepped earlier before ball release for change-ups and consistently later for fastballs. The exception to that pattern was the condition with conflicting ball flight, PCB100. The reversal in the PCB100 condition indicated that batters coupled the start of the step to the pitcher’s movement pattern and not to ball flight. Post hoc comparisons indicated that experts stepped earlier before ball release for change-ups in the PB100 condition but earlier for fastballs in the PCB100 condition ($p < .05$). That trend was not significant for novices.

**Step Duration**

The analysis of the step duration indicated a coupling to the pitcher’s movement pattern similar to that for the start of the step. The Pitch $\times$ Visual Condition interaction approached significance, $F(4, 64) = 2.33$, $p = .065$, $\eta^2_p = .127$ (Figure 6A). In the PCB100 condition, the general tendency for batters to have longer duration steps for change-ups was reversed; their step duration was significantly shorter for the change-up than for the fastball in that condition ($p < .05$). In contrast, in both the PB100 and the FULL conditions, the batters had longer step durations for the change-up.

**Swing Time**

Supporting the results observed for the analysis of the constant timing error, the analysis of swing time also provided evidence that the batters regulated their swing by using ball flight information after the first 100 ms (Figure 6B) A significant main effect of visual condition, $F(2.83, 50.98) = 5.86$, $p = .002$, $\eta^2_p = .246$ confirmed that finding. Post hoc comparisons showed that swing duration was shorter for the FULL condition than for all other visual conditions ($p < .05$). The main effect of skill also approached significance, $F(1, 18) = 3.32$, $p = .085$, $\eta^2_p = .156$. Experts had a shorter swing time ($M = 222$ ms $\pm 58$ ms) than novices did ($M = 268$ ms $\pm 64$ ms).

**Discussion**

**Coupled Versus Uncoupled Responses**

The results showed that, contrary to findings from Farrow and Abernethy’s (2003) previous study, batters were significantly more accurate in predicting the type of pitch in the uncoupled response mode than they were in the coupled response mode, irrespective of visual condition and skill level. The differences in results may be the consequence of two interrelated factors: task difficulty and response time. In contrast to the players in Farrow and
Abernethy’s study, who had to move in the direction of the serve, the batters in our study had to swing a bat with temporal precision to intercept the ball. That requirement may have made the task relatively difficult, which could account for their low prediction accuracies in the coupled response mode. The uncoupled response may have been relatively unaffected, however, because batters had more time to make their decision. The difference in batters’ response time (measured from the instant of ball release to the initiation of the response) between the uncoupled response mode ($M = 814$ ms ± $248$ ms) and the coupled response mode ($M = 422$ ms ± $86$ ms) was approximately 400 ms. Even if the duration of the swing is added to the response time in the coupled condition (approximately 200 ms), uncoupled responses were still later than coupled responses. That means that in the uncoupled response mode, batters had the advantage of being able to use later ball flight information that provided the most reliable cues and also of having more time to process information.

Farrow and Abernethy (2003) did not report response times for coupled and uncoupled responses, making it difficult to make comparisons. In regard to that issue, it is important to note that if motor actions are delayed in time, they may be organized through the ventral stream instead of the dorsal stream (van der Kamp, Oudejans, & Savelsbergh, 2003). In the current study, the short response times in the coupled response mode and the longer response times in the uncoupled response mode are consistent with the idea that responses are organized, respectively, through the dorsal and the ventral streams (Milner & Goodale, 1995), even though the virtual hitting task may have enhanced the ventral stream’s contribution.

**Effect of Skill**

The finding that there were no significant differences between experts’ and novices’ prediction accuracy in uncoupled responses is in agreement with Farrow and Abernethy’s (2003) results and suggests that differences between experts’ and novices’ uncoupled responses tend to be eliminated when the response is uncoupled. That could be the case especially in tasks in which the kinematic differences of the opponent are minimal, forcing experts to rely on ball flight information.

In the coupled response mode, we found evidence both for and against skill-related differences. When we classified the swings by using a relative criterion (i.e., each participant’s own mean contact time), we found no differences between experts’ and novices’ prediction accuracy. That finding could have been the result of a floor effect caused by the difficulty of the task. Because we did not include the pitcher’s grip or the rotations on the ball in the animation, batters were not able to use those sources of information. The absence of background information also may have hampered their perception of ball velocity. Our speculations are in line with those of Shim, Carlton, Chow, and Chae (2005), who showed that experts are better able to use contextual information in addition to relative motion.
pattern information. Gray (2002) also reported that experts are more adept than novices at using rotational cues from the ball. Moreover, Dessing et al. (2004) observed that virtual-reality environments may not provide sufficient detail to enable participants to optimize performance.

When the performance was analyzed in an absolute sense (i.e., how often the batters got close to hitting the ball), however, differences between experts and novices emerged. When we analyzed the percentage of appropriate swings, we found that experts were more accurate than novices in the PCB100 condition. That finding suggests that experts may have a better calibrated “ballpark response” (cf. Greene, 1972) and are therefore able to produce a distribution of swings that is closer in the region of hitting fastballs and change-ups, even though they may not be able to perfectly discriminate between the two types of pitches. Those results are partly consistent with previous researchers (Burroughs 1984; Paull & Glencross, 1997) who suggested that experts are capable of using the first 100 ms of ball flight to decide on the type of pitch when the instant of ball release is known. Because pitchers can adjust the speed and motion of the ball without large kinematic changes in their overall motion pattern, experts may learn to focus on the ball when producing the bat swing and to ignore the pitcher’s movement pattern because excessive reliance on the movement pattern may hinder rather than facilitate anticipation.

One possible explanation for the experts’ better ballpark responses than the novices’ is related to the swing time. The experts had a swing time that was approximately 50 ms shorter than that of novices. The shorter swing time could have allowed the experts more time to look at ball flight before initiating their swings. Novices, however, did not have that advantage and may have had to rely on the pitcher’s kinematics to make their decisions, although they were not good at using that information. The strategy of delaying the onset of movement to increase viewing time has been shown to improve performance in other interceptive actions for two reasons. (a) Shorter movement times improve temporal accuracy (e.g., Newell, Carlton, Kim, & Chung, 1993), and (b) longer viewing times could improve perceptual estimates (e.g., Tresilian, 2005).

Pitch–Swing Coupling

In the present study, we found evidence that experts adjust their movements on the basis of the kinematics of the pitcher. The start of their step, in general, was later for fastballs; in the PCB100 condition, however, the start of their step was later for change-ups. Because the change-ups in the PCB100 condition actually showed the pitcher throwing with a fastball movement pattern, that finding indicates that the experts started their step later when the pitcher’s kinematics corresponded to that of a fastball. The duration of their step was also related to the pitcher’s kinematics: Their step duration was longer when the pitcher used a change-up movement pattern than when he used a fastball movement pattern. It is worth noting that although the experts started to step earlier when facing change-ups (Figure 5), they used longer step durations so that at the instant of stepping back on the ground, they ended up approximately at the same time or slightly later than they did for fastballs (see PB100 and FULL conditions in Figure 6A). The opposite held true for experts when facing pitches in the PCB100 condition (see PCB100 in Figures 5 and 6B).

Those results are contrary to findings of Hubbard and Seng (1954). Their results showed that the start of the step was related to ball release and that step duration was related to ball speed. Hubbard and Seng possibly ignored the role of information from the pitcher’s kinematics when they assumed that the changes in step duration with pitch speed could have resulted only from the batters’ ability to perceive ball speed. In the current study, we manipulated the ball trajectories independently of the pitcher’s kinematics, and the results indicated that both the start of the step and step duration were coupled to the pitcher’s kinematics.

There was, however, an influence of ball flight information on the swing for both experts and novices. The
swing time tended to be shorter by about 20 ms in the FULL condition. That trend was also reflected in the constant timing error data. The errors for fastballs decreased in the FULL condition. Those results suggest that the batters initially started off with a slow swing and then speeded up their swing when they could see more of ball flight. That result is also consistent with findings from Gray (2002) that the swing time was adjusted on the basis of pitch speed.

Overall, the results of this study provide evidence that the prediction accuracy of expert batters is primarily associated with visual information of the ball rather than the movement pattern of the pitcher. However, experts coupled their step and swing initiation to the pitcher’s movements. Although it is unclear whether performers use pitching motion and ball flight sources of information in an integrative fashion or whether they suddenly transition from one source to another, the results indicated that performers are capable of using appropriate information at different time instants when performing the task. Therefore, an examination by researchers of a single source of information such as ball flight may provide an insufficient account of the performers’ behavior. That notion reinforces researchers’ need to study interceptive tasks in tightly coupled perception–action environments that mimic the performer’s natural environment and allow the performer to access different sources of information. Manipulating those sources instead of eliminating them may potentially lead us to a better understanding of the processes involved in interception tasks. The direct manipulation of ball flight in the conflicting ball flight condition in the present study resulted in systematic reversals in stepping patterns for experts and novices. Animation and virtual reality methods provide the ideal environment for creating such manipulations.

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**APPENDIX A**

**Algorithm for Classifying Swings in Each Visual Condition**

(\textit{Note.} Variables shown in bold represent mean values)

For the eight trials in a condition, compute the timing error for each trial \((T_i)\) as the difference between the time when the bat crossed home plate \((C_i)\) and the ball flight time \((B_i)\) as

\[ T_i = C_i - B_i. \]

Let \(T_f\) and \(T_c\) denote the timing errors for the fastball and change-up trials, respectively.

1. Compute the mean ball flight time for the four fastball trials \((B^f)\) and the four change-up trials \((B^c)\) in that visual condition.

2. For each of the fastball trials, compute the adjusted crossing time \((AC^f)\) by adding the mean fastball flight time to the timing error (i.e., \(AC^f_i = B^f + T^f_i\)). Similarly, for each of the change-up trials, compute the adjusted crossing time (i.e., \(AC^c_i = B^c + T^c_i\)). \textit{Note.}\n
3. Group the adjusted crossing times \((AC^f)\) and \((AC^c)\) into one variable \((AC)\) and compute the mean \((AC)\). \textit{Note:} \((AC)\) now contains the adjusted crossing times for all eight trials in the condition and provides the distribution of batters responses.

4. Compare each element of \((AC)\) with the mean \((AC)\). If \(AC_i < (AC)\), then classify the swing as a fastball; otherwise, classify the swing as a change-up. \textit{Note.}\n
Thus, if the batter always tends to swing late, swings that occur earlier than the average crossing time are labeled \textit{fastball} because that swing is relatively early for the batter.

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