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Deciding How To Act Is Not Achieved by Watching Mental Movies

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In the early days of research on visual imagery, it was believed that visual images are like pictures in one's head. Only as the field matured did it come to be appreciated that visual images do not bear a first-order isomorphic relation to visual percepts. Now that the early days of research on motor imagery are coming to an end, it is important to ask whether motor images bear a first-order isomorphic relation to movements. We asked whether they do by focusing on internal simulations for motor planning. Our participants indicated which of two possible actions they preferred either by performing the preferred action or by indicating which action they would prefer to perform. We reasoned that if internal simulations of physical actions bear a first-order isomorphic relation to actual physical actions, the choices would be the same in the two conditions. They were not. We discuss the reasons for this outcome, including the adaptive advantage of a representational system for action which, like the representational system for vision, does not bear a first-order isomorphic relation to its external analog.

Keywords: aiming, motor control, prospective judgments

A popular idea in the study of human perception and performance is that predictive models of action consequences play a crucial role in the selection and initiation of actions (Lötze, 1852; McIntyre, Zago, Berthoz, & Lacquaniti, 2001; Rosenbaum, in press; Wolpert & Flanagan, 2001; Wolpert, Miall, Kawato, 1998). In support of this idea, many studies have shown a close correspondence between the time course of actual movements and the time course of imagined movements in tasks as diverse as writing, drawing, walking, and adoption of hand postures (Decety & Jeannerod, 1996; Decety, Jeannerod, & Prablanc, 1989; Decety & Michel, 1989; Parsons, 1994). Similarly, other studies have demonstrated that subjective assessments of prospective movement difficulty are positively correlated with actual movement durations (Augustyn & Rosenbaum, 2005; Grosjean, Shiffrar, & Knoblich, 2007; Johnson, 2000; Parsons, 1994; Slifkin & Grilli, 2006), and still other studies have shown that ratings of awkwardness for imagined actions are positively related to the biomechanical resistance that accompanies those same actions when they are actually performed (Frak, Paulignan, & Jeannerod, 2001; Johnson, 2000). All of these observations accord with the hypothesis that people can accurately imagine the temporal and physical costs of their actions. Such accuracy is necessary if one is to base action selections on internal simulations (Johnson, 2000).

Because so much research has emphasized the similarities between motor imagery and actual motor performance, the state of the literature on this topic is reminiscent of the state of the literature on visual imagery in the early days of that research. Following the appearance of the influential work of Perky (1910) and others, visual imagery was thought to be virtually the same as actual visual perception, the only difference being that visual imagery used "pictures in the head" whereas visual perception used "pictures in the world." As the study of visual imagery matured, students of visual imagery came to appreciate that visual imagery is not the same as visual perception. The ways in which visual imagery and visual perception differ are reviewed in virtually all cognitive psychology textbooks (e.g., Anderson, 2005), as is Shepard and Cooper's (1982) elegant way of capturing the degree of difference between visual imagery and visual perception—their introduction of the notion of degree of isomorphism between the two. Shepard and Cooper argued that because visual imagery and visual perception share many, but not all features, the relation between the two forms of experience qualifies as a second- or higher-order isomorphism, but not as a first-order isomorphism. Students of motor imagery have not yet picked up on this distinction, at least to the best of our knowledge. As a step in that direction, we asked whether motor imagery bears a first-order isomorphic relation to motor performance. Our more specific question was whether internal simulations of possible actions bear a first-order isomorphic relation to the actions themselves.

A moment's reflection reveals one way in which internal simulations of possible actions may differ from actual action performance: Durations of internal simulations should, in general, be

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shorter than durations of actual performance; otherwise, planning would take too long to be adaptive. Studies of the relation between the time to initiate movement sequences and the time to complete those sequences have indeed shown that a positive relation exists between the two measures, with the slope of the function relating initiation time to execution time being reliably less than 1 (for a review, see Rosenbaum, in press). This outcome suggests that internal simulations of possible actions do not bear a first-order isomorphic relation to movement execution in a chronometric sense.

The possibility remains, however, that internal simulations may depart from actual performance in additional ways. We sought to explore this possibility and to identify one or more ways in which internal simulation and actual performance might differ. To pursue this goal, we conducted two experiments in which we compared participants' judgments of how they *would* move with observations of how they actually *did* move in the same circumstances.

In the first experiment, participants chose which of two circles they would prefer to pass through while moving a computer cursor from a starting cross into an ending ellipse. Participants in one condition actually performed the preferred movements. Participants in the other condition simply reported which movements they would prefer to perform.

In the second experiment, participants chose which of two ellipses they would prefer to end in after moving a cursor from a starting cross through an intermediate circle. This manipulation clarified questions remaining from the first experiment and provided a further test of the equivalence of actual and potential movement under different circumstances. In the second experiment, we also replaced the between-subject design of the first experiment with a within-subject design. This change allowed for a stronger test of the first-order isomorphism hypothesis, which predicted that choices in actual movement conditions and corresponding potential movement conditions would be the same.

Experiment 1

Participants were shown a cross at the center of a computer monitor as well as two circles and an ellipse (Figure 1, top). In the actual movement condition, each participant moved a cursor from the cross, through one of the two circles, and into the ellipse. In the potential movement condition, each participant indicated how they *would* do the same task.

We expected participants to favor the intermediate circle that was more closely aligned with the main axis of the ending ellipse. Thus, in response to a configuration like the one shown in the top panel of Figure 1, participants would be likely to select circle *A*. Such a selection would be sensible for two reasons. First, although the distances between each circle and the center of the ellipse are equal, the minimum possible distance from the circle that is collinear with the *major* axis of the ellipse is less than the minimum possible distance from the circle that is collinear with the *minor* axis of the ellipse. Second, because end point variability is greatest along the major axis of motion (Gordon, Ghilardi, & Ghez, 1997; van Beers, Haggard, & Wolpert, 2004), selecting the intermediate circle that is more closely aligned with the ellipse's major axis would allow participants to align the more-variable axis of motion with the widest portion of the ellipse, ensuring greater accuracy.

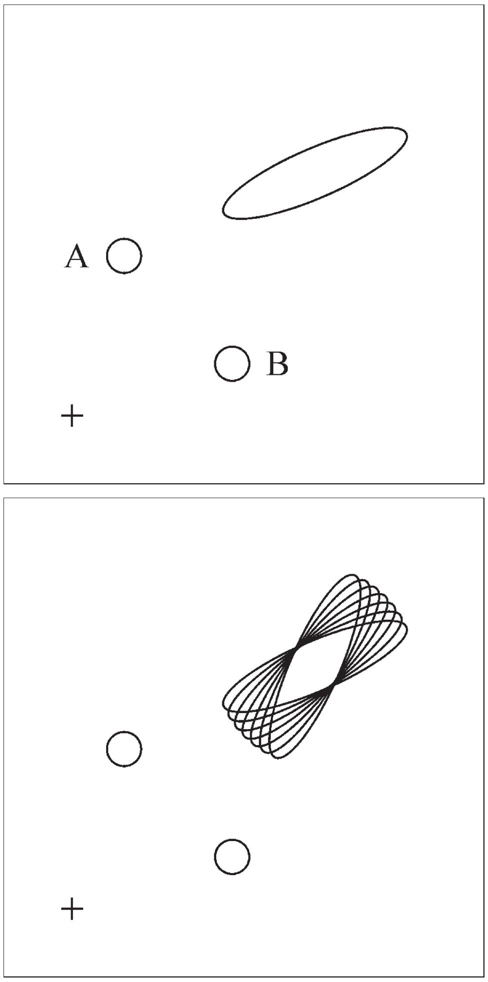

Figure 1. Displays used in Experiment 1. Top panel: Example of a configuration from one trial. Bottom panel: All configurations superimposed, from top-right quadrant.

The most critical question given these considerations was whether participants would make the same choices in the actual and potential movement conditions. If internal simulations of possible actions bear a first-order isomorphic relation with actual actions, one would expect the choices to be the same in the two cases.

Method

Participants. Twenty undergraduates participated for course credit. Eight were female, and 12 were male. All participants were right-handed, none reported a history of neurological impairment, and all were naive to the hypotheses.

Movement condition was treated as a between-subjects factor. Half the participants were assigned to the actual movement condition, and half the participants were assigned to the potential movement condition.

Procedure. Participants sat at eye level with a Dell Ultrasharp 17-inch flat panel monitor (1280 × 1024 pixels) set 25 inches away on a desk. The experiment was conducted in a MATLABbased environment. Participants interacted with the computer using a Logitech G5 gaming mouse. Each participant operated the mouse with the right hand.

At the start of each trial, a black cross appeared at the center of the computer screen. In the actual movement condition, participants began each trial by clicking the left button of the mouse, which initiated two events. First, the mouse cursor automatically centered on the cross. Second, a red circle, a blue circle, and a black ellipse appeared. The orientation of the main axis of the ellipse varied in seven linearly spaced steps from 23.5° to 66.5° with respect to the axis defining the lower boundary of the quadrant in which the stimuli appeared. The red and blue circles occupied positions that were offset from the starting cross at angles of 27° and 63° with respect to the quadrant of presentation (see Figure 1, bottom). The configurations were presented in all four quadrants, forming a total of 28 unique trial configurations. Both choice circles were centered 4.5 cm from the cross and had a diameter of .925 cm. The ellipse was centered 9.25 cm from the cross and had major and minor axes measuring 2.68 and .67 cm, respectively.

The circle colors, blue and red, were chosen because they are easily distinguished visually and because they have been found to evoke similar movement patterns during mouse-guided, rapid aiming tasks (Kong, Ren, & Shinomori, 2007). The mapping of circle color to circle position was randomized over trials, as were ellipse orientations and quadrants of presentation. Data were collected in 10 blocks of 28 trials each, the first block being treated as practice.

Participants were told to choose the circle that would permit the most rapid and accurate movement from the cross through the chosen circle and into the ellipse. Participants in the actual movement condition were to move the mouse into the chosen circle, click on it, and then move into the ellipse, and click on it. Accurate clicks caused target borders to change from solid to dotted lines. Because of this aspect of the method, each event relied on successful completion of the preceding event, so there were no errors as such. Clicking also provided unambiguous time stamps in the data record that allowed us to determine times spent moving from the starting cross to the chosen circle, as well as times spent moving from the chosen circle to the ellipse.

Feedback was provided after every 14 trials (i.e., midway through a block and then at the end of the block). Participants saw the sum of their movement times for the preceding 14 trials as well as the lowest summed movement time from any previous 14-trial half block. Participants were encouraged to beat their smallest movement time so far. Timing of movement began after the cursor passed beyond .185 cm from the center of the starting cross. Participants were told that movement time would be recorded after the cursor left the start cross. Participants were also told that their scores were based solely on their movement times.

The apparatus, procedure, and design in the potential movement condition were essentially the same as in the actual movement condition. To initiate each trial, participants pressed the spacebar key. After a brief delay that was distributed uniformly between 400 and 500 ms, the red circle, blue circle, and black ellipse appeared. Participants indicated their choices by striking an associated key on the keyboard, using the index finger of either hand. The "D" button bore a red sticker to mark its association with the red circle, and the "L" button bore a blue sticker to mark its association with the blue circle. The red button was struck with the left index finger, and the blue button was struck with the right index finger.

Results

For each circle, we defined offset angle by considering the intersection of two straight lines. One was the straight line connecting the center of the circle to the center of the ellipse. The other was the straight line extending through the major axis of the ellipse. The closer the offset angle was to zero, the more closely aligned that circle was with the ellipse. Assuming that participants would prefer the more closely aligned circle to the less closely aligned circle, we predicted that the probability of choosing a circle would be high when the ratio of its offset angle to the offset angle of the other circle was low. In the sections that follow, we consider the results relative to this prediction, first for the actual movement condition and then for the potential movement condition.

Actual movement condition. Pursuant to global analyses of the data in the actual movement condition, we tested whether circle color or quadrant of presentation affected participants' selections. Consistent with the expectation that circle selections would not depend on circle colors, we found that the correlation between the observed probabilities for the two colors in the same presentation conditions (the same ellipse orientations relative to the circles) exceeded .99. And consistent with the expectation that selections would not depend on the quadrant in which the stimuli appeared, we found that preferences were consistent across quadrants, as confirmed by a 3 (offset ratio) × 4 (quadrant of presentation) within-subjects ANOVA. The interaction between offset ratio and quadrant of presentation was not significant, $F(6, 54) = .53$, $p > .7$, $\eta_p^2 = .05$. Based on these outcomes, we pooled the data over quadrants and circle colors.

Figure 2 shows the proportion of times that participants selected the circle with the smaller offset angle. These proportions are displayed as a function of the ratio of the two possible circles' offset angles. All the proportions exceeded .5, indicating that participants always favored the circle that was closer to collinear with the major axis of the ellipse. This preference was strongest

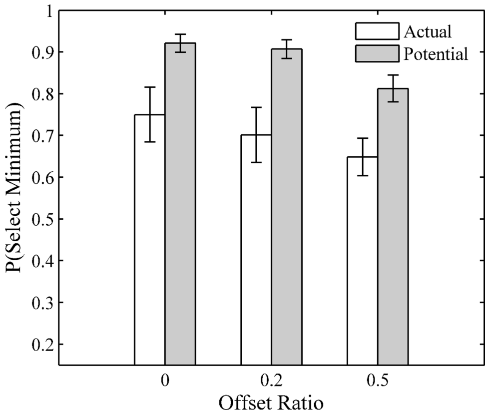

Figure 2. Probability of selecting the circle with the smaller offset angle as a function of the ratio of the smaller to the larger offset angle in the circle pair (±1 SE). Data from Experiment 1.

when the offset-angle ratio was smallest, $F(2, 18) = 4.93$, $p = .019$, $\eta_p^2 = .35$.

Participants quickly adopted the strategy of selecting the circle more closely aligned with the ellipse. Figure 3 shows the proportion of times that participants selected this circle over the nine experimental blocks. To test whether these proportions increased across experimental blocks, we performed a multiple regression analysis for each participant. The average intercept term (.704) was significantly greater than .5, $t(9) = 2.65$, $p = .026$, but the average slope term (–.0009) was not significantly different from zero, $t(9) = .08$, $p > .9$. These results indicate that participants selected the optimal circle a majority of the time and did so at a statistically fixed rate.

Potential movement condition. As in the actual movement condition, we found that we could pool the data over the red and blue targets because the correlation between the observed probabilities for the two colors in the same presentation conditions (the same ellipse orientations relative to the circles) exceeded .99. We also determined that we could pool the data over quadrants although, somewhat to our surprise, the interaction between offset ratio and quadrant of presentation turned out to be significant, $F(6, 54) = 2.74$, $p = .02$, $\eta_p^2 = .23$. The interaction stemmed from the fact that participants' selections were slightly less sensitive to differences in offset angle in the top right quadrant than in the other quadrants. Nonetheless, the direction of the relationship between offset angle and probability of selection was the same across quadrants, so for purposes of simplification, we pooled the data over quadrants as well as circle colors. (In terms of the bottom-line conclusion of this article, we are confident that the pooling of data over quadrants did not matter.)

As in the analysis of data from the actual movement condition, we grouped trials according to the ratio of the smaller offset angle to the larger offset angle. As shown in Figure 2, participants in the potential movement condition selected circles that were closer to collinear with the main axis of the ending ellipse. This preference was greatest when the offset-angle ratio was smallest, $F(2, 18) = 31.27$, $p < .0001$, $\eta_p^2 = .78$.

To test whether the proportion of optimal selections changed across experimental blocks (see Figure 3), we again performed a multiple regression analysis. The average intercept term (.891) was significantly greater than .5, $t(9) = 9.44$, $p < .0001$, but the average slope term (–.002) was not significantly different from zero, $t(9) = .27$, $p > .7$. Hence, in the potential movement condition, as in the actual movement condition, participants selected the optimal circle a majority of the time and did so at a statistically fixed rate.

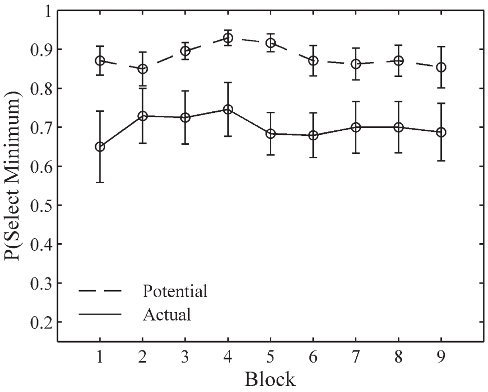

Figure 3. Comparison of choice performance in the actual and potential movement conditions of Experiment 1. Each data point is the mean probability (±1 SE) of choosing the circle with the smaller offset angle.

Comparison of selections. Thus far, we have considered the selections made in each condition separately. Now we compare the selections in the two conditions directly. As seen in Figure 2, participants selected the more closely aligned circle more consistently in the potential movement condition than in the actual movement condition. To evaluate this difference statistically, we conducted a mixed-model ANOVA, treating potential/actual condition as a between-subjects factor and offset angle ratio as a within-subjects factor. The analysis revealed a main effect of potential/actual condition, $F(1, 18) = 8.51$, $p = .009$, $\eta_p^2 = .32$, and a main effect of offset-angle ratio, $F(2, 36) = 18.39$, $p < .0001$, $\eta_p^2 = .51$. However, the interaction between potential/actual condition and offset-angle ratio was not significant, $F(2, 36) = .79$, $p > .4$, $\eta_p^2 = .04$.

The difference between choices in the actual and potential movement conditions did not seem to depend on learning (see Figure 3). This statement is supported by the earlier regression analyses, which showed that proportions of optimal selections did not increase as a function of experimental block within either condition. A further comparison between the two conditions showed that the average slope term did not differ between them, $t(18) = .09$, $p > .9$, though the average intercept was significantly higher in the potential movement condition than in the actual movement condition, $t(18) = 2.13$, $p = .047$.

Discussion

In the first experiment, we asked participants to indicate which of two circles they preferred to move into before moving into an elliptically shaped target. One group of participants actually performed the chosen movements. The other group of participants indicated which movements they *would* perform. We reasoned that if internal simulations of possible actions bear a first-order isomorphic relation with actual actions, the choices would be the same in the two cases.

Participants in both groups favored the circle that was more closely aligned with the major axis of the ending ellipse. By selecting that circle, participants could align the more variable axis of motion with the widest portion of the ellipse. This strategy was probably adaptive in terms of what is known about properties of movement variability. However, participants selected the optimal intermediate circle more consistently in the potential movement condition than in the actual movement condition. This difference could not be ascribed to different learning rates in the two conditions because the trend was apparent from the earliest experimental blocks and was consistent across the course of the experiment. We turn to the interpretation of this surprising result later in this article.

Experiment 2

The first experiment left two issues unresolved. The first was whether participants were actually basing their choices on offset angle. Another possibility is that they were basing their choices on offset *distance*. Ellipse offset angle and ellipse offset distance were confounded in Experiment 1, making it impossible to tell which factor contributed more to participants' choices.

To determine the relative importance of collinearity and distance, we modified the procedure. Rather than asking participants to move to either of two circles and then to one ellipse, we asked participants to move to one circle and then to either of two ellipses. We switched to the latter procedure after realizing that there was no set of circle pairs and single ellipses that would allow us to disentangle the two variables unambiguously.

Figure 4 shows two choice situations in which participants saw one circle and two ellipses. In both, a single circle was located at a 45° angle from the starting cross. From the circle, the participant could access ellipse *A* or ellipse *B*. In response to the configuration on the top, participants would likely select ellipse *A* because it is closer to the circle and because its main axis is collinear with the direction of movement that would be followed if one went directly from the circle into the ellipse. Regarding the configuration on the bottom, however, the prediction depends on which factor is more important. Ellipse *B* is closer to the circle than is ellipse *A*, but the main axis of ellipse *A* is collinear with the direction of movement that would be followed if one went directly from the circle into that ellipse; the same cannot be said about ellipse *B*. If participants were more sensitive to distance, they would favor *B*, but if participants were more sensitive to degree of collinearity, they would favor *A*. The second experiment was designed to test these alternative predictions.

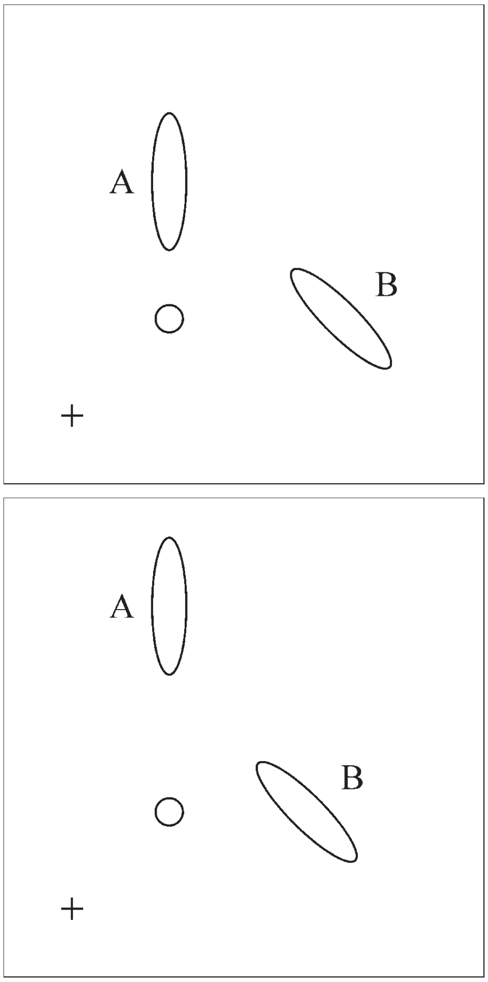

Figure 4. Examples of configurations from two trials in Experiment 2.

The second unresolved issue was whether differences between selections for the potential and actual movement groups were reliable or instead were just an artifact of some unidentified difference between the two groups. To address this issue in Experiment 2, we made task (potential movement versus actual movement) a within-subjects rather than a between-subjects factor. This change attenuated the concern that participant differences could account for group differences.

Method

Participants. Sixteen undergraduates participated for course credit. Eight participants were male, and eight were female. All participants were right-handed, none reported a history of neurological impairment, and all were naive to the hypotheses. None had participated in Experiment 1.

Procedure. At the start of each trial, a black cross appeared at the center of the computer screen. In the actual movement condition, participants initiated trials by clicking the left mouse button. This caused the cursor to center in the cross, whereupon a black circle, a blue ellipse, and a red ellipse appeared.

Within each configuration, one ellipse was always centered at 0° from the intermediate circle, and one ellipse was always centered at 90° from the intermediate circle (with respect to the lower boundary of the quadrant of presentation). Each ellipse varied along two dimensions: orientation and distance from the circle (see Figure 5). Ellipses were offset from the intermediate circle at distances ranging from 3.7 cm to 6.475 cm, in .925 cm steps. The main axis of each ellipse was offset from the intermediate circle at angles ranging from 0° to 45° in 15° steps. Thus, the 4 (ellipse orientation) × 4 (distance) combination created 16 unique ellipses and 256 unique ellipse pairs.

We chose not to present participants with all possible configurations in all four quadrants of the screen as this would have made for a very long session. Instead, each participant viewed all configurations in a single quadrant only, making quadrant of presentation a between-subjects factor in this experiment.

Participants were told to select the ellipse they thought would enable the most rapid and accurate movement from the cross, through the circle, and into the ellipse they chose. In the actual movement condition, participants were told to move the mouse into the circle, click on it, and then move into the chosen ellipse and click on it. Accurate clicks caused target borders to change from solid to dotted lines, as in Experiment 1. After every series of 16 trials, participants in the actual movement condition received feedback about the sum of their movement times from the preceding 16 trials, as well as the lowest summed movement time from any previously completed 16-trial half block. As in Experiment 1, participants in this condition were told that movement time would be recorded after the cursor left the start cross. They were also told that their scores would be based solely on their movement times.

In the potential movement condition, participants initiated trials by pressing the computer keyboard's space bar. They were told to indicate which ellipse would be easier to reach by pressing the key

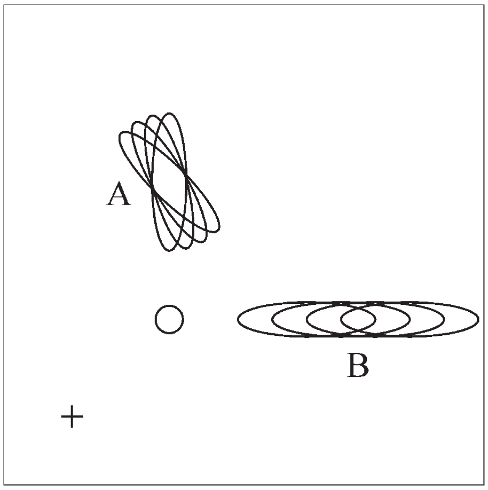

Figure 5. Possible ellipses. Cluster A shows the four possible ellipse offset angles. Cluster B shows the four possible ellipse offset distances.

bearing the red sticker for the red ellipse or by pressing the key bearing the blue sticker for the blue ellipse. The order of conditions was counterbalanced.

Results

To assess participants' sensitivity to ellipse offset distance, we considered trials in which ellipses were offset at unique distances. We calculated the number of times participants selected ellipses offset at each of the four distances, divided by the total number of times that participants could have selected ellipses offset at each of the four distances. We assessed participants' sensitivity to ellipse offset angle in the same way.

With regard to movement distance, participants favored the closer of the two ellipses both in the potential behavior condition and in the actual behavior condition. This conclusion was supported by one-way rank-order ANOVAs (Potential: $F(3, 45) = 294.67$, $p < .001$, $\eta_p^2 = .95$; Actual: $F(3, 45) = 625.00$, $p < .001$, $\eta_p^2 = .98$). The reason we used rank-order ANOVAs was that frequent selection of an ellipse at one offset distance required infrequent selection of ellipses at other offset distances. Rank-order ANOVAs mitigated these dependencies.

With regard to offset angle, participants favored the ellipse that was more closely aligned with the circle both in the potential behavior condition and in the actual behavior condition (Potential: $F(3, 45) = 2.98$, $p = .04$, $\eta_p^2 = .17$; Actual: $F(3, 45) = 8.64$, $p = .0001$, $\eta_p^2 = .37$).

With regard to the consistency of the effects of offset angle and distance between the potential behavior and actual behavior conditions, the summary data are shown in Figure 6. As shown in the left panel of Figure 6, choice probabilities in the actual and potential behavior conditions were statistically indistinguishable when computed as a function of ellipse offset angle. This result was confirmed in a nonsignificant interaction between ellipse offset angle and choice condition, $F(3, 45) = .09$, $p > .9$, $\eta_p^2 < .01$. By contrast, choice probabilities in the actual and potential behavior conditions differed when computed as a function of ellipse offset distance (Figure 6, right panel), as confirmed in a highly significant interaction between ellipse offset distance and choice condition, $F(3, 45) = 7.04$, $p = .0006$, $\eta_p^2 = .32$.

The difference in the outcomes between the potential and actual movement conditions for the distance-based choice effects was not due to learning (i.e., to participants becoming more sensitive to distance after having first performed the moves). There was no effect of testing order on the percentage of responses per offset distance in the potential behavior condition, as reflected in a non-significant interaction between testing order and ellipse distance, $F(3, 42) = 1.08$, $p > .3$, $\eta_p^2 = .07$.

The difference in outcomes between the potential and actual movement conditions for the distance-based choice effects was also not due to stimulus-response compatibility in the potential behavior condition. It did not matter whether the button that was pressed to indicate a potential behavior choice was on the same side or on the opposite side as the similarly colored ellipse, as reflected by a nonsignificant interaction between stimulus-response compatibility and ellipse offset distance, $F(3, 45) = 1.76$, $p > .1$, $\eta_p^2 = .11$.

To gain a better understanding of the factors that led to participants' choices in the actual behavior condition and in the potential behavior condition, we considered participants' choices for subsets of trial configurations. On some trials, both sources of information, ellipse offset distance and ellipse offset angle, were complementary, that is, one ellipse was closer to and also more closely aligned with the circle. On these trials, participants selected the ellipse that was closer to and more closely aligned with the circle with similar frequency in the actual (83%) and potential (75%) behavior conditions, $t(15) = 2.01$, $p = .06$.

On other trials, one source of information favored the selection of one ellipse, whereas the other source of information did not favor the selection of either ellipse. When ellipses were offset from the intermediate circle at equal distances, participants selected the ellipse that was more closely aligned with the circle with similar frequency in the actual (64%) and potential (69%) behavior conditions, $t(15) = 1.14$, $p > .2$. However, when ellipses were oriented at equal offset angles, participants selected the ellipse that was closer to the circle with greater frequency in the actual (80%) than in the potential (62%) behavior condition, $t(15) = 4.62$, $p = .0003$.

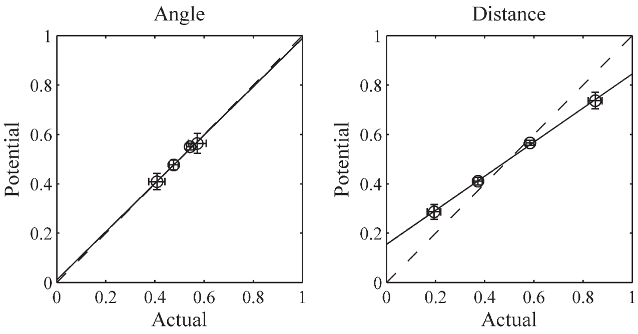

Figure 6. Proportion of selections (±1 SE) in the actual and potential behavior conditions for ellipses at each of the four offset angles (left) and at each of the four offset distances (right). The dashed diagonal line is the unity line. The solid diagonal line is the best-fitting straight line for the observed values. Data from Experiment 2.

On still other trials, the two sources of information favored the selection of different ellipses. When deciding between one ellipse that was closer to the circle and another ellipse that was more closely aligned with the circle, participants favored the ellipse that was closer to the circle with slightly higher frequency in the actual (78%) than in the potential (70%) behavior condition, $t(15) = 2.52$, $p = .02$.

Discussion

In the second experiment, we asked participants to choose which of two ellipses they preferred to move into after passing through an intermediate circle. All participants made choices both in the actual behavior condition and in the potential behavior condition. We found that participants favored ellipses that were closer to the intermediate circle, and that they favored ellipses that were more closely aligned with the intermediate circle.

Of greatest interest given the primary aim of this study, the choices that participants made differed in the actual and potential movement conditions. Whereas participants treated ellipse offset angle similarly in the two conditions, participants were less sensitive to ellipse distance in the potential movement condition than in the actual movement condition. This decreased sensitivity to distance was shown in trials where ellipses were oriented at identical angles but offset at different distances. The decreased sensitivity to distance was also shown in trials in which one ellipse was closer to the circle but the other ellipse was more closely aligned with the circle. We comment on these findings in the next section after returning to the main questions underlying this study.

General Discussion

In the early days of research on visual imagery, it was believed that visual images are like pictures in one's head. Only as the field matured did it come to be appreciated that visual images do not bear a first-order isomorphic relation to visual percepts (Shepard & Cooper, 1982). Contemporary excitement about motor imagery is comparable to the enthusiasm that characterized the early days of visual imagery research. Because recent articles have emphasized the close correspondence between imagined and performed movements, one may get the impression that motor imagery bears a first-order isomorphic relation to motor performance itself.

The present study was designed to test whether motor imagery and motor performance do indeed bear such a relation. If they do not, this need not impugn the possible value of internal simulation for motor planning. Indeed, it might be preferable to have internal simulations of actions that highlight only critical features of those actions. For example, if motor planning works by first specifying goal postures and then specifying movements to goal postures (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001, Rosenbaum, Vaughan, Meulenbroek, Jax, & Cohen, 2009), it might be wise to represent goal postures alone before determining what movements should be made. Representing goal postures alone without representing movements between goal postures would be an example of a second- or higher-order isomorphic relation to simulation and actual performance.

Previous studies, not yet mentioned in this article, have shown that there are differences between imagined and performed movements. The timing of task components has been found to differ in actual and imagined performance (Calmels, Holmes, Lopez, & Naman, 2006; Grealy & Shearer, 2008), timing variability has been found to be greater for imagined movements than for actual movements (Papaxanthis, Pozzo, Skoura, & Schieppati, 2002), and estimates of imagined walk durations have been found to exceed actual walk durations when heavy weights are carried, either in imagination or in actuality (Decety et al, 1989). It has also been shown that people misrepresent costs associated with movements of different amplitudes (Young, Pratt, & Chau, 2008).

All of the foregoing results concern tasks in which people were specifically instructed to imagine movements. The present study, by contrast, was designed to see whether differences would also be found in tasks where people indicated how they *would* move (our potential movement condition) as compared to tasks in which people actually did move (our actual movement condition). Our study was concerned therefore with movement planning; the studies just mentioned were concerned with movement imagery. The two activities might or might not be the same.

We sought to determine whether the internal simulations used in movement planning bear a first-order isomorphic relation to actual movements. We reasoned that if internal simulations of movement do bear such a relation to actual movements, decisions in our potential and actual movement conditions would be the same; but if internal simulations of movement do not bear a first-order isomorphic relation to actual movements, decisions in our potential and actual movement conditions would differ. We found that the decisions did indeed differ. This outcome rules out the first-order isomorphism hypothesis.

Is there some advantage to using a second- or higher-order isomorphic relation between movement simulations and movement executions as opposed to a first-order relation? A possible advantage of a second- or higher-order isomorphism is that internal simulations of potential movements might highlight the critical features of movements, as allowed in hierarchical planning theories such as the theory of Rosenbaum et al. (2001, 2009). From this perspective, direction judgments may have been more strongly highlighted or may have been more veridically represented than distance judgments because direction is a more important planning variable than distance. The fact that direction corrections take longer than distance corrections (Vince & Welford, 1967) fits with this interpretation, as does the fact that direction specification of forthcoming movements takes longer than distance specification of forthcoming movements (Rosenbaum, 1980).

Our results raise additional questions. One relates to Experiment 1, where participants selected the intermediate circle that was more closely aligned with the ending ellipse more consistently in the potential behavior condition than in the actual behavior condition. Why did participants come closer to seemingly optimal selections in the potential movement condition, where they received no information about selection consequences, than in the actual movement condition, where they received such information?

One possibility is that selections made in the absence of motion may have been overly conservative. Participants may have overestimated the degree of variability inherent in their aiming performance and opted for the safer bet. The idea that prospective judgments are more conservative than actual performance is supported by the finding that people underestimate the limits of their reach and step size to avoid initiating difficult and dangerous moves (Jiang & Mark, 1994; Mark et al., 1997). An interesting possibility, then, is that participants in the potential behavior condition exercised similar caution.

Alternatively, the finding that selections were more consistent with optimality in the potential movement condition may relate to findings from reinforcement learning where it has been found that failure to maximize selections (to always select the more profitable option) may reflect a tradeoff between exploration and exploitation (Hardy-Vallée, 2007). In exploration, individuals explore the range of options to derive accurate utility estimates. Conversely, in exploitation, individuals select the option with the greatest expected utility. Because participants in our potential movement condition did not actually implement selections in their overt cursor movements, they could not directly assess their selection outcomes, so they may have tended towards exploitation. By contrast, because participants in our actual movement condition did implement selections in their overt cursor movements, they could directly assess their selection outcomes and may have tended towards exploration.

A second question raised by our results relates to Experiment 2, where participants selected the ellipse that was closer to the intermediate circle more often in the actual behavior condition than in the potential behavior condition. Why were participants in Experiment 2 equally sensitive to orientation information in the actual and potential behavior conditions but less sensitive to distance information in the potential behavior condition than in the actual behavior condition?

There are several possible answers to the question. Regarding the high quality of orientation judgments in the actual and potential behavior conditions, collinear elements may contribute directly to perception of continuity (Field, Hayes, & Hess, 1993). Furthermore, orientation perception is a relatively basic perceptual accomplishment, as measured by its early age of acquisition compared to the age of acquisition of distance perception (Kellman & Arterberry, 1998). Also, to our knowledge, orientation perception has not been found to depend on whether one is perceiving for recognition or perceiving for action (Aglioti, DeSouza, & Goodale, 1995; Goodale & Westwood, 2004; Milner & Goodale, 1995). On the other hand, as far as distance is concerned, participants may have been less sensitive to distance information in the potential behavior condition, because distance perception is more difficult than orientation perception, insofar as distance perception develops later than orientation perception (for a review, see Rosenbaum, in press). In addition, distance perception, in contrast to orientation perception, has been shown to depend on whether one is perceiving for recognition or perceiving for action (Aglioti et al, 1995; Goodale & Westwood, 2004; Milner & Goodale, 1995).

Apropos of perceiving for recognition or perceiving for action, one might say that the difference in sensitivity to distance in the actual and potential behavior conditions constitutes little more than a replication of the finding that distance perception is different when the task to be performed involves the visual processing system's ventral stream (perception for recognition) rather than the visual processing system's dorsal stream (perception for action). On the other hand, there has been so much recent research on similarities between imagination of physical tasks and actual performance of those physical tasks (Decety et al, 1989; Parsons, 1994) that one would not expect the dorsal-stream-ventral-stream difference to apply here. Similarly, there has been such a strong chorus of support for internal simulation in motor planning (e.g., Wolpert & Flanagan, 2001; Wolpert et al, 1998), that one might reasonably expect that deciding how to act would not differ from deciding how one *would* act. Our study is one of the first to uncover a difference between these two conditions, perhaps because it is one of the few that has explicitly compared behavioral choices in imagination and in actual performance of the same task.

Our data vitiate any simple story in which the same "movie" is run in the head to decide among actual and potential behaviors. Saying that people watch that same movie is another way of saying that people rely on internal simulations that bear a first-order isomorphic relation to actual performance. Our results cast doubt on such an account. Knowing which movie to play begs the question to be solved, as does identifying the little person in the head occupying the theater.

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