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Integrating visual trajectory and probabilistic information in baseball batting

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ABSTRACT

Objectives: The present study examined how pitch probability and visual trajectory information are integrated to guide motor behavior in a simulated baseball batting task.
Design: The reliability of probability information was varied by comparing conditions in which the different simulated pitch types were equiprobable with conditions in which one pitch type had a high probability. The reliability of visual trajectory information was varied by changing the instant at which the simulated ball was occluded (from 50 to 150 ms after pitch release).
Method: In Experiment 1 there were two simulated pitch types (fastball and curveball) while in Experiment 2 a third type (changeup) was added. Repeated measures designs were used in both experiments.
Results: In both experiments, there were significant probability x occlusion time interactions for both batting performance and batting kinematics. Varying pitch probability had a larger effect on batting performance and led to kinematic changes earlier in the swing when the occlusion was early in the ball's flight as compared to when it was late.
Conclusions: Batters can flexibly integrate different sources of information based on their relative reliability and the time at which they become available during the course of the swing.

1. Introduction

When performing a fast interceptive action like hitting a baseball or cricket ball there are three distinct types of information a performer can use: situational probabilities, advance cues and visual information from the ball's trajectory (reviewed in Muller & Abernethy, 2012). In the context of sport, the term *situational probabilities* refers to the fact that the probability of different events (e.g., a pitcher throwing a fastball) varies as function of the game situation (e.g., the number of balls and strikes aka "the count"; Abernethy, Gill, Parks, & Packer, 2001). It is proposed that through knowledge of the relationship between event probability and game situation in their particular sport, a skilled athlete can reduce event uncertainty by preparing a movement for the highest probability event (Gottsdanker & Kent, 1978). The term *advance cue* is used to refer to any aspect of the behavior (in particular, the movement kinematics) of an opponent that can be used to anticipate trajectory. For example, advance cues in baseball batting include: variations in the hand position at the point of ball release (e.g. a "skinny wrist" for a curveball) as shown in Fig. 1 and the pitcher's rate of arm movement (sometime slower for changeups compared to fastballs) (Williams & Underwood, 1970). Finally, once the ball begins moving, there are several potential sources of *visual trajectory information* (e.g., the rate of expansion of the ball's image size) that can be used to control the action (Watts & Bahill, 1990).

While there is abundant empirical and anecdotal evidence that skilled performers utilize each of these information sources in isolation (reviewed in Watts & Bahill, 1990; Williams, Davids, & Williams, 1999; Muller & Abernethy, 2012) there has been little previous research which has examined how these different information sources are integrated (for critical reviews, see Cañal-Bruland & Mann, 2015; Loffing & Cañal-Bruland, 2017). Understanding this integration process is important because each of the three information sources described above has limitations. For example, in baseball, skilled pitchers can take advantage of hitters that anticipate the most probable pitch (i.e., "sit on a pitch") by throwing a pitch type with a low probability (e.g., a changeup in a fastball count). Research has shown that even skilled batters can be poor at adjusting their swing in such situations (Cañal-Bruland, Filius, & Oudejans, 2015; Gray, 2002). Similarly, to be effective at the highest levels of sport most athletes have minimized the advance cues they present to their opponent (e.g., a baseball pitcher will practice

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Fig. 1. Grips for different pitch types. Left: fastball (FB), Center: curveball (CB), Right: changeup (CU). Note: these photographs are not what participants actually saw in the batting simulation.

using the same delivery for each different pitch type), as evidenced by expertise research on disguise and deception in sports (Cañal-Bruland & Schmidt, 2009; Jackson, Warren, & Abernethy, 2006). Finally, due to the extreme time constraints in fast-ball sports (with flight times frequently less than 0.5 s) there is limited time to process visual trajectory information before the appropriate motor response must be initiated (Watts & Bahill, 1990).

Muller and Abernethy (2012) have proposed that these different information sources may be combined with the relative importance of each depending on the stage of the action: "the continued refinement of the prediction of flight direction … requires a progressive switching from situational probability information to more localized kinematic sources“ (p.181). In other words, it is proposed that hitters may use situational probabilities to generate an initial prediction about the pitch type (i.e., direction and speed) before the ball is released that is later either confirmed or altered when the pitcher begins his/her delivery and advance cues become available, then potentially adjusted again when the ball is released and visual trajectory information becomes available. A model of this adjustment process for baseball batting was developed by Gray (2009a) and used to explain "check swing" (i.e., stopping a swing after it has been initiated) behavior. According to this model, the relative importance of these different information stages vary as a function of the time since the initiation of the event.

Another factor that would seem to be important in this integration process is the relative reliability of the different information sources. As has been shown for other perceptual processes (e.g., depth perception, Landy , 1995, and multisensory integration, Ernst & Banks, 2002), observers tend to place less weight on information sources that are more variable, noisy and generally less reliable (see also Vilares & Körding, 2011). Presumably, a similar process occurs when performing fast interceptive tasks. For example, a performer might rely less on situational probabilities when an opponent does not have specific tendencies in different game situations or rely less on visual trajectory information when their opponent can serve or throw a ball at a high velocity. To our knowledge, how the usage of probabilities, advance cues, and visual trajectory information varies as a function of reliability has not been studied in previous research.

The goal of the present study was to investigate how two of these information sources (probability and visual trajectory information) are integrated in a simulated baseball batting task. In particular, we sought to determine how varying the reliability of each of these information sources altered their usage, batting performance, and hitting kinematics. Across two experiments, the reliability of probability information was manipulated by comparing conditions in which the different simulated pitch types (e.g., fastball, changeup, curveball) were equiprobable with conditions in which one pitch type had a high probability. The reliability of visual trajectory was varied by changing the instant at which the simulated ball was occluded from the batter's view during its flight (e.g., Higuchi et al., 2016). Advance cues in the form of grip variations for different pitch types were available but their reliability was not varied. It was hypothesized that decreasing reliability of visual information would be associated with an increased reliance on probability information and vice versa.

2. Experiment 1

2.1. Purpose & rationale

The goal of Experiment 1 was to investigate the relative importance of visual trajectory information and pitch probability information in baseball batting by systematically varying the reliability of each of these information sources. The reliability of visual trajectory information was varied by changing the instant at which the ball was occluded from the batter's view during its flight using three occlusion times (Higuchi et al., 2016). The reliability of pitch probability information was manipulated by varying the probability of a fastball from 0.5 to 0.8. The experiment was designed to test the following hypotheses:

i) Batting performance would be significantly better for later occlusion times.
ii) Batting performance would be significantly better for higher fastball probabilities.
iii) There would be a significant interaction between occlusion time and pitch probability in that variations in occlusion time would have a smaller effect on performance when the probability of a fastball was high.
iv) Consistent with the phenomenon of "sitting on a fastball" (Cañal-Bruland et al., 2015), the onset times of the later stages of the swing (e.g., the first downward movement of the bat) would occur earlier as fastball probability increased.
v) There would be a significant interaction between occlusion time and pitch probability in that the change in onset time for the later stages of the swing as a function of fastball probability would be larger for short occlusion times.

2.2. Participants

Twenty male baseball batters completed Experiment 1. All participants were experienced baseball players that played for a college baseball team affiliated with the National Junior College Athletic Association (NJCAA USA) at the time of participation. The sample size of 20 per group was determined based on power analysis (power = 0.8) using the mean effect size ($f = 0.7$) from previous studies comparing similar hitting conditions using the same batting simulator (Gray, 2009a,b; Gray, 2015). The mean age of these participants was 20.2 (SE = 0.6) and the mean number of years of competitive playing experience was 11.9 (SE = 0.5). All participants gave informed consent and the experiment was given ethics approval by the Arizona State University Institutional Review Board (IRB).

2.3. Apparatus

Variations of the baseball batting simulation used in the present study has been used in several previous experiments (e.g., Gray, 2002, 2009a,b, 2004; Gray, 2015). Previous research has shown that for this simulation there is a significant positive correlation between simulated batting performance and batting statistics in league play (average r = 0.65), and training in the simulation results in positive transfer of training to real batting performance (Gray, 2017). Briefly, participants swung a baseball bat at a simulated approaching baseball. The image of the ball, a pitcher and the playing field were projected on a 2.11 m (h) x 1.47 m (v) screen using a Proxima 6850 + LCD projector updated at a rate of 60 Hz. Mounted on the end of the bat [Rawlings Big Stick Professional Model; 84 cm (33″)] and the batter's lead foot (i.e., closest to the pitcher) were sensors from a Fastrak (Polhemus) position tracker. The x, y, z position of the end of the bat and the batter's lead foot were recorded at a rate of 120 Hz. The position of the ball in the simulation was compared with the recording of bat position in real-time in order to detect collisions between the bat and ball. Batters received auditory, visual and tactile feedback about the success of their swing (see Gray, 2009b, for details).

Each trial began with a 10-s view of the playing field and the virtual pitcher in a starting pose. The simulated pitcher then executed a simulated pitching delivery that lasted roughly 3 s before the virtual ball approached the batter. The delivery was identical for all pitch types except for the simulated pitcher's grip on the ball (described below).

Two pitch types were used: (i) a “four seam” fastball (FB) with a speed of 90 mph ± 1.5 mph (40 ± 0.7 m/s), thrown with backspin, and with a spin rate of 1900 rpm, and (ii) a “12–6” (i.e., only movement in the vertical axis) curveball (CU) with a speed of 75 ± 1.5 mph (33.5 ± 0.7 m/s), thrown with topspin, and with a spin rate of 1700 rpm. The grips used by the simulated pitcher for the two pitches are shown in the left and center panels of Fig. 1.

The height at which the ball crossed the plate was at the batter's waist level on every pitch. The lateral location of the pitch when it crossed the plate (X_p) was varied to simulate pitches that were “strikes” (i.e., crossed over the plate) and pitches that were “balls” (i.e., did not cross over the plate). “Strikes” and “balls” were selected randomly for each pitch with a “strike” probability of 0.7. For “strikes”, the value of X_p was chosen randomly between 30 and 75 cm (11.8–29.5″) as measured from the participant's waist. These location values correspond to pitches that would cross the inside edge and outside edges of the plate for a batter standing 30 cm (11.8″) from the plate. For “balls”, the value of X_p was either 20 cm or 85 cm (7.9″ or 33.4″) from the batter's waist with both values having equal probability. Note, the values for all pitches used in this study were based on typical differences found between pitches in major league baseball (http://www.brooksbaseball.net). The probability of each pitch type and the viewing duration were varied as described below.

Participants were instructed to attempt to “achieve as high a proportion of hits as possible within each block of trials where hit proportion was defined as the number of hits/(number of pitches-number of balls)”. It was emphasized to batters that if they did not swing at pitches outside the strike zone they would not be included in the average calculation. The definition of a hit included homeruns and balls that travelled in the air beyond the infield, with a launch angle less than 50 deg, and landed in fair play. This meant that ground balls and pop flies were counted as outs. Strikes also included foul balls, pitches for which the batter swung and missed, and pitches for which the batter did not swing but the ball crossed the plate in the strike zone. Balls were pitches for which the batter did not swing at the ball did not cross the plate in the strike zone. The Major League Baseball (MLB) definition of the strike zone (Triumph Books, 2004) was used to determine balls and strikes: “the strike zone is that area over home plate the upper limit of which is a horizontal line at the midpoint between the top of the shoulders and the top of the uniform pants, and the lower level is a line at the top of the knees”. The motion tracker on the end of the bat was used to determine if the batter swung (i.e., their bat crossed the front of the plate).

2.4. Procedure

Following a 10 pitch practice session, all batters were asked to complete 9 blocks of 20 simulated pitches with 5 min breaks between each block. The 9 blocks represented all possible combinations of 3 occlusion times, (50, 100, 150 ms measured relative to the instant the virtual pitcher released the ball) and 3 probabilities that the pitch would be a fastball (0.5, 0.65 and 0.8). Occlusion times were defined relative to the instant the simulated pitcher released the ball. So, for example, for a pitch with a 100 ms occlusion time, the simulated ball would be visible to the batter from the point of release until 100 ms after release at which time it disappeared from the simulation for the remainder of the simulated flight to the plate. The ball would reappear if the batter made contact and it travelled onto the simulated field. The other parts of the simulated scene (e.g., the pitcher and the field) were always visible for the entire trial. The specific occlusion times used were based on previous research which has shown that beyond 150 ms visual information about the flight trajectory is not used by batters (Higuchi et al., 2016). A simulated scoreboard in the simulation displayed the number of hits and the number of balls they had accumulated during a given block. Participants were told what the occlusion time and fastball probability would be before each block. We chose to explicitly inform participants about the conditions in this manner to avoid them having to learn what the pitch probability was during the block (for alternative approaches, see Mann, Schaefers, & Cañal-Bruland, 2014).

2.5. Data analysis

Batting performance was assessed by analyzing the proportion of hits (i.e., total number of hits/total number of pitches) using a 3 × 3 repeated measures ANOVA with occlusion time and fastball probability as factors. Perceptual-motor control during batting was assessed by analyzing the following temporal variables which previous research (Cañal-Bruland et al., 2015; Gray, 2002, 2009a; Shaffer, Jobe, Pink, & Perry, 1993) has shown to vary as function of pitch type: (i) *Windup onset time*, defined as the instant the batter's lead foot breaks contact with the ground, (ii) *Pre-swing onset time*, defined as the instant the batter's lead foot re-establishes contact with the ground, (iii) *Swing onset time*, defined as the instant at which downward motion of the bat begins and (iv) *Minimum bat height,* defined as the instant in time when the bat reached its minimum height above the ground. These times were analyzed using a 3 × 3 × 4 repeated measures ANOVA with occlusion time, fastball probability and temporal marker as variables.

3. Results

3.1. Batting performance

Fig. 2 shows the mean proportion of hits as a function of occlusion time and fastball probability. The ANOVA performed on these data revealed a significant main effect of occlusion time, $F(2, 38) = 34.9$, $p < 0.001$, $\eta_p^2 = .65$, a significant main effect of fastball probability, $F(2, 38) = 104.3$, $p < 0.001$, $\eta_p^2 = .85$, and a significant occlusion time x fastball probability interaction, $F(4, 76) = 6.4$, $p < 0.001$, $\eta_p^2 = .25$. To further evaluate the interaction, we compared the proportion of hits for the earliest and latest occlusion times (i.e., 50 and 150 ms) separately for all 3 fastball probabilities using a set of Bonferroni corrected pairwise t-tests (critical $p = 0.17$). For both the 0.5 and 0.65 probability conditions the proportion of hits was significantly higher for the 150 ms occlusion time as compared to 50 ms, $t(19) = 9.8$, $p < 0.001$, $d = 2.6$

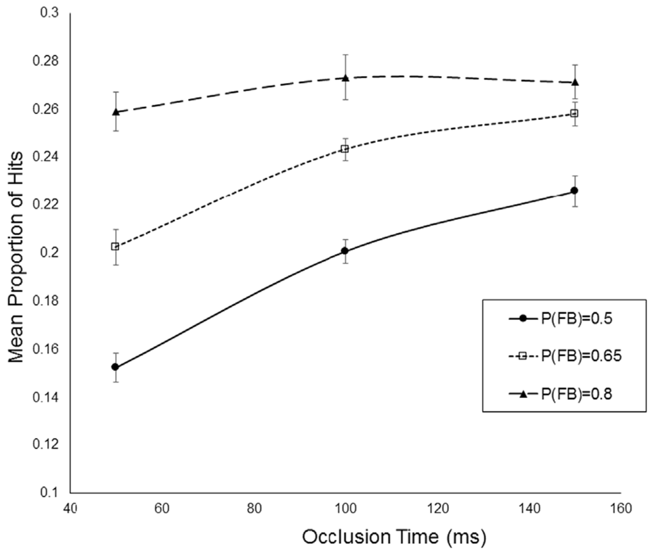

Fig. 2. Mean proportion of hits for the different occlusion time (50 ms, 100 ms, 150 ms after ball release) and fastball probability conditions in Experiment 1. Error bars show ± one standard error.

and $t(19) = 7.2$, $p < 0.001$, $d = 1.9$. There was no significant difference for the 0.8 fastball probability condition, $p = .29$, $d = 0.26$.

3.2. Swing timing

Fig. 3A–C shows the mean onset times for the four temporal markers. The ANOVA performed on these data revealed a significant main effect of occlusion time, $F(2, 38)$ 9.5, $p < 0.001$, $\eta_p^2 = .33$, a significant main effect of fastball probability, $F(2, 38) = 16.5$, $p < 0.001$, $\eta_p^2 = .47$, and a significant main effect of temporal marker, $F(3, 57) = 534.6$, $p < 0.001$, $\eta_p^2 = .98$. There was also two significant two way interactions: occlusion time x temporal marker, $F(6, 114) = 5.5$, $p < 0.001$, $\eta_p^2 = .22$, and fastball probability by temporal marker, $F(6, 114) = 23.6$, $p < 0.001$, $\eta_p^2 = .55$. The occlusion time x fastball probability interaction was not significant, $p = 0.35$, $\eta_p^2 = .06$. These effects were qualified, however, by a significant occlusion time x fastball probability x temporal marker 3-way interaction, $F(12, 228) = 3.6$, $p < 0.001$, $\eta_p^2 = .16$. To breakdown the significant three-way interaction we next performed a simple effects analysis by conducting separate two-way ANOVAs (with fastball probability and temporal marker as factors) for each of the three occlusion times. The results of this analysis are shown in Tables 1 and 2.

As shown in Table 1, for the 50 ms occlusion time (Fig. 3A), there was a significant main effect of temporal marker and a significant fastball probability x temporal marker interaction. The main effect of fastball probability was marginally significant. To further analyze the significant interaction, separate repeated measures ANOVAs were performed for each temporal marker with fastball probability as a factor. As shown in Table 2, this analysis revealed significant effects of fastball probability for all four temporal markers. As can also be seen in Fig. 3A, the direction of the effect was opposite for the early and late temporal markers with the onset time occurring later as fastball probability increased for the windup and pre-swing and onset time occurring earlier as fastball probability increased for the swing and contact. This effect occurred because the swing velocity (shown in Table 3) significantly increased as fastball probability increased, $F(2, 38) = 3.7$, $p = 0.03$, $\eta_p^2 = .26$.

Table 1
Simple effects of analysis of the effects of temporal marker and pitch probability at each level of occlusion time for Experiment 1.

Occlusion Time (ms)	Temporal Marker $F(3, 57)$	Pitch Probability $F(2, 38)$	Marker x Probability $F(6, 114)$
50	347.5*, $\eta_p^2 = .99$	3.2, $\eta_p^2 = .14$, $p = .051$	22.0*, $\eta_p^2 = .54$
100	233.5*, $\eta_p^2 = .98$	15.3*, $\eta_p^2 = .45$	9.1*, $\eta_p^2 = .32$
150	238.7*, $\eta_p^2 = .98$	4.7*, $\eta_p^2 = .20$, $p = .02$	1.6, $\eta_p^2 = .10$, $p = .19$

*$p < .0001$.

Table 2
Simple effects analysis of the effect of pitch probability at each level of temporal marker for Experiment 1.

Occlusion Time (ms)	Temporal Marker	$F(2, 38)$	p	η_p^2
50	Windup	13.7	$p < 0.001$	.41
	Pre-Swing	16.2	$p < 0.001$	.46
	Swing	8.3	$p = 0.001$	.30
	Min Bat Height	21.4	$p < 0.001$	.53
100	Windup	8.6	$p = 0.001$	.31
	Pre-Swing	1.7	$p = .32$	.02
	Swing	1.3	$p = .47$	.04
	Min Bat Height	35.2	$p < 0.001$	.65

For the 100 ms occlusion time (Fig. 3B), there were significant main effects of fastball probability and of temporal marker, and a significant fastball probability x temporal marker interaction. To further analyze this effect, separate repeated measures ANOVAs were performed for each temporal marker with fastball probability as a factor. This analysis revealed significant effects of fastball probability only for swing onset time and minimum bat height. For the 100 ms occlusion time, there was no significant effect of pitch probability on swing velocity, $p > 0.3$, $\eta_p^2 = .02$.

Finally, for the 150 ms occlusion time (Fig. 3C), there were significant main effects of fastball probability and of temporal marker. The fastball probability x temporal marker interaction was not significant. For the 150 ms occlusion time, there was no significant effect of pitch probability on swing velocity, $p > 0.1$, $\eta_p^2 = .1$. Therefore, for the 150 ms occlusion time, the primary effect appeared to be an overall reduction in onset times as fastball probability increased.

4. Discussion

The goal of Experiment 1 was to investigate the combined effects of altering event probabilities (by varying the probability of fastball pitches) and altering the visual information about the flight of the ball (by varying the occlusion time). Consistent with previous research on batting (Higuchi et al., 2016), reducing the occlusion time below 150 ms had a significant negative effect on hitting performance – overall, in the present study, there was a 0.047 difference in the proportion of hits between the 150 and 50 ms occlusion time conditions. Also consistent with previous work (e.g., Gray, 2002), the proportion of hits was significantly higher (by 0.074 on average) when pitch type was predictable (i.e., the fastball probability was 0.8) as compared to when both pitch types were equiprobable. Finally, a novel finding of the present study was the interaction between occlusion time and pitch probability. Specifically, as can be seen in Fig. 2, an increase in the probability of a fastball from 0.5 to 0.8 had a significantly larger effect on the proportion of hits when the occlusion was early in the ball's flight as compared to when it was late.

These changes in batting performance were mirrored by changes in batting kinematics. As predicted, there was a significant interaction between occlusion time, probability and temporal marker. As can be seen in Fig. 3, the effect of changing the fastball probability on swing execution was very different for the three occlusion times. When the batter had a longer view of the ball's flight (i.e., in the 150 ms

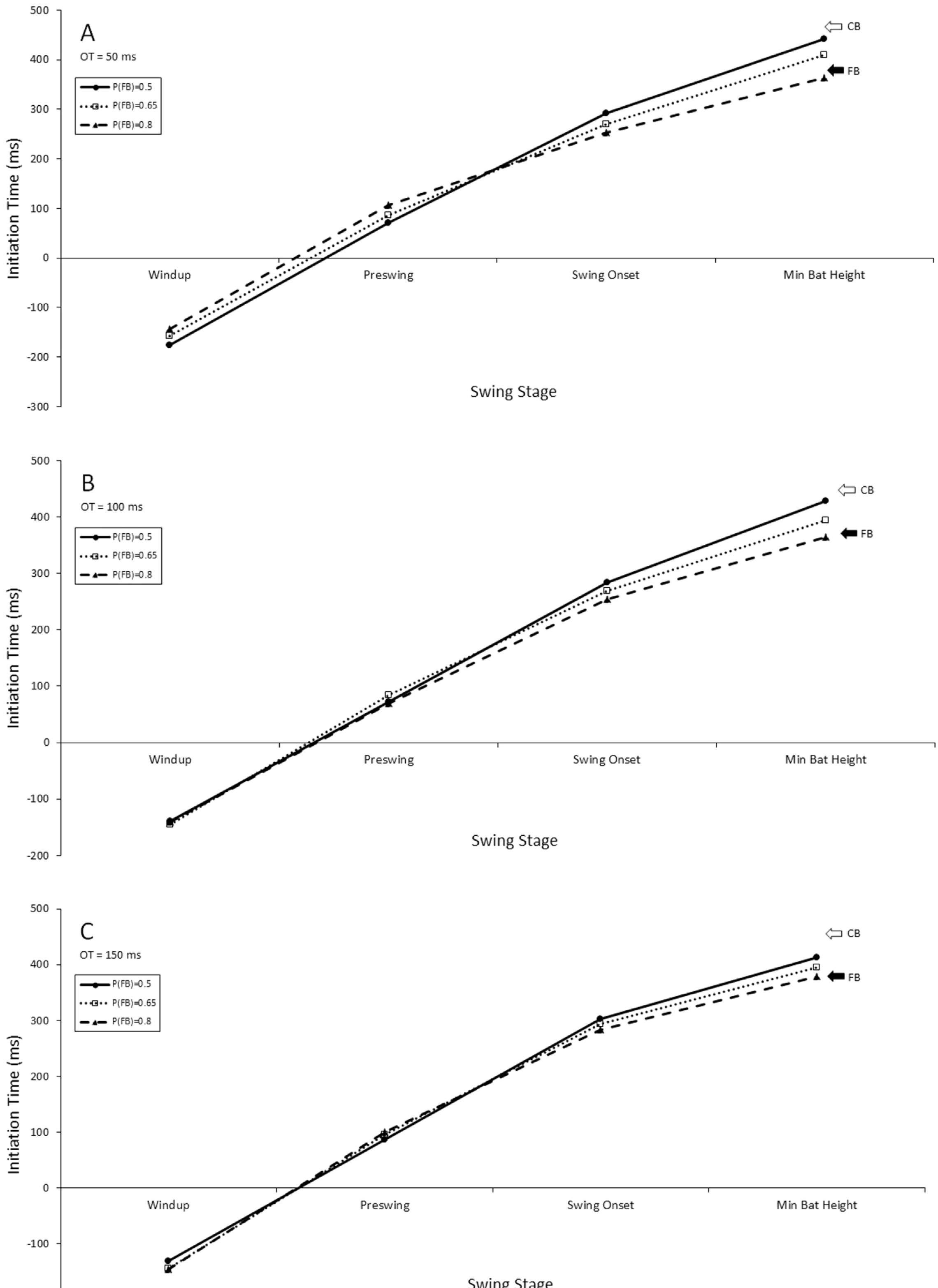

Fig. 3. Mean initiation times for the different swing stages for the 50, 100 and 150 ms occlusion times. Small arrows indicate the times at which the two different pitches crossed the plate.

conditions), increasing the probability of the fastball appeared to result in them starting the initial, windup stage of the swing slightly earlier and then not using pitch probability to alter the relative timing of any of the later stages (as evidenced by the lack of a temporal marker x pitch probability interaction). This would seem to be a reasonable strategy because with the longer occlusion time, batters could presumably use visual trajectory information to alter the later stages of their swing (particularly, the swing onset time). It is also effective because it allows the batter to be ready for faster pitches (by getting things moving earlier when the probability of a fastball is high) while not leaving themselves unable to react to a lower probability curveball.

For the intermediate 100 ms occlusion time conditions, the pattern

Table 3
Mean swing velocity in mph (measured at the point of minimum bat height) for Experiment 1.

Occlusion Time (ms)	p(FB) = 0.5	p(FB) = 0.65	p(FB) = 0.8
50	71.2(SE = 2.1)	74.6(SE = 1.9)	77.0(SE = 1.4)
100	73.4(SE = 1.6)	72.5(SE-2.00	72.9(SE = 1.8)
150	71.8(SE = 2.1)	73.5(SE = 2.2)	72.6(SE = 1.6)

of behavior was highly similar to the "sitting on a fastball" results reported by Cañal-Bruland et al. (2015). Specifically, the early stages of the swing appeared to be unaffected by the pitch probability while the later stages (in particular, the onset of the bat movement) occurred earlier as fastball probability increased. This presumably occurred because the occlusion time was too short to allow batters to alter the later stages of their swing on the basis of visual trajectory information, therefore, they adjusted swing onset time primarily using pitch probability information.

Finally, for the shortest 50 ms occlusion conditions, increasing the probability of a fastball resulted in the early stages of the swing occurring slightly earlier and the later stages occurring slightly later. This occurred because batters both started their windup earlier and swung with a higher velocity as fastball probability increased.

5. Experiment 2

5.1. Purpose & rationale

As discussed above, because many batters have a natural tendency to "sit on a fastball" (Cañal-Bruland et al., 2015) it is possible the higher proportion of hits for higher fastball probabilities found in Experiment 1 occurred because participants used this strategy for all conditions. To address this possibility, in Experiment 2 we used three pitch types (fastball, curveball and changeup). Four probability conditions were compared: one in which all 3 pitches had an equal probability and three in which one of the pitch types had a probability of 0.8 while the other two were equiprobable. These four conditions were crossed with two values of occlusion time (50 and 100 ms). The experiment was designed to test the following hypotheses:

i) Batting performance would be significantly better for later occlusion times.
ii) Batting performance would be significantly better in all conditions in which one of the pitch types had a probability of 0.8 as compared to the equal probability condition.
iii) There would be a significant occlusion time × probability interaction in that variations in occlusion times would have a smaller effect on performance for all conditions in which one of the pitch types had a probability of 0.8 as compared to the equal probability condition.
iv) The onset times of the later stages of the swing (e.g., the first downward movement of the bat) would vary systematically as function of which pitch had the highest probability (e.g., onset times would occur later for the slower changeup than the fastball).
v) There would be a significant occlusion time × probability interaction in that the change in onset time for the later stages of the swing as a function of pitch probability would be larger for short occlusion times.
vi) Consistent with Experiment 1, for the short occlusion time there would be a significant change in the onset time for the early swing stages.

5.2. Participants

Twenty male baseball players that did not participate in Experiment 1 completed Experiment 2. All participants were experienced baseball players that played for a college baseball team affiliated with the National Junior College Athletic Association (NJCAA USA) at the time of participation. The mean age of these participants was 19.9 (SE = 0.8) and the mean number of years of competitive playing experience was 11.5 (SE = 0.9). All participants gave informed consent and the experiment was given ethics approval by the Arizona State University Institutional Review Board (IRB).

5.3. Apparatus & procedure

The apparatus and procedure were identical to that described for Experiment 1 except for the following. The changeup (CU) added in Experiment 2 was a "straight change" that travelled with a speed of 80 ± 1.5 mph (36 ± 0.7 m/s), was thrown with backspin, and with a spin rate of 1800 rpm. The simulated grip is shown in the right panel of Fig. 1. Participants completed 8 blocks of 20 pitches which represented all possible combinations of two occlusion times (50 and 150 ms) and four probability conditions:

(i) p(FB) = 0.33, p(CB) = 0.33, p(CU) = 0.33
(ii) p(FB) = 0.8, p(CB) = 0.1, p(CU) = 0.1
(iii) p(FB) = 0.1, p(CB) = 0.8, p(CU) = 0.1
(iv) p(FB) = 0.1, p(CB) = 0.1, p(CU) = 0.8

Blocks were presented in random order and batters were again given a 5 min break between conditions. As was the case in Experiment 1, participants were told what the occlusion time and fastball probability would be before each block.

5.4. Data analysis

The same performance and timing variables and analyses described for Experiment 1 were used.

6. Results

6.1. Batting performance

Fig. 4 shows the mean proportion of hits as a function of occlusion time for the four different pitch probability conditions. The ANOVA performed on these data revealed a significant main effect of occlusion

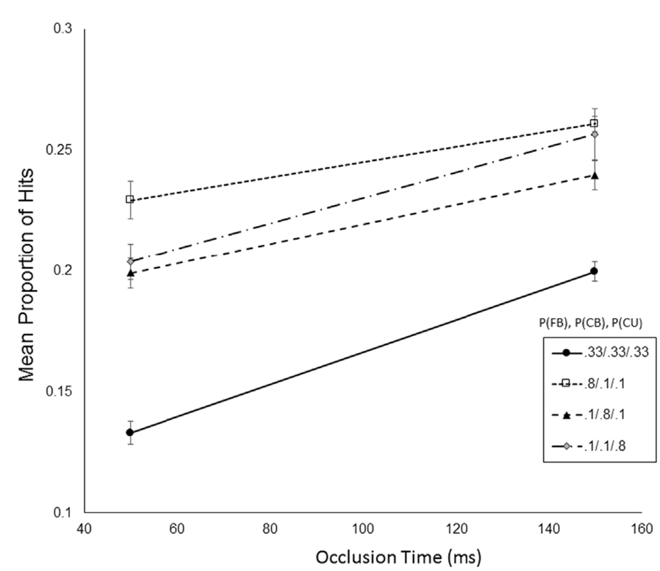

Fig. 4. Mean proportion of hits for the different occlusion time and pitch probability conditions in Experiment 2. Error bars show ± one standard error.

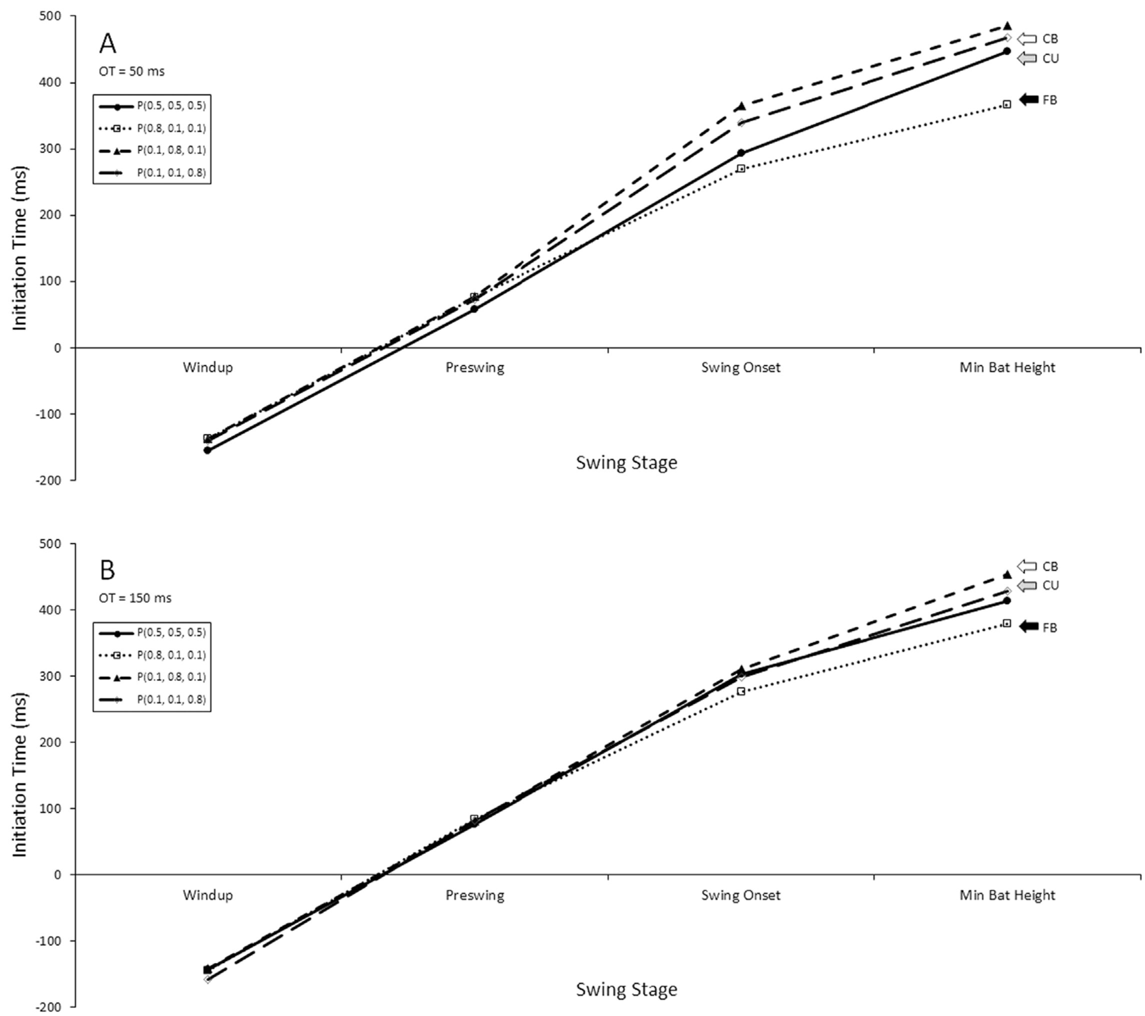

Fig. 5. Mean initiation times for the different swing stages for the 50 and 100 ms occlusion times. Small arrows indicate the times at which the two different pitches crossed the plate.

Table 4
Simple effects of analysis of the effects of temporal marker and pitch probability at each level of occlusion time for Experiment 2.

Occlusion Time (ms)	Temporal Marker $F(3, 57)$	Pitch Probability $F(3, 57)$	Marker x Probability $F(9, 171)$
50	189.9*, η_p^2 = .56	24.1, η_p^2 = .56	7.1*, η_p^2 = .27
100	422.9*, η_p^2 = .98	11.3*, η_p^2 = .37	5.2*, η_p^2 = .21

*$p < .0001$.

time, $F(1, 19) = 93.3, p < 0.001, \eta_p^2 = .83$, a significant main effect of pitch probability, $F(3, 57) = 44.3$, $p < 0.001$, $\eta_p^2 = .7$, and a significant occlusion time x pitch probability interaction, $F(3, 57) = 3.8$, $p = .016$, $\eta_p^2 = .17$. As can be seen in Fig. 4, the significant interaction occurred because the difference in proportion of hits for the two occlusion conditions was significantly higher for the equiprobable pitch probability condition as compared to the other three conditions.

6.2. Swing timing

Fig. 5 shows the mean onset times for the four temporal markers for the two different occlusion conditions. The ANOVA performed on these data revealed a significant main effect of occlusion time, $F(1, 19) = 7.8$, $p = .012$, $\eta_p^2 = .29$, a significant main effect of pitch probability, $F(3, 57) = 32.1$, $p < 0.001$, $\eta_p^2 = .63$, and a significant main effect of temporal marker, $F(3, 57) = 546.1$, $p < 0.001$, $\eta_p^2 = .99$. All of the two significant two way interactions were also significant: occlusion time x temporal marker, $F(3, 57) = 4.7$, $p = .005$, $\eta_p^2 = .2$, pitch probability x temporal marker, $F(9, 171) = 10.9, p < 0.001, \eta_p^2 = .37$, and occlusion time x pitch probability, $F(3, 57) = 6.1$, $p = 0.001$, $\eta_p^2 = .26$. These effects were qualified, however, by a significant occlusion time x pitch probability x temporal marker 3-way interaction, $F(9, 171) = 2.0$, $p = .038$, $\eta_p^2 = .10$. To breakdown the significant three-way interaction, we next performed a simple effects analysis by conducting separate two-way ANOVAs (with pitch probability and temporal marker as factors) for each of the three occlusion times. The results of this analysis are shown in Tables 4 and 5.

For the 50 ms occlusion time (Fig. 5A), there were significant main

Table 5
Simple effects analysis of the effect of pitch probability at each level of temporal marker for Experiment 2.

Occlusion Time (ms)	Temporal Marker	$F(3, 57)$	p	η_p^2
50	Windup	1.9	$p = .58$	.03
	Pre-Swing	82.7	$p = 0.03$	.18
	Swing	18.6	$p = 0.001$	.50
	Min Bat Height	14.4	$p < 0.001$	.43
100	Windup	2.0	$p = .52$	.07
	Pre-Swing	1.3	$p = .68$	.08
	Swing	4.5	$p = .007$	.19
	Min Bat Height	9.7	$p < 0.001$	.33

Table 6
Mean swing velocity in mph (measured at the point of minimum bat height) for Experiment 2.

Occlusion Time (ms)	p(FB) = 0.33, p(CB) = 0.33, p(CU) = 0.33	p(FB) = 0.8, p (CB) = 0.1, p (CU) = 0.1	p(FB) = 0.1, p (CB) = 0.8, p (CU) = 0.1	p(FB) = 0.1, p (CB) = 0.1, p (CU) = 0.8
50	72.6(SE = 1.5)	76.9(SE = 1.7)	70.7(SE = 1.5)	71.5(SE = 2.1)
100	72.5(SE = 2.1)	71.8(SE = 1.9)	72.5(SE = 2.1)	73.0(SE = 2.3)

effects of pitch probability and of temporal marker and a significant probability × marker interaction. To further analyze the significant interaction, separate repeated measures ANOVAs were performed for each temporal marker with pitch probability as a factor. This analysis revealed significant effects of pitch probability for pre-swing onset time, swing onset time, and minimum bat height. There was also a significant effect of pitch probability on swing velocity (shown in Table 6), $F(3, 57) = 17.2$, $p < 0.001$, $\eta_p^2 = .38$, with swing velocity being significantly higher in the condition in which the fastball had a higher probability.

For the 100 ms occlusion time (Fig. 5B), there were significant main effects of pitch probability and of temporal marker and a significant probability × marker interaction. To further analyze the significant interaction, separate repeated measures ANOVAs were performed for each temporal marker with pitch probability as a factor. This analysis revealed significant effects of pitch probability for only swing onset time and minimum bat height. There was no significant effect of pitch probability on swing velocity, $p = .41$, $\eta_p^2 = .04$.

7. Discussion

The goal of Experiment 2 was to determine if the interactions between pitch probability and occlusion time observed in Experiment 1 would still occur if the probability of pitch types other than a fastball were varied. The findings suggest that this was indeed the case. In Experiment 2, the effect of varying the occlusion time on batting performance was significantly influenced by the pitch probability. Specifically, when one of the three pitches had a high probability the effect of reducing occlusion time (on average a −17% change in the proportion of hits) was much smaller than the comparable effect for the condition in which all pitches were equiprobable (on average a −55% change in the proportion of hits). In other words, and similar to Experiment 1, batters in the present study could partially offset the performance decrements produced by decreasing the reliability of visual trajectory information by using pitch probability information. It is further important to note that the batting performance effects did not differ significantly depending on which of the pitch types had a probability of 0.8.

Results similar to those found for Experiment 1 were also found for the batting kinematics in Experiment 2. Specifically, for the short 50 ms occlusion time batters appeared to adjust both the timing of early and late stages of their swing and their swing velocity. While for the longer 100 ms occlusion time batters primarily used pitch probability information to adjust the later stages of their swing, the early stages and the swing velocity were not influenced by pitch probability.

Finally, it is interesting to consider the effect of adding an additional pitch type in Experiment 2. As predicted by Hicks-Hyman law, adding an additional pitch type the batter has to look for should result in a decline in performance. To address this, we compared the proportion of hits in the conditions in the two experiments for which p(fastball) = 0.8 and occlusion time = 100 ms. An independent samples t-test revealed that for these conditions the proportion of hits was significantly lower in Experiment 2 than in Experiment 1, $t(38) = 2.3$, $p = 0.03$. Therefore, even when the fastball probability and occlusion times were identical, adding an additional pitch did have a negative effect on batting performance.

7.1. General discussion

For many of the actions involved in sports there are multiple sources of information that can be used to control movement. These information sources, which include situational probabilities, advance cues and visual trajectory information, can vary in both the time relative to the start of the event at which they are available and their relative reliability/saliency. Therefore, being able to flexibly integrate these different information sources would seem to be critical for successful performance. When all sources of information are reliable it has been proposed that an effective strategy would be to use information that becomes available later in the event to confirm or alter predictions based on information available early (Gray, 2009a,b; Muller & Abernethy, 2012). But, when one (or more) of the information sources is less reliable the most effective strategy would be to weight the reliable sources more heavily in the information integration process as has been shown, for instance, for perceptual judgements (e.g., Ernst & Banks, 2002). Given the potential importance of this integration process, it is not surprising that there have been recent calls for research on skilled performance to move away from studying these information sources in insolation (Cañal-Bruland & Mann, 2015; Loffing & Cañal-Bruland, 2017).

In the present study, we examined the integration of probability and visual trajectory information in baseball batting. There were several important findings that emerged. First, as would be predicted based on studies that have examined the various sources of information in isolation (e.g., Gray, 2002; Higuchi et al., 2016), batters appeared to make use of both sources: the proportion of hits improved both when occlusion time occurred later and one pitch type had a higher probability than the others. In both experiments the best batting performance occurred in the conditions with the combination of the latest occlusion time and one pitch having a high probability. Second, when the reliability of both sources was high, they appeared to be used at different time points during the action. Specifically, for the latest 150 ms occlusion time, batters appeared to only use pitch probability information to adjust the early stages of their swing (e.g., their leg kick) while presumably relying on visual trajectory information to alter the later stages (e.g., the onset of bat movement) if necessary. Finally, how the different information sources were used depended on their relative reliability. Specifically, in both experiments, pitch probability had a significantly greater effect on both batting performance and swing timing when occlusion times were shorter.

The analysis of swing kinematics from the two experiments revealed that the manner in which batters adjust their movement in response to the manipulation of the reliability of information sources can be quite complex. Across experiments, batters used a variety of different adjustments to their swing including: (i) altering movement onset time without changing the relative timing of the different stages of the swing, (ii) keeping the initial stage of the movement the same, but instead making adjustments to the later stages, and (iii) varying the swing velocity. As discussed in detail above, on the surface, all of these adjustments seem reasonable given the different constraints faced by the batters. However, it will be important for future research to investigate how these different kinematic changes relate to performance outcomes.

While the present study thus provides first empirical evidence that probability and visual trajectory information are integrated in baseball batting, several questions remain to be addressed in the future. First, obviously, other than the presence of grip cues, we did not manipulate one of the major information sources available in real batting: advance cues from the pitcher's delivery. Although there was a simulated pitcher, the delivery was identical for each pitch type. It will be interesting to see how the present results might be affected if, for example, kinematic cues (e.g., differences in arm angle as function of pitch type) were added to the simulated pitcher and their reliability was varied.

Second, we did not manipulate the pitch count in the present study so the pitch probability was not dependent on the situational context as it is in real baseball. Other studies have reported that the count or game score, for example, in tennis provides relevant contextual information that influences anticipatory judgments (see Farrow & Reid, 2012).

When performing a fast interceptive action like hitting a baseball there are multiple sources of information an actor can use to get the end-effector to the right place at the right time. A critical issue that has not been addressed in previous research is how these different sources are integrated and how this integration process varies as function of the reliability of the different information sources. In the present study, it is demonstrated that experienced, college baseball players use situational probabilities and visual trajectory information in a flexible manner which depends on their reliability. Furthermore, these information sources are used to adjust different movement components of the swing depending on when the information becomes available.

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