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Metacognitive control of action: Preparation for aiming reflects knowledge of Fitts's law

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Metacognitive control has been studied in intellectual skills but has not yet been studied in perceptual–motor skills. To probe metacognitive control in a perceptual–motor context, we developed a task in which participants chose the position of a cursor relative to two targets. One of the two targets was randomly erased. Participants tried to move the cursor into the remaining target within a limited amount of time. The target widths were varied, making the difficulty of moving to either target dependent on the chosen cursor position. Predictions were based on the assumption that participants could use an analogue of Fitts's law to choose optimal positions. The fit between observed and predicted positions was excellent, suggesting that participants used information about movement speed–accuracy trade-offs to guide movement preparation. The findings suggest that metacognition applies to both perceptual–motor skills and intellectual skills, and that these two domains are more similar than traditionally assumed.

The past several years have witnessed growing interest in metacognition—in how people's knowledge of their own cognitive abilities affects the way they prepare for and perform intellectual tasks (Nelson, 1996). People can, for example, assign confidence ratings to their ability to recall recently learned information, and these ratings are predictive of subsequent test performance (Koriat & Goldsmith, 1996; Nelson & Dunlosky, 1991, 1992). Similarly, people allocate more time to learning more difficult study items than to learning less difficult study items (Metcalfe & Kornell, 2003). The ability to reflect on one's own cognitive abilities appears to be a defining feature of human cognition (Nelson & Narens, 1994).

Research on metacognition has focused on intellectual skills such as verbal fact retrieval and study time allocation but has not been concerned with perceptual–motor skills such as reaching for targets. Nonetheless, there has been a growing appreciation of similarities between intellectual skills and perceptual–motor skills. For example, learning rates for both kinds of skills can be approximated by power functions (Logan, 1992; Newell, Liu, & Mayer-Kress, 2001; but see Heathcote, Brown, & Mewhort, 2000), and skill development in both domains follows similar progressions from controlled to automatic stages (Anderson, 1982; Fitts & Posner, 1967). Reviewing studies that revealed such similarities, Schmidt and Bjork (1992) and Rosenbaum, Carlson, and Gilmore (2001) concluded that the psychological substrates of intellectual and perceptual–motor skills are more alike than different, a view that accords with the embodied-cognition approach to the study of mind and behavior (Clark, 1997).

If intellectual and perceptual–motor skills rely on similar mechanisms, one would expect metacognition to apply to the guidance of perceptual–motor skills, just as it does to the guidance of intellectual skills. At a general level, this conjecture is not controversial. People with ambulatory difficulties know that they need canes, swimmers make conscious decisions about how close they should stay to shore, and so on. Furthermore, there is evidence that metacognitive control governs the selection and maintenance of high-level intentions and strategies (Gollwitzer & Schaal, 1998). But what about more fine-grained aspects of perception and performance? Does metacognitive control extend to subtler, quantitative aspects of perceptual–motor skill?

To pursue this question, we focused on one of the premier features of perceptual–motor control, the trade-off between movement speed and accuracy. This trade-off is captured in Fitts's law (Fitts, 1954). According to the most common expressions of Fitts's law (e.g., Crossman & Goodeve, 1983; but see MacKenzie, 1989, for a discussion of alternative forms), the time, T, to move as quickly

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as possible to a target is a logarithmic function of the distance, D, from the start position to the center of the target and the target's width, W,

$$T = a + b \times \log_2\left(\frac{2D}{W}\right), \quad (1)$$

where a and b are positive constants. The ratio of target distance to target width is called the *index of difficulty* (ID). A target with a high ID (one that is far away and/or small) takes more time to reach than a target with a small ID, as has been confirmed in many studies in which participants tried to move as quickly as possible from a predefined start position to a single target or back and forth between two targets (e.g., Elliott, Helsen, & Chua, 2001; Meyer, Smith, Kornblum, Abrams, & Wright, 1990; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979).

To explore the metacognitive control of perceptual–motor performance in a situation relevant to Fitts's law, we developed a variant of the prototypical manual aiming task (see Figure 1). Participants saw a video display consisting of two rings connected by a straight line. The participants positioned a cursor along the line between the two rings, knowing that after choosing the cursor position, one of the two rings, whose identity was unpredictable, would be erased. The participants then tried to move the cursor into the remaining target ring within a limited amount of time. This "capture time" was long at first, but it got shorter as the session continued. Reducing the capture time motivated the participants to move as quickly as possible, in keeping with the provision that Fitts's law pertains to movements made under speeded conditions. Especially important was that we varied the relative widths of the two initially presented rings. In one condition, the widths of the two rings were the same, but in other conditions, the widths of the two rings differed.

By indicating a start position for the cursor, participants could establish the distance of the cursor from each of the two rings. They thereby controlled the IDs for the rings and, by implication, the expected times to reach them. We tested the hypothesis that participants could recruit knowledge of Fitts's law, or an implicit analogue thereof, to choose a position that maximized the probability of capturing the target ring within the prescribed capture time. With sufficiently long capture times, the optimal start position simply equated the indices of difficulty for the two rings. More specifically, for any given pair of rings, P and Q, with widths W_P and W_Q, respectively, participants could choose a start position that yielded distances D_P and D_Q that equated the two IDs:

$$\log_2\left(\frac{2D_P}{W_P}\right) = \log_2\left(\frac{2D_Q}{W_Q}\right). \quad (2)$$

Because the sum of D_P and D_Q equals the total distance, D_{Total}, between the two rings, the location that equates the IDs can be found by solving for either distance, thus:

$$D_P = D_{\text{Total}}\left(\frac{W_P}{W_P + W_Q}\right). \quad (3)$$

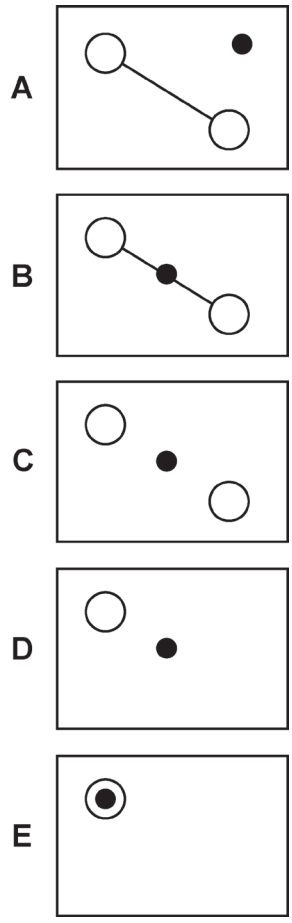

Figure 1. Series of events in the task. (A) Two rings are shown with a straight line between them, along with a cursor (represented here by the black dot). (B) The participant chooses a start position by placing the cursor somewhere along the line between the rings. The line (C) and then one ring (D) disappear after the participant raises a lever (not shown here). (E) The participant succeeds in moving the cursor into the remaining target within the capture time (i.e., before the one remaining target disappears).

We tested the hypothesis that participants have access to information about their own perceptual–motor capabilities commensurate with Fitts's law. The prediction of this hypothesis was that they should behave in accordance with Equation 3.

METHOD

Participants

Sixteen right-handed Pennsylvania State undergraduates participated in exchange for course credit. All had normal or corrected-to-normal hearing and vision, and none reported neurological or physical disabilities.

Apparatus

Participants sat at a 76-cm-high table and wore a light fabric glove on their right hands, with the palm attached with Velcro to a 20.5-cm-diameter felt-backed plywood disk that slid easily on the table. An infrared emitting diode (IRED) was attached to the tip of the participant's gloved index finger. The position of the IRED

was registered with an Optotrak motion recording system (Northern Digital Corporation, Waterloo, ON). Motion of the hand resulted in motion of a green dot, 0.7 cm in diameter, on a monitor 150 cm in front of the participant. Hand movements toward the left or right yielded left and right cursor movements, respectively, and hand movements in or out yielded down or up cursor movements, respectively. The metric mapping of IRED to cursor displacement was 1:1 (e.g., a 1-cm hand movement caused a 1-cm cursor movement). There was no perceptible delay between movement of the IRED and movement of the cursor. Besides displaying the cursor, the monitor also displayed pairs of blue rings (Figure 1A) whose diameters were 1.5, 3.0, 4.5, or 6.0 cm. A straight line connected the pair of blue rings at the start of each trial.

The participants indicated their satisfaction with their placement of the cursor on the line by pressing on one end of a spring-loaded lever with the left hand. When the lever was pressed, an IRED attached to the opposite end was raised into view of the Optotrak cameras from behind a wooden block. The spring tension on the lever was low enough to prevent fatigue but high enough to prevent the lever from accidentally rising if a participant simply rested his/her finger on it.

The participants received auditory feedback through Koss TD-65 headphones. A C/C++ program controlled stimulus presentation and data collection.

Procedure

Prior to the start of the experiment, the participants were invited to explore the hand–cursor relation by freely sliding the hand on the table. All participants indicated that they found the hand–cursor relation natural and agreed that it was like moving a computer mouse and seeing a cursor move on a screen. (We used an Optotrak rather than a computer and mouse to take advantage of the higher sampling rate afforded by the Optotrak. The sampling rate was 100 Hz.)

The experiment began with 1 practice block of 12 trials in which the participants were exposed to all the experimental conditions (see below). Afterward, they completed 12 blocks of 24 trials each. The capture time changed every 4 blocks. The capture time was 1,250 msec in the first 4 blocks, 700 msec in the second 4 blocks, and 550 msec in the third 4 blocks. These values, chosen on the basis of pilot testing, enabled the participants to capture at least half the targets on any block. Four levels of relative ring width were presented within each capture time. In each block, at a given capture time, the ratio between the widths of the rings was 1:1 (both rings 1.5 cm wide), 1:2 (a 1.5-cm ring paired with a 3-cm ring), 1:3 (a 1.5-cm ring paired with a 4.5-cm ring), or 1:4 (a 1.5-cm ring paired with a 6-cm ring). The order of relative ring widths was counterbalanced across participants. The distance between the rings was fixed, but the positions of the rings on the monitor alternated over trials to prevent participants from always choosing the same start position.

At the start of the experiment, the participants were instructed that they would need to choose a start position for the cursor anywhere along the line connecting the two rings but not within either ring. They were asked to press the lever when they were satisfied with their choice. They were instructed that soon thereafter the connecting line and one of the rings would be erased and that they would have to bring the cursor to rest inside the remaining ring before it too disappeared. The participants were informed that the capture time (i.e., the amount of time available for moving into the remaining target) would decrease over the course of the experimental session.

At the start of each block, the capture time was displayed in sec (e.g., "1.25 seconds"). The participants began each block at their own pace by pressing the lever. On each trial, the participants chose a start position and pressed the lever. When the IRED attached to the lever was detected by the Optotrak system, the computer evaluated the cursor position. The participants were informed that they could take as long as they needed in order to choose the start position. The experimenter took care to avoid suggesting specific strategies. If participants asked about the adequacy of a start position, the experimenter told them just to rely on their own judgment.

If the cursor was not on the line or inside one of the rings when the Optotrak detected the lever-mounted IRED, a low-pitched buzzing noise was played, whereupon the participant lowered the lever and tried again. Otherwise, a delay of 260–400 msec commenced, after which the connecting line disappeared. After another 260- to 400-msec delay, one of the two rings disappeared and the capture time began. The participants tried to move the cursor into the remaining target ring and bring it to rest there for at least 150 msec before the capture time ended. If they succeeded, the target disappeared and a high-pitched computer bell sounded. If they failed, the target disappeared and the low-pitched buzz sounded. A new trial began immediately after the auditory feedback.

At the end of each block, two scores were shown. One was based on the number of targets captured by the participant up to and including the just completed block. The other was a reference value, indicating the best score so far. The reference value was described as a goal to be beaten. The first value of the reference score was based on pilot work.

RESULTS

The first block was treated as practice and was excluded from analysis. This was necessary because the practice block was interrupted by instructions from the experimenter. For all trials in subsequent blocks, we evaluated the start positions chosen by the participant, defined, for convenience, as the proportional distance, D_L, from the center of the lower of the two displayed rings to the center of the cursor, divided by the distance between the centers of the upper and lower rings. These distances were evaluated in a repeated measures ANOVA with relative ring width (1:1, 1:2, 1:3, 1:4), capture time (1,250, 700, 550 msec), and size of the lower ring (smaller or larger) as factors. In the 1:1 condition, the rings were of the same size. To avoid an empty cell in the ANOVA design (which included smaller vs. larger lower ring as a factor), two values of mean D_L were calculated by randomly splitting the data from the 1:1 condition into two samples. A repeated measures ANOVA with sample and capture time as factors confirmed that these means did not differ (all Fs $<$ 1). For the primary ANOVA, there was a main effect of the size of the lower ring [$F(1,15) = 93.55, p < .01; \eta^2 = .86$]. Participants chose start positions closer to the lower ring when it was smaller ($M = .32$, $SD = .08$) than when it was larger ($M = .64$, $SD = .08$). The only other significant effect was the interaction between relative ring width and size of the lower ring [$F(3,45) = 65.14, p < .01; \eta^2 = .81$]. As can be seen in Figure 2, the participants chose start positions closer to the smaller ring as the difference between the ring widths increased.

To determine whether the start positions conformed to Equation 3, we calculated the predicted proportional distance for each level of relative ring width. (Capture time was not included in the derivation of predictions because the preceding ANOVA showed that it had no influence on the participants' choice of start positions.) Given that our definition of distance treated the lower ring as the zero

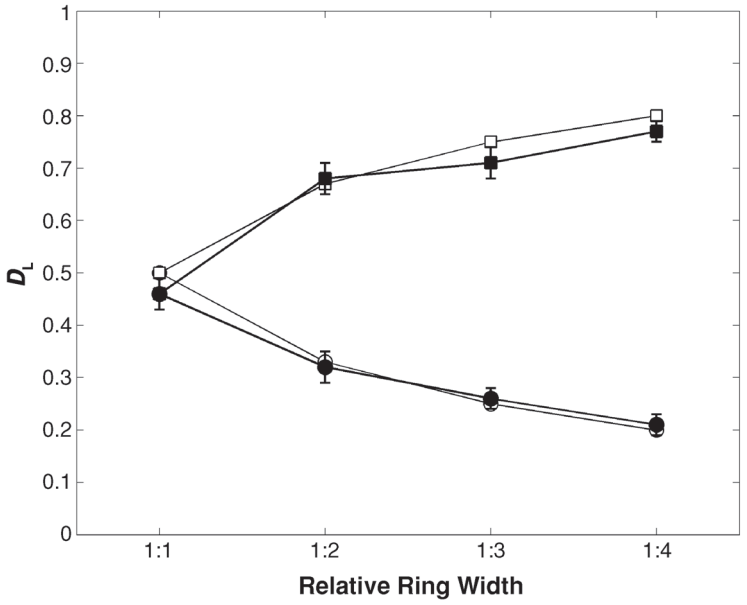

Figure 2. Observed and predicted values of distance, D_L, from the chosen start position to the lower of the two target rings as a function of relative ring width and the size of the lower ring. Filled points represent the observed data. Error bars represent ±1 *SE*. Unfilled points represent the predictions. Circles correspond to cases in which the lower ring was the smaller member of the pair, whereas squares correspond to cases in which the lower ring was the larger member of the pair.

point, we generated two predicted values for each level of relative width, one for the case in which the lower ring was the smaller member of the pair, and one for the case in which the lower ring was the larger member of the pair. For example, in the 1:2 relative width condition, the predicted distances were .33 when the lower ring was smaller and .67 when the lower ring was larger. The least squares fit between the observed distances, pooled across participants, and the predicted distances (Figure 2) was excellent [$r^2 = .99$; $t(6) = 26.33$, $p < .0001$]. Equation 3 was also fitted to individual participants' data. Individual r^2 values ranged from .79 to .99, with a median value of .94.

To determine whether the close correspondence between the predicted and observed start positions depended on practice, we computed mean squared deviations of participants' chosen start positions from the start positions predicted by Equation 3. A repeated measures ANOVA with block as the factor indicated that these values did not vary, but instead remained small ($M = .03$, $SD = .02$) [$F(11,165) = 1.39$, $p = .18$; $\eta^2 = .09$]. Capture time was not included in this analysis because it was already shown to have a negligible effect on participants' choice of start positions. A power calculation indicated that the probability that this ANOVA could have rejected the null hypothesis if it were false was .72.

A second analysis was carried out to determine whether participants made use of end-of-trial feedback to tune their start position choices. We computed the mean change in D_L from one trial to the next depending on whether the first trial in the pair was successful (i.e., the target was captured) or unsuccessful (i.e., the target was not captured). The data were analyzed with a repeated measures ANOVA, using size of the lower ring relative to the upper ring (equal, smaller, or larger) and success/failure as factors. Relative ring width was not included in this analysis, because of insufficient numbers of failed trials (see below) in the 1:3 and 1:4 conditions. The interaction between relative size and success/failure was not significant [$F(2,30) = 0.81$, $p = .46$; $\eta^2 = .05$], although the probability that this ANOVA could have rejected the null hypothesis if it were false was only .18.

Finally, given the novelty of our task, we thought it would be useful to characterize the participants' overall ability to capture the targets. We did so by analyzing the proportion of targets captured with a repeated measures ANOVA with relative ring width (1:1, 1:2, 1:3, 1:4), capture time (1,250, 700, 550 msec), and size of the lower ring (smaller or larger) as factors. As with D_L, we partitioned the data for the 1:1 relative size condition into two means to avoid an empty cell in the design. There was a significant main effect of relative ring width [$F(3,45) = 31.22$, $p < .001$; $\eta^2 = .68$]. The participants captured fewer targets in the 1:1 condition ($M = .62$, $SD = .08$) than in the 1:2 condition ($M = .72$, $SD = .10$), 1:3 ($M = .77$, $SD = .12$) or 1:4 ($M = .80$, $SD = .08$) condition. There was also a main effect of capture time [$F(2,30) = 125.08$, $p < .001$; $\eta^2 = .89$], with participants capturing fewer targets at the 500-msec capture time ($M = .55$, $SD = .14$) than

at the 700-msec ($M = .68$, $SD = .12$) or 1,250-msec capture time ($M = .96$, $SD = .03$). Relative ring width and capture time interacted [$F(6,90) = 4.99$, $p < .001$; $\eta^2 = .25$]. The interaction was driven by participants' capturing fewer targets in the 1:1 condition than in the 1:2 or 1:4 conditions as capture time decreased. Finally, relative ring width interacted with the size of the lower ring [$F(3,45) = 3.42$, $p < .05$; $\eta^2 = .19$]. The participants captured the lower ring more often when it was larger than the upper ring than when it was smaller than the upper ring.

DISCUSSION

The main result of this experiment was that participants chose start positions closer to the smaller ring as the difference between the ring widths increased. Furthermore, the participants' choices corresponded to predictions based on Fitts's law. Thus, participants appreciated the relations among movement distance, target width, and movement time conveyed by Fitts's law and apparently used that knowledge to guide their choices of start positions. Evidently, the participants brought this knowledge into the lab from their prior experience, judging from the fact that their start position choices were optimal from the start of the experiment and did not depend on success or failure on the preceding trial.

This study adds to the growing evidence for the similarity of intellectual and perceptual–motor skills by suggesting that metacognitive control can apply within both domains. In the present experiment, participants used information about movement speed–accuracy trade-offs—a fundamental characteristic of human motor control—to choose optimal start positions. Their performance suggests that the role of metacognition in perceptual–motor skills might extend beyond high-level stages of intention formation and planning to encompass relatively low-level, quantitative details of perceptual–motor control.

Although the present data are consistent with a metacognitive account, other explanations are possible. For example, participants could have chosen start positions by relying on end-of-trial feedback, adjusting their choice on the basis of whether or not they successfully captured the target on the preceding trial. In principle, these adjustments could have occurred automatically and without the degree of conscious deliberation that often characterizes metacognitive control. We found no evidence of feedback-driven adjustments, even in the earliest experimental blocks. Nonetheless, given the relative simplicity of the task, it is possible that a feedback-driven mechanism could have converged on optimal start positions during the practice block. In postexperiment interviews about their strategies, the participants said they were aware that smaller targets would be more difficult to reach within the capture time than larger targets. Such an awareness is more consistent with a metacognitive account than with an automatic, feedback-driven account. However, the interview process was informal, and we cannot eliminate the possibility that participants' awareness of their method for choosing start positions arose either epiphenomenally or as a result of post hoc attempts at supplying a rationale for their behavior. More research should help resolve this question.

Our finding that participants could use information about movement speed–accuracy trade-offs to choose optimal start positions accords with current conceptions of motor control that emphasize the role of internal simulation in motor planning (Jeannerod, 2001; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001; Wolpert, 1997). In these accounts, it is proposed that actors use models of the perceptual–motor apparatus to predict the sensory consequences of prospective actions. Such predictions can be used to alter the way in which actors perform, depending on what they will do next. Thus, to use one example from a recent study in the second author's lab, participants (university students) grabbed a vertical cylinder at different heights, depending on the height to which the cylinder would be brought next (Cohen & Rosenbaum, 2004). Such results indicate that actors have advance information about the future demands of their unfolding actions. Such results do not imply that advance information about forthcoming action leads to deliberate choices rather than unconscious or automatic ones, but the results of the present experiment lend credence to the view that deliberate decision making may in fact occur.

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