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The Effects of Handedness and Reachability on Perceived Distance

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Previous research has suggested that perceived distances are scaled by the action capabilities of the body. The present studies showed that when "reachability" is constrained due to a difficult grasp required to pick up an object, perceived distance to the object increases. Participants estimated the distances to tools with handle orientations that made them either easy or difficult to grasp with their dominant and nondominant hands. Right-handed participants perceived tools that were more difficult to grasp to be farther away than tools that were easier to grasp. However, perceived distance did not differ in left-handed participants. These studies suggest that, when reaching toward a target, the distance to that target is scaled in terms of how far one can effectively reach, given the type of reaching posture that is executed. Furthermore, this effect is modulated by handedness.

Keywords: handedness, distance scaling, near space, spatial perception, affordances

Understanding the relationship between action and perception has motivated a considerable amount of recent research (see Proffitt, 2008). In the past, it was assumed that perception precedes and informs action but that perception itself is not influenced by intended actions (Fodor & Pylyshyn, 1981; Foley, Riberiro-Filho, & Da Silva, 2004; Gogel, 1990; Loomis, Da Silva, Philbeck, & Fukusima, 1996). There are obvious exceptions in which actions do influence perception; for example, eye movements determine how the optical array is sampled, and locomotion-produced optic flow informs the perception of spatial layout and heading. In these instances, optical information is affected by action and, consequently, perceptions are affected as well. Aside from such cases in which optical information is directly affected, it is typically assumed that intended actions do not affect spatial perceptions; for example, it is generally assumed that the intent to pick up an object should not affect the perception of the object or its surroundings. Contrary to this assumption, recent studies on embodied perception, which are discussed later, have found that people's intent and ability to act can influence their perception of spatial layout.

When viewing the spatial layout of the environment, the available optical information consists of visual angles, changes in visual angles, and ocular–motor adjustments, the latter of which can also be scaled in terms of angular changes. For properties such as distance and size to be perceived, these angles must be transformed into distance-appropriate units. The body and its potential for action can provide the necessary units for scaling spatial layout. In other words, the body and its action capabilities could be used as a perceptual ruler with which to measure distance and size. Gibson (1979) defined these possibilities for action in the given environment as an *affordances*. For example, an affordance of the ground plane is walking or running, whereas an affordance for an object in near space is reaching to or grasping. Affordances provide the crucial link between the capabilities of the perceiver and the environment, and in turn, the affordances of objects may be perceived through scaling distances by the extent to which one can perform an action.

Following Sedgwick's (1973) proposal of eye height scaling, several studies have shown that the perceiver's eye height is used to scale the relative sizes of distant targets (Bertamini, Yang, & Proffitt, 1998; Dixon, Proffitt, Wraga, & Williams, 2000; Wraga, 1999). It seems implausible, however, that eye height would be used to scale the size of small objects within near space. Here, we propose that perceived "reachability," or how far people perceive the extent of their reach to be, provides a metric with which close distances can be scaled. For example, targets that are just out of reach of the hand appear closer when a tool is used to extend reach (Witt & Proffitt, 2008; Witt, Proffitt, & Epstein, 2005). The tool expands the reach of the actor and, presumably, stretches the "ruler," which is used to scale apparent distance, leading to a decrease in the apparent distance to the target object.

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In support of this notion, individuals can accurately identify the possible affordances for reaching that suit their body size or shape in a given situation. Typically, people's sensitivity to affordances is measured by the individual's assessment of their critical boundary for a given action. A critical boundary is the minimum or maximum extent over which an action can be performed; for example, the farthest object that a person can reach would be at their critical boundary for reaching. The accuracy typically found in these estimates suggests that people can detect whether an environmental context affords a specific action, and several studies have shown that people can determine their critical boundaries for a variety of actions such as stair climbing, sitting in chairs, and crossing over gaps (Mark, 1987; Warren, 1984; Warren & Wang, 1987). It is interesting that people use the capabilities of their bodies to determine their critical boundaries. For example, Carello, Grosofsky, Reichel, Solomon, and Turvey (1989) showed that people use their arm length to determine how far they can reach. Hand size is also used to determine the maximum size of an object that can be grasped (Newell, Scully, Tenenbaum, & Hardiman, 1989). Carello et al. (1987) found that, in addition to being sensitive to the extent of one's limbs, individuals are also sensitive to changes in their body or the intended action that increase or decrease their reaching ability. For example, participants retuned their critical boundary for reachability when their reach was constricted by limiting the degrees of freedom in their reach or when their balance was compromised. Mark (1997) found that participants retune their reaching boundary when postural stability is manipulated by altering the support provided by the chair on which participants sat. In addition, Gardner, Mark, Ward, and Edkins (2001) demonstrated that an increase in the difficulty of a grasp also leads to a shift in the critical boundary of the reach. Changing action capabilities by wearing arm weights or providing a tool can also lead to a change in the critical boundary of reachability (Rochat & Wraga, 1997). Given that individuals are sensitive to the critical boundaries of their action capabilities, we believe these critical boundaries may be used as bodily units on which to scale apparent distance.

Previous studies have suggested that a person's reachability can affect the perception of spatial layout. Rochat and Wraga (1997) found that, when reaching with arm weights, participants perceived the extent of their reach to be less than when reaching without arm weights. Similarly, Linkenauger, Zadra, Witt, and Proffitt (2009) found that targets at the same distance appear farther away when the perceiver is wearing arm weights and intends to reach toward the object than when the perceiver intends to reach toward the target without wearing arm weights. Together, these findings imply that by limiting the perceived reaching capabilities of the actor by increasing the weight of the arm, the perception of distance to targets is increased. Extending the capacity to reach has also been shown to influence the perceived distance to a target through tool use. When the distance a person can reach is expanded by using a tool, targets just outside of arm's reach appear closer when intending to reach with the tool than when intending to reach without the tool (Witt & Proffitt, 2008; Witt et al., 2005). These studies indicate that the ability to reach a target can affect its apparent distance.

Given that the body and its capabilities have been found to scale perceived distances to targets, it seems plausible that the perceived spatial properties of an object that affect its "graspability" may also influence its apparent distance. In the present studies, we investigated the hypothesis that the ability to reach toward and grasp an object influences its apparent distance. More specifically, for a given distance, an object that is oriented so that it is difficult to grasp should constrain the actor's reachability to that object. If the apparent distances to targets in near space are scaled with respect to reachability, then an object that is difficult to grasp should appear farther away than an object at the same distance that is easier to grasp and therefore does not constrain reachability. To assess this hypothesis, we manipulated the graspability of tools by changing the left/right orientation of the tools' handles. Tools that were more difficult to grasp were perceived as farther away than tools that were easier to grasp, but only for right-handed people. Unexpectedly, we found that ease of grasp did not affect left-handed people's perception of spatial layout. The remainder of this introduction will motivate the possibility that ease of grasping an object could influence its apparent distance. A discussion of why this effect is only found in right-handed people is taken up in the General Discussion section.

The present studies were motivated by the conjecture that the ease with which a tool can be grasped should influence its perceived reachability, and in turn, affect the perceived distance to that tool. As opposed to nontool objects, tools are most frequently used to enhance a person's ability to perform a specific motor task, such as digging with a shovel or loosening nuts with a wrench. Tools often have a visually distinct handle for grasping and are associated with a specific affordance. As a result, the visual representations of tools could be strongly associated with the actions for which they are used. Empirical evidence supports this notion by indicating that when a person perceives a tool, the motor action associated with the tool is elicited (Grafton, Fadiga, Arbib, & Rizzolatti, 1997; Järveläinen, Schürmann & Hari, 2004; Perani et al., 1995; Tucker & Ellis, 1998). For example, when people see a screwdriver, they become primed or attentive to the twisting of the specific wrist associated with using the screwdriver regardless of whether this action is actually performed. Consequently, when viewing the screwdriver, motor programs associated with the tool's use may be automatically activated.

Several behavioral studies suggest that a motor plan is included in the representations of tools. Tucker and Ellis (1998) presented participants with pictures of tools with handles, and participants had to judge whether the tool was inverted or right side up. Participants were told to decide on a tool's inversion by considering how the tool would be used. The participants responded by pushing one button for right side up with one hand and pushing another button for upside down with the other hand. Tucker and Ellis found that participants correctly responded faster when the handle of the tool was oriented toward the hand with which the participant responded, although the handle orientation was unrelated to the task the participant was told to perform. In addition, patients with corticobasal degeneration will inadvertently act on objects. For example, patients will spontaneously grasp objects in front of them without intending to, and the effector the patient uses to perform these actions is contingent on the orientation of the handle of the object (Riddoch, Edwards, Humphreys, West, & Heafield, 1998). Hence, it is likely that there is a direct route from vision to action, which is sensitive to the position of the object with respect to the actor (Riddoch et al., 1998). Similarly, Yoon and Humphreys (2007) found that making action judgments about pictures of tools was impaired if the tool's handle was oriented away from the observer, whereas making semantic judgments about the tools was not affected by handle orientation. Therefore, if the actor just viewed tools' handles and thought about how the tool would be used, the hand that could form the appropriate grasp around the handle was primed and responded more quickly and accurately.

Because tools are seen in terms of the actions they afford, it is possible that the orientation of a tool could affect the perception of a tool's graspability. Perceived ease of grasp would, in turn, affect the critical boundary for reaching, which could influence the apparent distance to the tool. Tool use has been shown to enhance reaching extent and compress the apparent distance to relevant targets (Witt et al., 2005; Witt & Proffitt, 2008). In accord with this finding, we predicted that, if tools are more difficult to grasp because their handles are oriented away from the grasping hand, then the maximum extent for effectively being able to reach and grasp them will be foreshortened, which could result in an expansion of their apparent distance.

In the first study, we assessed whether a tool that was oriented so that it was difficult to grasp affected the perceived extent of reachability. In subsequent studies, participants viewed tools at orientations that made tools either easy or difficult to grasp and then judged the distance to the tool. We found that tools that were more difficult to grasp led to a decrease in perceived reachability and were consequently seen as farther away than tools that were easier to grasp.

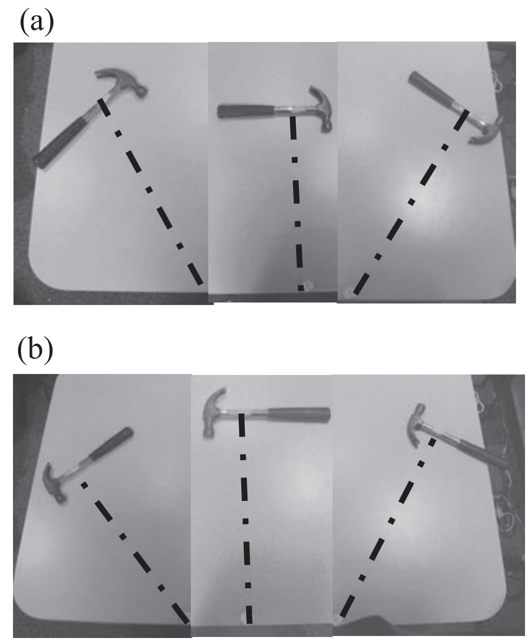


Figure 1. Possible orientations of the stimulus during a difficult grasp with the right hand or an easy grasp with the left (a) and possible orientations of the stimulus during a difficult grasp with the left hand or an easy grasp with the right (b).

Experiment 1: The Perception of Reachability to Hand Tools With Different Grasp Types

The purpose of this study was to assess the effect of easy and difficult grasps on the perception of whether hand tools are within or outside of reach. Ease of grasp was manipulated by orienting the handle of the tool toward the left or right of the participants' reaching hands. Presumably, if the handle is oriented away from the reaching hand, it will be more difficult to grasp than if it is oriented toward the reaching hand. The hand tools were moved toward the participants, and the participants indicated when they thought that the tool was within reach if they were to use the grasp, as instructed, to pick up the hand tool in a way that was appropriate for its use (see Figure 1).

Method

Participants. Ten (6 female, 4 male) right-handed and 10 (8 female, 2 male) left-handed students at the University of Virginia volunteered to receive course credit in an introductory psychology course and had not participated in any other reaching studies in our laboratory. Handedness was assessed with the Edinburgh Handedness Survey (right-handed participants, $M = 90.1$, $SD = 11.03$; left-handed participants, $M = -70.4$, $SD = 30.73$). All participants gave informed consent and had normal or corrected-to-normal vision.

Apparatus and stimuli. Participants sat in front of a square table that measured 91.5 cm × 91.5 and was 74.5 cm tall. Reachability judgments were made with regard to a hammer placed on the uniformly white table surface, which minimized landmarks. A small, circular sticker was placed at the center of mass on the hammer. This was used as a reference point for measuring the distance to the hammer. The dynamometer, which measures grip strength, was manufactured by Jamar (Model no. 5030J1).

Procedure. Participants sat at a close but comfortable distance to the table, with the edge of the table a few centimeters from their torso. Before estimating their reachability with the instructed arm, the experimenter demonstrated the appropriate functional grasp required to pick up the hammer at both the easy- and hard-to-grasp handle orientations. The hammer was then placed on the table directly in front of participants, and they were instructed to pick up the hammer, using the appropriate grasp, and hand the hammer to the experimenter. The hard-to-grasp handle orientation was when the handle of the hammer was oriented in the opposite direction of the grasping hand (to the right if grasping with the left and to the left if grasping with the right). The hard-to-grasp handle orientation required participants to contort their arm in an underhanded contralateral (across the body) reach to grasp under the handle of the tool, which presumably changed the actual reachability to the object as well. The easy-to-grasp handle orientation was when the handle of the hammer was oriented toward the grasping hand. The easy-to-grasp handle orientation required participants to use a straight reach and grasp the tool over the top of the handle. Each participant picked up the hammer 10 times (5 times with each grasp type) with the arm used to estimate their reachability after their grasps. In all, participants grasped the hammer 20 times (10 with each arm). These practice grasps were conducted so that the participant was aware of the appropriate way to grasp the hammer (or could estimate by using the grasp) for the reachability task, and so that the difficulty and estimate of the type of grasp did not vary across participants. A concern is that the practice trials may have evoked memory-based strategies during the experimental trials. However, at no time during the study (even during the practice trials) did participants ever test their reach over the table. The practice grasps were performed to the leftmost and rightmost bottom corners of the table, an area of the table over which none of the actual estimates were performed.

Participants were told to estimate their reach without leaning forward with their shoulders against the back of the chair. This limitation in mobility was implemented so that participants would not estimate their reaching in different ways and so that every participant knew exactly which reach they were to imagine using. From the opposite side of the table, an experimenter moved a hammer toward the participants. Participants estimated their reachability by informing the experimenter when they thought the hammer was close enough that they could just grasp the hammer with the specified arm using the grasp that was appropriate for the hammer's use (specified by the orientation of the hammer's handle) without leaning forward from the back of the chair. The initial position of the hammer was always far away from the participants and the hammer was always moved closer. Thus, we were able to measure when participants perceived the hammer to be just within reach (as opposed to just beyond reach). Although having the object always move toward the perceiver rather than away may bias responses, our interest is in differences within groups given the ease to grasp the tool. Because the bias is consistent between the conditions of interest, the bias should not interfere with the conclusions from this study. Participants were not allowed to reach or move their arms on top of the table while making their reachability judgments. They were encouraged to instruct the experimenter to make fine adjusts to the position of the hammer. After participants indicated their reachability, they closed their eyes while the experimenter measured the distance from a dot placed on the center of mass on the hammer to a small reference dot on the edge of the table directly in front of the participants.

The initial location of the hammer was at a spot that was contralateral (−30° from center), ipsilateral (30° from center), and central to the participant's location. Participants made three judgments of reachability in each direction with the hammer at one handle orientation and then made the three judgments of reachability with the tool at the other orientation. Participants estimated all 6 reachability estimates with a specific arm and then made the same 6 reachability estimates with the other arm, for a total of 12 reachability estimates. Order of arm was counterbalanced across participants, and order of direction and handle orientation was randomized. Between right and left arm reachability estimates, we assessed participants' grip strength using a dynamometer to distract them from remembering the reachability estimates that they made for the first arm. At no time during the reachability estimates were participants allowed to place their arms or hands over the table.

Results and Discussion

Ease of grasp influenced reachability judgments where reachability was defined as the farthest extent to which participants estimated they could reach to grasp the target in a functional way. Participants estimated that they could grasp a tool that was farther away when the tool was at an orientation that allowed for an easier grasp than when the tool's orientation made grasping more difficult. Arm (left and right) × grasp type (easy and difficult) × reaching direction (ipsilateral, central, and contralateral) were included in a repeated-measures analysis of variance (ANOVA), with handedness (left and right) as a between-participants variable[1] and reachability estimates as the dependent measure. Grasp type resulted in a significant main effect, with participants estimating that they could reach farther for easier-to-grasp tools ($M = 48.85$, $SE = 1.62$) than they could for those that were more difficult to grasp ($M = 43.13$, $SE = 1.91$), $F(1, 18) = 48.25$, $p < .0001$, $\eta_p^2 = .73$. As expected, the direction of reach was also significant, with farther estimations when reaching ipsilaterally ($M = 47.8$, $SE = 1.63$) then when reaching contralaterally ($M = 45.48$, $SE = 1.85$), $F(2, 8) = 7.63$, $p = .01$, $\eta_p^2 = .41$. Overall, right-handed participants did not perceive their reachability to be any farther than left-handed people, $F(1, 18) = 0.64$, $p = .43$. However, there was a significant interaction between arm and handedness, $F(1, 18) = 5.14$, $p = .036$, $\eta_p^2 = .22$, as well as a significant interaction between grasp type and handedness, $F(1, 18) = 8.44$, $p = .009$, $\eta_p^2 = .32$.

To explore the interactions in more detail, we performed separate repeated-measures ANOVAs for each handedness condition (left and right) with arm (left and right), grasp type (easy and difficult), and reaching direction (ipsilateral, central, and contralateral) as within-participant variables and reachability estimates as the dependent measure. Left-handed people perceived the extent of their reach with the easy grasp as being farther ($M = 46.28$ cm, $SE = 1.89$) than they did with the difficult grasp, ($M = 42.94$ cm, $SE = 1.92$), $F(1, 9) = 10.9$, $p = .009$, $\eta_p^2 = .55$, (see Figure 2). In addition, right-handed people perceived the extent of their reach to be much farther with the easy grasp ($M = 51.43$ cm, $SE = 2.63$) than they did with the difficult grasp, ($M = 43.31$cm, $SE= 3.30$), $F(1, 9) = 38.79$, $p < .0001$, $\eta_p^2 = .81$ (see Figure 3). However, the magnitude of perceived reachability across easy and hard grasps between the right- and left-handed participants suggests that right-handed participants showed a much larger difference in perceived reachability between the two grasp types than did left-handed participants. This is supported by the interaction between handedness and grasp, as well as the difference in the effect size between left- and right-handed groups.

Also, as found in other reachability studies (Linkenauger, Witt, Bakdash, Stefanucci, & Proffitt, in press; Rochat & Wraga, 1997), right-handed participants estimated that they could reach farther with their right arm ($M = 49.13$ cm, $SE = 2.71$) than with their left arm ($M = 45.61$ cm, $SE = 3.27$), $F(2, 8) = 5.62$, $p = .042$, $\eta_p^2 = .38$; whereas left-handed participants estimated their reach with their left arm ($M = 44.84$ cm, $SE = 1.74$) and right arm ($M = 44.38$

[1] In this experiment, right-handed and left-handed participants participated in the experiment at two different times. However, because participants could not be randomly assigned to handedness conditions anyway, we conducted statistics on the group as a whole. With the exception of the last experiment, all of the experiments were originally conducted on whoever signed up for the experiment, so the group comprised mostly right-handed participants with a few left-handed participants. We did not expect an effect of handedness, but we began to see a different pattern emerge between the two groups. We decided to exclude left-handed participants, resulting in the data for Experiments 1–3. However, we then decided to document the (lack of) effect in left-handed participants, so we replicated Experiments 1–3 in left-handed participants. For Experiment 1, we grouped right- and left-handed participants. For Experiments 2 and 3, we reported data from the left-handed participants as separate experiments (4–5). However, as not much time elapsed between data collection (a few weeks for Experiments 3 and 4, and 2 months between Experiments 2 and 5), we also calculated the statistics to directly compare right-handed and left-handed participants. It is important to note that none of our claims rely on this group statistic. These statistics just allow for a more quantitative comparison, yet the qualitative comparison reveals the obvious differences between the two groups.

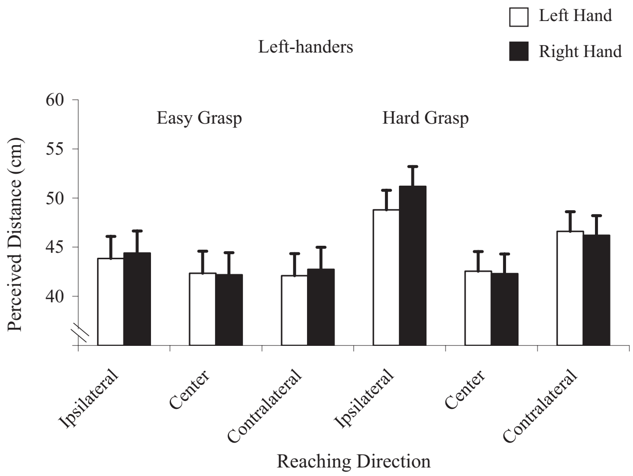


Figure 2. Left-handed participants' perceived distance to the tools on the basis of hand and grasp type. Error bars represent 1 standard error and are calculated on the basis of within-participant error with the method provided by Loftus and Masson (1994).

cm, $SE = 2.04$) to be nearly the same, $F(1, 9) = .25$, $p = .63$. This finding parallels previous research suggesting that left-handed people have a more bilaterally, symmetrical assessment of their action capabilities (Gonzalez, Ganel, & Goodale, 2006; Linkenauger et al., in press).

These results showed that the perceived reachability to a tool was affected by the type of grasp used to pick it up. In addition, these results also suggested that perceived reachability in left-handed people was not as affected by the type of grasp as with right-handed people. As a result, if near distances are scaled by reachability, then the perceived distance to tools should be affected by the grasp that one may use to pick up the tool.

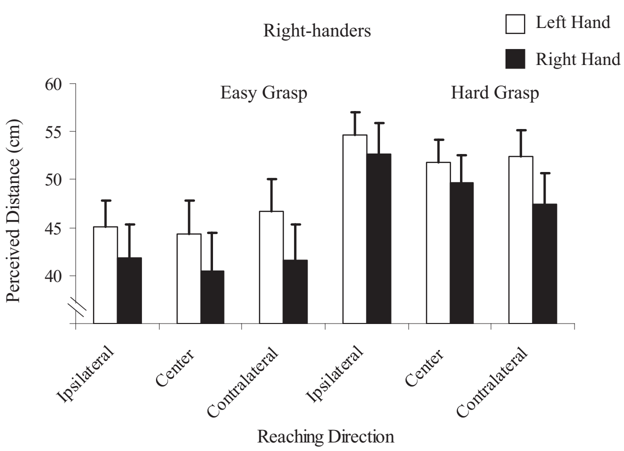


Figure 3. Right-handed participants' perceived distance to the tools on the basis of hand and grasp type. Error bars represent 1 standard error and are calculated on the basis of within-participant error with the method provided by Loftus and Masson (1994).

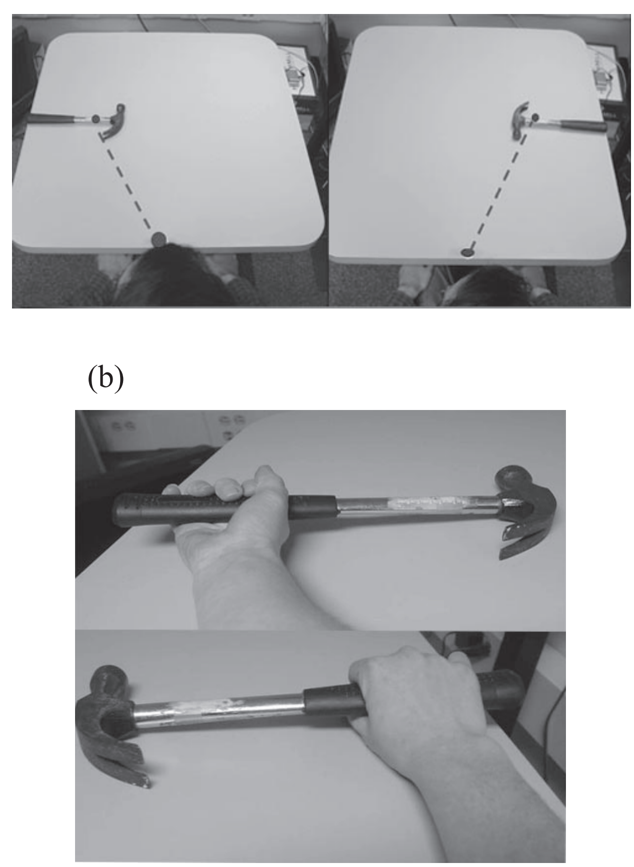
Experiment 2: Right-Handed Participants Reaching Contralaterally and Ipsilaterally

The purpose of this study was to investigate whether constraining perceived reachability by manipulating the ease to grasp a tool influences its apparent distance. Ease of grasp was manipulated by placing the tools on either the contralateral or the ipsilateral side of the participant's dominant right hand and orienting the tools' handles. When tools were on the contralateral side, participants reached with their right hand across their body, awkwardly grasping the handle, which was oriented to the participant's left. Tools on the ipsilateral side had their handles oriented to the right, making them easier for the participant to grasp (see Figure 4). Participants indicated the perceived distance to the tool using a visual matching task.

Method

Participants. Twelve (6 female, 6 male) right-handed students from the University of Virginia participated for $4 compensation or course credit in an introductory psychology course and had not participated in any other reaching studies in our laboratory. All

(a)



(b)

Figure 4. Possible orientations of the stimulus (a) and type of grasp required to pick up the stimuli appropriately at both orientations (b) in Experiments 2 and 5. The dotted line in Panel a was added to the picture to illustrate the distance that participants estimated; it was not visible to the participants.

participants gave informed consent and had normal or corrected-to-normal vision.

Apparatus and stimuli. The table was the same as in Experiment 1. The surface was uniformly white, which minimized landmarks that could aid in distance judgments. The tools consisted of a hammer, a wrench, and a metal pasta strainer. Each tool was marked with a round yellow sticker that was placed at its center of mass. This dot served as a reference point for distance judgments. A white paper circle (3.2-cm diameter) was placed on the edge of the tabletop, directly in front of the participant, and also served as a reference point for distance judgments.

Procedure and design. Participants were seated at the center of the table directly in front of the reference point on the table. A tool was placed either on the right or on the left side of the table so that the end of the tool's handle lined up with the side edge of the table. When placed on the left, the handle of the tool was oriented toward the left and when placed to the right, the handle of the tool was oriented to the right (see Figure 4a). The spatial location and orientation of the tools defined whether they were difficult (left side) or easy (right side) to grasp. The tools were placed at three distances from the reference point on the table (50, 60, and 70 cm). Recent research has shown that distance perception is influenced by the perceiver's ability to act, but only when the perceiver intends to perform the action (Witt et al., 2005). Although tools automatically elicit appropriate motor programs (see Introduction), we wanted to reinforce the intention to act on the tool, so participants were asked to imagine picking up the tools with their dominant hand before making a distance estimate and were asked to reach toward and grasp the tool after making the distance estimate.

Participants made a distance estimate using a visual matching task. In the visual matching task, the experimenter stood across the table from the participants and held up a tape measure with the numbers facing the experimenter so that only the blank side of the tape measure faced the participants. Participants instructed the experimenter to adjust the visible portion of the tape measure so that its length matched the perceived distance from the center of the reference point on the table to the yellow dot on the tool. The tape measure was extended horizontally by the experimenter. Participants were told to make their estimates as accurate as possible and were allowed to make as many adjustments as needed by telling the experimenter how to adjust the tape measure. They were allowed to look back and forth between the tape measure and the tool as much as they liked. After the visual matching task, participants picked up the tool by the handle with their dominant hand in a way that was appropriate for using the tool, then handed it to the experimenter. Each participant completed estimates to all three tools at every distance and at both orientations, for a total of 18 trials. The tools, distances, and orientations were randomized within the session.

Results and Discussion

Ease of grasp influenced perceived distance; tools that were easier to grasp were perceived to be closer than those that were more difficult to grasp (see right panel of Figure 5). Tool, distance, and object orientation were included in a repeated-measures ANOVA, with perceived distance as the dependent measure and all factors as within-participant variables. A main effect of tool orientation was found, $F(1, 11) = 41.25$, $p < .0001$, $\eta_p^2 = .79$. Tools oriented toward the right looked significantly closer than tools oriented to the left. As expected, there was a main effect with actual distance, $F(2, 22) = 184.67$, $p < .0001$, $\eta_p^2 = .94$. No main effect of tool was found, $p > .34$.

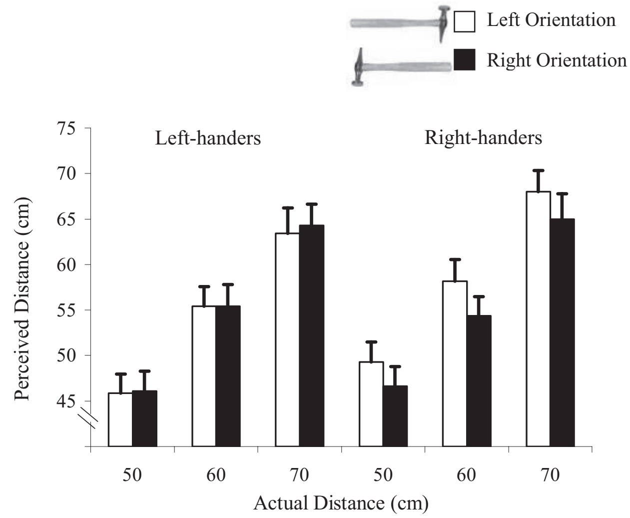


Figure 5. Perceived distance to the tools at each distance and in each orientation found in Experiments 2 (right side of the graph) and 5 (left side of the graph). Error bars represent 1 standard error and are calculated on the basis of within-participant error with the method provided by Loftus and Masson (1994).

These results indicate that participants perceived tools to be farther away when the spatial location and orientation of the tool's handle made them more difficult to grasp. However, two possible factors may have influenced grasping ease. When positioned to the participants' left, the tools were farther away from their dominant right hand. Also, participants may have judged the distance to the object's handle rather than the distance to the reference point, which would have resulted in farther estimates when the handle was oriented to the left. This potential concern will be allayed in the following experiment and in experiments with left-handers. Recall that all participants were right-handed and grasping was always performed with the right hand. Participants had to reach across their body to pick up a tool on the left side. In addition, when placed to the left, the tool's handle was oriented away from their right hand, whereas it was oriented toward their hand when placed to the right. For assessment of whether handle orientation alone would influence apparent distance, the design of this experiment was repeated except that the tools were placed directly in front of the participants and only handle orientation was manipulated.

Experiment 3: Right-Handed Participants Reaching to Centrally Presented Tools

Ease of grasp was manipulated by orienting the handle of the tools either toward or away from participants' dominant hands, whereas the spatial location of the tool remained constant.

Method

Participants. Twelve (8 female, 4 male) right-handed students from the University of Virginia participated for $4 compensation or course credit in an introductory psychology course and had not participated in any other reaching studies in our laboratory. All participants gave informed consent and had normal or corrected-to-normal vision.

Apparatus and stimuli. The same materials and stimuli were used as in Experiment 2.

Procedure and design. The procedure and target distances were the same as in Experiment 2, except that the tools were placed directly in the center of the table, aligned with the reference point used for making distance judgments. The handle of the tool was either oriented toward the left or the right, and the yellow dot on the tool was lined up vertically with the reference point. As in Experiment 2, right-handed participants imagined grasping the tool and then estimated the distance to the tool using the same visual matching task (see Figure 6). Each participant estimated the distances to all three tools at all three distances and at both handle orientations, for a total of 18 trials using the same visual matching task as in Experiment 2.

Results and Discussion

Perceived distance was affected by ease of grasp (see right panel of Figure 7). When tools' handles were oriented toward the participants' right hands, which made the tools easier to grasp, the tools were perceived as closer than tools with handles that were oriented toward the left and thus more difficult to grasp. Tool, distance, and orientation were included in a repeated-measures ANOVA, with perceived distance as the dependent measure. Tool orientation resulted in a main effect, with the right orientation being estimated as significantly closer than the left orientation, $F(1, 11) = 7.41$, $p = .02$, $\eta_p^2 = .40$ (see right panel of Figure 4). Estimated distance also significantly increased with an increase in actual distance, $F(1, 11) = 256.22$, $p < .0001$, $\eta_p^2 = .96$. There was not a significant effect of tool, $F(1, 11) = 0.32$, $p = .73$. Participants perceived the tools as farther away when the tools' handles were not oriented toward participants' dominant right hands. These results show that the apparent distance to a tool is influenced by the ease to grasp the tool.

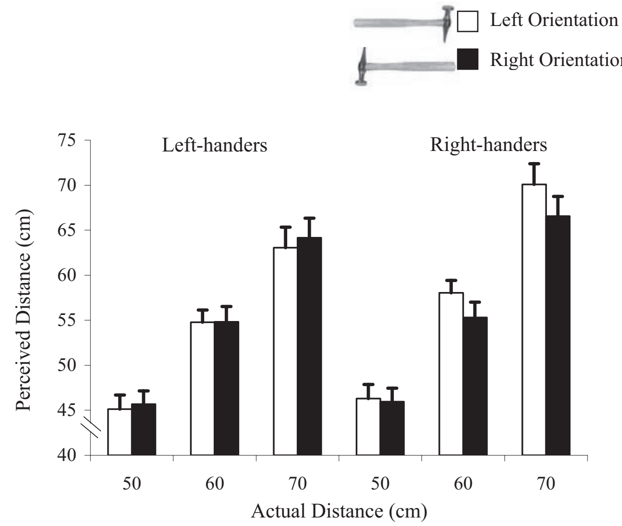


Figure 7. Mean estimated distance to the tools at each distance and in each orientation found in Experiments 3 (right side of the graph) and 4 (left side of the graph). Error bars represent 1 standard error and are calculated on the basis of within-participant error with the method provided by Loftus and Masson (1994).

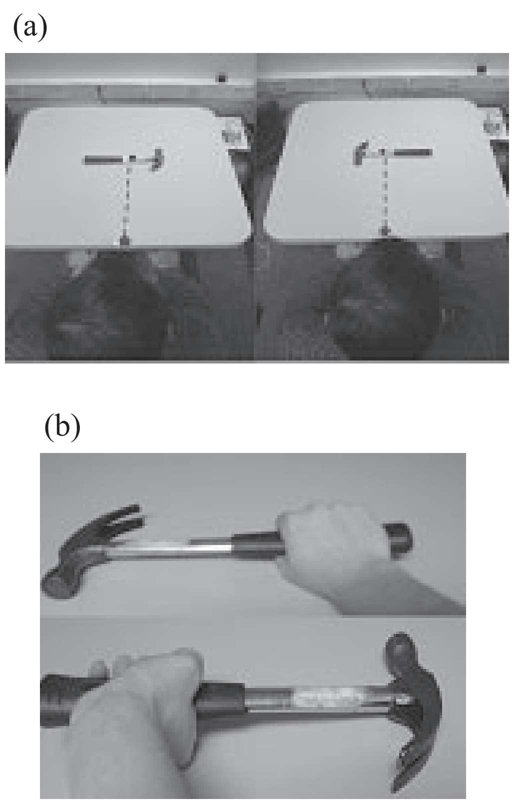


Figure 6. Both possible orientations of the stimulus (a) and type of grasp required to pick up the stimulus appropriately at both orientations (b) in Experiments 3, 4, and 6. The dotted line in Panel a was added to the picture to illustrate the distance that participants estimated; it was not visible to the participants.

Experiment 4: Left-Handed Participants Reaching Toward Centrally Presented Tools

The results from Experiments 2 and 3 showed that right-handed people saw tools as appearing closer if the handle was in an orientation that made it easier to grasp. Right-handed people rely heavily on their right hand, which might account for the effect of graspability on right-handed people's distance perceptions. Because left-handed people tend to be more ambidextrous (Tan, 1989), and thus are less reliant on their dominant hand, tool orientation may not result in a difference in the perceived ease to grasp the tools. As shown in Experiment 1, left-handed people's perceived reachability was less affected by grasp type than right-handers' reachability. As a result, we should expect a smaller, or even absent, effect of graspability on distance perception. To assess this, we used the design of Experiment 3 and tested left-handed participants to ascertain whether tool handle orientation affects perceived ease of grasp in left-handed people.

Method

Participants. Twelve left-handed students (7 female, 5 male) from the University of Virginia participated for $4 compensation or course credit in an introductory psychology course and had not participated in any other reaching studies in our laboratory. Handedness was determined by participants' self-report of handedness and by the observation of the hand used when the participant signed the consent form. All participants gave informed consent and had normal or corrected-to-normal vision.

Apparatus and stimuli. The materials and stimuli were the same as those used in Experiments 2 and 3.

Procedure and design. The procedure and target distances were the same as in Experiment 3. The tools were placed directly in front of the landmark, and the handle of the tool was either oriented to the left or the right (see Figure 6). Each participant estimated the distances to all three tools at all three distances and at both handle orientations using the same visual matching task as in the previous experiments.

Results and Discussion

Ease of grasp did not influence perceived distance in left-handed people (see left panel of Figure 7). Tool, distance, and orientation were assessed in a repeated-measures ANOVA, with perceived distance as the dependent measure. No main effect for tool orientation was found, $F(1, 11) = 1.33$, $p = .27$. Once again, perceived distance increased as actual distance increased, $F(1, 11) = 295.21$, $p < .0001$, $\eta_p^2 = .96$. In addition, no difference in estimated distance was found between the three tools, $F(1, 11) = 1.70$, $p = .22$.

The orientation of the handle did not affect left-handed people's perception of the distances to the tools, whereas right-handed people's perception of the distances to tools was affected by this manipulation. To examine this effect more closely, we compared the results from Experiments 3 and 4 in a 2 (handedness) × 3 (tool) × 3 (distance) repeated-measures ANOVA, with the difference scores of the distance estimates between difficult and easy grasp types as the dependent measure and handedness as the between-participants variable. The results showed a main effect for handedness, $F(2, 22) = 8.22$, $p = .009$, $\eta_p^2 = .27$ (see Figure 7). The difference in the perceived distance to tools that were either easy or difficult to grasp was greater in right-handed participants than in left-handed participants. There was a main effect of distance, $F(2, 22) = 10.13$, $p = .004$, $\eta_p^2 = .32$. As the distance to the tool increased, the difference in the perceived distance to tools at different orientations increased as well. There was no main effect of tool, $F(2, 22) = .05$, $p = .83$.

Because left-handed people live in a man-made environment created for right-handed people, left-handed people may have more experience interacting with objects at awkward orientations. Ease of grasp may affect left-handed people's distance perceptions to objects; however, because of left-handed people's experience in reaching toward awkwardly oriented objects, altering the spatial location of the tools may be necessary to observe the effect of graspability on distance perception in left-handed people. To answer this question, we replicated the design used in Experiment 2 with left-handed participants.

Experiment 5: Left-Handed Participants Reaching Contralaterally and Ipsilaterally

Ease of grasp was manipulated by placing the tool at an orientation and spatial location that made the tool easier or more difficult to grasp with the participants' left hands.

Method

Participants. Twelve (6 female, 6 male) left-handed students from the University of Virginia participated for $4 compensation or course credit in an introductory psychology course and had not participated in any other reaching studies in our laboratory. Handedness was determined by participants' self-report of handedness and by the observation of the hand used when the participant signed the consent form. All participants gave informed consent and had normal or corrected-to-normal vision.

Apparatus and stimuli. The same materials and stimuli were used as those in the previous experiments.

Procedure and design. The procedure and target distances were the same as in Experiment 2. When tools were placed in a spatial location on the left side of the table, the handle was oriented to the left, and when tools were placed on the right side of the table, the handle was oriented to the right (see Figure 4). Each participant estimated the distances to all three tools at all three distances and at both handle orientations using the same visual matching task as in previous experiments.

Results and Discussion

Ease of grasp did not affect perceived distance in left-handed people (see the left panel of Figure 5). Tool, distance, and orientation were assessed in a repeated-measures ANOVA, with perceived distance as the dependent measure. We did not find a significant effect for tool orientation, $F(1, 11) = .23$, $p = .64$. Surprisingly, neither the orientation of the tool's handle nor the spatial location of the tool affected left-handed participants' perception of distance to tools. Perceived distance increased as actual distance increased, $F(1, 11) = 756.30$, $p < .0001$, $\eta_p^2 = .99$. Estimated distance did not differ between tools, $F(1, 11) = .15$, $p = .70$. Neither manipulation of graspability affected left-handed participants' perception of distance.

We compared perceived distance in these participants to the right-handed participants in Experiment 2. Tool and distance were included in a repeated-measures ANOVA, with the difference scores between right and left orientation as the dependent measure and handedness as the between-participants variable. The results showed that right-handed people's perception of the difference between the two tools' orientations significantly differed from left-handed people's perception of the difference between the two orientations, $F(2, 22) = 18.93$, $p < .0001$, $\eta_p^2 = .46$. These results indicate that, when right-handed participants reached with their dominant hand, ease of grasp affected their perception of distance but not left-handed participants' perception of distance. Tools appeared farther away to right-handed people when the tools' orientations were positioned on the dominant side of their body. Left-handed people perceived tools to be the same distance, regardless of the side of their body toward which the tool was oriented.

This finding may be due to right-handed people's tendency to rely solely on their dominant hand, as they live in a world that has been structured for the right hand (Solodkin, Hlustik, Noll, & Small, 2001). Left-handers must rely more on their nondominant hands to use tools made for right-handed people. Consequently, left-handed people may be less sensitive to a change in graspability resulting from the hand they intend to use and the orientation of the tool, because they may not activate motor programs when viewing a tool in a handed way. Thus, left-handed individuals may perceive the world in a symmetrical way, whereas right-handed people may perceive the world in an asymmetrical way. If this were the case, then we would expect to replicate our results when participants reach with their nondominant hand.

Experiment 6: Right- and Left-Handed Participants Reaching With Their Nondominant Hand

Distance perception in right-handed people is biased on the basis of tool orientation. We interpret this bias because of their preference for grasping tools with their right hand. However, if right-handed people were forced to use their left hands, we predicted that the bias would be reversed so that tools oriented toward the left hand would look closer. In contrast, because this bias is not apparent in left-handed people, we predicted a symmetrical perception of distance to tools oriented in either direction when they are forced to use their nondominant hand. Experiments 3 and 4 were replicated with right- and left-handed participants, except that participants estimated distance with the intent to reach to the tool with their nondominant hand.

Method

Participants. Twelve (7 female, 5 male) right-handed students and 12 (6 female, 6 male) left-handed students from the University of Virginia participated for $4 compensation or course credit in an introductory psychology course and had not participated in any other reaching studies in our laboratory. We assessed handedness using the Edinburgh Handedness Survey and self-report of handedness: Left-handed participants were scored ($M = -52.68$, $SD = 34.70$) and right-handed participants were scored ($M = 99.02$, $SD = 3.40$) on the Edinburgh Handedness Survey. All participants gave informed consent and had normal or corrected-to-normal vision.

Apparatus and stimuli. The same materials and stimuli were used as in the previous experiments.

Procedure and design. The procedure and target distances were the same as in Experiment 3. The tools were placed directly in front of the landmark, and the handle of the tool was either oriented to the left or to the right. Participants were asked to imagine picking up the tool with her nondominant hand to strengthen the intention to act on the tool with the nondominant hand. After imagining picking up the tool, participants completed the same visual matching task as that used in previous experiments. Finally, participants picked up the tool with their nondominant hand and handed it to the experimenter. Distances to the three tools were estimated at all three distances and at both handle orientations.

Results and Discussion

For right-handed people, ease of grasp influenced distance perception, whereas in left-handed people, ease of grasp did not have an effect (see Figure 8). We assessed tool, orientation, and distance in a repeated-measures ANOVA, with only the right-handed participants' perceived distance estimates as the dependent measure. Tool orientation resulted in a main effect of orientation, with the left orientation being perceived as significantly shorter than the right orientation, $F(1, 11) = 5.14$, $p = .04$, $\eta_p^2 = .32$. A main effect of distance was found, $F(1, 11) = 544.21$, $p < .0001$, $\eta_p^2 = .98$.

Tool, orientation, and distance were entered into a repeated-measures ANOVA with only the left-handed participants. Tool orientation did not affect perceived distance in left-handed people, $F(1, 11) = .00$, $p = .99$. Perceived distance increased as actual distance increased, $F(1, 11) = 370.01$, $p < .0001$, $\eta_p^2 = .97$. Right-handed participants perceived the tool as farther away if the orientation of the tool's handle did not match their nondominant hand; however, the orientation of the tool did not affect left-handed people's perception of distance to the tool (see Figure 5).

To examine this effect more closely, we computed difference scores between perceived distance for tools oriented to the right and tools oriented to the left. We used this score as the dependent measure in a 2 (handedness) × 3 (tool) × 3 (distance) repeated-measures ANOVA. The results did not show a main effect for handedness, $F(2, 22) = 2.05$, $p = .17$. This lack of significance is surprising, given the absence of a difference of an effect of orientation for left-handed participants, $p = .99$, and the significant effect of orientation for right-handed participants, $p = .04$. However, the nonsignificant result may be due to the fact that the effect in right-handed participants was smaller than in the previous experiments. This suggests that although intention may play a large role in these effects, there may also be an inherent bias to use the dominant hand.

The left-handed people did show more variability than the right-handed people on the handedness questionnaire. If the

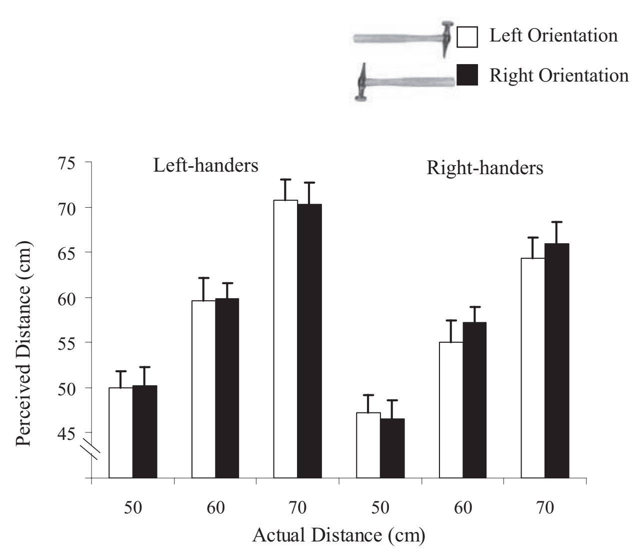


Figure 8. Mean estimated distance to the tools at each distance and in each orientation found in Experiment 6. Error bars represent 1 standard error and are calculated on the basis of within-participant error with the method provided by Loftus and Masson (1994).

lack of effect in left-handed people was due to an increase in the variability of the strength of handedness, then a difference in the variability of the effect between left- and right-handed participants should have been found in the experimental data. However, the variability in the size of the effect in the experimental data did not differ between left- and right-handed people, *p*s $>$ .05 (see Figures 4, 6, and 7). In addition, no relationship was found between handedness scores in left-handed participants and the amount of difference between distance estimates at opposing orientations. Because left-handed people live in a world structured for right-handed people, it is to be expected that left-handed people will vary more than right-handed people in the activities that they perform with each hand. These results support the notion that right-handed people perceive the world in an asymmetrical way, whereas left-handed people perceive the world in a symmetrical way.

General Discussion

The results from these studies indicate that the perceived extent of reach is used to scale distances in near space. Orienting a tool's handle to make it more difficult to grasp affects the extent to which one can reach the tool with the intended hand. Hence, the tool appears farther away compared with when the handle's orientation makes grasping easier. Grasping ease affects perceived reachability and, in turn, the scaling of perceived distance. Although the visual information specifying distance is, of course, unaffected by a tool's orientation, apparent distance is scaled, in part, by the perceived extent to which one can reach. However, this change in perceived distance because of the orientation of the tool's handle appears to be limited to right-handed people.

For left-handed people, the orientation of the tools' handles did not affect the perceived distance to the tool. A possible reason for this finding is that left-handed people are typically more ambidextrous than right-handed people (Annett, 1967). Perhaps, left-handed people perceived their ability to reach to and grasp the tools with respect to either hand, not specifically the hand that they intended to use. Consequently, in left-handed individuals, a change in the orientation of the tool's handle affected their perceived ability to reach to the tool less than in right-handed people. Therefore, they saw tools to be the same distance away regardless of the handle orientation. Overall, these studies demonstrate that ability to reach toward and grasp tools affected apparent distance for right-handers, but in the case of left-handers, handle orientation had a smaller impact on perceived reachability and, thus, apparent distance was less affected.

Because they have been manufactured to afford a specific function, tools often have a specific grasp that is appropriate for their use. The handle specifies where the tool should be grasped and the tool's function dictates the hand's relative orientation. For example, to hit with a hammer, one must grasp its handle so that the head is above the thumb, not below it. Several experiments demonstrate people's sensitivity to the appropriate grasp of tools. When grasping tools, people tend to pick up tools in a manner appropriate for use even when the initial grasp is awkward and inefficient and the task does not involve using the tool (Creem & Proffitt, 2001). In other words, even without an explicit intention to use the tool, people show sensitivity to how a tool should be grasped. Other experiments have shown that merely viewing pictures of tools can prime the motor system to the appropriate grasp and the effector that would be used to grasp the tool (Grezes, Tucker, Armony, Ellis, & Passingham, 2003; Tucker & Ellis, 1996). Hence, individuals are especially sensitive to the grasp posture that accommodates using a tool in an appropriate manner, even when the grasp is uncomfortable. In the present studies, this sensitivity to tools' appropriate grasps led to differences in the perceived reachability and distance to tools.

One possible reason why tools that require difficult grasps appeared farther away than tools that are more easily grasped is that the action capabilities of the body provide a scaling mechanism for the perception of distance. Distances are not necessarily perceived in terms of metric units but rather may be evaluated with units in a different kind of scale that is based on the body's ability to interact with the environment (Fajen & Turvey, 2003; Warren & Wang, 1987). For example, in reachable space, a "perceptual ruler" could be defined as the extent to which a person can reach. If reachable distances are measured in this manner, then changing the body's ability to reach should affect the apparent distance to targets within reach. Concordantly, it has been found that by extending reachability through tool use, participants perceived distances as closer than when they did not use the tool (Witt & Proffitt, 2008; Witt et al., 2005). Presumably, if the perceptual ruler is stretched by providing participants with a tool, then the same distances appear closer because they measure as shorter on the longer ruler. In the present studies, differences in the handle orientation of tools may have changed the extent to which the tools could be reached using a functional grasp, thereby changing reachability. In cases in which the tool required a difficult grasp, the distance to which one could reach was compressed because of the contortion of the arm required to grasp the tool appropriately. Because tools appeared farther away when their appropriate grasps limited reachability, the results in the present studies support the idea that close distances are scaled by reachability. Although we have demonstrated a link between reachability and perceived distance, we have only manipulated reachability with direction of hand orientation. In future studies, we expect other manipulations of reachability to also influence perceived distance.

These studies also support previous findings that distance scaling is based on the capacities for intended actions rather than the ability for any actions that could be performed, at least for right-handed participants. With respect to distances of reachable targets, the scaling of the distances to those targets is based on how far one can reach in the present environment using a specific hand, rather than some average of both hands or just the dominant hand. In the present set of studies, when right-handed participants intended to use their right hands, tools with handles that were oriented to the left were seen as farther away than tools oriented toward the right; however, when right-handed participants anticipated using their left hand, tools oriented to the right appeared farther away. Correspondingly, when reaching to a target, the distance to the target appears closer if the person intends to use a tool to expand their reach but not if the tool is available yet the person does not intend to use it (Witt & Proffitt, 2008; Witt et al, 2005). In addition, previous studies have found that increasing the effort to walk to a target increases the apparent distance to the target when the participant intends to *walk*, not when the participant intends to *throw* to the target (Witt, Proffitt, & Epstein, 2004). Likewise, effort for throwing influences perceived distance for people who intend to throw but not for those who intend to walk (Witt et al., 2004). Hence, the capabilities for action that are used to scale distances are specific to the actions that the perceiver intends to perform.

One alternative explanation for the effect of nonoptical variables on perception is that they alter a postperceptual representation, inducing a response bias rather than actually affecting perception itself. The results from these studies do not support such a response bias account because the effect is limited to right-handed people. When manipulating the ease to grasp, both groups were required to pick up the object using an awkward grasp. The task was equally difficult for both groups. Handedness was the main difference between the groups and was independent of the actual action performed during the task. Consequently, if participants corrected their estimates postperceptually on the basis of a response bias, then both left and right-handed participants should have corrected their distance estimates in the same way. However, only right-handed participants exhibited differences in distance estimates. Left-handed participants were unaffected by the manipulation, presumably because of their ambidexterity. These striking individual differences between right- and left-handed people suggest that the ease of grasp of the tool affects perception of distance, and this effect cannot be accounted for by a general postperceptual response bias.

It is interesting that left-handed participants did not see tools as farther away when the tool's handle orientation made the tool more difficult to grasp. An intuitive explanation for the lack of an effect in left-handed people derives from the fact that left-handed people are more ambidextrous than right-handed people, perhaps because they are accustomed to having to interact in a world that is often structured for right-handed people. As a result, left-handed people are more experienced and efficient at reaching in an awkward manner, and changes in the handle orientation of a tool did not drastically increase their ease of grasp. However, this explanation does not appear to account for the lack of an effect in left-handed people, because left-handed people usually avoid using uncomfortable grasps by switching hands, whereas right-handed people are more willing to engage in uncomfortable grasps to avoid using their nondominant hand (Gonzalez et al., 2006). Hence, it is probably just as easy or easier for right-handed people to engage in uncomfortable grasps with their dominant hand as it is for left-handed people, because they would rather use an uncomfortable grasp with their dominant hand than a comfortable grasp with their nondominant hand. As a result, left-handed people probably do not engage in awkward grasps any more efficiently or comfortably than right-handed people do; therefore, experience with awkward grasps cannot explain the lack of an effect in left-handed people.

Although unlikely, another potential explanation for the difference between left- and right-handed people is that perhaps when left-handed people thought about grasping the tool, they actually thought about using the hand that is most comfortable for them to use rather than the hand they were told to think about using. Thus, left-handed people intended to use the arm that allowed for a comfortable rather than an awkward grasp. Although it is possible that left-handed people thought about using a different arm than the one they were told to use, this seems unlikely because participants did actually engage in the awkward grasp after thinking about the type of grasp that they would use. Therefore, while making distance estimates, left-handed people must have intended to use the hand that required an awkward grasp because that was the hand they actually used to grasp the tool.

Because the actual ease of grasp probably did not differ between left- and right-handed people and both left- and right-handed people intended to use the same hand to grasp tools at different orientations, the difference between left- and right-handed people is most likely due to whether they *see* the tool's graspability with respect to a specific hand. Left-handed people probably do not see the tool in a handed way because, usually, handle orientation does not matter when they are grasping because of their ability to use either hand in a proficient manner. Hence, left-handed people do not take into account a change in handle orientation when assessing their grasping capabilities as right-handed people do. To right-handed people, handle orientation is an extremely important factor in their perceived ease of grasp because they are heavily reliant on their dominant hand. For right-handed people, handle orientation determines the type of grasp for a *specific* hand, and for left-handed people, handle orientation determines which hand to use. Therefore, left-handed people may not be as sensitive to how changes in handle orientation affect ease of grasp and, consequently, they perceive the distance to tools at different handle orientations to be the same.

Past research has also found that left-handed people tend to rely less on a certain arm's abilities to perform a task, compared with right-handed people who typically rely heavily on their right hand. In a mental rotation task in which participants must identify whether an image of a hand is a right or left hand, right-handed people seem to mentally rotate their own dominant hand as a way to evaluate the pictured hand (Gentilucci, Daprati, & Gangitano, 1998; Nico, Daprati, Rigal, Parsons, & Sirigu, 2003). As such, they are faster to recognize that a right hand is a right hand. Left-handed people do not show the same preference for their dominant hand, suggesting either that they are equally likely to use either hand as a reference or that they use a different strategy altogether (Gentilucci et al., 1998). In precision grasping tasks, left-handed people use their nondominant hand much more often than do right-handed people (Gonzalez et al., 2006). Left-handed people use their left hand 52% of the time, whereas right-handed people use their right hand 78% of the time (Gonzalez et al., 2006). Consequently, it is not surprising that left-handed people did not rely on a specific hand's abilities when viewing tools at different orientations. For left-handed people, tool orientation specifies which hand should be used to grasp the tool, not the ease of grasp with their dominant hand, which is the case for right-handers.

Summary

These studies show that the ease of the intended grasp to reach a tool affects the extent to which one anticipates being able to reach and thereby influences the scaling of the perceived distances to that tool. Reachable distances are scaled by the extent of one's reach. By this account, people perceive the distance to a tool by scaling the available optic information to the extent of their arm and contortion of their wrist. In general, the present findings support the notion that the perception of spatial layout is action specific and is scaled by the body's abilities to perform intended actions.

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