What is chosen first, the hand used for reaching or the target that is reached?

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BRIEF REPORT

What is chosen first, the hand used for reaching or the target that is reached?

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Abstract Models of information processing generally assume that stimuli are processed before actions are selected, at least in typical laboratory experiments where stimuli are presented and responses follow. In everyday life, however, there are generally fewer constraints on the ordering of decisions pertaining to stimuli and actions. This raises the question of which sorts of decisions normally precede which others. To address this question, we asked participants to aim for either of two targets with either hand on the basis of whichever combination seemed easiest. We analyzed the choices made in this free condition with choices made when the hand was specified or when the target was specified. We found that a model assuming similar selection processes in the hand-specified condition and the free condition provided the best account for the data. The data accord with the hypothesis that hand was generally chosen first in the free-choice condition.

Keywords Action · Information processing · Reaching · Response selection

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Introduction

For more than a century, experimental psychologists have had subjects (human and animal) respond to stimuli in the laboratory. From such research, it has been possible to develop models in which stimuli are assumed to be dealt with first and responses are assumed to be dealt with second. These models have included serial (e.g., Sternberg, 1969) and parallel or cascade (e.g., McClelland, 1979; Spivey, 2007) processing.

Whereas these traditional models suggest that individuals primarily engage in stimulus processing before action processing, this view has been challenged by observations that actors' predispositions to act one way or the other may affect what they perceive (Linkenauger, Witt, Stefanucci, Bakdash, & Proffitt, 2009) or choose to do (Proffitt, 2006). Likewise, neurophysiological findings indicate that there is no clear dividing line between neural systems for stimulus selection and action specification (Cisek & Kalaska, 2010). For example, the parietal reach region of the posterior parietal cortex, traditionally associated with action planning, turns out to contribute to the selection of reaching targets (Scherberger & Andersen, 2007).

We have been wary of the assumption that stimulus processing normally precedes action processing, so we asked whether there is a specific ordering of stimulus and action processing when it is possible to select among many stimuli and actions concurrently. Our question was whether the selection of the stimulus determines (and so precedes) the selection of the action, whether the selection of the action determines (and so precedes) the selection of the stimulus, or whether neither of these two methods predominates.

We asked university students to aim with one or the other hand for either of two target stimuli, one blue and one green, with the left/right positions of the two colors uncertain on each trial. In the condition of greatest interest, the *free* condition, we constrained neither the target nor the hand.

The same participants could choose either the blue target or the green target with either the left hand or the right hand. We compared choices in the free condition with choices in a *target-specified* condition and a *hand-specified* condition, in which the target or hand, respectively, was specified prior to the remaining aspect of the choice. In the target-specified condition, we told participants they had to touch the *blue* target with either hand or, in other blocks, the *green* target with either hand. This condition required participants to select the hand given the target. In the hand-specified condition, we told the same participants to use the *left* hand to touch whichever target they wanted or, in other blocks, the *right* hand to touch whichever target they wanted. This condition required participants to select the target given the hand.

We considered three hypotheses about the free condition. According to the *hand-first* hypothesis, hand choice would determine target choice, so choices in the free condition would be similar to choices in the hand-specified condition. We associated this hypothesis with the perspective endorsed by Linkenauger et al. (2009) and Proffitt (2006). According to the *target-first* hypothesis, target choice would determine hand choice in the free condition, so choices in the free condition would be similar to choices in the target-specified condition. We associated this hypothesis with stimulus–response perspectives, such as those endorsed by Sternberg (1969), McClelland (1979), and Spivey (2007).[1] According to the third, *neither-first* hypothesis, hand choice would not reliably determine target choice, nor would target choice reliably determine hand choice in the free condition, so choices in the free condition would differ from choices in the hand-specified *and* target-specified conditions. We associated this hypothesis with the model endorsed by Cisek and Kalaska (2010).

To test the predictions, we used two general methods. The first let us determine whether target choice depends on hand choice or whether hand choice depends on target choice. The second allowed for a direct comparison of the three hypotheses via a modeling approach.

In pursuit of the first method, we reasoned that if the specification of one aspect X (e.g., target) of the choice determined (and preceded) the other Y (e.g., hand), the choice of Y would not depend on what led to the selection of X. Thus, if hand choice was determined by target choice, hand choice would be unaffected by whether a specific target was selected freely or by instruction. Likewise, if target choice was determined by hand choice, target choice would be unaffected by whether a specific hand was selected freely or by instruction. If neither aspect of the choice consistently determined the other, choices in the free condition would be expected to differ from those in the other conditions. To test these predictions, we compared the conditional probabilities of choice with respect to one aspect (target or hand) given a choice with respect to the other aspect (hand or target) in the free, hand-specified, and target-specified conditions.

The foregoing predictions let us judge the extent to which target and hand choice depended on the selection of the respective remaining aspect. We also directly compared the hypotheses against one another by pitting them against each other in computational models. The models were distinguished by the processes they assumed for predicting choices in the free condition. Those processes were assumed to rely on (1) ones used to predict choices in the hand-specified condition (the hand-first model), (2) ones used to predict choices in the target-specified condition (the target-first model), or (3) neither (the neither-first model). We asked which of the three models' theoretically derived data provided the best fit to the obtained data. We assumed that whichever model provided the best fit was the one that was most likely.

Finally, to complement the choice analyses, we also studied the reaction times to start moving either hand after the target was displayed, as well as the subsequent movement times to reach either target. With regard to reaction times, we reasoned that these times would be similar in conditions that triggered similar processes. So according to the hand-first hypothesis, the reaction times would be similar in the hand-specified condition and free condition but would not necessarily be as similar in the target-specified and free conditions. By contrast, according to the target-first hypothesis, the reaction times would be similar in the target-specified condition and free condition but would not necessarily be as similar in the hand-specified condition and free condition. Finally, according to the neither-first hypothesis, the reaction times would not necessarily be similar in any of the three conditions.

With regard to movement times, we studied these values to rule out a potentially trivial interpretation of our data—that participants might have specified the target only after starting to move the hand in the free condition and in the hand-specified condition, but not in the target-specified condition. If that were the case, the reaction times would be smaller and movement times would be larger in the hand-specified and free conditions than in the target-specified condition. Additionally, if only some participants postponed target selection until after movement onset, we would expect more negative correlations between reaction times and movement times in the hand-specified and free conditions than in the target-specified condition. Finally, comparing the general magnitude of the reaction times and movement times with that in previous research (e.g., Rosenbaum, 1980), we

[1] The focus of these authors was on the inner dynamics of processing, rather than on defending the view that perception always leads action. The kinds of experiments to which they directed their models happened to be of the classic stimulus–response kind.

could judge whether it was plausible to assume that part of the decision process was or was not postponed until after movement onset.

Method

Participants

Twenty right-handed Penn State University undergraduates (13 women and 7 men, average age 20 years) took part for course credit after giving informed consent. The experiment was approved by the Penn State Institutional Review Board.

Apparatus and stimuli

Participants sat before a 17-in. touch screen monitor in a dimly lit room. The target pairs were two roughly isoluminant, horizontally aligned, 3-cm diameter circles that were always 6 cm apart. The midpoint between each pair of circles could be positioned at a distance of −6 cm (left), −3 cm (left), 0 cm (centered), 3 cm (right), or 6 cm (right) from the screen's midline. The assignment of color (blue or green) to side (left or right) was random on each trial. A standard keyboard was centered beneath the screen, with the F-keys facing the participant (i.e., with the keyboard turned 180° relative to its normal orientation). The F5 and F9 keys served as the home positions for the right and left index fingers, respectively, and were marked with orange tape.

Procedure and design

At the start of each trial, the participant pressed the exposed keys with his or her index fingers. Once both keys were pressed, a centrally positioned fixation cross appeared for 2 s. If the participant released one of the start keys during presentation of the fixation cross, the trial was restarted. Otherwise, both targets were shown. The participant was then supposed to reach for and touch one of the targets with one of his or her index fingers. The touched target then disappeared.[2] An error message appeared if the participant released both keys, used the wrong hand in the hand-specified condition, touched the wrong target in the target-specified condition, or took more than 4 s to touch the target.

There were 18 blocks of trials. Six were for the free condition, 6 were for the hand-specified condition (3 for the left hand, 3 for the right hand), and 6 were for the target-specified condition (3 for the blue target, 3 for the green target). Block order was randomized except for the constraint, over participants, that each condition was represented equally often in each serial position.

Every possible pair of target pair positions and color-defined target arrangements was repeated twice per block in random order. There were at least 22 trials per block. The first 2 were treated as warm-up trials when it came to later data analysis and were not announced as such to participants. Any trials with mistakes were retested during the block.

Before each block, the participant was presented with on-screen written instructions about the upcoming choice. Representative instructions were: (1) "In the following trials hit EITHER target with EITHER hand as quickly as possible"; (2) "In the following trials hit EITHER target with the LEFT hand as quickly as possible"; (3) "In the following trials hit the BLUE target with EITHER hand as quickly as possible." Participants were told to perform the task as quickly as possible without making errors and to make whatever choice seemed easiest.

End-of-block feedback rewarded speed and accuracy. The higher the score the better. A point was added for every 10 ms below 2,000 ms for the sum of reaction time (time to lift the key) and movement time (time to touch the target). The score was reduced by 100 points if participants made an error.

Data analysis

The dependent variables were the hand used (left or right), the target touched (left or right), the reaction time, and the movement time. The data came from 397 trials on average per participant, or just one more trial on average than necessary to accommodate the 22 trials (2 warm-ups plus 20 experimental trials) per 18 blocks per participant.

Results

Errors or slow reactions comprised just 0.3 % of the experimental (non-warmup) trials. Error trials were excluded for data analysis purposes. From the remaining trials, 3.7 % were removed because of premature reactions (reaction times shorter than 100 ms) or unusually slow responses (reaction times plus movement times greater than 1,000 ms).[3] Excluded trials came from all the conditions to a statistically equivalent degree.

The subsequent presentation of results is divided into three subsections. First, we present the choices in the free

[2] Touches outside both targets were marked with a red dot and could be corrected. Corrections occurred on 2 % of trials.

[3] The 1,000-ms threshold was defined after inspection of the distribution of reaction times plus movement times, independent of the time window allowed for participants to complete their responses. A reanalysis of the data including premature and slow reactions resulted in a similar pattern of results.

condition and the extent to which the hand choices and target choices were determined by target and hand choices, respectively. Then we describe the model-based comparisons. Finally, we discuss reaction times and movement times.

Hand and target choices

Figure 1 shows how often each hand and target was selected in the free-choice condition. The right hand was generally preferred over the left hand for all target pairs. A one-sample t-test against .5 showed that the t value for all target pairs, $t(19)$, exceeded 4.45, with all $ps < .001$ and all $gs \geq 0.996$. The right target was preferred over the left target if the target pair was presented centrally or on the left, whereas the left target was preferred if the targets were presented on the right, as confirmed in one-sample t-tests against .5, all $t(19)$s > 4.50, all $ps < .001$, all $gs \geq 1.006$.

To test the extent to which one aspect of the choice determined the other, we compared the conditional probabilities when one feature (hand or target) was specified, as compared with when neither feature was specified (Fig. 2).[4] As can be seen in the top two panels of Fig. 2, the selection of target was virtually identical if the hand was freely chosen or if the hand was specified in advance. This was true regardless of whether the instructed hand was left or right, as can be seen in Fig. 2a and b, respectively, suggesting that hand choice determined target choice. By contrast, as can be seen in Fig. 2c and d, the selection of hand depended on whether the target was freely chosen or was prespecified. This was especially true if the specified target was on the left (Fig. 2c) but was also true if the specified target was on the right (Fig. 2d).[5]

[4] We used conditional probabilities to compare the choices in the free condition with those in the other conditions, despite differences in the overall frequency of specific target or hand choices. Conditional probabilities could not be computed when the prior probability was zero (e.g., p[LT] = 0 for p[LH|LT]). Therefore, for each target pair position separately, we included data only from participants for whom the relevant prior probability was nonzero. The aggregated data closely resembled the data of the 3 participants who could contribute to all conditions.

[5] Since not all participants provided data for all target pair positions, we evaluated the effect of choice condition on the probabilities, using pairwise t-tests performed independently for each target pair position, using data only from participants who could contribute to both sides of each pair. The tests showed that target selections were not significantly affected by whether hand was specified in advance, either for p(LT|LH), all ps >.102, all η_p^2s < .224, or for p(LT|RH), all ps >.230, η_p^2 < .075. By contrast, hand selections were affected by whether target was specified in advance. p(LH|LT) depended significantly on choice condition for all target pair positions, all ps < .047, all η_p^2s > .192. p(LH|RT) was significantly affected by choice conditions for target pair positions 0 and 3 cm, all ps < .045, all η_p^2s > .198.

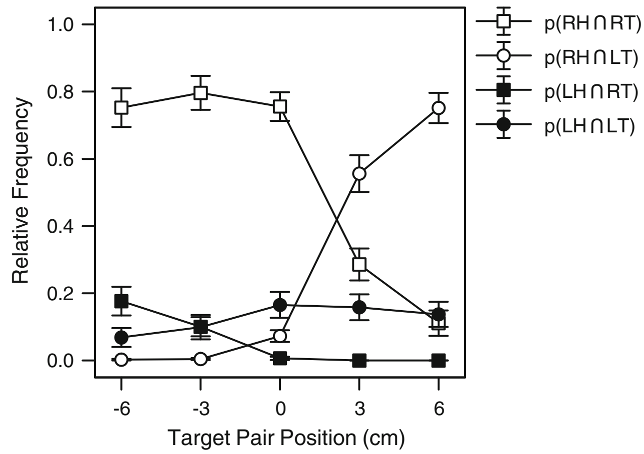

Fig. 1 Frequency of hand and target choices in the free condition plotted as a function of target pair position (most leftward to most rightward). Error bars show standard errors of the means

Model-based comparison of the target-first, hand-first, and neither-first hypotheses

We turn now to our model-based comparisons. First, we directly compared the target-first and hand-first hypotheses, using two computational models. Both models were equivalent in structure and in number of parameters. For the target-first model, we used parameters to predict choices in the free condition that overlapped with the parameters used in the target-specified conditions. For the hand-first model, we used parameters to predict choices in the free condition that overlapped with the parameters used in the hand-specified conditions. The question was which model provided a better fit.

Each model included as parameters four conditional probabilities; p(LH|LT), p(LH|RT), p(LT|LH), and p(LT|RH), where LH denotes the left hand, LT denotes the left target, RH denotes the right hand, and RT denotes the right target. We used these conditional probabilities to predict choices in the target-specified and hand-specified conditions. In the case of the target-first model, we added a parameter, p(LT), corresponding to the probability of selecting the left target in the free condition, independently of hand choice. We then used that parameter, in conjunction with the conditional probabilities p(LH|LT) and p(LH|RT), to predict the probabilities of the four possible choices in the free condition. Similarly, in the case of the hand-first model, we added a parameter, p(LH), corresponding to the probability of selecting the left hand, independently of target choice. We then used that parameter, in conjunction with the conditional probabilities p(LT|LH) and p(LT|RH), to predict the prob-

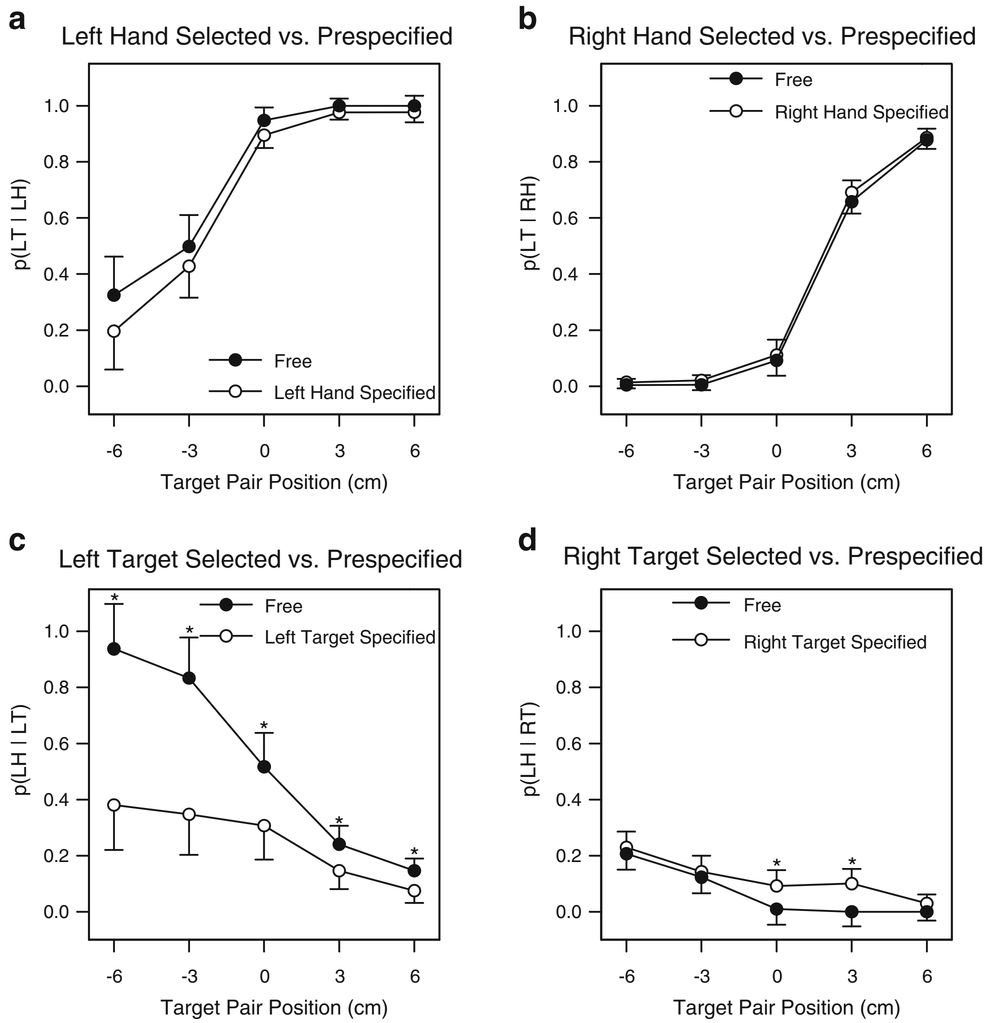

Fig. 2 Frequency of target selections (upper panels) and hand choices (lower panels) plotted as a function of target pair position. **a** Probability, p(LT|LH), of choosing the left target when the left hand was either prespecified or freely chosen in condition. **b** Probability, p(LT|RH), of choosing the left target when the right hand was either prespecified or freely chosen. **c** Probability, p(LH|LT), of choosing the left hand when the left target was either prespecified or freely chosen. **d** Probability, p(LH|RT), of choosing the left hand when the right target was either prespecified or freely chosen. Error bars are 95 % within-subjects error bars for the comparison of data points with the same target pair position (Loftus & Masson, 1994). Asterisks show significant differences ($p < .05$)

abilities of the four possible choices in the free condition. We computed maximum likelihood estimates for the five parameters of both models for each participant and each target pair position. The result was that the hand-first model provided a significantly better fit than did the target-first model, in terms of both log likelihood and R^2, $t(19) = 2.40$, $p = .027$, $g = 0.536$, and $t(19) = 2.386$, $p = .028$, $g = 0.533$, respectively.

Next, we tested whether a significantly better fit could be provided by assuming some other process than the one specified in the hand-first model. We compared the hand-first model with a neither-first model that reflected the assumption of a choice process specific to the free condition. Here, we used three parameters to predict choices in the free condition that did not overlap with any of the parameters used to model the remaining conditions. Those parameters were chosen just to permit the best possible fit to the choice probabilities in the free condition and so were ad hoc by design. If the hand-first model could do as well as the neither-first model—the latter having not only more parameters, but also ad hoc parameters chosen only to maximize the fit in the free condition—that outcome would corroborate the view that the hand-first model was a good and sufficient description of the actual process used in the free condition.

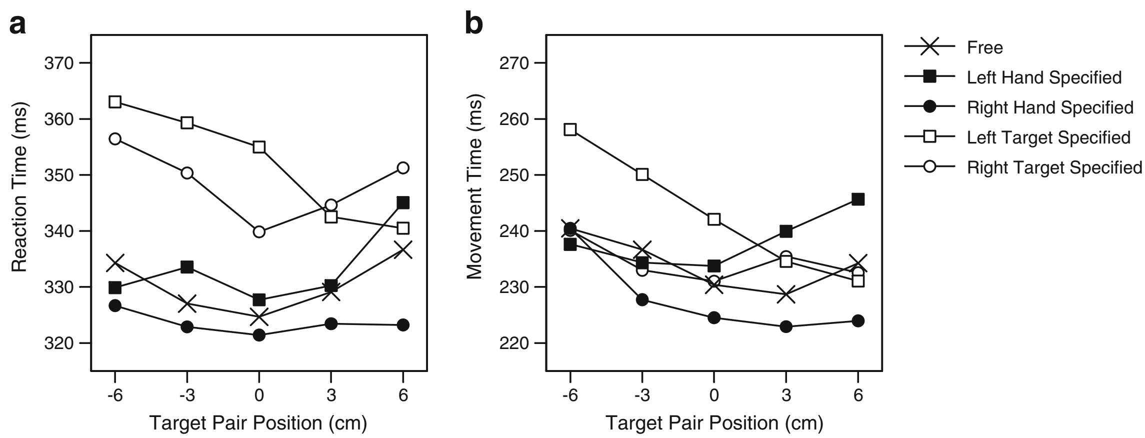

Fig. 3 Reaction times (**a**) and movement times (**b**) as a function of target pair position (most leftward to most rightward) and choice condition

The outcome attested to the power of the hand-first model. Likelihood ratio tests did not show a significant difference between the hand-first model and the neither-first model at the level of any individual participant, all $\chi^2(20) < 15.8$, all ps $> .104$, or when analyzing the data for all the participants as a whole, $\chi^2(400) = 132.7$, $p = 1.0$. Thus, the hand-first model could be viewed as a good description of the actual process used in the free condition.

Reaction times and movement times

We first conducted ANOVAs on reaction times and movement times separately, with the factors being target pair position and choice condition.[6] In case of significant effects of choice condition, we conducted post hoc ANOVAs comparing the data from the free condition with those from each of the other conditions, using the Bonferroni–Holm procedure, with a global alpha of .05.

Figure 3a shows that the reaction times depended on choice condition, $F(4, 76) = 16.31$, $p < .001$, $\eta_p^2 = .462$, and target position, $F(4, 76) = 5.43$, $p = .002$, $\eta_p^2 = .222$, and the interaction between both, $F(1, 19) = 3.98$, $p = .001$, $\eta_p^2 = .173$. Reaction times in the free condition were shorter than those in the left-target-specified condition, $F(1, 19) = 33.97$, $p < .001$, $\eta_p^2 = .641$, and the right-target-specified condition, $F(1, 19) = 23.47$, $p < .001$, $\eta_p^2 = .553$. The difference between the free and left-hand-specified condition was more pronounced for targets on the left, $F(4, 76) = 6.62$, $p = .002$, $\eta_p^2 = .258$. By contrast, reaction times did not differ between the free condition and the right-hand-specified or left-hand-specified condition, nor were any significant interactions found, all Fs ≤ 2.49, all ps $\geq .13$, all η_p^2s $\leq .116$. Overall and in summary, reaction times were similar in the hand-specified and free conditions but were different in the target-specified and free conditions.

Figure 3b shows that movement times depended on target pair position, $F(4, 76) = 8.47$, $p < .001$, $\eta_p^2 = .308$, as well as the interaction of target pair position and condition, $F(16, 304) = 2.78$, $p = .022$, $\eta_p^2 = .128$. None of the post hoc tests revealed a significant effect of condition or a significant interaction when tested with the Bonferroni–Holm correction.

The Pearson product–moment correlations between reaction times and movement times (over participants) were positive in every condition and did not differ between any pair of conditions. Reaction times and movement times were affected comparably in all conditions, as revealed by an ANOVA with factors of choice condition, target pair position, and variable (reaction time vs. movement time); all ps for interactions with factor variable >.05. Movement times were also smaller than reaction times, $F(1, 19) = 122.79$, $p <. 001$.

Discussion

In this study, we addressed a question that has received short shrift in experimental psychology: How are choices made when both targets and actions can be freely chosen? We addressed this question by comparing choices in a manual aiming task in which participants could freely choose both hand and target, hand only (target specified),

[6] We report Greenhouse–Geisser corrected p-values but uncorrected dfs.

or target only (hand specified). The analysis of conditional choice probabilities and a model-based comparison both revealed that the choices made when our participants could freely choose both hand and target were similar to the choices they made when hand was specified before the target could be chosen.

The reaction times and movement times supported this conclusion. The reaction times were similar in the hand-specified and neither conditions but were less similar in the target-specified and neither conditions, suggesting that similar processes were used in the hand-specified and neither conditions, whereas different processes were used in the target-specified and neither conditions. In addition, reaction times and movement times were positively correlated to an equal degree in all three conditions and were statistically equivalent. Moreover, movement times were sufficiently short in all conditions to suggest that participants specified the target and hand before moving the hand in all conditions. The latter two results forestall the possibility that participants specified the target only after starting to move the hand in the free and hand-specified conditions, but not in the target-specified condition.

Another explanation of our results can also be rejected. Perhaps it was more important for participants to choose the hand wisely than to choose the target wisely. We doubt that this interpretation is correct, however. If our participants had simply attached greater importance to hand selection than to target selection, we would have expected participants who had a strong hand preference to show a stronger bias toward hand-first processing than did participants who had a less strong hand preference. This was not the case, however. As shown in Fig. 4, the hand-first model outperformed the target-first model considerably for the 3 participants who used the left hand and right hand with about equal frequency in the free condition. There was no systematic relation between self-reported handedness and which model performed better, as expressed by the difference of the log likelihoods of the hand-first and target-first models (i.e., the log Bayes factor), $r = -.079$, $t(18) = -0.33$, $p = .741$. Moreover, targets were selected consistently and systematically, indicating that participants cared about target selection. Consequently, we do not think our participants simply cared more about hand choices than about target choices.

Still another possibility that can be rejected is that the requirement to react quickly might have biased participants to specify the hand as early as possible just to reduce reaction times. If this had been the case, we would have expected participants with shorter reaction times to be better described by the hand-first model than would participants with longer reaction times. If anything, the reverse was true, however, as was expressed by a (nonsignificant) positive correlation between reaction times and the difference of the log likelihoods of the hand-first model and the target-first model (log Bayes factor), $r = .122$, $t(18) = 0.52$, $p = .609$.

Considering all these arguments, we believe that our main conclusion, that participants chose hand before target in the free condition, was not an artifact of some specific, subtle feature of our experiment. Instead, we think that the hand-first model is the best model for what happened in the free condition. This model comports best with affordance-based theories such as the one championed by Linkenauger et al. (2009) and Proffitt (2006), which is traceable, of course, to Gibson (1977).

Still, we must ask about the generalizability of our conclusion. Do we mean to suggest that action selection always precedes stimulus selection? The answer is *no*. When a politician makes a positive statement, gesturing with his or her dominant hand, for example, versus a negative statement, gesturing with his or her nondominant hand (Casasanto & Jasmin, 2010), we do not mean to suggest that he or she chooses a hand and then decides to say something up- or downbeat. On the other hand, to the extent that our task is similar to many that have been used in traditional information-processing studies, we do want to raise the possibility that response (or action) selection may lead stimulus processing more often than has generally been assumed in the hundred plus years that experimental psychologists have had subjects (human and animal) respond to stimuli in the laboratory.

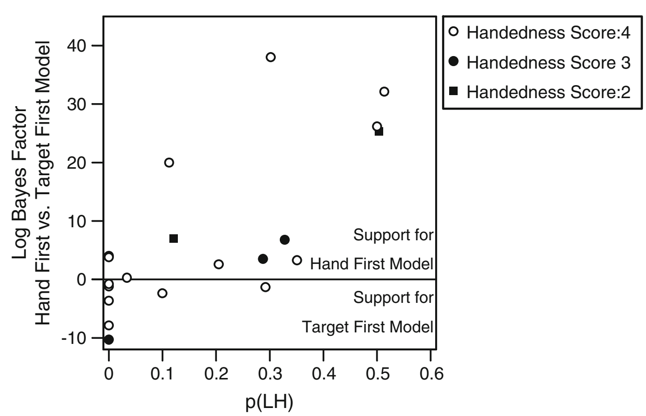

Fig. 4 Log Bayes factor (log likelihood of hand-first model − log likelihood of target-first model) of model fits to individual participants plotted as a function of the probability of left-hand use, p(LH), in the free condition. Symbols refer to self-reported handedness (Handedness scale of Lateral Preference Inventory; Coren, 1993), where four (dots) corresponds to a strong right-hand preference and three and two to a lesser degree of right-handedness. Positive log Bayes factors indicate that the hand-first model provides a better fit than the target-first model

Author Note This study was conducted while the first author visited the second author's lab. We thank Martin V. Butz, Kate Chapman, Chase Coelho, Sarah Creem-Regehr, Lanyun Gong, Judith Kroll, Wilfried Kunde, Thomas Schenk, Janet van Hell, and an anonymous reviewer for helpful comments.

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