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RESEARCH ARTICLE

Switching tools: perceptual-motor recalibration to weight changes

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Abstract In order to effectively switch between tools, an actor must re-calibrate perceptual-motor control appropriately for the new tool's kinetic properties. This study explored changes in perceptual-motor control in response to switching to a tool of a different weight when performing a complex control task with moving objects. In Experiment 1, 30 participants were each randomly assigned to one of three groups in a baseball batting simulation: a standard group that always used the same bat weight (1.08 kg), a Lighter group that switched from the standard bat to a 0.79 kg bat, and a Heavier group that switched from the standard bat to a 1.36 kg bat. For both the Heavier and Lighter groups, temporal swing errors were significantly larger (as compared to the standard group) in the first block of trials following the bat change. Both groups re-calibrated quickly: within 5–10 trials after the bat change there were no significant difference between the groups. Analysis of swing kinematics indicated that the two change groups used different means for re-calibrating perceptual-motor control: the Lighter group altered swing velocity while the Heavier group altered swing onset time. In Experiment 2, when batters switched from a 0.79 kg bat to a 1.08 kg bat, perceptual-motor calibration depended on the recommended bat weight for each participant (Bahill and Freitas in Ann Biomed Eng 23:436–444, 1995): batters with a heavier recommended weight altered swing velocity while batters with a lower recommended weight altered onset time. The strategy used for perceptual-motor recalibration and time required to re-calibrate in a complex motor task is dependent on the action boundaries of the actor.

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Introduction

In everyday life, we use a variety of tools to interact with objects in our environment. On the sports field we use racquets and bats, in the workplace we use hammers and scalpels, and at home we use forks and brooms. In order for these tools to be used effectively, the actor must be able to calibrate perceptual-motor control to the kinetic and geometric properties of the particular tool being used. For example, the muscle activation required to intercept a baseball with an 86 cm (34′) bat that weighs 850 g (30 oz) is very different from the activation required to intercept a table tennis ball with a 30 cm (12″) racquet that weighs 170 g (6 oz). This perceptual-motor calibration process becomes even more complex when the actor is asked to suddenly switch from one tool to another. Sudden changes in perceptual-motor dynamics can produce proactive interference which can degrade motor learning and the consolidation of motor memories (Brashers-Krug et al. 1996; Tong et al. 2002; Cothros et al. 2006). The present study explored perceptual-motor re-calibration when switching between tools of different weights.

Previous research has shown that actors are highly attuned to the kinetic and geometric properties of tools and can accurately detect these properties from a brief period of dynamic wielding prior to use. In a study by Bingham et al. (1989) actors hefted a set of spherical objects varying in weight and volume and were asked to rate the object for preference in a throwing task. There was a high positive correlation between preference ratings and throwing distance for the set of objects. Carello et al. (1999) asked

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actors to indicate the optimal contact location on baseball bats and tennis racquets of various sizes following a period of dynamic wielding. Perceived locations were highly correlated with the actual location of the "sweet spot" for each tool (i.e., the center of percussion or point of minimum vibration). Finally, Wagman and Carello (2001) asked actors to rate a set of objects for how effectively each object could be used as a hammer. Effectiveness ratings were strongly related to rotational inertia.

This high degree of sensitivity to the action-relevant kinetic properties of tools suggests that actors should be able to quickly adjust perceptual-motor control when asked to switch between tools of differing properties. This question was addressed in a pair of studies by Bongers et al. (2003, 2004). In these experiments, actors were required to walk towards a table, stop, and then move a stationary object on the table using a rod. Rod length, mass and mass distribution were varied randomly from trial to trial and actors were allowed to explore the rod at the beginning of each trial. Actors could effectively adjust their action (both stopping distance and reaching posture) to the characteristics of each rod. In particular, the postural adjustments maintained a synergy between the shoulder and the elbow and the stopping distance was re-calibrated for the rod's length. Consistent with the research on sensitivity to tool properties described above, Bongers et al.'s studies suggest that our perception–action system can immediately reorganize in response to a change in tool properties on the basis of dynamic exploration of the tool alone. In other words, the actor does not have to go through a trial and error process of action execution to be able to switch between tools.

There are some limitations of Bongers et al.'s studies, however. First, adjusting the perception–action system in response to changes in a tool's properties is greatly simplified when interacting with a stationary object. For example, consider a task of hitting a stationary object on a table with the end of a rod. When switching from a long rod on trial n to a short rod on trail $n + 1$, the required adjustment is straightforward—the actor needs to increase arm extension on trial $n + 1$ so that the end of the rod contacts the same location it did on trial n. But what if the task is changed to that of hitting an object that is moving across the table with a random trajectory? The required adjustment when switching from a long rod to a short rod is now not so straightforward—it could involve an increase, decrease or no change in arm extension depending on the particular trajectory of the moving object on trial $n + 1$. When interacting with moving objects the perception–action system needs to be recalibrated in response to a change in tool properties in a manner that will allow control to be effective over a range of object speeds and trajectories. Furthermore, the required re-calibration may not be the same for all object trajectories and speeds. For example, it has previously been shown that actors use movement times (MT) proportional to a moving object's speed (Brouwer et al. 2000). Therefore, when switching from a light tool to a heavy tool it may be possible to maintain the required MT for striking slow moving objects by increasing the force of the movement, while for fast moving objects the actor may not be able to generate enough force to achieve the required (shorter) movement time.

A second, related limitation of these previous studies is that performance accuracy was not measured. The Bongers et al. studies purposely used a task with very low performance demands so that there would be less variance in movement kinematics. However, in many of the tool-use tasks humans perform (e.g., tennis or surgery) there are very small spatial and temporal margins for error involved. In order to effectively adjust to a change in tool properties the actor not only needs to be able to alter perceptual-motor control so that contact between the tool and goal object occurs, but he/she also needs to do so with the spatio-temporal accuracy and precision required for successful performance. Would the adjustments based on dynamic wielding alone observed by Bongers et al. be sufficient if the perceptual-motor control task was more demanding? For example, switching bats in cricket where the margins for error for successful hitting have been estimated at ±2–2.5 ms (Regan 1992).

The ability of actors to suddenly switch between tools with differing kinetic properties has also been studied in the context of baseball batting as this issue has practical significance. It is a commonly held belief by baseball players that completing warm-up swings with a bat that is heavier than the bat used during game play (made so by adding one of a variety of devices such as weighted rings or sleeves to the game bat) will result in a higher in-game swing velocity. A higher swing velocity can be advantageous in baseball because it gives the batter more time to use perceptual information during the ball's flight to judge where and when the ball will cross the plate (Gray 2002a) i.e., if the swing is faster it can be started later. Several studies have provided evidence that is inconsistent with this belief about warming-up with a heavier bat. DeRenne and Braco (1986) asked baseball players to warm-up with bats of various weights (both heavier and lighter than their preferred game bat). This warm-up period was immediately followed by six swings with the preferred game bat. The mean swing velocity for the six swings was significantly lower for warm-up bats that were heavier than the game bat and significantly faster for warm-up bats that were lighter than the game bat. In a follow-up study, DeRenne et al. (1992) performed a more fine-grained analysis and found that maximum bat velocity for a game bat of 850 g (30 oz) occurred when batters warmed-up with a bat that was within ±10% of the game bat weight. Perceived swing velocity (indicated by ratings after each swing) was highest for swings following warm-up with the heaviest bats. Similar results were reported by Otsuji et al. (2002) and Southard and Groomer (2003). An important limitation of these previous studies is that during the measurement phase batters swung at a stationary ball (on a tee or suspended by a string), therefore only swing kinematics could be evaluated. It is not clear from these studies how a sudden change in tool weight affects batting performance and perceptual-motor control.

The purpose of the present study was to investigate changes in perceptual-motor control in response to switching tools in a task involving interaction with a moving object. This was achieved using a baseball batting simulation (Gray 2002a). We modeled our experiment after the paradigm commonly used for prism adaptation experiments (e.g., Held 1965) in that participants switched from a standard bat to a heavier (or lighter) bat and then back to the standard. In order to expand on previous research in this area we measured both kinematic dependent variables (e.g., velocity, movement time) and performance variables (e.g., swing accuracy).[1] We predicted that there would be a decline in batting performance and a change in swing kinematics for the first few swings after each weight change followed a by a rapid re-calibration in perceptual-motor control.

Experiment 1

The purpose of Experiment 1 was to investigate perceptual-motor re-calibration for both increases and decreases in bat weight.

Methods

Participants

Thirty participants (19 male and 11 female) completed Experiment 1. The mean age of these participants was 23.4 (SE = 0.8) and the mean number of years of competitive baseball playing experience was 6.9 (SE = 0.9). Participants were randomly assigned to one of three bat weight conditions as discussed below. The experiment lasted approximately 1 h and participants were compensated $20 for their participation. All participants were naive to the aims of this experiment until the conclusion of their participation, when they were debriefed.

Apparatus

The baseball batting simulation used in the present study has been used in several previous experiments (Gray 2002a, b, 2004, 2009; Castaneda and Gray 2007; Gray et al. 2007). Participants swung a baseball bat at a simulated approaching baseball. The simulated ball was an off-white sphere texture mapped with red laces. The image of the ball, a pitcher and the playing field (shown in Fig. 1) were projected on a 2.11 m (h) × 1.47 m (v) screen using a Proxima 6850+ LCD projector updated at a rate of 60 Hz. Batters stood beside a standard 0.45 m × 0.45 m home plate that was placed on the floor 2.5 m in front of the screen. The area around the plate and the area between the plate and the screen were covered with green indoor/outdoor carpet. Each batter stood on the side of the plate from which they most commonly batted during actual games. Mounted on the end of the bat [Rawlings Big Stick Professional Model; 84 cm (33″), 0.79 kg (28 oz)] was a sensor from a Fastrak (Polhemus) position tracker. The x, y, z position of the end of the bat and the batter's foot were recorded at a rate of 120 Hz. The estimated static positional precision of our tracking system (<0.2 mm) was derived from the standard deviation of 50 samples with the receivers at a constant position. The dynamic precision of the system (<1 mm) was estimated using the method described by Tresilian and Longergan (2002).

For each pitch, the ball was released from the pitcher's hand at a simulated distance of 16.9 m (55.5ft) (Bahill and Karnavas 1993). At the release point the ball subtended 0.24° visual angle. As shown in Fig. 1, a sensation of motion towards the batter was created by increasing the size (defined by visual angle) of the ball. The visual angle of the ball as a function of time since the pitch release (θ_t) was changed according to

$$\theta_t = \frac{0.24}{1 - t/T} \quad (1)$$

where T is the time remaining until the ball crossed the front of plate (determined by the pitch speed as described below). The size of the ball, pitcher and other objects was based on the visual angle subtended by these objects from the batter's perspective. The vertical position of the ball on the display was changed to simulate the drop of the ball as it approached the batter. The height of the simulated pitch $Z(t)$ was changed according to

$$Z(t) = -1/2gt^2 \quad (2)$$

[1] Fajen (2007) conducted a related study on perceptual-motor re-calibration in the task of braking to avoid a collision. In this study, the strength of the brake was suddenly changed (unbeknownst to the participant). Although this study has some important implications for the present work we do not consider it to be the same type of re-calibration process because a brake is not a tool in the same sense.

Fig. 1 Visual display in the batting simulation

where g is acceleration of gravity (9.8 m s^{-2}). The effects of air resistance and spin on the ball's flight were ignored. The ball disappeared from view at a simulated distance of 2.1 m (7ft) from front of the plate (i.e., when it reached the bottom of the screen). Therefore, the batter needed to extrapolate the final part of the ball's motion towards the plate. Note that for the range of pitch speeds used in the present study the ball would be off the fovea in the final 2–3 m before it reached the plate for most batters (Bahill and LaRitz 1984).

All pitches had an extrapolated trajectory that crossed the plate within the batter's strike zone. The Major League Baseball (MLB) definition of the strike zone (Triumph Books 2004) was used: "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". Pitches ranged in speed between 37 m/s (84 mph) and 40 m/s (89 mph) and had underspin (i.e., rotated from the ground to the sky as it approached the plate). The launch angle of the pitch varied between −1 to 1 deg to create different pitch crossing heights. All pitches travelled down the center of the plate.

Each trial began with a 10 s view of the playing field and the virtual pitcher. The simulated pitcher then executed a pitching delivery that lasted roughly 3 s before the virtual ball approached the batter. 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 and visual feedback about the success of their swing. The timing of presentation of this feedback was as follows. If no contact between the bat and the ball occurred an audio file of an umpire saying strike was played over a loudspeaker. If contact between bat and ball was detected the sound of the "crack" of a bat was played at the instant contact was detected and the location of the bat, bat speed, ball speed and bat angle were used to visually simulate the ball flying off the bat (i.e., moving away from the batter) into the simulated playing field. For ball trajectories into foul territory (i.e., outside the simulated playing field), an audio file of an umpire saying "foul ball" was played. For homeruns [(fair balls that traveled further than 107 m (350ft)], an audio file of an announcer's home run call from an actual game was played. The duration between the completion of the feedback and the onset of the pitcher's delivery for the next trial was 5 s.

Bat weight was varied using an adjustable bat weight sleeve (Pro Performance™) that slid over the end of the bat barrel and was held in place with Velcro straps. The sleeve had four pockets that each held small weights of either 70.9 g (2.5 oz) or 141.7 g (5 oz). In this study, the weights were always evenly distributed around the barrel of the bat.

Procedure

All participants began by completing one set of 15 practice trials (i.e., pitches), to allow them to get acclimated to batting simulation. During practice all participants used the standard bat defined as the wooden bat plus four 70.9 g (2.5 oz) weights added in the bat sleeve for a total bat weight of 1.08 kg (38 oz). Following practice, all participants completed two experimental blocks of 15 swings using the standard bat (called Blocks 1 and 2 below). Participants were then given a 5-min break to reduce any fatigue effects. The next two blocks of trials (Blocks 3 and 4) differed among the three groups. Participants were randomly assigned to one of the three Conditions (10 participants/Condition): Lighter (i.e., bat weight reduced), Heavier (i.e., bat weight increased) and a Control group. The control group continued used the standard bat (1.08 kg) for Blocks 3 and 4. The Lighter group completed Blocks 3 and 4 using the bat with all the weights removed resulting in a bat weight of 0.79 kg (28 oz). The Heavier group completed Blocks 3 and 4 using the bat with four 5 oz weights added for a total bat weight of 1.36 kg (48 oz). All participants were then given another 5-min break, followed by two final blocks (Blocks 5 and 6) using the standard bat.

Participants were handed the bat 1 min prior to the start of each block and were allowed to explore the bat in any manner they choose e.g., hefting, practice swings, etc. Note, however, there were no simulated pitches during this interval. No specific instructions were given about how the bat should be explored. It was observed that all batters completed practice swings with the bat before each block began. The number of practice swings ranged from 3 to 6.

Data analysis

Four dependent variables were used: mean temporal error (MTE), mean spatial error (MSE), swing onset time, and bat velocity. MTE is a measure developed by Gray and colleagues (e.g., Gray 2002a) and is defined as the difference between the time the ball crossed the front of the plate and the time when the bat crossed the front of the plate. This measure assumes that the batter is trying to hit the ball at the exact point it crosses the front of the plate. A positive MTE indicates the batter swung too early (i.e., the bat crossed the front of the plate before the ball had arrived) and a negative MTE indicates the batter swung too late. Mean spatial error is defined as the difference in height between the center of percussion of the bat and the center of the ball at the instant when the bat crossed the front of the plate (see Gray 2002a). A positive MSE indicates the batter swung too high while a negative error indicates the swing was too low. Swing onset time (SOT) was defined as the time elapsed between the pitcher releasing the virtual ball and the downward motion of the bat occurring. The criterion for the onset of downward bat motion was identical to that used in previous simulated hitting studies (e.g., Gray 2002a): five consecutive height samples that were lower than the previous sample. Finally, bat velocity was defined as the maximum velocity of the end of that bat that occurred between swing onset and the bat crossing the front of the plate.

MTE and MSE were used to quantify batting performance because previous research has shown that they provide measures that are more sensitive than other variables such as number of hits or home runs (Gray 2002a). SOT and velocity were the two kinematic variables chosen because our previous research had shown that they are two of the primary components of the swing that are adjusted when batters calibrate their swing (Scott and Gray 2007).

The four dependent variables were analyzed using four separate 3 × 6 mixed ANOVAs with Condition (Lighter, Heavier, Control) as the between-subjects factor and Block (1–6) as the within-subjects factor. We conducted planned comparisons between the experimental Conditions (Heavier, Lighter) and Control Condition within each block.

Results

Swing accuracy

Figure 2 shows the MTE (averaged across the 10 participants in each group) for the six experimental blocks. In this figure, a negative MTE indicates that batter swung late (i.e., that bat crossed the front of plate later than the ball) and a positive MTE indicates the batter swung early. For the range of pitch speeds used in the present study, the margin for error for hitting the ball into fair play was roughly ±0.015–0.02 s (Watts and Bahill 1991).

Clearly, the change in bat weight effected performance differently for the Lighter and Heavier groups. The ANOVA performed on MTE revealed a significant Condition × Block

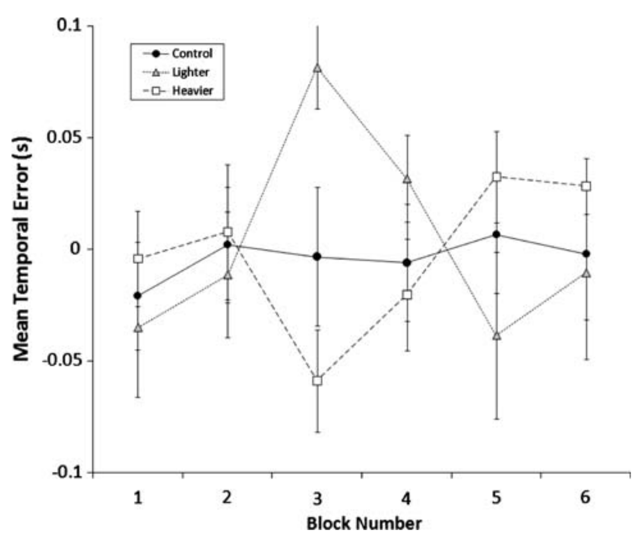

Fig. 2 Mean temporal errors for the six experimental blocks. Each block was comprised of 15 pitches per batter. The “Lighter” and “Heavier” groups switched bat weights between Blocks 2 and 3 and Blocks 4 and 5. *Error bars* are standard errors

interaction [$F(10, 135) = 8.5$, $p < 0.001$]. Neither of the main effects was significant. Planned pairwise comparisons revealed that in Block 3 there were significant differences in MTE between the Control group and Lighter group [$t(18) = -3.8, p < 0.05$] and the Control group and Heavier group [$t(18) = 2.6$, $p < 0.05$]. There were no significant differences in any of the other intervals (p all >0.1).

To further explore batting performance in Blocks 3 and 4, the data for each of these blocks was subdivided into groups of five pitches (e.g., for Block 3, separate means were calculated for the first set of five pitches, the second set of five pitches and the third set of five pitches—labeled 3.1, 3.2, and 3.3, respectively). These data (shown in Fig. 3a) were analyzed using a 3 × 6 mixed factor ANOVA with Condition and Block as factors. This analysis revealed a significant main effect of Condition [$F(2, 27) = 5.4$, $p < 0.05$] and a significant Condition × Block interaction [$F(10, 135) = 4.2$, $p < 0.001$]. Pairwise comparisons revealed that the difference in MTE between the Lighter group and Control group was significant in Block 3.1 [$t(18) = -5.6$ $p < 0.05$] but was not significant in Blocks 3.2 and 3.3 (p both >0.1). The difference in MTE between the Control and Heavier groups was significant in Blocks 3.1 [$t(18) = 2.3$, $p < 0.05$] and 3.2 [$t(18) = 2.1$, $p < 0.05$] but was not significant in Block 3.3 ($p > 0.5$). There was no significant difference between the groups in Blocks 4.1, 4.2, or 4.3 (p all >0.1).

To determine whether the switch back to the standard bat in Block 5 also had an effect on performance, this block was also subdivided into its three component five pitch sets of trials (labeled 5.1, 5.2, and 5.3) as shown in Fig. 3b. Pairwise t tests revealed that the difference between the Control and Heavier groups was significant in Block 5.1 [$t(18) = -4.9$, $p < 0.05$)] but was not significant in either Block 5.2 or 5.3 (p both >0.1). The difference between the Control and Lighter groups was not significant in Blocks 5.1, 5.2 and 5.3 (p all >0.1).

Mean spatial error values are shown in Table 1. A 3 × 6 mixed-factor ANOVA performed on these data revealed no significant main effects nor was there a significant interaction.

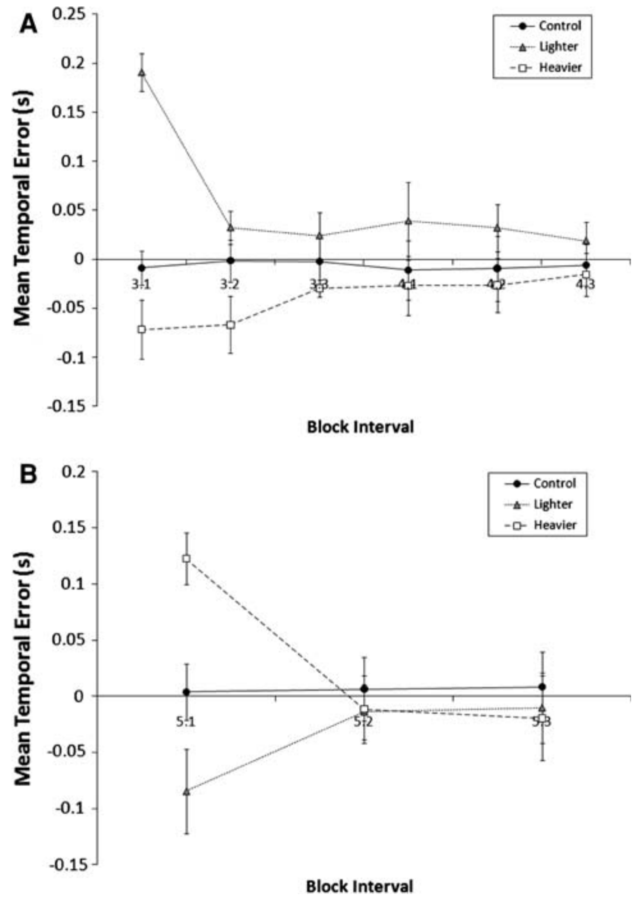

Fig. 3 Temporal batting error data breakdown. **a** Breakdown of Blocks 3 and 4 into fibe-pitch intervals. **b** Breakdown of Block 5 into fibe-pitch intervals. *Error bars* are standard errors

Table 1 Mean spatial errors (cm)

Block	Control	Lighter	Heavier
1	1.79	−1.83	−0.99
2	−1.65	1.91	−1.56
3	−1.87	−1.66	−1.91
4	1.52	1.67	2.03
5	−2.01	1.87	1.65
6	1.88	−2.00	1.78

Bat speed

The mean bat speed for the three different groups is shown in Fig. 4. The 3 × 6 ANOVA performed on these data revealed a main effect of Block [$F(5, 135) = 10.1$, $p < 0.001$] and a significant Condition × Block interaction [$F(10, 135) = 13.4$, $p < 0.001$]. Planned pairwise comparisons revealed that in Block 3, there was a significant difference in mean bat speed for Lighter versus Control [$t(18) = -2.3$, $p < 0.05$] and for Heavier versus Control [$t(18) = 4.3$, $p < 0.005$]. In Block 4, there was a significant difference in mean bat speed for Heavier versus Control [$t(18) = -2.3$, $p < 0.05$]. None of the other contrasts were significant (p all >0.1).

Blocks 3 and 4 were again subdivided into groups of 5 trials. These data for bat speed are shown in Fig. 5a. For this analysis, the main effects of Block [$F(5, 135) = 2.4$, $p < 0.05$] and Condition [$F(2, 27) = 12.7$, $p < 0.001$] were significant as was the Condition × Block interaction [$F(10, 135) = 3.5$, $p < 0.001$]. Mean bat speed was significantly different in Block 3.1 for the Control versus Lighter [$t(18) = -3.4$, $p < 0.05$)] and the Control versus

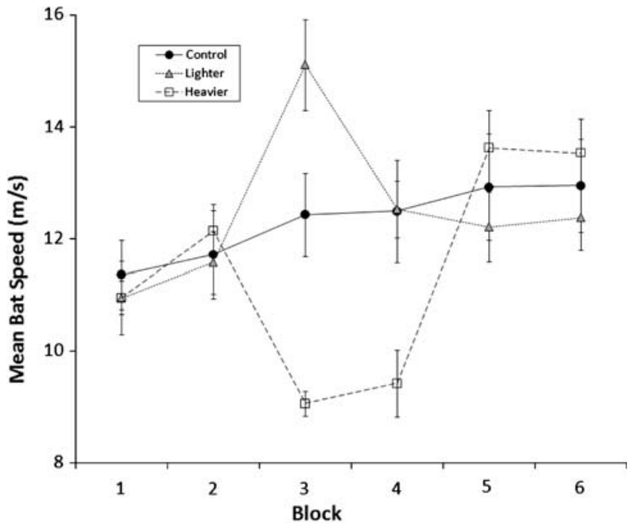

Fig. 4 Mean bat speeds for the six experimental blocks. Each block was comprised of 15 pitches per batter. The "Lighter" and "Heavier" groups switched bat weights between Blocks 2 and 3 and Blocks 4 and 5. *Error bars* are standard errors

Heavier groups [$t(18) = 4.4$, $p < 0.05$]. In addition, the mean bat speed was significantly different for the Heavier versus Control comparisons in Blocks 3.3 [$t(18) = 2.3$, $p < 0.05$] and 4.1 [$t(18) = 2.4$, $p < 0.05$]. None of the other comparisons between blocks was significant.

The breakdown of Interval 5 (shown in Fig. 5b) revealed a significant difference between the Control and Lighter groups in Block 5.1 [$t(18) = 2.4$, $p < 0.05$]. None of the other comparisons between blocks was significant (p all >0.1).

Swing onset time (SOT)

The mean swing onset time for the different groups is shown in Fig. 6. The ANOVA performed on these data revealed a Main effect of Block [$F(5, 135) = 7.3$, $p < 0.001$]. Neither the main effect of Condition nor the Condition × Block interaction were significant. Planned pairwise comparisons revealed a significant difference between the Heavier and Control groups in Interval 4 [$t(18) = 2.5$, $p < 0.05$]. All other comparisons were not significant (p all >0.1).

The breakdown of Intervals 3 and 4 is shown in Fig. 7a. The ANOVA performed on these data revealed a significant Condition × Block interaction [$F(10, 135) = 2.2$, $p < 0.05$]. The difference in SOT between the Control and Heavier groups was significant in Intervals 3.2 [$t(18) = 3.9$, $p < 0.05$], 3.3 [$t(18) = 2.6$, $p < 0.01$] and 4.3 [$t(18) = 2.4$, $p < 0.05$]. None of the other comparisons were significant (p all >0.1).

The breakdown of Interval 5 (shown in Fig. 7b) did not reveal any significant effects nor was the interaction

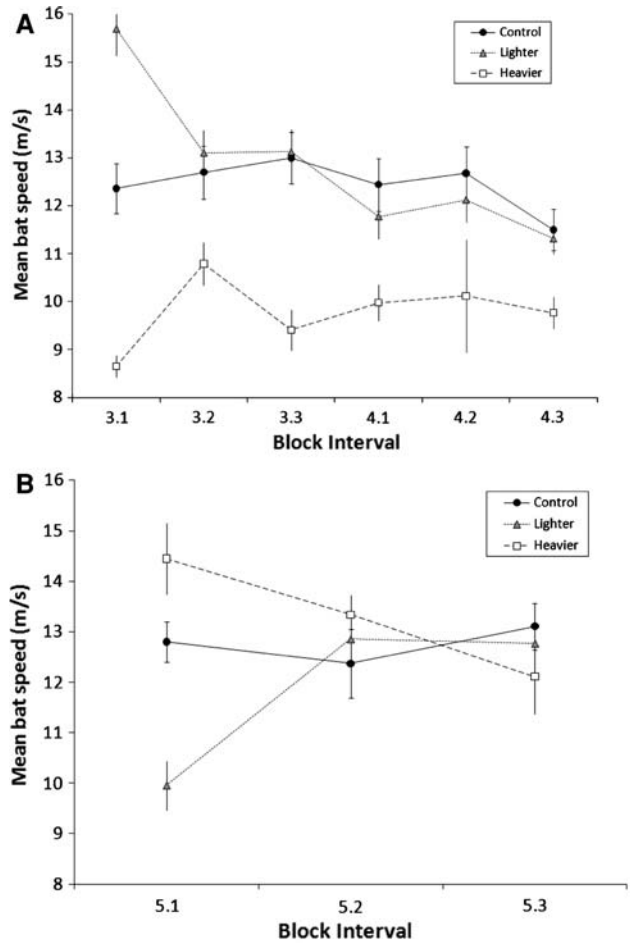

Fig. 5 Bat speed data breakdown. **a** Breakdown of Blocks 3 and 4 into five-pitch intervals. **b** Breakdown of Block 5 into five-pitch intervals. *Error bars* are standard errors

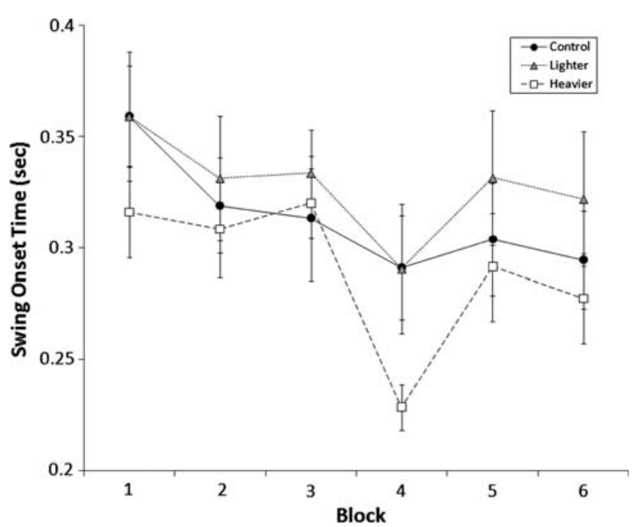

Fig. 6 Mean swing onset time for the six experimental blocks. Each block was comprised of 15 pitches per batter. The "Lighter" and "Heavier" groups switched bat weights between Blocks 2 and 3 and Blocks 4 and 5. *Error bars* are standard errors

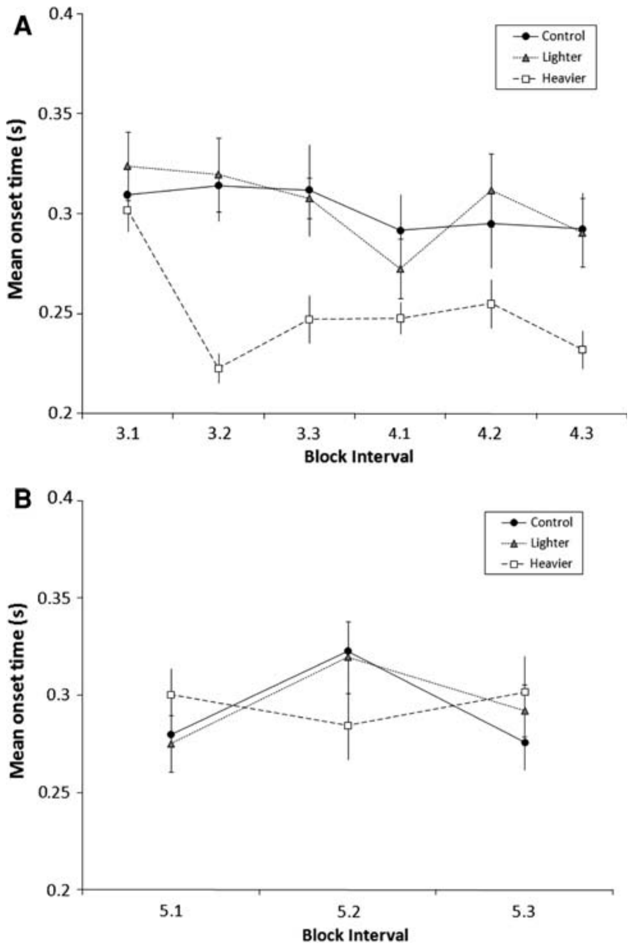

Fig. 7 Swing onset time breakdown. **a** Breakdown of Blocks 3 and 4 into five-pitch intervals. **b** Breakdown of Block 5 into five-pitch intervals. *Error bars* are standard errors

significant. None of the comparisons between groups were significant for any of the Intervals 5.1, 5.2 and 5.3.

Discussion

Experiment 1 investigated the ability of actors to switch tools in a task involving intercepting a moving object: switching between bats of different weights in baseball. As shown in Figs. 2 and 3, both switching to a lighter bat and switching to a heavier resulted in a decrease in the temporal accuracy of the swing. In the first Block of trials after the bat change, participants in the Lighter group swung too early (by 77 ms on average) and participants in the Heavier group swung too late (by 64 ms on average). These differences are quite substantial given that the estimated margin for error for the speed range used in the present study was roughly 15–20 ms (Watts and Bahill 1991). As shown in Table 1, the error produced by the weight change was purely a timing error: changing bat weight did not have an effect on the spatial accuracy of the swing. Presumably spatial accuracy would be significantly affected by a change in bat length and we plan to investigate this in future experiments.

Although the effects of changing bat weight on temporal accuracy were large, they were relatively short lasting. As shown in Fig. 2, there was no significant difference in MTE between the three groups in Block 4. When the data in Blocks 3 and 4 were broken down further, there was a significant difference between the Control and Lighter groups only in Block 3.1, suggesting that the Lighter group adapted to the change in bat weight within five pitches. When comparing the Control to the Heavier group, the difference in Blocks 3.1 and 3.2 were significant, suggesting that the Heavier group adapted to the change in bat weight within 10 pitches. These findings raise some interesting questions: How did batters change perceptual-motor control to reduce the timing errors produced by the change in bat weight? Why did it take longer for batters in the Heavier group to re-calibrate? To address these questions we next turn to the results for the kinematic variables.

As shown in Fig. 4, in Block 3 mean bat velocity was significantly faster following a change to a lighter bat (by 2.7 m/s on average compared to the control group). A more fine-grained analysis (shown in Fig. 5a) revealed that the bat velocity for the Lighter group was significantly different from the Control group only in block interval 3.1. Note that this pattern of bat velocity results for the Lighter group was identical to the pattern of results for MTE. These findings suggest that participants in this group re-calibrated the timing of their swing in response to a reduction in bat weight by reducing bat velocity (back to the rate used with the standard bat). This re-calibration method is somewhat surprising given that a higher bat velocity is generally considered advantageous in baseball batting because it gives the batter more time to use visual information during the ball's flight to judge where and when the ball will cross the plate (Gray 2002a) and generally produces a higher ball speed after contact (Watts and Bahill 1991). However, there are two possible reasons why the increased bat speed associated with the lighter bat would not have been advantageous to the batter. First, it has been shown that the speed of the ball after bat–ball contact is not necessarily increased by increasing bat speed (Bahill and Freitas 1995), instead it depends on particular combination of bat weight and bat speed. Second, if the batter uses a higher bat velocity they may less able to inhibit (i.e., "check") their swing after it has been initiated. Gray (2009) has shown that some form of swing inhibition is used on a high proportion of swings (>40% of all swings in a batting simulation) and the ability to effectively inhibit a swing is positively correlated with league batting statistics for experienced players.

Turning to the Heavier group, bat velocity decreased significantly when participants switched to the heavier bat in Block 3 (by 3.4 m/s on average compared to the control group). As shown in Figs. 4 and 5, unlike the Lighter group, batters in the Heavier group did not appear to re-calibrate their swing by changing bat velocity with the new heavier bat. Mean bat velocity for the Heavier group was significantly slower than for the Control group during Blocks 3 and 4. Why did batters in the Heavier have a significantly slower bat velocity even after several trials with heavier bat? The 1.36 kg (48 oz) bat weight used by the Heavier group was much heavier that is typically used by the amateur baseball players in our study as the highest self-reported game bat weight by our participants was 0.94 kg (33 oz). For the participants in Experiment 1, the recommended bat weights from the mathematical model developed by Bahill and Freitas (1995) ranged from roughly 0.79 to 0.94 kg (28–33 oz). Therefore, it is likely that the required bat velocity for the perceptual-motor calibration used with the standard bat weight could not be achieved comfortably for the full range of pitch speeds following the switch to the heavier bat. This hypothesis is tested directly in Experiment 2.

If batters in the Heavier group did not re-calibrate their swing by changing bat velocity then how did they reduce temporal swing errors from Block 3 to 4? The swing onset time data shown in Figs. 6 and 7 suggests that the Heavier group re-calibrated by changing when the swing was initiated instead of changing swing velocity. During Block 4, batters in the Heavier group initiated their swing significantly earlier (by 62 ms on average as compared to the Control group). The breakdown of Block 3 indicates that this effect occurred after 10 pitches. Note that there were no significant differences in swing onset time when comparing the Control group and Lighter group. This finding provides a likely explanation for the why there was a difference in the number of pitches required for re-calibration between the Lighter and Heavier groups (as shown in Fig. 2a): the two groups adjusted different components of their swing in the re-calibration process.

Overall, switching back to the standard bat in Block 5 had only small and inconsistent effects on batting performance and swing kinematics. Although the pattern of results for swing accuracy in Fig. 1 was what would be expected (i.e., temporal swing errors were in the opposite direction to those observed in Block) the difference was only significant for the Heavier group during the first five pitches (i.e., Block Interval 5.1 in Fig. 4b). Similarly, the change of bat weight from Block 4 to 5 produced only a significant effect on bat velocity for the Lighter group in Block 5.1 (Fig. 5b). Why did the change in bat weight from Block 4 to 5 not produce effects similar in magnitude to those observed for the first bat change? One possibility is that the batters could quickly switch back to the calibration state developed for the standard bat without having to go through any re-calibration process. It has been proposed that if an actor is required to frequently switch between tools they may be able to develop multiple calibration states that can be enacted based on the situational context (Osu et al. 2004). Another possibility is that the 'standard' bat weight may reflect a more optimal weight for subjects and/or may have been more similar to that which had been practiced over a lifetime of baseball batting.

Experiment 2

As discussed above, one limitation of Experiment 1 was that the bat weight used in the Heavier Condition (48 oz) was substantially greater than the typical (and recommended) bat weight for each participant. Therefore, it is perhaps not surprising that participants could not increase their bat speed sufficiently to reduce the temporal swing error. The purpose of Experiment 2 was to investigate adaptations when switching to a heavier bat that was closer to a typical bat weight used during baseball game play.

Methods

Participants

Twenty participants (that were not involved in Experiment 1) completed Experiment 2. The mean age of these participants (14 male and 6 female) was 24.1 (SE = 0.6) and the mean number of years of competitive baseball playing experience was 7.4 (SE = 1.2). The experiment lasted approximately 1 h and participants were compensated $20 for their participation. All participants were naive to the aims of this experiment until the conclusion of their participation, when they were debriefed.

Apparatus and procedure

The apparatus and procedure were as described for Experiment 1 except for the following. In Experiment 2, participants were randomly assigned to one of two groups: Control or Heavier. The Control group used the 0.79 kg (28 oz) wooden bat with no additional weights (i.e., the "Lighter" bat from Experiment 1) for the entire experiment. The Heavier group completed Blocks 3 and 4 using the bat with four 106.3 g (2.5 oz) weights added for a total bat weight of 1.36 kg (38 oz) (i.e., the "Control" bat from Experiment 1).

Data analysis

Data were analyzed using planned comparisons between the Conditions (heavy, control) within each block. The MSE dependent variable was not used in Experiment 2 since it was not significantly affected by bat weight changes in Experiment 1.

Results and discussion

Figure 8a shows the MTE for the six experimental blocks. The pattern of results was similar to that found for the Control and Heavier groups in Experiment 1 (shown in Fig. 2). Switching to the heavier bat resulted in swings that were too late (by 48 ms on average) in Block 3 with this error effectively eliminated in Block 4. Planned pairwise comparisons revealed that in Block 3 there was a significant difference in MTE between the Control group and Heavier group [$t(18) = 3.6$, $p < 0.05$]. There were no significant differences in any of the other intervals (p all >0.1).

The mean bat speed for the two groups is shown in Fig. 8b. For this dependent variable the pattern of results was somewhat different from that found in Experiment 1 (shown in Fig. 4). Similar to Experiment 1, batters in the Heavier group in Experiment 2 had significantly lower mean bat velocity in Block 3 [$t(18) = 5.1$, $p < 0.01$]. However, unlike the results shown in Fig. 4, there was no significant difference between the bat velocity for the Control and Heavier groups in Block 4 ($p > 0.1$). It can also be seen in Fig. 8b that the variability of bat velocity for the Heavier group in Block 4 was much higher than for any of the other Conditions in "Experiment 2". This effect is discussed in more detail below.

The mean swing onset time for two groups is shown in Fig. 8c. Again, the results for this dependent variable were somewhat different from those observed for comparable Conditions in Experiment 1 (shown in Fig. 6). In Experiment 2, there were no significant differences between the Control and Heavier groups for any of the intervals (p all <0.05). Note, also that the variability was again higher for the Heavier group in Block 4 than for any of the other Conditions in Experiment 2.

The large variability in bat speed and swing onset time found in Block 4 for the Heavier group suggests that there were individual differences in the recalibration process following the bat weight change. To address this possibility we compared the values of these two variables in Block 2 (standard bat) versus Block 4 (heavier bat) for each individual batter in the Heavier Condition. These comparisons are shown in Table 2. For bat speed, six of the batters (designated participants 1–6) had a relatively small difference in bat speed (> -0.5 m/s) between Blocks 2 and 4

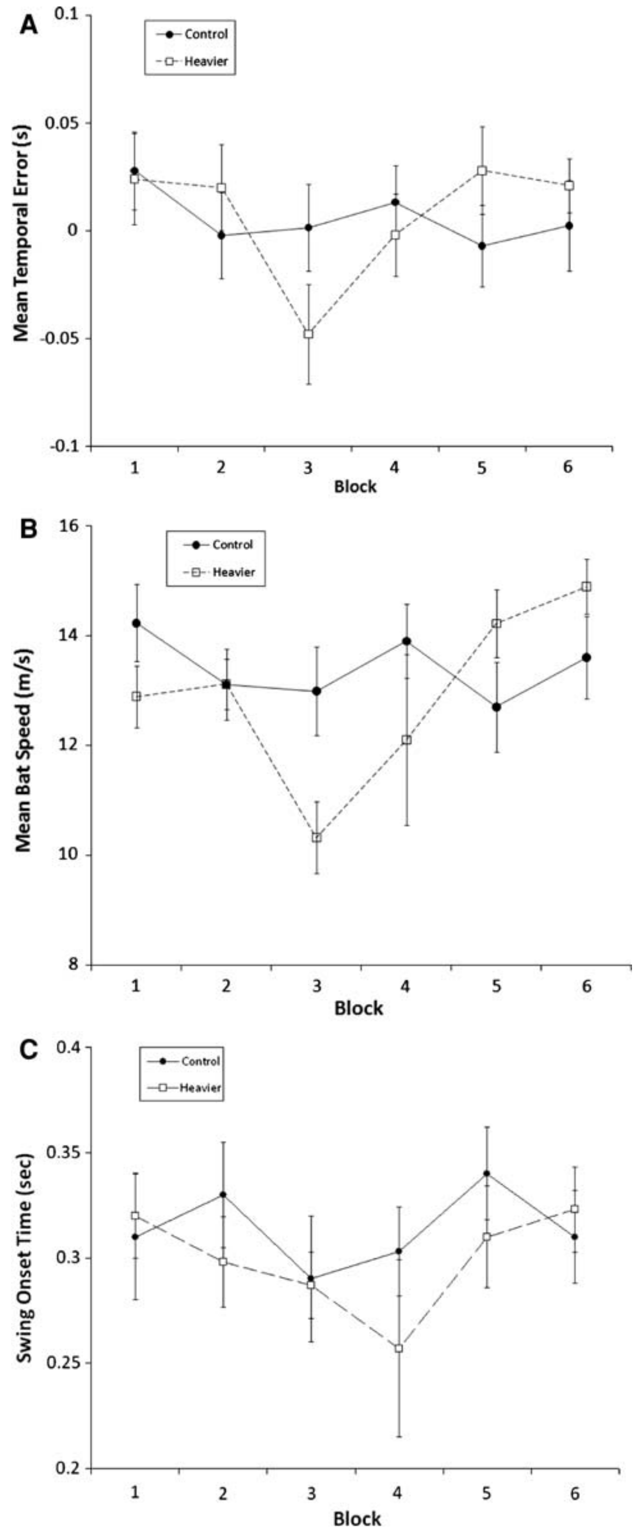

Fig. 8 Experiment 2 data. **a** Mean temporal errors. **b** Mean bat speeds. **c** Mean swing onset times. *Error bars* are standard errors

suggesting that they re-calibrated by increasing speed to that used for the standard. Conversely, four of the batters (designated participants 7–10) had a relatively large

Table 2 Difference between Block 2 and Block 4 for "Heavier" group in Experiment 2

Participant	Speed (m/s)	Onset time (sec)	Recommended bat weight (oz)
1	−0.7	−0.043	31
2	−0.4	0.015	33
3	−0.9	−0.023	32
4	−0.5	−0.06	33
5	−0.5	−0.055	32
6	−0.7	−0.024	32
7	−1.5	−0.089	30
8	−2	−0.08	29
9	−1	−0.049	30
10	−1.3	−0.104	28

difference (< -1 m/s) in bat speed between these two blocks suggesting that they did not re-calibrate by increasing bat speed. For the most part, similar results were obtained for onset time: participants 1–6 had a relatively small difference between Blocks 2 and 4 while the onset time difference for participants 7–10 was larger. This later effect combined with the bat speed results suggests that participants 7–10 re-calibrated by swinging earlier.

Why might individual batters use different strategies for re-calibrating in response to the same magnitude of bat weight increase? Again, we propose that this effect is related to the batter's ability to increase swing velocity with a heavier bat. Shown in the rightmost column of Table 2 is the recommended bat weight for each participant calculated using the model developed by Bahill and Freitas (1995). Correlational analyses revealed a significant positive correlation between recommended bat weight and the Blocks 2–4 difference in bat speed ($r = 0.8$, $p < 0.01$) and a significant positive correlation between recommended bat weight and the Block 2–4 difference in swing onset time ($r = 0.81$, $p < 0.01$). In other words, batters with a lower recommended bat weight tended to have a large (negative) difference in bat speed and swing onset time.

General discussion

Switching between tools of differing kinetic properties poses a challenge to our perceptual-motor system. For example, when playing a long hole a golfer may need to switch from a driver to a 3-iron to a pitching wedge to a putter. These clubs differ in weight, length, weight distribution, and club head angle. How does the golfer adjust the control of their swing when switching from club to club so that the ball is hit with desired trajectory and distance? This switching task would be relatively simple if the golfer could hit several practice shots (in which the ball was actually struck) with each new club, but, of course this is not allowed. Adjustment of perceptual-motor control must occur without actually fully completing the action itself.

Consistent with the observation that expert golfers can effectively switch between clubs, previous research suggests that dynamically exploring a tool is sufficient for successful perceptual-motor re-calibration. Through hefting and dynamic wielding (e.g., practice swings in the golfing example) actors can detect action-relevant properties of a new tool (Carello et al. 1999) and can adjust motor control to achieve success on the first trial with the new tool (Bongers et al. 2003). The perceptual feedback gained through dynamic exploration of a new tool is sufficient to re-calibrate motor action, even in the absence of feedback about the outcome of an action performed with the new tool (Fajen 2007).

In the golfing example described above and in most the research on switching tools, the recalibration process was simplified due to fact that the control task involved interacting with a stationary object. For example, when a golfer switches from a 3-iron to a shorter pitching wedge an obvious control adjustment that will need to be made for the next shot is to stand closer to the ball. When interacting with a moving object, the required adjustment following the tool switch will depend on speed and trajectory of the moving object. In this situation, the actor cannot simply make a pre-planned adjustment to motor control (e.g., stand closer for a shorter tool, use more force for a heavier tool). Instead, he/she must re-calibrate the relationship between the relevant perceptual variables (e.g., time to collision, direction of motion) and the control variables for the motor action (e.g., force, velocity, acceleration, etc). Therefore, the actual adjustment required for the action performed after the tool switch is variable and is not known to the actor until the action begins (i.e., the object starts moving). Furthermore, if the difference between the two tools is large enough (e.g., so that the required movement velocity for some object speeds is now above the maximum velocity that can be produced with the new tool) a new control strategy may be required. Whether dynamic exploration of a tool is sufficient for this more complex type of perceptual-motor re-calibration is not clear from previous research.

Tool switching in a complex interception task

The present study investigated the ability of actors to switch tools in a task involving intercepting a moving object: switching between bats of different weights in baseball. Our results indicate that in this situation actors cannot re-calibrate perceptual-motor control solely on the basis of practice swings alone. In Experiment 1, when batters switched from a 1.08 kg (38 oz) bat to a 1.36 kg

(48 oz) bat, temporal swing errors averaged over the next 15 swings ranged from −58 to −347 ms (i.e., roughly 3–17 times the required margin for error). When batters switched from a 1.08 kg (38 oz) bat to a 0.79 kg (28 oz), temporal swing errors ranged from 36 to 258 ms (i.e., roughly 2–13 times the margin for error). In Experiment 2, when batters switched from a 0.79 kg (28 oz) bat to a 1.08 kg (38 oz) bat, temporal swing errors ranged from −38 to −263 ms (i.e., roughly 2–13 times the required margin for error). Clearly, a sudden change in bat weight has a detrimental effect on batting performance and the batter must use feedback about the outcome of their swing to re-calibrate perceptual-motor control.

How does a batter re-calibrate their swing in response to a sudden change in bat weight? Results from the present study suggest that the nature of the re-calibration process depends on the action capabilities of the batter. One way of quantifying action capability in baseball is the recommended bat weight (Bahill and Freitas 1995): a heavier recommended weight indicates a batter is more capable of generating high swing velocities with a heavier bat. On one hand, when a batter switched to a bat that was lighter than their recommended bat weight (Lighter group in Experiment 1) or was heavier but was within roughly 15–20% of their recommended weight (participants 1–6 in Experiment 2), re-calibration involved adjusting the swing velocity (either increasing or decreasing). On other hand, when a batter switched to bat that was >20% of their recommended bat weight (Heavier group in Experiment 1, participants 7–10 in Experiment 2), re-calibration involved adjusting the swing onset time. (Note that as discussed below, more research is needed to precisely define these action boundaries). Therefore, it appears as though changing bat velocity is the preferred re-calibration strategy. Why might this be the case? We have previously shown that batters alter their bat speed in response to changes in pitch speed while holding the swing onset time roughly constant i.e., they hit faster pitches by swinger faster not by swinging earlier (Gray 2006). Therefore, altering bat speed is more familiar to most batters than altering swing onset time. Consistent with this proposal, the re-calibration strategies in the present study appeared to have different time courses: adjusting bat speed was complete after roughly five swings while adjusting swing onset time required roughly ten swings. These finding provides further support for the idea that action boundaries must be taken into account in models of perceptual-motor control (Fajen 2005).

Practical implications

As discussed above, it is a common practice in baseball for a batter to perform several warm-up swings with a weighted bat before entering the game (DeRenne and Braco 1986). More germane to the present study, during this warm-up period batters also frequently simulate batting by attempting to swing in time with the pitches being thrown in the game (Will 1990). In other words, batters not only dynamically wield the weighted bat during warm-up but they also re-calibrate their swing timing with it. The data shown in Fig. 2 suggests that re-calibrating one's swing with a heavy bat could negatively affect hitting performance by introducing timing errors for the first few pitches when switching to the lighter game bat. However, these negative effects may not occur once the batter has had enough practice switching between the warm-up bat and the game bat because they could potentially develop a stored calibration state (Osu et al. 2004) that could be immediately evoked when using the game bat. Either way, the results of the present study bring into question the value of re-calibrating one's swing with a heavy bat during warm-up. If the batter does not have a game-bat calibration state that can be immediately enacted then swing errors should occur, while if a calibration state does exist re-calibrating using a heavy bat during warm-up should have no effect on performance once the batter switches to the game bat.

Limitations and future research

The results of the present study suggest that re-calibration of perceptual-motor action in a task involving intercepting moving objects may require more than just practice swings. But there are many open questions not addressed in this study. Although baseball batting does involve some online adjustments to the swing (Gray 2009) it is a largely open-loop action. Would dynamic exploration of a tool be sufficient for an interception action that involves continuous, closed-loop control (e.g., catching a flyball in baseball)? How does the re-calibration process change when the actor switches between two tools multiple times? As suggested above, it may be possible for an actor to develop stored calibration states that can be immediately recalled so that no re-calibration is needed. So for example, in the present study it might be expected that if batters had continued switching between the standard bat and the heavier (or lighter) bat they would eventually show no decrement in performance after a bat switch. It will be interesting for future research to investigate if and how these calibration states develop, whether they transfer to tools with intermediate properties (e.g., a bat with a weight between the standard and heavy bat), and what brain activity is associated with their development.

There are also some limitations to the present study that should be addressed in future research. First, the number of trials participants were given to adapt to the new bat weight

(15) was relatively small especially given that it can require 50–100 trials for a participant to adapt to an increase in mass during simple reaching movements (e.g., Wang and Sainburg 2004). Second, due to the nature of our apparatus the changes in bat weight were quite large (±10 oz). It will be important for future experiments to use smaller changes in weight to more precisely determine the action boundaries for the different control strategies. Finally, it will be interesting for future research to directly compare how the batters exploration of the bat following the bat change influences perceptual motor re-calibration (e.g., no exploration vs. dynamic wielding vs. practice swings).

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