Journal of Experimental Psychology:
Human Perception and Performance
2011, Vol. 37, No. 5, 1432–1441

0096-1523/11/$12.00 DOI: 10.1037/a0024248

Taking a Hands-On Approach: Apparent Grasping Ability Scales the Perception of Object Size

Sally A. Linkenauger
Max Planck Institute for Biological Cybernetics,
Tübingen, Germany

Jessica K. Witt
Purdue University

Dennis R. Proffitt
University of Virginia

We examined whether the apparent size of an object is scaled to the morphology of the relevant body part with which one intends to act on it. To be specific, we tested if the visually perceived size of graspable objects is scaled to the extent of apparent grasping ability for the individual. Previous research has shown that right-handed individuals perceive their right hand as larger and capable of grasping larger objects than their left. In the first 2 experiments, we found that objects looked smaller when placed in or judged relative to their right hand compared to their left. In the third experiment, we directly manipulated apparent hand size by magnifying the participants' hands. Participants perceived objects to be smaller when their hand was magnified than when their hand was unmagnified. We interpret these results as demonstrating that perceivers use the extent of their hands' grasping abilities as "perceptual rulers" to scale the apparent size of graspable objects. Furthermore, hand size manipulations did not affect the perceived size of objects too big to be grasped, which suggests that hand size is only used as a scaling mechanism when the object affords the relevant action, in this case, grasping.

Keywords: visual perception, affordances, embodied perception

> Where would we be without the hand? Our lives are so full of commonplace experience in which the hands are so skillfully and silently involved that we rarely consider how dependent upon them we actually are. No serious account of human life can ignore the central importance of the human hand.
>
> —Frank Wilson (1998, p. 3)

Like any other animal, our functional morphology provides the means for enacting our species' behavioral repertoire. Of relevance to the work presented here, humans have hands with independently controlled digits including a long, well muscled, opposable thumb. Although easy to overlook, the independence of the thumb from other digits makes us very "hands-on" creatures, capable of manipulating objects in our environment with an unparalleled level of precision. However, the ability to use our hands depends on having a corresponding visual system that provides relevant information. Such integration between the functional capabilities of the hand and a complementary visual system allow us, for example, to perform surgery on nerves and muscles, which are no thicker than a strand of hair, or simply pass a thread through the eye of a needle. Our hands allow us to construct our world to a degree unmatched by other animals.

Our visual system has developed in ways that takes advantage of, as well as complement, the activities that our hands afford. For example, only animals with effective hands, specifically humans, nonhuman primates, and praying mantes, are capable of performing smooth pursuit eye movements, presumably an adaptation that makes possible tracking our hands and held objects through space (Land, 1992). In a similar fashion, humans have a circular fovea instead of a slit-shaped area of high density photoreceptors, which are found in most other mammals. Possibly, the round fovea coupled with smooth pursuit eye movements allows us to see with great acuity what we are manipulating with our hands. Although at the expense of a wider field of view, humans have a high degree of binocular overlap, which allows for excellent depth perception in front of the body where one interacts with held objects. This discussion derives from the behavioral ecology literature and serves to introduce our perspective on human visual perception. From a behavioral ecology perspective, people, like any other animal, have evolved to extract and process information that promotes successful adaptation to their environment.

Put generally, organisms' functional morphology accommodates the ecological niche to which they are adapted and defines what type of information is important for them to extract within this niche. In turn, sensory systems have adapted to selectively pick up information that is relevant for the actions that an organism can perform given its functional morphology. As described above, for humans, visual information supporting the movement of our hands is of primary importance and our sensory systems have

---

Sally A. Linkenauger, Max Planck Institute for Biological Cybernetics, Tübingen, Germany; Jessica K. Witt, Department of Psychological Sciences, Purdue University; Dennis R. Proffitt, Department of Psychology, University of Virginia.

This work was supported by a grant from National Science Foundation (BCS–0957051) to Jessica K. Witt and National Institute of Mental Health (RO1MH075781) to Dennis R. Proffitt.

Correspondence concerning this article should be addressed to Sally Linkenauger, Spemannstrasse 44, 72076 Tübingen, Germany. E-mail: sal3g@virgina.edu

adapted to promote these activities. However, the sensory organs are not the only systems that have coevolved with the morphology of the body; the perceptual system also utilizes the morphology of the body to perceive spatial layout at an action-relevant scale. Several studies have shown that the perceptual system scales aspects of the perceived environmental to the functional morphology of the body. In other words, individuals perceive sizes and distances as a proportion of the action-relevant aspect of their phenotype (e.g., Linkenauger, Ramenzoni & Proffitt, 2010; Linkenauger, Witt, Stefanucci, Bakdash, & Proffitt, 2009; Witt, 2011b; Witt & Proffitt, 2008; Witt, Proffitt, & Epstein, 2005; Wraga, 1999a). This action-specific approach to perception (e.g., Proffitt, 2006, 2008; Witt, 2011a) is by no means a new way of thinking, but an extension of some very elegant research in biology and behavioral ecology into the realm of spatial perception.

The optical information specifying spatial layout comes to the eye in the form of visual angles, changes in visual angles, retinal disparities, and ocular-motor adjustments, the latter two are also specified in angular form. These angles provide a rich amount of information about the environment, and allow for successful guidance for many, possibly all, actions through visual control heuristics. For example, to locomote successfully to a target at a specific visible location, the perceiver only has to walk so as to nullify the target's angular elevation. Similarly, to catch a fly ball, an outfielder does not need to know where the ball is going to land; in fact, even professional baseball players have difficulty predicting where fly balls will land (Oudejans, Michaels, Bakker, & Dolné, 1996). To catch a fly ball, fielders need only run in a manner that keeps the trajectory of the ball moving upward in a straight line and perhaps with a constant velocity in their visual field (Fink, Foo, & Warren, 2009; McBeath, Shaffer, & Kaiser, 1995). In general, individuals learn couplings between optic flow and their movements allowing them to adopt control strategies associated with these couplings.

There are several interesting ways in which people use visual control heuristics to guide their movements (see Fajen, 2007; Van der Kamp, Oudejans, & Savelsbergh, 2003, for a more in depth review); however, successful environmental interaction requires more than just the ability to guide overt movements. One must also determine whether the action can be performed successfully. For example, to successfully jump across a crevasse, the jumper not only needs visual information to guide the action of jumping, but the jumper also needs to use the visual information specifying the size of the gap to determine whether she is capable of jumping far enough to successfully land on the other side. This requires the perceiver to scale apparent extents to the action capabilities of their bodies.

Given that visual information specifies spatial layout in angular units, to visually perceive an extent, relevant information must be rescaled into units that are appropriate for extents. Traditionally, units used for scaling are considered to be behaviorally independent. In contrast, we propose that the action capabilities of the body can provide perceptual rulers with which to transform manifest visual angles into extent-appropriate units. For example, the visual information specifying extents of graspable objects might be scaled to the action boundary for grasping. This type of scaling provides perceivers with information that specifies the spatial layout of the environment with respect to their bodies and abilities. For example, the width of the crevasse would be perceived as a proportion of the maximum extent over which one can jump. The meaning of an extent is grounded in the metric to which it is scaled; by using this metric, perceived extents convey information that is functional, informative, and grounded in the body.

If such action-based scaling occurs, then manipulating the action capabilities of the body should affect perceptions of extent. If the action capabilities of the body are expanded, then the perceptual ruler is expanded as well. Consequently, the object at the same physical distance will appear to be closer because the distance to the target measures as shorter on the expanded ruler. In a similar way, if the action capabilities of the body are constrained, then the perceptual ruler becomes compressed. Thus, the object at the same physical distance will appear to be farther because the distance to the target measures as farther on the compressed ruler. Consider a target that is 50% of the perceiver's action boundary for reaching (as in the line labeled A in Figure 1). If that perceiver's reach is subsequently increased by 50%, then the target now measures as 25% of one's maximum reach (compare A and B in Figure 1). Similarly, if that perceiver's reaching ability was reduced by 50% rather than increased, than the target measures as 100% of one's maximum reach (compare A and C in Figure 1). Hence, as the ruler changes, the measurement of the object's apparent size changes accordingly.

In terms of using the body's action capabilities as a perceptual ruler, several studies have found support for eye height and maximum reaching extent as being the metric to which certain extents are scaled. Eye height is used as a metric to scale the apparent heights of objects (Sedgwick, 1973). When eye height was implicitly manipulated by placing participants on a false floor or manip-

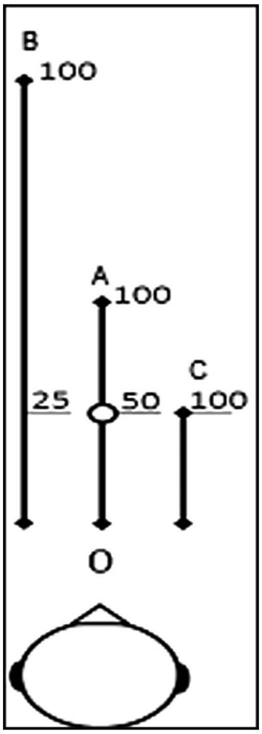

Figure 1. Illustration of how manipulations of action capabilities can affect the scaling of apparent extents.

ulating the altitude of the virtual camera in a head-mounted display virtual environment, visually perceived object height was a function of apparent eye height, leading to changes in the apparent sizes of the objects (Dixon, Wraga, Proffitt, & Williams, 2000; Wraga, 1999a). When participants overestimated their eye height, they scaled the size of the objects to the apparent eye height rather than their true eye height. This led to a decrease in the perceived size of the target (Dixon et al., 2000; Wraga, 1999a). Eye-height manipulations have in turn affected individuals' judgments of whether they can perform actions on targets, presumably because of the corresponding changes in perceived height (Warren & Whang, 1987; Wraga, 1999a).

Eye-height scaling is apparent in some aspects of perception but not all. For example, changes in eye height did not affect the apparent width of the targets, suggesting eye height is used to scale height but not width (Wraga, 1999a). In a similarly way, for objects much larger than one's eye height, such as tree size, perceivers lessen their dependence on eye height as a scalar (Bingham, 1993; Wraga & Proffitt, 2000). For standing and seated observers, eye height is only used as a scaling metric when objects are within 20 to 250% of the perceiver's eye height (Wraga, 1999a; Wraga & Proffitt, 2000). Furthermore, eye height is also not an effective source of information for individuals in prone positions (Wraga, 1999b). Therefore, it has been suggested that eye height is only used when it is effective and relevant as a scale, which implies that other metrics need to be employed when scaling the distances to and sizes of objects outside of the eye-height effective regions.

Reaching extent also has been shown to scale extents that are within near space. As a result, manipulating one's reach has been shown to affect the visually perceived distance to reachable objects. By extending one's reach via a hand tool, objects appeared closer than when participants did not reach with a tool (Witt & Proffitt, 2008; Witt et al., 2005). In a similar fashion, the apparent distances to targets appeared farther when one's reach was constricted by having the actor employ an awkward grasp or by having the actor wear arm weights (Linkenauger, Witt, Stefanucci, et al., 2009; Linkenauger, Zadra, Witt, & Proffitt, 2011). Individuals also appear to perceive targets within reach differently than targets beyond arm's reach as evidenced by line-bisection tasks and patients with neglect (Cowey, Small, & Ellis, 1994; Halligan & Marshall, 1991; Longo & Lourenco, 2007). This result implies different scaling mechanisms in near and far space. In near space, perceiver's tend to bisect lines with a slight bias to the left; whereas, in far space, the bias is slightly to the right. Several studies have shown that the rightward bias can occur farther from the body when one's reach is extended or the leftward bias can occur closer to the body when one's reach is restricted (Berti & Frassinetti, 2000; Lourenco & Longo, 2009). In summary, both reaching and eye height provide examples of how the body provides a perceptual ruler for transforming visual angles into units appropriate for apparent extents.

Taken together, these findings suggest that reaching ability and eye height are not the only bodily metrics used to scale space, but rather are part of a larger ensemble of perceptual rulers. Several aspects of our functional morphology that are relevant to acting on the environment may be used as scaling mechanisms to perceive sizes and extents. Because humans are constantly using their hands to manipulate and interact with objects in space, it stands to reason that maximum grasping ability also may be used as a scaling metric. Some evidence has indicated that this might be the case. When perceived hand size was increased, via the rubber hand illusion, participants estimated objects to be heavier (Haggard & Jundi, 2009). Bearing in mind that the size-weight illusion leads individuals to estimate that larger objects of the same weight feel lighter than smaller objects of the same weight, this finding suggests that a perceptually larger hand (and in turn, a larger action boundary for grasping) resulted in objects that appeared smaller and therefore felt heavier. When viewed with magnifying goggles, objects similarly appear smaller when viewed simultaneously with the hand (also magnified) than when viewed in the absence of the hand (Linkenauger et al., 2010). Presumably, when in the absence of the hand, the apparent size of the object when magnified is scaled to the known graspability of the unmagnified hand. However, when the hand is viewed simultaneously (also magnified), the size of the object is rescaled to the graspability of the magnified hand. The perceptual ruler has been expanded through magnification, and thus, the object measures as smaller on the larger ruler.

The current studies expand on this previous research in two ways. First, we demonstrate a link between apparent grasping ability and perceived object size using direct measures of visually perceived size. Second, we show that the link between graspability and object size is specific to objects that are within the apparent graspability of the hand. Objects that are too big to be grasped are not scaled to grasping ability, which demonstrates specificity in these effects.

Experiment 1: Visually Perceived Size of Objects in the Right and Left Hands

First, we took advantage of naturally occurring differences in right-handed people related to their right and left hands. About 90% of the population relies more heavily on their right hand than their left to perform a range of different task. Several studies have shown that right-handed people tend to neglect the left side of their body, whereas left-handed individuals show little or no neglect for either side (Hach & Schütz-Bosbach, 2010; Sampaio & Chokron, 1992). Right-handed individuals perceive their right hand as about 6% larger than their left, and consequently, think that they can grasp larger objects with their right than their left, when there is no actual size or capability difference between the two (Linkenauger, Witt, Bakdash, Stefanucci, & Proffitt, 2009). In other words, right-handed participants anticipate that they can grasp larger objects with their right hand than their left hand. Therefore, right-handed people provide us with naturally occurring differences in perceived hand size and apparent action capabilities between their left and right hands. Thus, if we use the apparent action boundary for grasping to scale the apparent sizes of objects, we should expect differences in the perception of size depending on whether the right or the left hand is relevant to the task the perceivers are performing.

Method

Participants. Fifteen right-handed students (9 women) 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 using the Edinburgh Handedness Survey (M = 90.80, SD = 9.80; Oldfield, 1971). All participants gave informed consent and had normal or corrected-to-normal vision.

Stimuli and apparatus. Participants were seated at a square table that measured 91.5 cm by 91.5 and was 74.5 cm tall. Two sets of six black disks were constructed from foam board that was 5-mm thick; the disks were constructed to be 22.5, 24, 26.6, 28, 30, or 32 mm in diameter.

A Dell laptop with a 33 by 21 cm display was used for a size visual matching task. The task consisted of a white circle, 5 mm in diameter, presented centrally, on a black screen. The size of the circle could be made larger by pressing the right-arrow key and could be made smaller by pressing the left-arrow key.

Procedure. Participants were seated at a close but comfortable distance from the table and were instructed to place their hands on the table with their palms facing upward. The research assistant was seated directly across from the participant. Participants then closed their eyes, and the research assistant placed one disk in their left hand and one disk in their right hand. Participants were then instructed to open their eyes and indicate which disk appeared larger: the disk in their right hand or the disk in their left hand by saying "left" or "right." Participants were then instructed to close their eyes again, and the next trial began. One set of disks were placed in the left hand, and one set of disks were placed in the right (this was counterbalanced across participants to ensure that minor differences between the pairs of disks, though tightly controlled for, could not account for our results). Every possible combination of one set of disks was paired with every possible combination of the other set of disks for a total of 36 trials.

After participants completed all 36 comparison trials, they then engaged in a size estimation task in which they estimated the sizes of all six disks in their left and right hands. One set of the disks was used for this task. Participants placed either their right or left palm face up on the table. They were asked to close their eyes and one of the six disks was placed into their palm. They then were instructed to open their eyes and estimate the size of the disks that was on their palm. Participants estimated size using a visual matching task in which they used the arrow keys on the laptop computer to make the size of a circle presented on the laptop display to be the same size as the disks on their palm. Participants estimated the sizes of all six disks in one hand and then estimated the sizes of all six disks in the other hand. Order of the disks was randomized, and hand order was randomized.

Results and Discussion

Given that diameter is the relevant dimension for grasping, for the comparison task, size ratios were determined by dividing the diameter of the disk presented in the right hand by the diameter of the disk presented in the left hand. For each participant, an individual binary logistic regression was calculated with the size ratio as the independent variable and the response as the dependent variable. From the resulting regression equation, the point of subjective equality (PSE) for each participant was determined. The PSE is the difference between the two disks that is required for the participant to be at a chance (0.5 probability) of choosing the disk in the left hand. In other words, the PSE is the point at which both disks appeared to be the same size. A PSE above 1 implies that disks in the left hand appear larger. A PSE below 1 implies that disks in the right hand appear larger. A PSE of 1 implies that hand did not influence perceived size. In a one-sample t test that compared the PSEs to 1 revealed that the PSE (M = 1.01, SE = .004) was significantly larger than 1, $t(14) = 2.60$, $p = .02$, two-tailed (see Figure 2). Hence, participants perceived objects in the left hand as larger than objects in the right hand.

To analyze the data in the size visual matching task, a repeated-measures analysis of variance (ANOVA) was performed with circle size and hand (right or left) as independent variables and estimated size in cm as the dependent variable. The effect of physical disk size was significant, $F(5, 70) = 175.35$, $p < .001$, $\eta_p^2 = .93$. As hypothesized, disks in the right hand, M = 30.20 cm, SE = 1.1, were estimated to be smaller than disks in the left hand, M = 31.40 cm, SE = 0.90, $F(1, 14) = 5.00$, $p = .04$, $\eta_p^2 = .26$, see Figure 3.

These finding could be attributable to three different sources. First, because participants had tactile feedback, the disk in the left hand could have felt larger than the disk in the right hand. There is a larger representation in the somatosensory cortex for the right hand than the left hand, suggesting that the right hand has smaller receptive fields than the left hand (Sörös et al., 1999). However, if this were the case, then the disk in the right hand should have felt larger than the disk in the left hand and, instead, we found that participants visually perceived the disk in the right hand as smaller. We find it interesting that inducing the feeling that one's hand is bigger leads to judgments that haptically perceived objects and objects that are passively touching the body are also bigger (Bruno & Bertamini, 2010; de Vignemont, Ehrsson, & Haggard, 2005). It is not clear why visual comparisons between the hand and the object led to a contrast effect while haptic comparisons led to complimentary effects. In fact, Taylor-Clarke, Jacobsen, and Haggard (2004) showed that visual magnification of the arm and minification of the hand can make the same sized visual stimulus appear smaller when on the arm than when on the hand as found in these studies; however, when they found the opposite effects

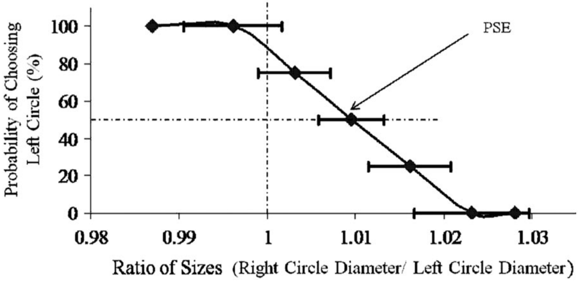

Figure 2. Results from the size comparison task in Experiment 1. The probability of choosing the disk in the left hand as being larger is plotted as a function of the ratio of the sizes—between the disk in the right versus left hand as indicated by a ratio of right circle diameter divided by the left circle diameter. From each individual's slopes and intercepts calculated from individual logistic regressions, we calculated the difference in size required for the individual to choose the left instead of right circle 100%, 75%, 50%, 25%, and 0% of the time as shown in the graph. The point of subjective equality (PSE), which is the point at which both disks look the same, requires that the disk in the right hand be larger than the disk in the left hand. Error bars represent one standard error of the mean.

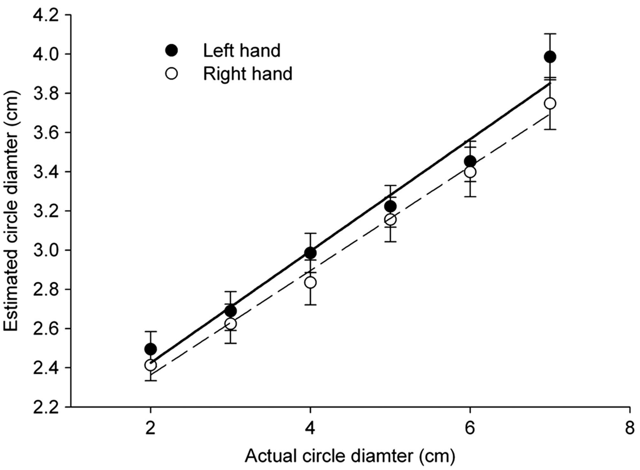

Figure 3. Estimated disk size as a function of actual disk size and by whether the disk was resting in the left or right hand. Error bars represent one standard error of the mean.

when estimating the sizes of objects that where passively touching the body parts without vision. This finding suggests that altering the apparent sizes of body parts results in opposite effects depending on whether visual size or proprioceptive/haptic size. With regard to visual effects, and, as proposed by the action-specific perception perspective, we believe that the participants used the capabilities of each hand to scale the apparent size of the object. Because the right hand appears larger and is deemed to be able to grasp larger objects (Linkenauger, Witt, Bakdash et al., 2009), the same object measures as smaller on the right hand's larger ruler, and therefore, appears smaller than when it is placed on the left hand. This interpretation corresponds with the approach that the angular information specifying the size of graspable objects is scaled to the action capabilities of the body. Third, however, is that this finding could also result from a visual size-contrast illusion. Because the disk is surrounded by an object that is perceived to be larger (the right hand; Linkenauger, Witt, Bakdash et al., 2009), then by contrast, the disk in the right hand might have appeared smaller than the disk surrounded by a smaller object (the left hand). Although both latter explanations are possible and not mutually exclusive, the next experiment was designed to test the action-specific perspective in a scenario that does not also include a potential size-contrast effect.

Experiment 2: Visually Perceived Size of Objects to Be Grasped by the Left and Right Hands

In Experiment 1, participants judged the relative sizes of objects that they held in either their right or left hands, which could have led to a size contrast illusion instead of differences between the right and left hand in scaling the perceived sizes of objects. Therefore, in this experiment, participants looked at objects on a table. However, they were told to imagine grasping the object. If the previous results were due to scaling by graspability, then the perceived size of the objects should be affected by which hand would grasp them. If the previous results were due to a visual size-contrast effect, then we would not expect differences in perceived size when the objects are located on the table rather than held in the hands.

To test this, right-handed participants estimated their ability to grasp several differently sized blocks and then estimated the size of the blocks. We also expected that blocks that were too large to be grasped should not be affected by the intent to grasp with the right and left hands because they are too large to be scaled by the action boundary for grasping, making the intended hand no longer relevant to scaling.

Method

Participants. Fourteen students (6 women) 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 using the Edinburgh Handedness Survey ($M = 87.35$, $SD = 22.87$). All participants gave informed consent and had normal or corrected-to-normal vision.

Stimuli and apparatus. Participants were seated at the same square table as in Experiment 1. Sixteen square, white blocks constructed out of foam board that was 1.25-cm thick served as stimuli. The blocks were 4, 6, 8, 10, 12, 14, 15, 16, 17, 18, 19, 20, 21, 22, 24, and 26 cm wide. Each block was marked with two parallel black lines, placed along the edge on opposite sides of each block. These lines were 2 cm long and 0.25 of a cm thick. The lines served as reference points for the distance estimations and indicated where the participant was supposed to grasp the stimulus.

A laptop computer on top of a stool (76 cm high) was situated to the side of the participant opposite of the hand being used to grasp. The monitor on the laptop was 33.5 cm wide and 21 cm long. The monitor displayed a black screen with 2 white dots (0.5 cm in diameter) centered in the middle of the screen that served as comparison circles. The circles originated 1.75 cm away from each other. By using the up-arrow key, the circles could be moved farther apart from each other, horizontally. By using the down-arrow key, the circles could be moved horizontally closer to one another.

Procedure. Participants were assigned to start the experiment grasping with their left or right hand in alternating order. Participants were seated at a close but comfortable distance from the edge of the table. On each trial, participants closed their eyes and the center of block was placed 25.4 cm away from the edge of the table. The block was positioned so that the black lines that marked the opposite edges of the stimulus were vertical to the participant (see Figure 4). Participants opened their eyes and judged whether they could grasp the stimulus square with their assigned hand with their thumb on one black mark and any other finger positioned on the other black mark. Making this judgment presumably led participants to perceive the object in terms of grasping it. Previous research demonstrates that the intention to act on the object is necessary to perceive objects in terms of ability (Witt & Proffitt, 2008; Witt, Proffitt, & Epstein, 2004, 2005), although some objects may have a default affordance with which they are scaled and perceived such as locomotion on the ground plane (Proffitt et al., 1995, 2003) or grasping hand tools (Tucker & Ellis, 1998). In this case, explicit manipulation of intention would not be necessary. Although the participants in this experiment did not grasp the blocks until the end of the experiment, the idea was that making

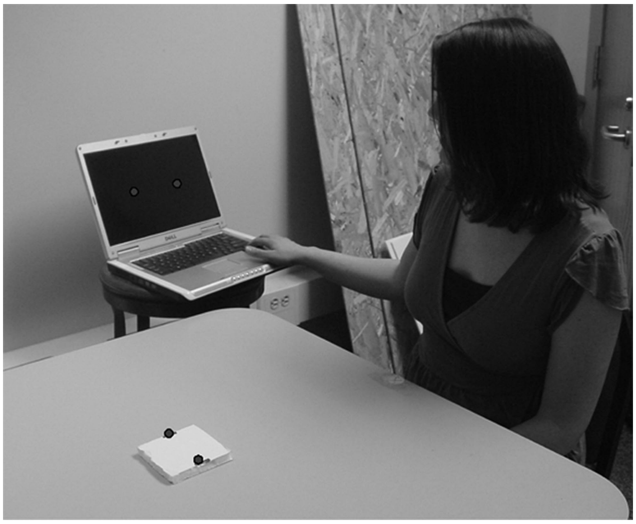

Figure 4. A picture of a participant estimating the size of a block in Experiment 2.

the judgment as to the possibility of the action would be sufficient for perception to scale the information based on graspability. After participants responded whether they thought they could grasp the block, participants positioned the two comparison circles on the laptop so that the width between these circles matched the width of the stimulus as defined by the two black lines. The laptop was positioned on the side opposite of the assigned grasping hand, and participants used the nongrasping hand to press the arrow keys to manipulate the width between the comparison circles. After participants estimated the size of the stimulus, participants closed their eyes, and the research assistant placed a new block in front of the participant for the next trial. The order of block presentation was randomized. Participants estimated the size of all 16 blocks with the intention to grasp with one hand and then all 16 blocks again with the intention to grasp with the other hand. Hand order was counterbalanced across participants.

At the end of the experiment, blocks of different sizes were placed in front of the participant and the largest block that the participant could actually grasp (using the same grasp that they used in their graspability estimations) was determined. We defined grasping as being able to pick up the stimulus and lift it at least 10 cm from the table.

Results and Discussion

Participants perceived objects that they evaluated grasping with their right hand to be smaller than objects that they evaluated grasping with their left hand, but only for objects that were small enough to be graspable (see Figure 5). Perceived grasping ability was calculated by dividing estimated grasping ability by actual grasping ability. As expected, right-handed individuals estimated their grasping ability to be greater with their right hand, $M = 1.13$, $SE = .04$, than their left hand, $M = 1.08$, $SE = .04$, $t(13) = 2.00$, $p = .03$, one-tailed.

To assess perceived object size, block size estimates were transformed into ratios by dividing the estimate by the actual size. The size ratios are a measure of accuracy and allowed for the comparison of estimates across different sizes. To test our hypothesis, we performed independent analyses for size ratios that were within and outside of perceived grasp. For size ratios of objects within grasp (as determined for each individual participant), we performed a univariate ANOVA with block size and hand (right, left) as fixed factors, participant as a random factor, and size ratios for blocks judged as being graspable as the dependent factor. As predicted, we found a significant effect of hand, $F(1, 16.01) = 5.75$, $p = .03$, $\eta_{\mathrm{p}}^2 = .26$. Blocks were underestimated more when the participant intended to grasp with the right hand, $M = 0.85$, $SE = .009$, than with the left hand, $M = 0.88$, $SE = .01$ (see Figure 5, left side). We also found a significant effect of block size, $F(13, 153.02) = 3.\ 74$, $p < .001$, $\eta_{\mathrm{p}}^2 = .24$, with larger squares being underestimated more than smaller blocks. There was no interaction between block size and hand, $p = .72$, suggesting that the effect of the hand was consistent across all differently sized blocks so long as the blocks were all graspable.

For size ratios of objects outside of grasp, we performed a univariate ANOVA with block size and hand (right, left) as fixed factors, participant as a random factor, and size ratios of blocks that were too big to be graspable. As hypothesized, we did not find a significant effect of hand, $p = .36$, with blocks being estimated to be about the same size regardless if the participant intended to grasp the square with the right or left hand, $M = .90$, $SE = .09$, $M = .90$, $SE = .12$, respectively (see Figure 5, right side). We found a significant effect of block size, $F(9, 66.83) = 2.20$, $p = .03$, $\eta_{\mathrm{p}}^2 = .23$, with larger squares being underestimated more than smaller squares.

These results support the notion that perceivers use their action capabilities to scale the apparent sizes of graspable objects. Because the right hand is perceived to be larger and can grasp bigger objects than the left hand in right-handed individuals (Linkenauger, Witt, Bakdash et al., 2009), they perceived the size of objects that they would grasp with their right hands to be smaller than the objects that they would grasp with their left hands.

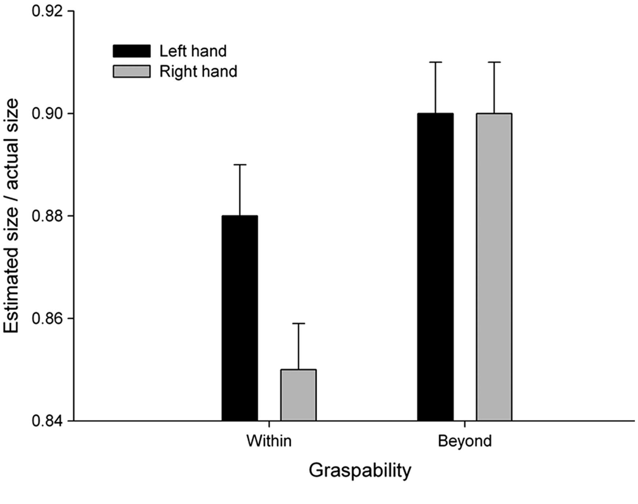

Figure 5. Results from size judgments in Experiment 2. Ratios of estimated size divided by actual size of the blocks is plotted as a function of whether the block was small enough to be grasped or not and whether participants intended to grasp with their left or right hands. Error bars represent one standard error of the mean.

Importantly, the sizes of objects that they could not grasp were perceived the same regardless of whether judgments were made with regard to the left or right hand. This result demonstrates specificity in the use of graspability for scaling object size, specifically that graspability scales perceived size only for objects that can be grasped.

Experiment 3: Visually Perceived Size of Objects to Be Grasped by a Magnified or Unmagnified Hand

In this experiment, we directly manipulated the perceived size of the hand by using a magnifying lens. We repeated the same basic design as in Experiment 2; however, instead of having participants make graspability judgments with their left versus right hand, participants made graspability judgments with their dominant hand, which was either magnified or not. We expected that magnifying the apparent size of the hand should also increase the perceived graspability of the hand. Therefore, if objects are scaled to the apparent action boundary for grasping, then objects should appear smaller when the hand is magnified than when it is not magnified because the objects measure as smaller on the larger perceptual ruler.

Method

Participants. Fifteen students (3 women) 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. All participants gave informed consent and had normal or corrected-to-normal vision.

Stimuli and apparatus. Participants were seated at the same table as used in Experiment 1. A magnifying box was constructed by using a sheet magnifier (3.5× magnification, 27.5 cm by 20 cm) that had legs on each corner that raised it 8.5 cm in height. The magnifying sheet comprised the top of the box and the sides of the box were covered with white felt. Looking inside the box from the top through the magnification sheet had the effect of making objects within the box appear larger. The same blocks that were used in Experiment 2 were used in this experiment. Also, the same laptop set up and size matching program used in Experiment 2 was used in this experiment except that participants used a mouse and clicked the left and right mouse key to manipulate the distance between the two white dots on the computer screen. The computer was on same stool but was always placed to the side of the participants' nondominant hands.

Procedure. The procedure was the same as Experiment 2 except for a few differences. First, participants always estimated their grasping ability with their dominant hand in both blocks and used their nondominant hand to manipulate the mouse to estimate object size. However, in one block of trials, participants' dominant hands were placed within the magnifying box, and participants were asked to estimate their grasping ability with their magnified hand. In the other block of trials, participants' hands were not inside the magnification box, but were placed in the same position on the table as in the other block. In this block, participants were asked to estimate their grasping ability with their unmagnified hand. As in Experiment 2, hand order was counterbalanced and block presentation was randomized.

Results and Discussion

Size estimates were transformed into ratios by dividing the estimated size by the actual size. The size ratios are a measure of accuracy and allowed for the comparison of estimates across different sizes. One participant was removed from the analysis for claiming that she could grasp all sizes of blocks and not following the research assistant's instructions about how the blocks were supposed to be grasped.

To test our original hypothesis that graspability would scale objects that could be grasped but not objects that were too big to be grasped, we performed separate analyses for size ratios that were within and outside of maximum grasp size. For size ratios within grasp, we performed a univariate ANOVA with block size and condition (magnified, unmagnified) as fixed factors, participant as a random factor, and size ratios as the dependent variable. Condition significantly affected perceived size. Participants perceived blocks as smaller when they made graspability judgments with respect to their magnified hand, $M = .87$, $SE = .008$, than to their unmagnified hand, $M = .92$, $SE = .01$, $F(1, 18.32) = 5.93$, $p = .03$, $\eta_p^2 = .25$ (see Figure 6). There was no interaction between size and condition, $p = .75$. As in Experiment 2, we found a significant effect of block size, $F(14, 179.46) = 5.00$, $p < .001$, $\eta_p^2 = .28$, with larger blocks being underestimated more than smaller blocks, see Figure 5.

For blocks outside of grasp, there was no effect of condition, $p = .27$, suggesting when outside of grasping ability, block size was perceived to be the same regardless of whether the hand was magnified or not (see Figure 6). The effect of block size was significant, $F(9, 94.40) = 2.38$, $p = .02$, $\eta_p^2 = .19$.

We find it interesting that when combining the data from Experiments 2 and 3, there is a significant correlation between participants mean size estimates for blocks within grasp and their maximum grasping ability, $r(28) = -.32$, $p = .05$ (see Figure 7a). This supports the action-based scaling hypothesis because the finding suggests that those with larger hands who are able to grasp larger blocks perceived the blocks to be smaller than those with

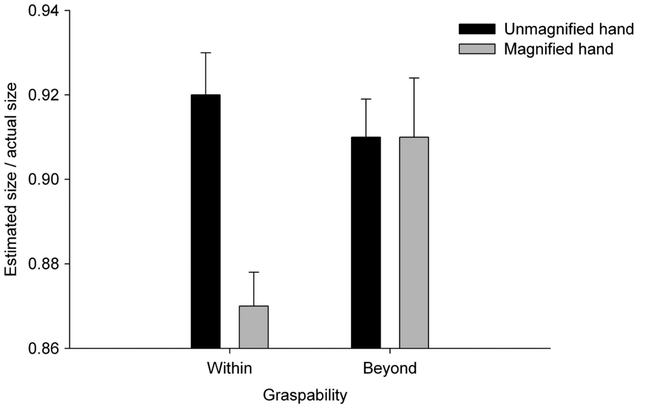

Figure 6. Results from size judgments in Experiment 3. Ratios of estimated size divided by actual size of the blocks is plotted as a function of whether the block was small enough to be grasped or not and whether participants intended to grasp with their visually magnified or viewed normally dominant hand. Error bars represent one standard error of the mean.

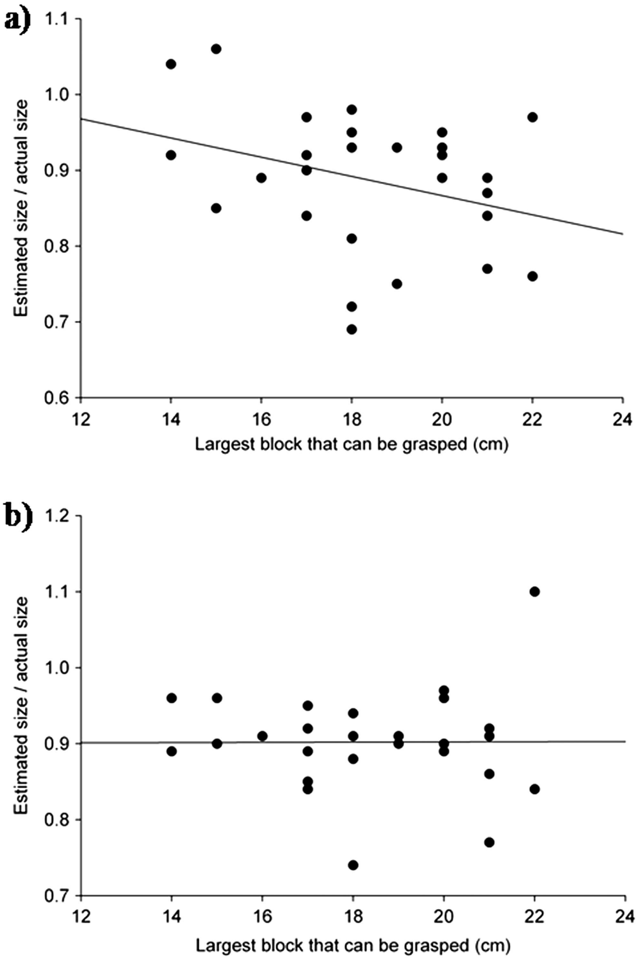

Figure 7. Results from size judgments collapsed across Experiments 2 and 3. Ratios of estimated size divided by actual size of the blocks is plotted as a function of grasping ability, which is measured as the largest block that can be grasped by each participant. (a) Perceived size across all blocks that are small enough to be graspable. (b) Perceived size across all blocks that are too big to be graspable. Each circle represents one or more participants' data.

smaller hands. However, as expected, there was no significant correlation between participants mean size estimates for blocks that were outside of their grasping ability, $p = .98$ (see Figure 7b).

General Discussion

These studies suggest that perceivers scale apparent extents of graspable objects using the apparent action boundary of their hands for grasping. In right-handed individuals, the right hand has a larger apparent action boundary for grasping than the left hand (Linkenauger, Witt, Bakdash et al., 2009). Objects held in the right hand were perceived to be smaller than objects held in the left hand. In a similar manner, right-handed individuals perceived graspable objects to be smaller when evaluated with respect to grasping with the right hand than when with their left hand. Finally, graspable objects were perceived as smaller when grasping with a visually magnified hand was relevant than when grasping with an unmagnified hand was relevant. None of these manipulations affected the apparent sizes of objects that were too large to be grasped. These findings suggest that the perceived sizes of graspable objects are scaled by the action capabilities of the hand relevant to the intended action, but only for objects that can be acted on.

To perceive the distances to and sizes of objects in the environment, optical information specifying extents must be scaled to some type of extent-appropriate metric. In these studies, we demonstrated that the perceived sizes of objects vary depending on the perceived action capabilities of the individual. We proposed that units used for scaling perceived extents can be based on the body and its action capabilities, and these findings support this notion. As the perceiver's grasping ability increased or decreased, the perceived sizes of graspable objects decreased or increased accordingly. Thus, the current results demonstrate that the body provides a scalar unit for the perception of size.

We presume that individuals use the functional morphology of their body as a "perceptual ruler" to transform visual angles specifying the spatial layout of the environment into extent appropriate, body-relevant metrics. The ruler that is selected depends on the action that is relevant to the task. When grasping is relevant, the action boundary for grasping is selected as the perceptual ruler. The length of the ruler depends on the perceiver's anticipated ability to perform the intended action. Given that right-handed people anticipate being able to grasp larger objects with the right relative to left hand (Linkenauger, Witt, Bakdash et al., 2009), the ruler associated with the right hand is expanded relative to the left hand. As a result, objects looked smaller when scaled by the expanded ruler associated with reaching with the right hand than when intending to reach with the left hand. In a similar manner, when the perceiver's hand was magnified, the associated ruler expanded, causing graspable objects to appear smaller.

Comparable findings also have been demonstrated on the perception of reachable extents. Enhancing perceivers' ability to reach by giving them a tool led to a decrease in apparent distance (Witt, in press-b; Witt & Proffitt, 2008; Witt et al., 2005). When wielding a tool, the perceptual ruler stretches to encompass the new maximum extent that one can reach. This expansion in the ruler that is used to scale distance leads to a compression in perceived distance. In other words, the same distance measures as closer on the expanded ruler. Likewise, decreasing a perceiver's ability to reach via difficult grasps, and therefore compressing the ruler, leads to an increase in apparent distance (Linkenauger, Witt, Stefanucci et al., 2009). The action boundary used to scale distances compressed when the reaching ability was impaired, so reachable objects appeared farther away.

More important, these studies revealed that the sizes of objects that are beyond one's perceived grasping ability were not influenced by manipulations of one's grasping ability. This suggests that perceiver's only scale the apparent sizes of objects to their grasping ability if the objects are perceived to be graspable. We presume that if the objects are of a size that surpasses the grasping ability of the hand, then grasping is no longer a relevant action that can be performed on the object; such objects are best scaled with an action boundary that can encompass its size, not graspability extent with a single hand.

As revealed by Experiment 3, this type of scaling is flexible. We found differences in scaling from merely magnifying the size of the hand, even when participants knew that the size of their hand had not actually changed. Although participants were told to estimate their action capabilities with the magnified hand, to find changes in perceptual scaling due to such a superficial change demonstrates the ability of the perceptual system to adapt to rapid changes in the body. This finding parallels other studies that have found that manipulating hand size via the rubber hand illusion can affect weight judgments (Haggard & Jundi, 2009), although haptically perceived objects reveal an opposite pattern such that objects feel bigger when the hand also feels bigger (Bruno & Bertamini, 2010; de Vignemont et al., 2005). Although we are not sure what causes seemingly opposite patterns for visual and haptic perception (Taylor-Clarke et al., 2004), it is reasonable that such scaling is also flexible. Our bodies are constantly changing as are the situational aspects of the environment in which we are interacting, and to succeed in our interactions, we must be able to adapt seamlessly to these changes. Supporting this notion, individuals are capable of detecting bodily changes and accurately adjusting their judgments of their action capabilities due to these changes even with limited experience or feedback (Mark, 1987; Ramonzoni, Riley, Shockley, & Davis, 2008). Furthermore, there has been a great deal of research in neuroimaging and single cell recording that has shown that neurons that code for objects within the action capabilities of the arms and hands change their receptive fields depending on changes in thesaction capabilities of the arms and hands (Gentilucci et al., 1988; Graziano & Gross, 1995; Iriki, Tanaka, & Iwamura, 1996). This type of flexibility may or may not be limited to only certain aspects of the perceivers' morphology that typically undergo changes or it could be a product of the perceptual system. However, this is a question that goes beyond the scope of this paper, but would be interesting to address in the future.

Although this action-scaling approach can account for the perception of sizes and distances on which we can act, it fails to account for the perceptions of spatial layout on which we cannot act. As of yet, it is unknown how we scale the perceptions of distances and sizes on which we cannot possibly act (such as the size of the moon). It is likely that things that are too small or large to be acted on are scaled in a completely different manner. Logically, it does seem that aspects of the world that cannot be acted on are scaled differently. For example, it is likely that the moon is perceived to be the same size regardless if you are a giant, human, or Lilliputian; whereas, a can of soda would appear drastically different across the three. It is also possible that these extents are not scaled at all, and resultantly, perceivers do not have definite perception of these extents. Does the moon appear to be as big as a basketball, a VW Beatle, a house, or a quarter of the earth's diameter?

The notion of body scaling in perception was central to the ecological approach proposed by Gibson (1979). Gibson introduced the notion of *affordances*, which are defined as "what the environment offers the animal, what it provides or furnishes, either for ill or for good" (p. 127). Essentially, the concept of an affordance is dependent on the relationship between the environment and the animal. For example, the sky affords flying for a bird, whereas for a human, the sky affords falling. Any aspect of the environment only affords a certain action if the organism is physically capable of the performing that action. Hence, the presence of affordances is reliant on the properties of the environment and the capabilities of the individual. Gibson proposed that affordances are perceived directly. If the perceived spatial layout is scaled by using the action capabilities of the body as units, then affordances can be perceived through the perception of apparent distance and size. By grounding apparent distance to the perceiver's capability to perform the intended action, the perceived extent looks longer or shorter depending on how efficiently the action can be performed or whether the action is possible.

One concern related to this line of research is that findings of this kind might be the result of demand characteristics. The findings in these studies provide evidence that is counter to this possibility because they demonstrate specificity. Grasping ability only influenced reports of perceived size for objects that could be grasped, but not objects that were too big to be grasped. It seems unlikely that participants not only correctly guessed that the differences in the relevant hand should affect perceived size, but additionally only for objects that could be grasped. Thus it is difficult to attribute the resulting effects on size perception to demand characteristics or any general right/left bias, which would have affected both objects within and outside of grasp. In addition, we found that individuals that could grasp larger objects saw objects within their grasp to be smaller than individuals with lesser grasping abilities. However, there was no relationship between grasping ability and size perception for objects that were too large to be grasped. The presence of these individual differences also reduces the possibility that our findings are a result of demand characteristics.

The present studies examined the role of the body in perceptual scaling and found support for the view that the capabilities of the body are used to scale apparent sizes. Here we show that the perception of spatial layout is not independent of the body and its action capabilities, but instead uses these capabilities as perceptual rulers. Consequently, the perception of spatial layout is tailored to the individual, which allows individuals to perceive directly what the environment affords for them specifically. The perceived sizes of objects are seen in terms of the actions that the object affords.

References

Berti, A., & Frassinetti, F. (2000). When far becomes near: Remapping of space by tool use. *Journal of Cognitive Neuroscience, 12,* 415–420.

Bingham, G. P. (1993). Perceiving the size of trees: Form as information about scale. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 1139–1161.

Bruno, N., & Bertamini, M. (2010). Haptic perception after a change in hand size. *Neuropsychologia, 48,* 1853–1856.

Cowey, A., Small, M., & Ellis, S. (1994). Left-visuo spatial neglect can be worse in far than in near space. *Neuropschyologia, 32,* 1059–1066.

de Vignemont, F., Ehrsson, H. H., & Haggard, P. (2005). Bodily illusions modulate tactile perception. *Current Biology, 15,* 1286–1290.

Dixon, M. W., Wraga, M., Proffitt, D. R., & Williams, G. C. (2000). Eye height scaling of absolute size in immersive and nonimmersive displays. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 582–593.

Fajen, B. R. (2007). Affordance-based control of visually guided action. *Ecological Psychology. 19,* 383–410.

Fink, P. W., Foo, P. S., & Warren, W. H. (2009). Catching fly balls in virtual reality: A critical test of the outfielder problem. *Journal of Vision, 9,* 1–8.

Gentilucci, M., Fogassi, L., Luppino, G., Matelli, M., Camarda, R., &

Rizzolatti, G. (1988). Functional organization of inferior area 6 in the macaque monkey. *Experimental Brain Research, 71,* 475–490.

Gibson, J. J. (1979). *The ecological approach to visual perception.* Boston, MA: Houghton Mifflin.

Graziano, M. S. A., & Gross, C. G. (1995). The representation of extrapersonal space: A possible role for bimodal visual-tactile neurons. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 1021–1034). Cambridge, MA: MIT Press.

Hach, S., & Schütz-Bosbach, S. (2010). Sinstral's upper hand: Evidence for handedness differences in the representation of body space. *Brain & Cognition, 72,* 408–418.

Haggard, P., & Jundi, S. (2009). Rubber hand illusions and size-weight illusions: Self-representation modulates representation of external objects. *Perception, 38,* 1796–1803.

Halligan, P. W., & Marshall, J. C. (1991). Left neglect in near but not far space in man. *Nature, 350,* 498–500.

Iriki, A., Tanaka, M., & Iwamura, Y. (1996). Coding of modified body schema during tool use by macaque postcentral neurones. *NeuroReport, 7,* 2325–2330.

Land, M. F. (1992). Visual tracking and pursuit: Humans and arthrodpods compared. *Journal of Insect Physiology, 38,* 939–951.

Linkenauger, S. A., Ramenzoni, V. C., & Proffitt, D. R. (2010). Illusory shrinkage and growth: Body-based rescaling affects the perception of size. *Psychological Science, 21,* 1318–1325.

Linkenauger, S. A., Witt, J. K., Bakdash, J. Z., Stefanucci, J. K., & Proffitt, D. R. (2009). Asymmetrical body perception: A possible role for neural body representations. *Psychological Science, 20,* 1373–1380.

Linkenauger, S. A., Witt, J. K., Stefanucci, J. K., Bakdash, J. Z., & Proffitt, D. R. (2009). The effect of handedness and reachability on perceived distance. *Journal of Experimental Psychology: Human Perception and Performance, 35,* 1649–1660.

Linkenauger, S. A., Zadra, J., Witt, J. K., & Proffitt, D. R. (2011). The effect of effort to reach and grasp on the distance to targets in near space. [Manuscript in preparation]

Longo, M. R., & Lourenco, S. F. (2007). Space perception and body morphology: Extent of near space scales with arm length. *Experimental Brain Research, 177,* 285–290.

Lourenco, S. F., & Longo, M. R. (2009). The plasticity of near space: Evidence for contraction. *Cognition, 112,* 451–456.

Mark, L. S. (1987). Eye-height scaled information about affordances: A study of sitting and stair climbing. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 361–370.

McBeath, M., Shaffer, D., & Kaiser, M. (1995). How baseball outfielders determine where to run to catch fly balls. *Science, 268,* 569–573.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9,* 97–113.

Oudejans, R. R. D., Michaels, C. F., Bakker, F. C., & Dolné, M. A. (1996). The relevance of action in perceiving affordances: Perception of catchableness of fly balls. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 879–891.

Proffitt, D. R. (2006). Embodied perception and the economy of action. *Perspectives on Psychological Science, 1,* 110–122.

Proffitt, D. R. (2008). An action-specific approach to spatial perception. In R. L. Klatzky, M. Behrmann, & B. MacWhinney (Eds.), *Embodiment, ego-space, and action* (pp. 179–202). Mahwah, NJ: Erlbaum.

Proffitt, D. R., Bhalla, M., Gossweiler, R., & Midgett, J. (1995). Perceiving geographical slant. *Psychonomic Bulletin & Review, 2*(4), 409–428.

Proffitt, D. R., Stefanucci, J., Banton, T., & Epstein, W. (2003). The role of effort in distance perception. *Psychological Science, 14,* 106–113.

Ramenzoni, V. C., Riley, M. A., Shockley, K., & Davis, T. (2008). Carrying the height of the world on your ankles: Encumbering observers reduces estimates of how high an actor can jump. *The Quarterly Journal of Experimental Psychology, 61,* 1487–1495.

Sampaio, E., & Chokron, S. (1992). Pseudoneglect and reversed pseudoneglect among left-handers and right-handers. *Neuropsychologia, 30,* 797–805.

Sedgwick, A. (1973). *The visible horizon: A potential source of visual information for the perception of size and distance.* Unpublished doctoral dissertation, Cornell University, Ithaca, NY.

Sörös, P., Knecht, S., Imai, T., Gürtler, S., Lütkenhöner, B., Ringelstein, E. B., & Henningsen, H. (1999). Cortical asymmetries of the human somatosensory hand representation in right- and left-handers. *Neuroscience Letters, 271,* 89–92.

Taylor-Clark, M., Jacobsen, P., & Haggard, P. (2004). Keeping the world a constant size: Object constancy in human touch. *Nature Neuroscience, 7,* 219–220.

Tucker, M., & Ellis, R. (1998). On the relations between seen objects and components of potential actions. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 830–846.

Van der Kamp, J., Oudejans, R., & Savelsbergh, G. (2003). The development and learning of the visual control of movement: An ecological perspective. *Infant Behavior and Development, 26,* 495–515.

Warren, W. H., & Whang, S. (1987). Visual guidance of walking through apertures: Body-based information for affordance. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 371–383.

Wilson, F. R. (1998). *The hand: How its use shapes the brain, language, and human culture.* New York, NY: Random House.

Witt, J. K. (2011a). Action's effect on perception. *Current Directions in Psychological Science, 20,* 201–206.

Witt, J. K. (2011b). Tool use influences perceived shape and parallelism: Indirect measures of perceived distance. *Journal of Experimental Psychology: Human Perception and Performance*. Published Online First: April 15.

Witt, J. K., & Proffitt, D. R. (2008). Action-specific influences on distance perception: A role for motor simulation. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 1479–1492.

Witt, J. K., Proffitt, D. R., & Epstein, W. (2004). Perceiving distance: A role of effort and intent. *Perception, 33,* 570–590.

Witt, J. K., Proffitt, D. R., & Epstein, W. (2005). Tool use affects perceived distance but only when you intend to use it. *Journal of Experimental Psychology: Human Perception and Performance, 31,* 880–888.

Wraga, M. (1999a). The role of eye height in perceiving affordances and object dimensions. *Perception & Psychophysics, 61,* 490–507.

Wraga, M. (1999b). Using eye height in different postures to scale the heights of objects. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 518–530.

Wraga, M., & Proffitt, D. R. (2000). Mapping the zone of eye-height utility for seated and standing observers. *Perception, 29,* 1361–83.

Received April 20, 2010
Revision received December 15, 2010
Accepted December 28, 2010 ■