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A kinematic analysis of hand selection in a reaching task

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A group of left- and right-handers was tested on a task requiring them to reach out and pick up an object with either the left or the right hand. We varied the eccentricity of the target object (a small glass) and the required accuracy level, by filling the glass with liquid. We recorded (a) frequency of left or right hand use, (b) hand preference using a handedness questionnaire, and (c) the trajectories of the reaches using a movement registration system. It was found that the stronger the hand preference, the further in contralateral space the shift occurred between left and right hand use. Not only did the transition point corresponding to the shift between the two hands correlate with the point where their deceleration times were equal, but these locations closely coincided. These findings suggest that people are highly skilled perceivers of their own action capabilities, and that they are able to select the action mode that is most suited to perform a given task. We argue that laterality should be understood in terms of asymmetries in action modes.

The consensus seems to be that handedness should be conceived as a continuum rather than a dichotomy (e.g., Bishop, 1990). However, it has proved surprisingly difficult to devise a quantitative measure of handedness. Handedness studies typically employ an inventory, consisting of a range of activities (e.g., writing, hammering, etc.), and participants are asked to indicate which hand they typically use in performing that activity. The examination of patterns of scoring allows the researcher to index the direction and the degree of handedness. However, handedness inventories suffer from a range of problems, such as the fact that the items that make up the inventory are usually assigned equal weights. In addition, some items may not give a fair reflection of handedness due to the existence of culture-specific practices of using a particular

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hand for certain activities, such as writing (e.g., Calvert & Bishop, 1998; Guiard, 1988).

To overcome some of these problems, a number of recent studies have tried to devise a measure of handedness using a behavioural continuum (e.g., Bishop, Ross, Daniels, & Bright, 1996; Bryden, Pryde, & Roy, 1999; Bryden, Singh, Steenhuis, & Clarkson, 1994; Calvert & Bishop, 1998; Gabbard, Rabb, & Gentry, 1998). In these tasks the participant is typically required to select a hand to manipulate an object in ipsilateral or in contralateral space. The relative frequency of use of the right or left hand is then used to index the direction and the degree of handedness. For instance, in the study of Bryden et al. (1994), left-handers and right-handers were asked to move a pair of small wooden pegs from one end of a long pegboard to the other end by ‘‘leapfrogging’’ the pegs in succession. The participants could shift between moving the pegs with one hand to moving the pegs with the other hand at any time it felt appropriate to do so. It was found that left-handers moved farther to the right of their body midline with the left hand to manipulate the pegs before switching to the alternate hand than did the right-handers. (The reverse pattern of results for the right-handers, however, was not statistically significant.) In addition, the Bryden et al. (1994) study found a strong positive correlation between performance on the long pegboard and scores on the Waterloo Handedness Inventory. Similar results were observed by Bishop et al. (1996) on her so-called Quantification of Hand Preference (QHP) task. Prior to the task, right-handed participants completed a 10-item version of the Edinburgh Handedness Inventory and, based on their scores, were classified as exclusive right-handers or as predominant right-handers[1]. In the QHP task, participants were asked to pick up a card that could be in different spatial locations relative to the body midline. It was found that the farther the card from the midline, the greater the likelihood that the ipsilateral hand was used to pick it up. In addition, most participants used their right (dominant) hand more often than their non-dominant hand, so as to pick up cards that were in their left (contralateral) hemispace. Moreover, the relative frequency with which a hand was selected appeared to be a function of the degree of hand preference, in that the exclusive right-handers used their right hand more often to pick up a card than the predominant right-handers. As a final example, Calvert and Bishop (1998), obtained a comparable pattern of results on the QHP task using exclusive and predominant left- and right-handers. Taken together, these studies demonstrate that the spatial location of the target object and the handedness of the actor are fundamental constraints on hand selection. Participants often select their preferred hand to reach across the body midline to manipulate objects in contralateral space, even though the use of their non-

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[1] Participants who said they used their right hand for all of the activities in the inventory were classified as exclusive right-handers, and those who said they used their right hand for most of the activities were classified as predominant right-handers.

preferred hand would involve a shorter distance of movement. Moreover, the relative frequency with which a hand is selected relates closely to handedness as assessed using a handedness questionnaire.

Although these studies have proved useful in distinguishing various subgroups of left- and right-handers, they have hardly addressed the question as to why people select one hand over the other in the first place. Recently, Bryden et al. (1999) have attempted to address this problem by investigating hand preference in relation to tasks of different complexity. Task complexity is a multidimensional problem and we believe it is more promising to investigate hand preference in terms of specific behavioural variables (e.g., speed, accuracy, etc). We hypothesise that choice of hand is a function of the level of accurate control that can be attained by the respective hands (see, for example, Bryden & Roy, 1999). We decided to test this hypothesis by examining the temporal evolution of reaching movements (i.e., their kinematics) when people select a hand to pick up an object placed in various locations. Students of motor control have examined numerous kinematic variables that might characterise goal-directed arm movements, such as movement time, percentage of time spent accelerating or decelerating, peak velocity, end point variability, curvature of the hand path, etc. The variable that seems to best capture accuracy of movement is the amount of time spent decelerating. Ballistic hand movements in reaching tasks typically exhibit a more or less bell-shaped velocity profile (e.g., Bullock & Grossberg, 1988). However, as the accuracy demands increase, the velocity profile tends to become skewed due to a lengthening of the decelerative phase relative to the accelerative phase (e.g., Marteniuk et al., 1987; Steenbergen, Marteniuk, & Kalbfleisch, 1995; Van der Kamp & Steenbergen, 1999). If accuracy is a fundamental constraint in hand selection, we expect the deceleration times to systematically vary with frequency of hand use.

In the present experiment, participants faced an array of target objects (seven in total) spaced symmetrically to their left and right. The objects were small glasses, and participants had to select a hand to pick up a predesignated glass. Other things being equal, the symmetrical arrangement of object locations should give rise to equal use of both hands, with the transition from the predominant use of the right hand to the left hand occurring at the midline. However, in line with the studies referred to earlier (Bishop et al., 1996; Bryden et al. 1994; Calvert & Bishop, 1998), we expect hand preference to break the symmetry of the probability distribution of the hand selection scores, with the transition from predominant use of the preferred hand occurring in contralateral space rather than at the body midline. Moreover, we predict that the point of transition from the use of the preferred to the non-preferred hand will closely correspond to the location where the deceleration times for the preferred and non-preferred hands are equal.

In addition to object location and hand preference we also manipulated the level of accuracy required to perform the task. A relatively consistent finding in the handedness literature is that hand differences are likely to be more marked when the performatory system is put under a certain amount of stress, such as tasks requiring tight spatial control (e.g., guiding a thread through the eye of a needle), or tight temporal control (e.g., rhythmic interlimb co-ordination at high frequencies, Treffner & Turvey, 1996). Although Bishop et al. (1996) did not provide a justification for their choice of target object, this is presumably why they asked their participants to pick up playing cards, as opposed to wooden cubes, say, because the former task involves a considerable level of accurate control, and hence should give rise to substantial differences between the hands. In our task, participants were presented with empty glasses and (in another condition) with glasses that were filled to the rim with liquid (cf Steenbergen et al., 1995). We predict that the added demands on accuracy of action when reaching to pick up a filled rather than an empty glass will not only lead to longer deceleration times, but will also cause the transition from the preferred to the non-preferred hand to occur further in contralateral space.

Finally, we tested to what extent these manifestations of handedness (frequency of hand use and movement kinematics) corresponded to scores on a handedness inventory.

METHOD

Participants

Seven self-professed right-handers (two males and five females) and seven self-professed left-handers (two males and five females) participated in this experiment. Participants were undergraduate students at the University of Portsmouth, and were naive as to the purpose of the experiment. At the end of the experiment, all participants except Participant 4 filled out the Annett (1970) hand preference questionnaire.

Apparatus and stimuli

Figure 1 shows a plan view of the experimental set-up. Participants were seated at a table (70 cm high, 122 cm wide, and 61 cm deep). Two small pieces of tape (the black squares in Figure 1) on the left and the right side of the table served as the starting positions of the left and right hands. The distance between the pieces was 72 cm. In front of the participant on the distal end of the table was a linear array of seven equidistant small round transparent glasses (the grey circles in Figure 1). The array of glasses was parallel to the line connecting the starting positions. The distance between the centres of the glasses was 12 cm. The distance between the starting position of the left hand and the extreme left glass (no. 1) was 33 cm, as was the distance between the right hand and the extreme right glass (no. 7). The middle glass (no. 4) was directly in line with the participant. The extreme left and right glasses could easily be reached by the

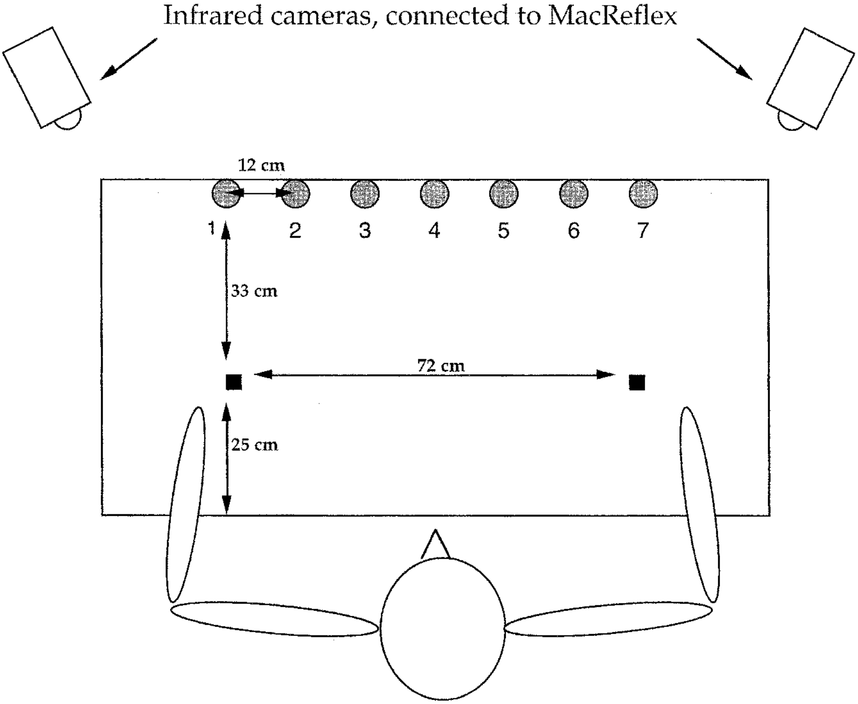

Figure 1. Plan view of the experimental set-up (not drawn to scale). Participants were seated at a table, with the fingertips of each hand resting on a small piece of tape (the black squares). A linear array of 7 glasses, each of which could serve as the target object, was in front of the participants. Two infra-red cameras recorded the reaching movements.

respective hands. However, a reach to the leftmost glass with the right hand (or vice versa) could only be accomplished by fully extending the arm, and leaning both sideways and forwards.

The glasses were 6.5 cm high and 4.5 cm wide. In one condition (see the Procedure section) all the glasses were empty, and in another condition all the glasses were filled with dark liquid (cold coffee). The empty glasses weighed 100 gm each, and the filled ones weighed 150 gm each. The position of each glass was marked by a square outline of white tape on the table. In addition, the numbers 1 to 7 were written on the table directly in front of the respective glasses.

Passive infra-red reflecting markers (1 cm diameter) were attached to the wrist of the left and the right hand. The position data of each of the markers were sampled at a frequency of 60 Hz by two infra-red cameras (MacReflex). The data were stored on a computer for off-line analysis.

The Annett (1970) questionnaire consists of 12 items. Each item asks which hand is habitually used to perform a certain activity, such as writing, throwing a ball, etc., and could be answered with L (left), R (right), or E (either). Details of the questionnaire can be found in the Appendix.

Procedure and design

Prior to each trial, participants brought their hands to their respective starting positions, such that (a) the palms of the hands rested on the table, and (b) the fingertips rested on the pieces of tape that served as the starting positions (Figure 1). In each trial, participants had to select the left or right hand, move the hand to one of the seven glasses, grasp the glass, lift it up a few centimetres, put it down again, and finally bring the hand back to the starting position, after which the following trial started (cf. Zaal, Bootsma, & Van Wieringen, 1999). Participants were instructed to perform the entire movement sequence (reach, grasp, lift, put down, bring back) in a fast and fluent fashion. The grip pattern of the hand had to be such that the thumb contacted one side of the glass, and the fingers contacted the opposite side.

Prior to the experiment, participants received both written and verbal instructions. In addition, the required movement was demonstrated by the experimenter.

The experiment consisted of two tasks: a ‘‘forced-choice task’’ and a ‘‘free-choice task’’. In the forced-choice task, participants were informed on each trial which glass (1 to 7) had to be picked up, and which of the hands had to be used. The experimenter called out a number (e.g., ‘‘no. 3’’), followed by a hand (e.g., ‘‘right’’), which was a signal for the participant to pick up the designated glass with the instructed hand (in this case, glass no. 3 with the right hand). The start of each trial coincided with the experimenter pressing a key on the keyboard that initiated a 6-s automatic movement recording sequence, after which the next trial was initiated. The free-choice task was similar to the forced-choice task, except that now only a glass (e.g., ‘‘no. 7’’) but no hand was specified by the experimenter. Instead, participants were explicitly asked to select the hand they felt to be most comfortable to pick up the designated glass. In other words, they should, in each trial, let the relative comfort determine choice of hand.

In addition to the type of task (forced vs free) we also manipulated the level of accuracy. This was done by filling all glasses to the rim with dark brown liquid (cold coffee) within one block of trials, and simply leaving all the glasses empty in the other block of trials. Participants were instructed not to spill any liquid when picking up a filled glass. In fact, spillage turned out to be rare and limited to a few drops, so that the glass never had to be refilled. The experiment thus consisted of a total of four blocks: two blocks (forced vs free) with all the glasses empty and two blocks with all the glasses full. The order of the blocks was such that, given a full or empty glass, the first block was always the forced task, and the second block was always the free task. Half the participants started with the two blocks involving the full glass, followed by the blocks involving the empty glass. This order was reversed for the other participants. Each block was preceded by two to four practice trials that were not analysed.

The forced condition consisted of 56 trials; four repetitions of each combination of glass (1–7) and hand (left/right) in a completely random order. The free condition consisted of 84 trials; 12 repetitions of each of the glasses, again in a completely random order. The entire experiment thus consisted of 280 ($2 \times 56+2 \times 84$) trials, which took about an hour to complete.

Data analysis

First, the recorded data were converted to 3-D (x, y, and z) co-ordinates by the MacReflex software, and filtered using a three-point moving average. From these data we calculated the resultant velocities of the movements, and we derived a number of kinematic variables to characterise the movement pattern. In addition, we also determined for each trial the hand that had been used to pick up the object. This allowed us to calculate the point—in the free condition—at which a switch occurred from using the left to using the right hand.

For each trial we determined the movement time (MT), the amount of time spent accelerating (acceleration time; AT), and the amount of time spent decelerating (deceleration time; DT) for the transport phase of the movement. Movement time was simply the time difference between the onset of the reaching movement, and the end of the movement (i.e., the moment at which contact with the glass was made). The onset of the movement was defined as the first moment preceding the peak velocity at which the velocity exceeded 10 cm/s. The end of the movement was defined as the moment after the peak velocity at which the velocity profile reached its absolute minimum. We could not use a velocity criterion similar to the onset of the movement, because on some trials the hand did not come to a full stop when grasping and lifting up the glass, especially when the glass was empty. The acceleration time (AT) was simply the difference between the time to peak velocity and the onset time. Similarly, deceleration time (DT) was the difference between the end of the movement and the time to peak velocity.

It should be noted that, on some trials, the reflective marker was occluded from the camera during a number of samples, e.g., due to rotation of the wrist. The MacReflex software interpolated these missing data points using a cubic spline algorithm. If, however, the number of consecutive missing data points during the transport phase was larger than four, we decided not to analyse the kinematics of that particular trial.

RESULTS

The following analyses begin by investigating how the hand selection scores, obtained in the free task, covaried with object location, degree of hand preference (as measured by the Annett Questionnaire), and the accuracy demands of the task (i.e. whether the container was empty or full). We then turn to the kinematic properties of the reaches performed in the forced task, and finally consider the main prediction of our study: that the point at which the preferred and non-preferred hands are used equally often coincides with the location where their deceleration times are equal.

Hand selection analyses

The mean percentages of left-handed reaches as a function of the experimental conditions, averaged over left-handed and right-handed participants and trials, are shown in Figure 2. Note that a high incidence of left-handed reaches implies a low number of reaches with the right hand, and that a high incidence of right-handed reaches implies a low number of reaches with the left hand[2]. From the figure it can be seen that most reaches directed at the leftmost glass (no. 1) were

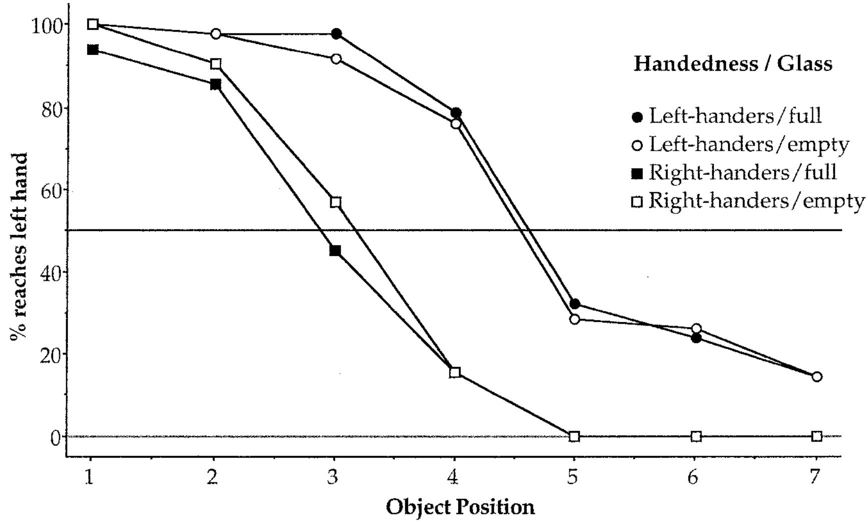

Figure 2. Percentage of reaches performed with the left hand as a function of Object Position (1–7), and Glass (full vs empty), averaged over left-handed and right-handed participants. The point on the abscissa corresponding to where the 50% line crosses the curve for each condition marks the point at which both hands were used equally often.

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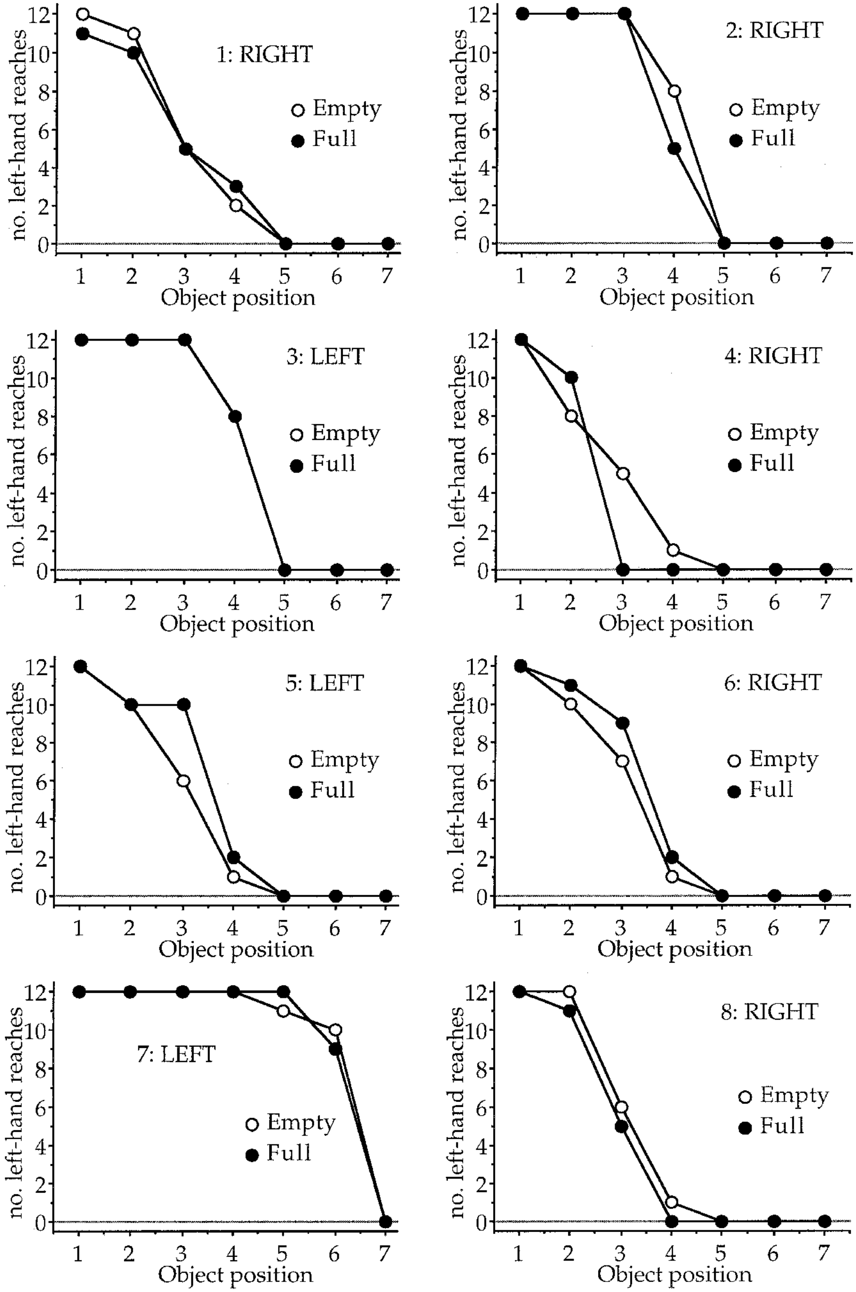
[2] An entirely equivalent way of presenting the data would be in terms of the percentage of reaches performed with the preferred hand. This amounts to simply flipping the graph for the right-handers around the 50% line.

performed with the left hand. Correspondingly, only a small percentage of reaches directed at the rightmost glass (no. 7) were performed with the left hand, which implies a high percentage of reaches with the right hand. In other words, most hand movements involved reaches in ipsilateral space. In addition, the figure shows an S-shaped curve for the left-handers that is clearly displaced to the right of the curve for the right-handers, which indicates that left-handed participants selected their left hand more often than right-handers.

In order to determine to what extent hand selection was affected by the experimental manipulations, we performed a three-factor ANOVA on the percentage of reaches performed with the left hand, with Glass (full vs empty), and Position (1–7) as within-subject factors, and Group (left-handers vs right-handers) as between-subjects factor. First, the main effect of Group was significant [$F(1, 12) = 10.230$, $p < .01$], indicating that left-handers selected their left hand more often than the right-handers (63% vs 36%). In other words, both the left- and the right-handers selected their preferred hand about 63% of the time. Second, the main effect of Object Position was significant [$F(6, 72) = 56.388$, $p < .001$], as was the Object Position–Group interaction [$F(6, 72) = 3.913$, $p < .01$]. The former effect simply reflects the increased likelihood of using the left hand as the to-be-grasped object is positioned more to the left. The latter effect indicates that choice of hand is a combined effect of handedness and the position of the object. As can be seen from Figure 2, the point on the abscissa corresponding to where the 50% line crosses the curves for the left-handers is to the right of the middle object (4), whereas the 50% line crosses the curves for the right-handers to the left of the middle object. In other words, both left- and right-handers tended to continue to operate their preferred hand in their contralateral body space.

Finally, the interaction of Glass and Group was marginally significant ($p < .063$). This effect indicates that there was a tendency to select the preferred hand slightly more often (about 2.3%) than the non-preferred hand when the glass was full rather than empty. In other words, participants tended to use their preferred hand somewhat more often when the task required a greater degree of accuracy.

Figure 3 shows for each participant (1–14) the number of reaches performed with the left hand. As can be seen from the graphs, the majority of participants showed a more or less gradual decline in the use of their left hand as a function of location, similar to the average data. However, the region in which both hands were used was limited (typically to three locations), and this pattern of gradual transition was violated by three of the participants; all left-handers. Participants 10 and 11 showed an abrupt transition from using the left to the right hand, in that the left hand was always used for glasses 1–4, and the right hand was always used for glasses 5–7. Participant 13 used her left hand on all trials. Thus, she never used her right hand in the experiment (neither for the full glasses, nor for the empty glasses). A post-experimental interview confirmed that this participant had clearly understood the instructions, and that she had no injury in her right hand.


1: RIGHT
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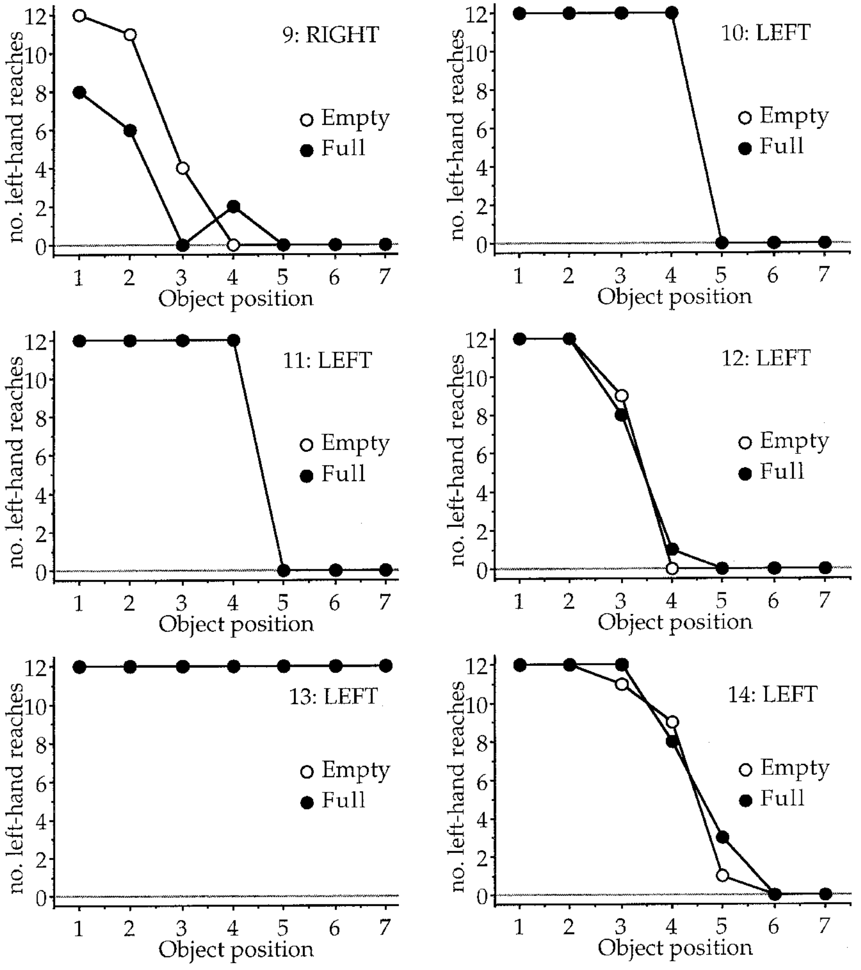

Figure 3 (above and opposite). Number of reaches performed with the left hand as a function of Object Position (1–7) and Glass (full vs empty), for each participant (1–14). The insets "RIGHT" and "LEFT" indicate the handedness of each participant. The open circles represent the empty glasses; the filled circles represent the filled glasses.

Hand preference analyses

All the participants in the study were self-professed right- or left-handers, and they indeed reported using their preferred hand for the majority of tasks covered in the Annett (1970) handedness questionnaire. For each participant, we determined their hand preference simply by assigning a score of −1, 0, or +1 to each "Left", "Either", or "Right" answer, respectively, and subsequently adding the scores. The resulting sum could range from minus 12 (strong left-hand preference) to plus 12 (strong right hand preference). Figure 4 shows, for each participant (except Participant 4), the percentage of reaches performed with the left hand as a function of hand preference.

As can be seen from the figure, the stronger the preference for a particular hand, the more often people tended to select their preferred hand in our reaching task. A *t*-test for correlations revealed that the R^2 of .54 significantly differed from 0; $t(11) = 3.59$, $p < .005$ (one-tailed). However, this linear-looking relation should be treated with some caution. The figure shows that the scores obtained with left-handers were more variable than those obtained with the right-handers. This is in agreement with previous observations in the handedness literature, which suggest that the population of left-handers exhibits a less consistent pattern of hand preferences than the population of right-handers. For example, due to cultural pressures many left-handers have been trained to use their right hand for writing. As a result, the manual asymmetry observed in the population of left-handers is not simply a mirror reversal of the pattern shown by the right-handers (e.g., Peters, 1990). These distributional characteristics of the hypothesised handedness continuum might cause difficulties in interpreting correlations obtained with left- and right-handers together (see also Steenhuis, 1996).

There is another sense in which hand preference as assessed with a questionnaire might be reflected in choice of hand, and that has to do with the "abruptness" of hand change. It might be the case that people who have

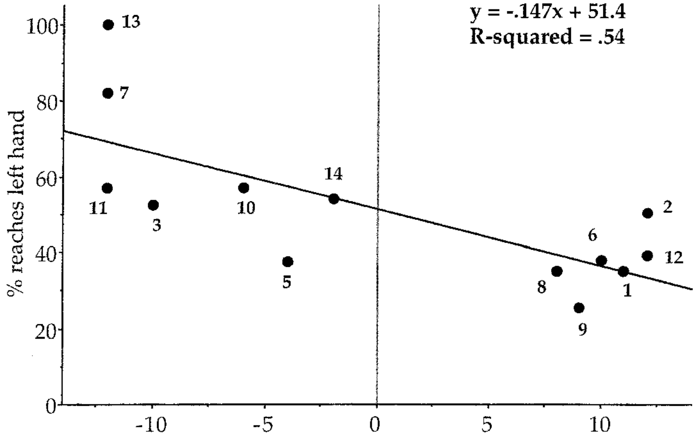

Figure 4. Percentage of reaches performed with the left hand as a function of hand preference as assessed with the Annett (1970) handedness questionnaire. The numbers 1 to 14 represent the individual participants.

extreme scores on a handedness questionnaire (i.e., those who are strongly lateralised) are also highly consistent in their choice of hand for picking up an object. In other words, strongly lateralised individuals are expected to have a sharp boundary between the workspaces of their respective hands (see, for example, Participants 10 and 11 in Figure 3). Alternatively, less strongly lateralised participants are expected to use both hands interchangeably for objects at a range of different places, i.e., the boundary between the workspaces of the hands is not so crisp (e.g., Participants 1 and 6 in Figure 3). If true, we expect to find a U-shaped relationship between the degree of hand preference and the abruptness of hand change. Hand preference was determined as in the previous analysis. Abruptness of hand change was determined as follows. We simply counted for each participant the number of occasions where both the left and the right hand were used to pick up the same glass. We then subtracted this value from 168 (the total number of reaches), to obtain our abruptness score. So, for example, Participant 2 in Figure 3 used both hands on four occasions to pick up the empty glass at position 4, and on five occasions to pick up the full glass at position 4. The glasses on other positions were always picked up by the same hand. Hence, this participant's abruptness score is 159 [168 – (4+5)].

The relationship between the degree of hand preference and the abruptness of hand change is shown for each participant (except Participant 4) in Figure 5. Our hypothesis of a U-shaped relationship between these variables seems to be confirmed; a second-order polynomial fit yielded an R^2 of .57. Thus, it seems to be the case that strongly lateralised left- and right-handers (e.g., Participant 11) are also consistent in their hand use, whereas less strongly lateralised individuals

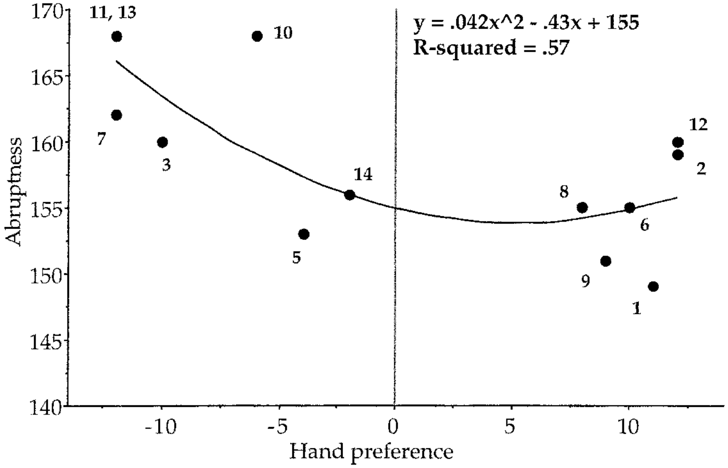

Figure 5. Abruptness of hand change as a function of hand preference as assessed with the Annett (1970) handedness questionnaire. The numbers 1 to 14 represent the individual participants.

(e.g., Participant 5) tend to use either hand interchangeably on a number of occasions. However, it should be noted that there is also a significant linear component in the data ($p = .008$). A linear fit produced an R^2 of .45. Moreover, results from a polynomial regression revealed that the second-order term was not significant. Further research is clearly needed before we can draw any firm conclusions about the relationship between hand preference and consistency of hand use.

Kinematic analyses

Kinematics of the forced task. We performed ANOVAs on the movement times (MT), the acceleration times (AT), and the deceleration times (DT), using the same factors as in our hand selection analysis. Due to recording errors, the kinematic data for Participant 3 could not be analysed. There were large effects involving object location, in that the MTs, the DTs, and, to a lesser extent, the ATs tended to increase with increasing hand–object distance. For present purposes, we will only report effects involving Hand and Glass.

The ANOVA on the movement times only revealed a main effect of Glass, [$F(1, 11) = 34.938$, $p < .001$], indicating that movements directed at a full glass took 153 ms longer than when directed at an empty glass (1059 vs 906 ms, respectively). The ANOVA on the acceleration times only revealed a main effect of Hand [$F(1, 11) = 5.058$, $p < .05$]; there was a 13 ms advantage of the right hand over the left hand (321 vs 334 ms, respectively). Finally, for the deceleration times the main effect of Glass was significant [$F(1, 11) = 44.53$, $p < .001$]; when the glass was full, the hand spent 724 ms decelerating, whereas when the glass was empty, the hand spent 586 ms decelerating—a 138 ms difference. Thus, as the task required more fine control as a result of having to pick up the filled glass, there was a marked increase in DT (and hence, in MT), but not in AT[3]. In addition, there were no significant differences involving handedness and choice of hand. However, it should be noted that both the DTs and the MTs showed a marginally significant difference between the preferred and the non-preferred hand at the .053 and the .075 level, respectively. The DTs and the MTs of the non-preferred hand were 20 ms and 15 ms longer, respectively, than those of the preferred hand.

We also performed separate ANOVAs on the DTs for the left-handers and the right-handers. The mean DTs, as a function of hand and glass, are shown in Figure 6A (right-handers), and Figure 6B (left-handers). These figures not only indicate an increase in deceleration time, but also a clear increase in DT with

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[3] Note that the added liquid not only increases the accuracy requirement, but also the weight of the glass. But we do not think that this potential confound can account for our data, because our analyses only involved the approach phase, i.e., prior to contact with the glass.

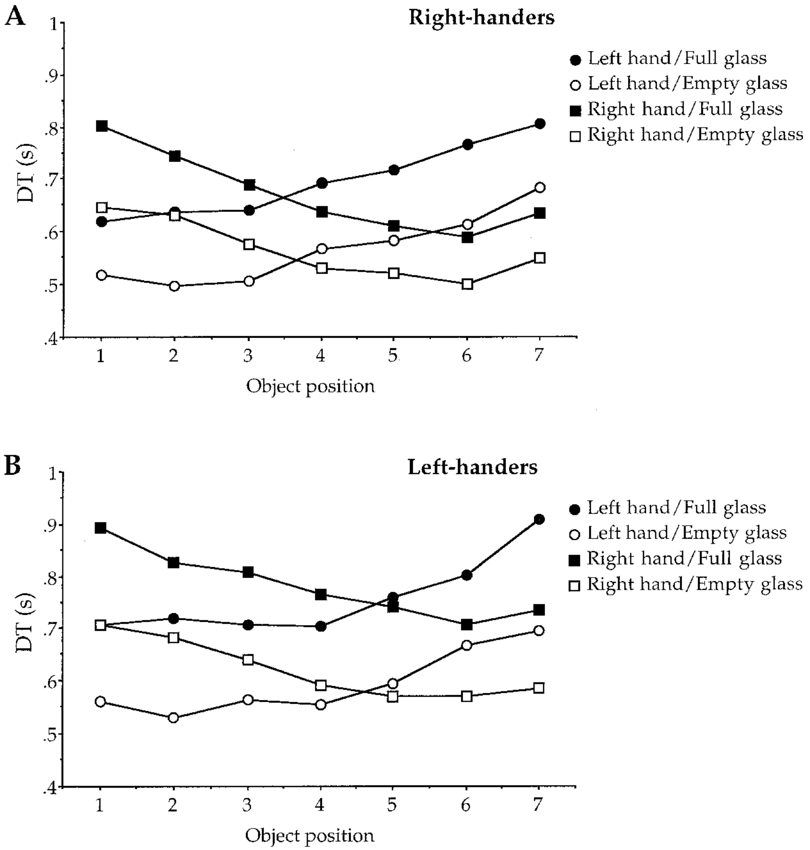

Figure 6. Deceleration times (in s), averaged over right-handers (A) and left-handers (B) as a function of Object Position (1–7), Hand, and Glass.

accuracy: When the glass was full the (left and right) hands spent more time in the deceleration phase than when the glass was empty. Finally, if we focus on the point where the lines cross, we see that for the right-handers this point is shifted to the left when the glass is full, and, conversely, for the left-handers it is shifted to the right when the glass is full. In other words, it seems to be the case that with increasing accuracy demands, the point where the deceleration times are equal is shifted in the direction of the non-preferred hand. But this finding was only partially confirmed by the results of the ANOVA: The crucial Hand by Glass interaction was marginally significant for the right-handers ($p = 0.07$), and non-significant for the left-handers ($F < 1$).

Deceleration time and the transition from preferred to non-preferred hand. In this final analysis we tested whether choice of hand was a function of the level of accurate control that could be attained by the respective hands. To this end, we investigated the deceleration times in the vicinity of the dividing line between the workspaces of the left and the right hand. More specifically, we compared the point where the left and the right hands were used equally often in the free task with the point where the DTs of the left and right hands were of equal magnitude.

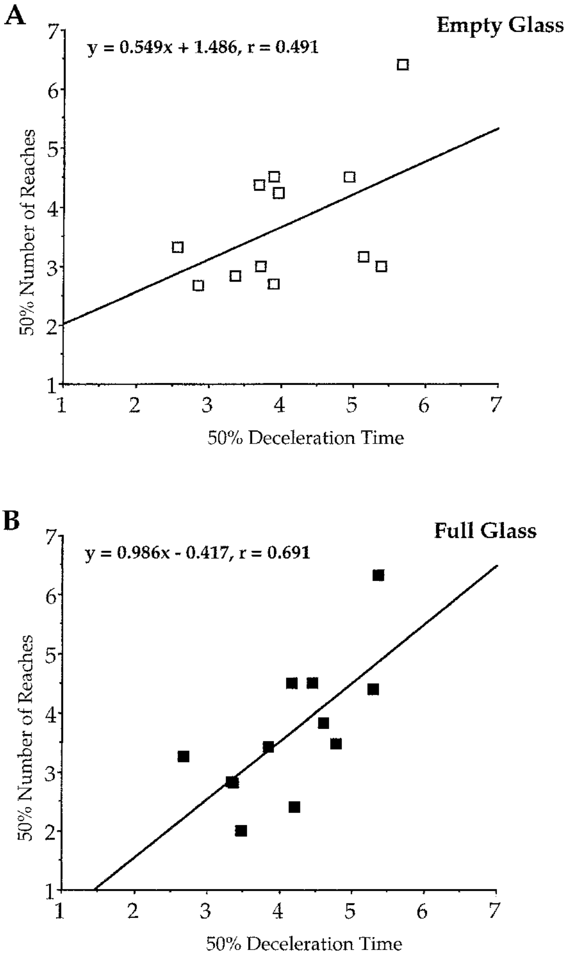

Figure 7. Point where each individual's hands were used equally often (50% Number of Reaches) as a function of the point where each individual's deceleration times were of equal magnitude (50% Deceleration Time), for the Empty Glass (A) and the Full Glass (B) conditions.

The point of transition between the hands in the free task was defined as the location where each hand was used equally often. This point corresponds to the location on the individual graphs of Figure 3 where the 50% line (i.e., 6 out of 12 reaches) intersected each individual's graphs for the full and empty glass. So, for example, the 50% point for Participant 1 was 2.8 for the full glass, and 2.83 for the empty glass. The point corresponding to equal deceleration times in the forced task was determined as follows. We first identified the two consecutive glass positions where the deceleration times for the two hands switched from being greater for the non-preferred hand to being greater for the preferred hand. For example, with Participant 1, full glass, the deceleration times for the left and right hand were 667 ms and 721 ms for stimulus position 3, whereas their deceleration times were 688 ms and 592 ms for stimulus position 4. We then simply determined the intersection point between the connecting two lines, which yielded a value of 3.36 in this case.

Figure 7 shows, for both glasses and for each participant, the 50% point of the number of reaches plotted against the point where the deceleration times of the two hands were of equal magnitude (labelled ‘‘50% Deceleration Time’’). A positive relationship was found both for the empty (Figure 7A) and full (Figure 7B) glass conditions. In addition, the correlation was higher for the full glasses ($r = .691$) than for the empty glasses ($r = .491$), although only the first correlation reached significance; $t(10) = 3.022$, $p < .05$. This suggests that, at least in the full glass condition, choice of hand was determined by the level of accurate control that could be attained by the hands.

GENERAL DISCUSSION

This experiment demonstrated that choice of hand was influenced by the position of the object relative to the hands, by the actor's hand preference, and the accuracy constraint. The further away from the body midline a target object was located, the greater the probability that the ipsilateral hand was selected to pick up the object. However, the tendency to continue using a hand in the contralateral space was greater for the preferred hand than the non-preferred hand. In addition, the size of workspace of the right (left) hand was positively correlated with the "degree" of preference for the right (left) hand, as determined by the Annett (1970) handedness questionnaire. In other words, our study suggests that when people prefer a particular hand to conduct a wide range of different activities, such as writing and hammering, this hand also tends to cover a larger area to accomplish tasks that are not highly lateralised, such as picking up an object (see also Bryden et al., 1994).

We also found an effect of manipulating accuracy as a fundamental task constraint with regard to hand preference. There was a marginally significant increase in the use of the preferred hand when the accuracy demands were high (glass filled with liquid), as opposed to low (empty glass). Moreover, the condition with the empty glasses gave rise to shorter deceleration times than the condition with the filled glasses (see also Annett, Annett, Hudson, & Turner, 1979; Elliott, 1991; Steenbergen et al., 1995). Most importantly, when participants reached out to lift a liquid-filled glass, we found that the point where people shifted from using one hand to using the alternate hand correlated significantly with the point where the deceleration times of the respective hands were equal. Furthermore, there was a close coincidence between the points of transition between the preferred and non-preferred hands and the points where their deceleration times were equal.

Numerous handedness studies have tried to elucidate the relationship between hand preference and hand dominance, where the dominant hand is the hand that exhibits superior performance in terms of speed, accuracy, strength, etc. over the alternate one (Marteniuk et al., 1987; Steenbergen et al., 1995). Several other studies have attempted to address this issue by investigating tasks of different complexity. Higher task complexity is expected to require a larger area of workspace covered by the dominant hand but some findings are inconsistent (Steenhuis & Bryden, 1989; Bryden, Pryde, & Roy, 1999). At present, the exact relationship between hand preference and hand dominance is unclear (see especially Guiard, 1988, 1990). Our study, however, suggests a promising strategy to investigate this issue by demonstrating that manual asymmetry for a specific task can be measured by asymmetries in three different aspects of the performance: (a) the size of work space, (b) the degree of handedness, and (c) task dynamics. Although these behavioural measures provide different values at different scales, normally, they should be positively correlated (see Figures 4 and 7).

Given the observed relation between a kinematic variable (deceleration time) and the boundary between the workspaces of the preferred and non-preferred hands, it is tempting to seek an explanation for the shift between the use of the two hands in terms of asymmetries in biomechanical complexity of the movements. After all, as the hand moves into the contralateral space, the length and probably the form of the movement will change. Indeed, as is clear in Figure 6, there was a clear increase in deceleration times as either hand moved further from the midline into the contralateral space, but hardly any change (within the limits of our study) when operating within the ipsilateral space. Some researchers have attempted to eliminate such asymmetries in biomechanical complexity by using a semicircular rather than (as in our study) a linear layout of targets (Bryden et al., 1999). However, it is clearly impossible to eliminate these effects entirely, given that both arms are not attached to the midline but at opposite sides of the body. The semicircular arrangement may reduce but cannot eliminate the use of abdominal and back muscles. However, even when such asymmetries *are* present (as is certainly the case in our experiment), they nevertheless can have no *direct* bearing on the problem at hand, namely, *laterality.*

Laterality is concerned with the *relation* between the two hands, and *interactions* between ‘‘handedness’’ and other variables. Now it is true that when each hand is considered in isolation, asymmetries of the kind we have been discussing exist. But considered as a bimanual task, the layout of the targets is bilaterally symmetrical and so also are the associated biomechanical constraints (reaching distance, movement of upper body, etc). Logically, factors that are symmetrical cannot explain laterality effects, as laterality by its very definition is to do with *asymmetries* between the two hands.

As we see it, an explanation of why there are asymmetries both in hand use and deceleration times needs to be sought at a deeper level, namely that addressed in studies of shifts between ‘‘action modes’’, such as those between walking and running, or in horses trotting and galloping (Hoyt & Taylor, 1981). Physiological factors including energy efficiency, such as oxygen uptake (Cruse et al. 1990; Iberall, 1990; Warren, 1983) may well differ between the preferred and non-preferred hands, but so too, we suggest, will psychological factors such as attentional demands and ‘‘comfort’’ (Kadar et al., 1991; Mark et al., 1997). As far as we are aware, such research, at least in relation to handedness, has hardly begun.

In sum, our findings imply that manual asymmetries are task-dependent and related to kinematic variables. Such asymmetries, we have argued, need to be understood in terms of asymmetries in the performance of the task. Although symmetry analysis of any task poses difficult theoretical problems for students of movement science, evidently people in their everyday activities are able to find practical solutions to these problems. Previous studies have shown that people are highly skilled perceivers of their own action capabilities, and are able to select the action mode that is most suited to perform a given task (see, for example, Warren’s, 1984 stair-climbing study). And this would seem to have been the case in our study, too, as indicated by the relation between the deceleration measures obtained in the forced-choice condition, and the boundaries between the workspaces of the preferred to the non-preferred hands observed in the subsequent free-choice condition.

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APPENDIX

The Annett (1970) handedness questionnaire consists of the following 12 items, where participants have to indicate which hand they habitually use:

1. To write a letter legibly
2. To throw a ball to hit a target
3. To hold a racket in tennis, squash, or badminton
4. To hold a match whilst striking it
5. To cut with scissors
6. To guide a thread through the eye of a needle (or guide needle on to thread)
7. At the top of a broom while sweeping
8. At the top of a shovel when moving sand
9. To deal playing cards
10. To hammer a nail into wood
11. To hold a toothbrush while cleaning their teeth
12. To unscrew the lid of a jar