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Perceiving Affordances for Fitting Through Apertures

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Affordances—possibilities for action—are constrained by the match between actors and their environments. For motor decisions to be adaptive, affordances must be detected accurately. Three experiments examined the correspondence between motor decisions and affordances as participants reached through apertures of varying size. A psychophysical procedure was used to estimate an affordance threshold for each participant (smallest aperture they could fit their hand through on 50% of trials), and motor decisions were assessed relative to affordance thresholds. Experiment 1 showed that participants scale motor decisions to hand size, and motor decisions and affordance thresholds are reliable over two blocked protocols. Experiment 2 examined the effects of habitual practice: Motor decisions were equally accurate when reaching with the more practiced dominant hand and less practiced nondominant hand. Experiment 3 showed that participants recalibrate motor decisions to take changing body dimensions into account: Motor decisions while wearing a hand-enlarging prosthesis were similar to motor decisions without the prosthesis when data were normalized to affordance thresholds. Across experiments, errors in decisions to reach through too-small apertures were likely due to low penalty for error.

Keywords: affordance, aperture, perception-action, psychophysics, reaching

Possibilities for motor action—or what Gibson (1979) termed *affordances*—depend on the match between environmental conditions and actors' physical characteristics (e.g., Adolph & Berger, 2006). The affordance concept is central to motor control because adaptive motor decisions must be based on actual possibilities for action (Gibson, 1979; Warren, 1984). On a perception-action account of motor control, observers must perceive affordances (or lack of them) with sufficient accuracy to select the appropriate movements and modify them appropriately to suit the constraints of the current situation. The perceptual problem is not trivial. Affordances can change from moment to moment due to variations in the environment and in actors' bodies and propensities. Perceiving affordances is an ongoing process of gauging the relationship between the current status of the body and the relevant environmental properties.

Navigating Through Apertures

A good example of coping with changing affordances is navigating various body parts through apertures. Fitting through an aperture—steering a path along a crowded sidewalk, squeezing between seats in a lecture hall, reaching the hand into the slot of a vending machine—is constrained by the dimensions and shape of the relevant body parts relative to the dimensions and shape of the opening. Visual guidance is critical for comparing body dimensions with the size of the opening and for determining how best to orient the relevant body parts relative to their shape. Indeed, even frogs and toads use visual information for guiding locomotion through apertures. They readily hop through large apertures for mealworms but detour around the obstacle when the aperture size approaches the size of their heads (Ingle & Cook, 1977; Lock & Collett, 1980).

Perceptual errors can be troublesome or dangerous (e.g., bumping into a pedestrian, bruising a hip, scraping your hand). For young children, entrapment of the head and hands is a serious cause of accidental injury (Tinsworth & McDonald, 2001). Children may push their head between the spindles of a crib, staircase, or piece of playground equipment, or wedge their hand into an impossibly small opening. Despite the costs associated with erroneous motor decisions, several studies indicated that even adults might fail to leave a sufficient safety margin and attempt to fit their bodies through impossibly small apertures. For example, participants slightly misjudged their ability to pass through doorways without becoming wedged while walking normally (Gordon & Rosenblum, 2004; Warren & Whang, 1987), walking while carrying a horizontal pole (Wagman & Taylor, 2005), rolling in a wheelchair (Flascher, Shaw, Kader, & Aromin, 1995; Higuchi, Takada, Matsuura, & Imanaka, 2004), and walking on a treadmill through a virtual oscillating aperture projected on a screen (Buekers, Montagne, de Rugy, & Laurent, 1999; Montagne, Buekers, de Rugy, Camachon, & Laurent, 2002). Similarly, observers slightly misjudged their ability to pass under an overhead barrier with sufficient clearance to walk without banging their heads (Gordon & Rosenblum, 2004).

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Current Studies

In a series of experiments, we examined adults' ability to gauge affordances for navigating their hands through apertures of varying size under various conditions. We chose a manual aperture task for its everyday relevance: Fitting the hand through apertures is a common motor action that requires precise planning and execution. Moreover, because both the aperture and the hand are in view while reaching through apertures, visual feedback can guide people's motor decisions in the course of the reach.

The primary aim of the current research was to assess the correspondence between actual affordances and participants' motor decisions for reaching through apertures. Using a psychophysical method, we estimated affordance thresholds based on a 50% success rate for apertures that they attempted. With the exception of Warren and Whang (1987), affordances were estimated on the basis of biomechanical models. Affordances for walking through doorways were based on measures of participants' static shoulder width relative to aperture size (Gordon & Rosenblum, 2004; Higuchi et al., 2004); affordances for rolling through doorways in a wheelchair were based on the dimensions of the wheelchair relative to aperture size (Flascher et al., 1995; Higuchi et al., 2004). However, adults' shoulders can be rotated, compressed, and contracted; elbows and hands are likely to protrude beyond the dimensions of the wheelchair; and both walkers and wheelchair riders must cope with the exigencies of steering.

Therefore, in the current work, we assessed affordances on the basis of participants' actual behaviors in the aperture task rather than on body dimensions. Using a psychophysical method, we established affordance thresholds on the basis of estimates of the 50% success rate for apertures on which they attempted. Similar to previous aperture research, we also examined the relationship between participants' hand measurements and affordance thresholds. Past work showed that participants' largest relevant dimension is related to affordances for navigating through apertures varying in width; for example, the width of participants' shoulders and the dimensions of a wheelchair were related to affordances for passage (Buekers et al., 1999; Flascher et al., 1995; Gordon & Rosenblum, 2004; Higuchi et al., 2004; Montagne et al., 2002; Warren & Whang, 1987). However, in the current study we measured participants' hands while they minimized their hand size by squeezing their fingers tightly together, on the assumption that this scrunched hand width would more closely approximate participants' hand size as they attempted to fit through the apertures. Adults' hand size varies widely. Thus, participants with narrower hand widths should be able to fit their hands through smaller apertures.

A second aim was to assess two components of participants' motor decisions. Like the affordance threshold, we indexed motor decisions on the basis of participants' behaviors in the task—that is, their attempts to reach through each opening relative to their affordance threshold. Motor decisions include the ability to discriminate the displays (i.e., visual sensitivity to the information for the affordance) coupled with a response criterion (i.e., participants' willingness to err). A precipitous drop in the motor decision function on closely spaced aperture increments would provide evidence for highly sensitive visual discrimination. Scaling motor decisions to actual ability would be evidenced by decreased attempts in the region surrounding and below the affordance threshold. The displacement of the motor decision function toward apertures larger or smaller than the affordance threshold reflects participants' response criterion (conservative or liberal, respectively).

A final aim was to describe the type of exploratory behaviors and navigation strategies participants displayed when fitting their hand through the apertures. In most previous studies, participants did not perform the target action; instead, participants judged their ability to pass through the apertures while viewing them from a distance. In addition, task definitions were highly constrained so that participants' behaviors were more stilted and constricted than in everyday life. For example, Wagman and Taylor (2005) asked participants to judge the widest aperture they could walk through while holding a horizontal pole at right angles from their hips and keeping their bodies straight. Participants were not allowed to walk around with the pole beforehand or while they gave their judgments. Occluder goggles also prevented participants from visually comparing the size of the pole with the size of the aperture. In everyday life, people are likely to explore affordances with a range of visual and motor behaviors and to produce a range of strategies for fitting their bodies through apertures while carrying large objects. Seeing the hand against the aperture, in particular, can provide rich visual information about which strategies to avoid and which to adopt. Rather than imposing stringent task constraints as in previous work, we allowed participants to explore the apertures visually and manually and to attempt to fit their hand through the apertures using any strategy they deemed feasible.

Experiment 1: Varying Aperture Size

In Experiment 1, we assessed how accurately participants gauged affordances for fitting their hand through apertures, and we verified the reliability of the psychophysical procedure for obtaining estimates of motor decisions and affordance thresholds across two blocked protocols. To determine whether fatigue or motivation would affect affordance thresholds or motor decisions, participants completed two identical conditions in which they navigated their dominant hand through apertures to retrieve small targets. It was necessary to establish the reliability of the testing procedure because the design for Experiments 2 and 3 required participants to complete two blocked conditions within a single session. In previous work with infants, despite lengthy protocols, estimates of affordance thresholds and motor decisions were nearly identical across two conditions (Adolph & Avolio, 2000). If reliable in the current experiment, then participants should show similar affordance thresholds and motor decisions between the conditions. To determine the relationship between affordance thresholds and hand dimensions, we measured the width of participants' hands.

Method

Participants. Fourteen adults (8 women, 6 men) were recruited from an introductory psychology subject pool and participated in exchange for course credit. Participants' mean age was 21.51 years (range = 18.28 to 35.46), and they reported their race as White ($n = 10$), Asian ($n = 2$), Hispanic, ($n = 1$), and other ($n = 1$). Twelve participants were right-handed and two were left-handed. Two additional participants were excluded from data analyses due to experimenter error.

Aperture apparatus. As shown in Figure 1, participants sat on a swiveling office chair in front of an adjustable aperture apparatus. The apparatus consisted of a wooden frame (111.44 cm × 84.60 cm) housing two 0.50-cm thick fiberboard panels with right triangles cut from their inner edge. The panels were offset to allow them to overlap like a camera shutter so that the total depth of the aperture was 1.00 cm. An aperture operator moved a handle on the outer edge of either panel to create a diamond-shaped opening with four equal sides. When closed, each side of the aperture was 0 cm long; when the panels were pulled completely apart, each side of the aperture was 40 cm long. The size of the aperture could be finely adjusted in 0.10-cm increments using a knob on top of the wooden frame. Calibration markings along the top and back of the apparatus indicated the length of one side of the aperture. A small camera attached to the apparatus magnified the calibration markings on a monitor so that the experimenter could correctly set the aperture size with millimeter precision. The center of the aperture remained fixed at 42.30 cm from the top and bottom edge of the frame. Sufficient clearance (75.40 cm) beneath the frame allowed participants to easily swivel their chair with their knees beneath the apparatus. Small targets (candies and snacks less than 2 cm in size) were placed in the center of the aperture on the end of a long, flat stick (91 cm × 2.54 cm).

Procedure. Participants were tested in a single session lasting 60 to 90 min. At the beginning of the session, the experimenter determined participants' dominant hand (the hand used for writing and playing sports) through a short interview. Participants removed all rings, watches, and bracelets. Next, the experimenter measured the length of participants' dominant hand, from the tip of the middle finger to the flexor *pollicis brevis* muscle (base of thumb), to determine the distance to place the target from the edge of the aperture. Pilot testing showed that this target distance required participants to fit the widest part of their hand through the aperture (from the second to fifth knuckles of all four fingers with the thumb folded in toward the palm). Then the experimenter adjusted the height of the chair so that participants' eyes were level with the center of the aperture. Pilot testing showed that this height enabled participants to see the target through the smallest apertures.

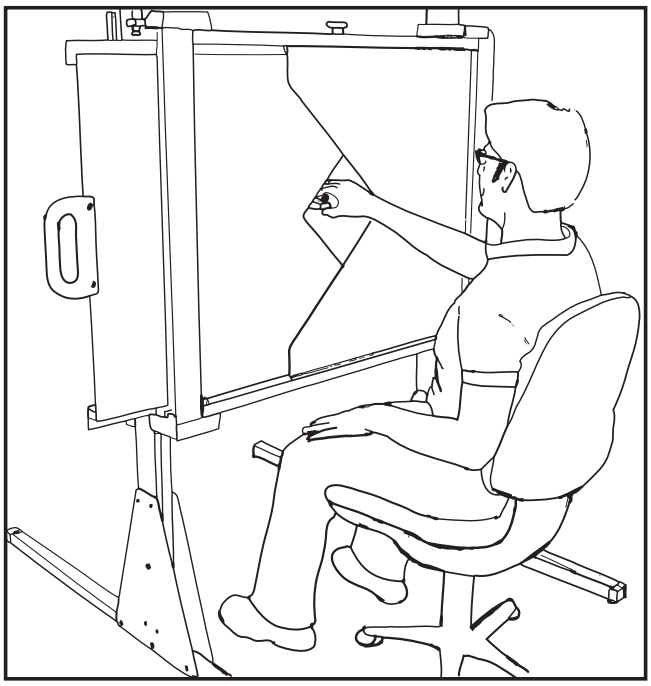

Figure 1. Adjustable aperture apparatus. Participants sat on a swivel chair and reached through the aperture for a target. Between trials, participants turned away from the aperture while an experimenter adjusted the size of the aperture by pulling the handle.

Two experimenters were required to run the reaching trials: a computer operator who ran a customized software program that suggested the aperture size for each trial and an aperture operator who adjusted the aperture to the appropriate size, replaced snacks at the specified target distance, and released participants' hands when they became entrapped in the aperture. After the aperture size flashed on a screen, the aperture operator adjusted it accordingly. The screen was hidden from participants' view. Participants faced away from the apparatus with their hands in their laps while the aperture was adjusted to the appropriate size. Participants were told that their task was to retrieve as much candy as possible and that they should reach their hand through the aperture if they thought it would fit. They were told that they would keep all of the candy that they retrieved. At the experimenter's prompt, participants swiveled to face the apparatus and decided whether to reach with their dominant hand. The computer operator timed 5 s for participants to make a decision.

Pilot testing showed that participants spontaneously produced a range of exploratory and reaching behaviors. They sometimes lifted their hand from their lap, brought it up to the aperture, and then replaced it without touching the aperture. They tentatively inserted their fingertips into the aperture before returning their hand to their lap. Sometimes they traced the perimeter of the aperture with their index finger. These types of behaviors appeared to reflect information-gathering functions rather than an attempt to fit their hand through the aperture. In contrast, shoving the fingers through the aperture until they became firmly wedged appeared to reflect attempts to retrieve the target. Indeed, in order to touch the target, participants had to insert their hand up to the base of their thumb through the aperture. Participants sometimes inserted two or more fingers through the aperture, then retracted their hand, then reinserted it. These reinsertions appeared to reflect a correction of a failed attempt to grasp the target.

On the basis of the pilot data, the outcome of each trial was scored online as a success (touched the target without retracting and reinserting the hand), failure (inserted hand past the second knuckle of the middle finger on the target side of the opening but failed to contact the target), or refusal to reach (avoided reaching for 5 s or did not insert hand past the second knuckle of the middle finger). Retractions and reinsertions were counted as failures if the initial reach involved insertion past the second knuckle of the middle finger. We defined the *motor decision function* as the ratio of attempted reaches to the total number of trials [(S + F)/(S + F + R)] as a function of aperture size. Similarly, we defined the *affordance function* as the ratio of successful reaches to the total number of attempted reaches [S/(S + F)] as a function of aperture size. The motor decision function indicates the rate at which participants attempted to fit through openings—participants' perception of affordances. The affordance function indicates how

successful participants were at fitting through the openings they attempted—the actual possibilities for action.

Cumulative normal distributions were fit by maximum likelihood (Berger, 1985) to both the motor decision and affordance functions while data were collected. For example, the affordance function was characterized by the affordance threshold (the opening size at which participants succeeded on 50% of trials) and the slope (i.e., the standard deviation). Note that only successes and failures were relevant for estimating affordance thresholds. In principle, participants might not produce failures. In that event, at the end of the session, the computer operator would ask participants to attempt to fit their hand through a range of smaller apertures until they failed a sufficient number of times for a consistent estimate of the affordance threshold. These trials would not be used to analyze participants' motor decisions. However, in practice every participant produced multiple failures so that affordance functions were fit in the course of determining motor decision functions. The average number of successes and failures in the region surrounding the affordance threshold was similar ($M = 5.1$ and 4.9, for successes and failures, respectively).

Trials began with a short series of predetermined intervals to show participants that some apertures would be clearly possible, some clearly impossible, and some indeterminate. After this, an adaptive algorithm was used to determine the increment for the next trial: A random aperture size was chosen within three standard deviations of the current estimate of the affordance threshold. This allowed us to quickly determine the affordance threshold using a limited number of trials. To maintain participants' motivation, the experimenter occasionally overrode the increment suggested by the program and presented the subject with a large aperture for an easy success or a very small aperture for a clear refusal.

To examine whether the estimate of the affordance threshold was stable, two identical blocks of approximately 60 trials were run. Participants took a 5-min break between blocks to relax their arms and hands. A cumulative normal distribution was fit separately to the data from each block, and the threshold and slope parameters were computed using a parametric bootstrap (Efron & Tibshirani, 1993; Maloney, 1990; Wichmann & Hill, 2001a, 2001b).

At the end of the session, the experimenter measured hand width of participants' dominant hand by placing a caliper at the second and fifth *metacarpophalangeal* joints while participants squeezed their fingers closely together as if trying to fit through the aperture. The measurement was obtained twice and then averaged for analysis.

Four video cameras recorded participants' actions. One camera directly above the aperture apparatus recorded the calibration markings. A second camera on the left side of the swivel chair recorded participants' entire body to determine when they turned to face the aperture at the start of each trial and when they turned away at the end of the trial. A third camera on the left side of the apparatus recorded participants' arm and hand movements during their approach to the aperture. A fourth camera to the right of the aperture recorded participants' movements on the target side of the apparatus. The four camera views were mixed onto a single video frame so that they could be viewed simultaneously for later coding.

Data coding. A primary coder rescored trial outcomes as a success, failure, or refusal from video recordings using a computerized video coding program, MacSHAPA (www.openshapa.org) that records the frequencies of specific behaviors (Sanderson et al., 1994). The primary coder also scored participants' exploratory behavior and reaching strategies for the initial reach: full hand reaching through the aperture with all fingers extended, inserting all of the finger tips before retracting the hand, inserting only the fingertips of the index and/or middle fingers or tracing the perimeter of the aperture with a single fingertip, lifting the hand to the aperture but withdrawing the arm without attempting to reach, and simply saying "no" without moving the hand. On trials in which participants attempted to fit their hand through the apertures, the primary coder scored the orientation of the participant's hand from the point at which the tip of the finger entered the aperture until it touched the target or retracted. There were five possible orientations: palm down, palm up, thumb up and palm sideways, thumb down and palm sideways, and wrist twisted upward. A secondary coder scored 25% of each participant's trials. Coders agreed on 99.2% of trials for outcome ($\kappa = .99$, $p < .001$), 98.7% of trials for reaching strategy ($\kappa = .98$, $p < .001$), and 97.1% of trials for orientation ($\kappa = .91$, $p < .001$). All discrepancies were resolved through discussion. Affordance thresholds were then recalculated using the computer program bootstrap.

Results and Discussion

Affordance thresholds. Figure 2A shows the proportion of successful attempts for one participant in one condition and the affordance function fitted to the data. The dashed line in the figure denotes the affordance threshold for this condition. Similar to this example, across conditions and participants, the slope of the affordance function tended to be relatively steep. That is, possibilities for manual navigation through the aperture transitioned sharply from possible to impossible around the affordance threshold. The distance covered along the x axis by the inflection of the affordance function (between .999 and .001) was relatively small in both conditions (Condition 1: $M = 0.38$ cm, $SD = 0.44$; Condition 2: $M = 0.32$ cm, $SD = 0.32$), $t(13) = 0.44$, $p = .67$.

As shown in Figure 3A, some participants could squeeze their hand through small apertures, and some participants could only fit their hand through large apertures, highlighting the importance of normalizing motor decisions relative to each person's ability. Affordance thresholds ranged from 4.87 cm to 7.76 cm. The mean and standard deviation of the affordance thresholds were very similar across the two blocked protocols (Condition 1: $M = 5.97$ cm, $SD = .64$; Condition 2: $M = 5.92$ cm, $SD = 0.69$), $t(13) = 1.08$, $p = .30$, suggesting that estimates of the affordance thresholds were reliable across the two conditions. Moreover, the average difference between conditions for individual participants was only -0.004 cm (range $= -0.25$ cm to 0.25 cm), and affordance thresholds were highly correlated between the two protocols, $r(14) = .97$, $p < .001$. Only 2 participants had affordance thresholds that differed by 0.25 cm between conditions.

Table 1 shows the width for participants' dominant hands in the scrunched position. Hand width was correlated with the affordance threshold for both Conditions 1 and 2, attesting to the validity of the threshold estimates derived from the psychophysical procedure, $r(13) = .73$, $p = .004$, and $r(13) = .74$, $p = .004$, respectively. Presumably, the correlation between hand width and affordance thresholds was not perfect because participants differed in

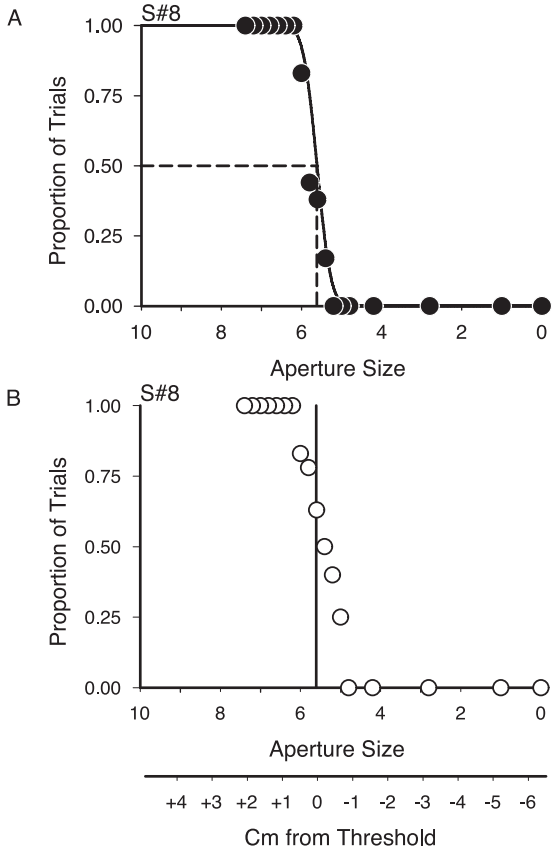

Figure 2. (A) Proportion of successful reaches [S/(S + F)] for S#8 in one condition plotted by absolute aperture size, overlaid with the affordance function fitted to the success rate. The horizontal dashed line denotes 50% success, and the vertical dashed line denotes the aperture size at the 50% success rate (affordance threshold). (B) Proportion of attempted reaches for S#8 plotted by absolute aperture size and normalized to the affordance threshold (lower axis). Solid vertical line denotes the affordance threshold.

how small they could contract their hands, in their willingness to press their hands through tight apertures, and in their strategies for navigating their hands through the apertures.

Motor decisions. Motor decision functions were fit to the probability of attempts [(S + F)/(S + F + R)] for each participant using the customized software program. Compared with the affordance function, the slope of the motor decision function—the distance covered along the *x* axis by the inflection of the motor decision function (between .999 and .001)—showed a wider range across conditions and participants. This distance was similar across conditions (Condition 1: $M = 1.94$ cm, $SD = 1.10$; Condition 2: $M = 1.97$ cm, $SD = 1.02$), $t(13) = 1.34$, $p = .20$. The distance covered by the inflection of the motor decision function was larger than the distance covered by the inflection of the affordance function [Condition 1: $t(13) = -5.17$, $p < .001$; Condition 2: $t(13) = -5.94$, $p < .001$], indicating that decisions were less consistent than actual abilities. However, the fact that participants' responses were graded over the 1.97-cm distance of the function's inflection reflects finely tuned visual discriminations based on tiny 2-mm increments in aperture size.

To facilitate comparisons across participants and aperture sizes, motor decisions—attempts to reach—were normalized to each participant's affordance threshold in each condition (shown in Figure 2B for one participant). Note that the online procedure ensured multiple trials at each 0.20-cm increment in aperture size. For each participant, we clustered responses into nine aperture groups relative to the affordance threshold. Each group spanned across a small range of apertures: affordance threshold (midpoint at 0 cm) and smaller or larger than affordance threshold (±0.50 cm and ±1.05 cm). Two data groups combined responses across a larger span of aperture sizes, also described by their midpoints (±2.20 cm), and two data groups included all larger and smaller aperture sizes (±3.00 cm). Thus, passable apertures are represented by positive numbers on the *x* axis to the left of the affordance threshold, and impassable apertures are represented by negative numbers to the right of the affordance threshold.

As shown by the overlapping motor decision curves in Figure 4A, attempts to reach were similar in the two conditions, indicating that participants' motor decisions remained consistent over two lengthy blocked experimental conditions. Most important, motor decisions appeared sensitive to the actual possibilities for action. Attempts were high on apertures larger than the threshold (e.g., $M = .98$ at the +0.50-cm aperture) and decreased sharply on apertures smaller than threshold (e.g., $M = .42$ at the −0.50-cm aperture). A 2 (gender) × 2 (condition) × 9 (aperture group) repeated measures ANOVA on attempts to reach revealed only a main effect for aperture group, $F(8, 88) = 181.51$, $p < .01$, partial $\eta^2 = .94$, confirming that participants scaled their motor decisions in line with relative aperture size. Trend analyses revealed linear effects, $F(1, 11) = 2{,}875.64$, $p = .001$, partial $\eta^2 = .99$, and quadratic effects, $F(1, 11) = 26.75$, $p = .001$, partial $\eta^2 = .71$, for motor decisions. Inspection of individual data revealed that 8 participants matched their motor decisions to their affordance thresholds; that is, their attempts to reach sharply decreased on apertures smaller than their affordance threshold. The remaining 6 participants slightly misjudged their abilities by attempting to fit through apertures that were slightly smaller than their affordance thresholds.

In contrast to previous work in which tasks were highly constrained, participants were allowed to solve the problem of passing through apertures however they liked. On successful trials, participants reached smoothly without touching the sides of the aperture or they pressed their hand through the aperture by compressing and/or twisting their hand. On failure trials, participants sometimes attempted to reach and then withdrew their hand or wedged their hand so tightly that the experimenter had to release the aperture to allow them to remove their hand. Most participants (10/14) always started their approach to the aperture with their hand palm down, presumably in anticipation of grasping the target (Figure 5, top row). The other 4 participants occasionally attempted to fit their hand through the opening with their palm sideways and thumb facing up, and with their palm sideways but their thumb facing down. With the palm sideways strategies, participants had to change the orientation of their hand to retrieve the target. Palm sideways strategies were most frequent for apertures surrounding the affordance threshold.

On refusal trials, participants showed a range of information-gathering behaviors (Figure 6, top row). Most commonly, they

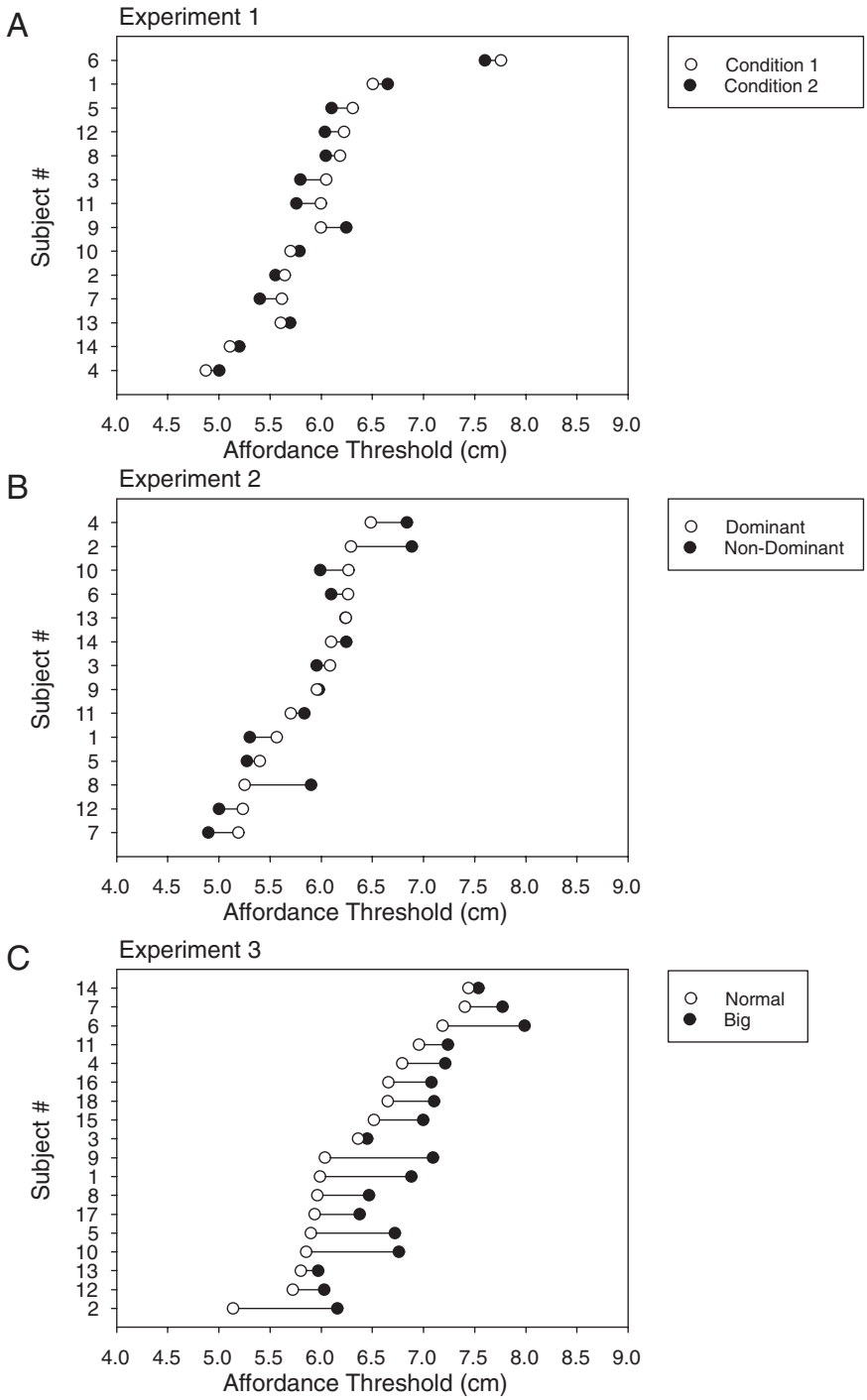

Figure 3. Individual affordance thresholds in (A) Experiment 1 for the first and second conditions, (B) Experiment 2 for dominant and non-dominant hands, and (C) Experiment 3 for normal hand and big hand conditions.

turned toward the aperture and said "no" without moving their hand, as if their decisions were based solely on visual information for the aperture. Sometimes they lifted their hand and held it up in front of the aperture, as if visually comparing their hand size with the aperture size. On other trials, they inserted their fingertips into the aperture as if to gain a clearer perspective of their hand size relative to the aperture size. Least frequently, they formed their hand into a point and inserted one or two fingertips into the aperture; this gesture may have reflected a compulsion to touch the aperture rather than exploration of the aperture size. Note, less than

Table 1
Participants' Mean Scrunched Hand Width

	Experiment 1	Experiment 2		Experiment 3	
Hand width	Dominant hand	Dominant hand	Non-dominant hand	Normal hand	Big hand
M (in cm)	7.42	7.41	7.13	8.11	8.88
SD	0.83	0.55	0.60	0.67	0.74
n	13	13	13	15	15

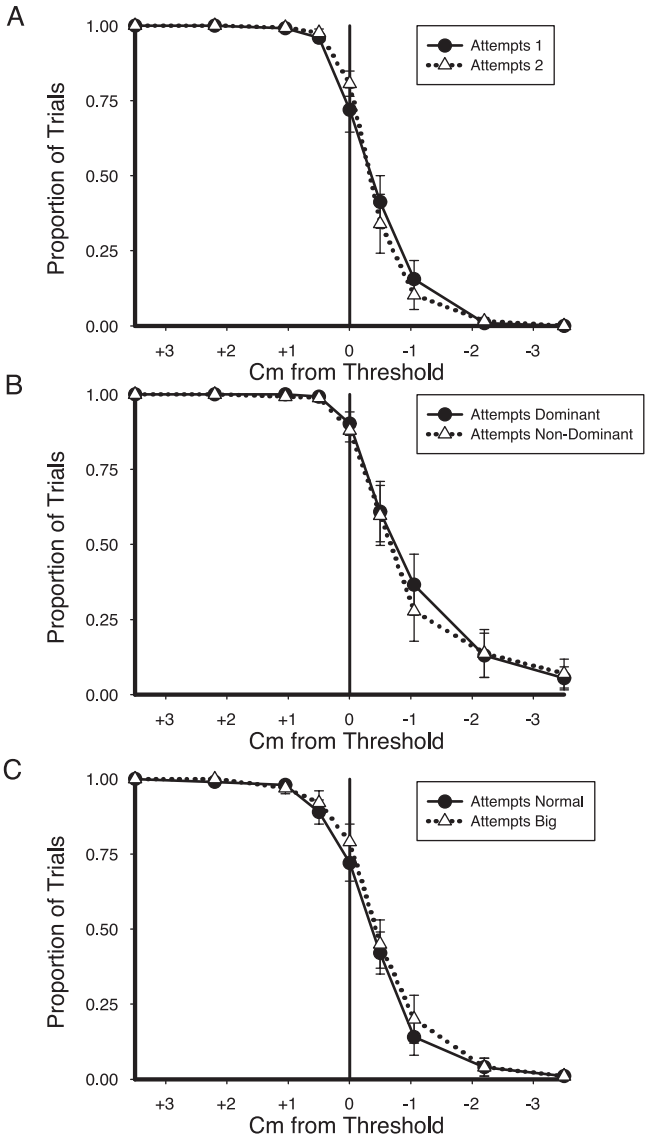

Figure 4. Mean proportion of attempts at each aperture group for (A) Experiment 1, (B) Experiment 2, and (C) Experiment 3. Attempts are normalized to each participant's affordance threshold, denoted by the solid vertical line at 0 cm, for each condition. On the *x* axis, passable apertures are represented by positive numbers to the left of the affordance threshold, and impassable apertures are represented by negative numbers to the right of the affordance threshold. Error bars denote standard errors.

half of the participants (denoted by the *n*s above the bars) contributed refusal data to the two largest aperture groups.

Summary. Experiment 1 validated the use of the psychophysical procedure across two lengthy blocked protocols: When tested with their dominant hand, participants displayed similar affordance thresholds, motor decisions, and reaching behaviors in both conditions. Thus, we could assume that differences between experimental and control conditions in subsequent experiments were due to the experimental manipulations.

Most important, we found that participants scaled their motor decisions to their own body dimensions and skills while reaching through apertures varying in size. However, motor decisions reflected a small bias to attempt apertures that were slightly smaller than the threshold size. As in previous work that relied on verbal judgments for walking through apertures, behavioral measures in the current study showed that participants did not ensure a safety margin for passage. Instead, they wedged their hands into apertures within a centimeter smaller than their affordance thresholds. In our experimental situation, such a response seems reasonable as the penalty for error was low (entrapment was not especially aversive) and the incentive for trying was high (adults were eager to obtain the candies).

Experiment 2: Varying the Fitting Hand

In Experiment 2, we examined whether habitual practice affects motor decisions for navigating through small and large apertures. Presumably, participants have more practice reaching, steering, and guiding their dominant rather than their non-dominant hand. Thus, we compared participants' motor decisions for fitting their dominant and non-dominant hands through apertures in two blocked conditions following the procedure outlined in Experiment 1.

Previous work is indeterminate about whether to expect intermanual differences in the aperture task. On the one hand, practice appears to facilitate verbal estimates of passable apertures for locomotion. For example, after 8 days of practice maneuvering a wheelchair, novice wheelchair users produced estimates of passable apertures that more closely approximated that of expert wheelchair users than their prepractice verbal estimates (Higuchi et al., 2004). Similarly, in industrial motor tasks such as hammering and using tweezers, participants were faster with their dominant hand (Salazar & Knapp, 1996). However, many studies have shown equal performance between hands. The same participants who hammered and tweezed faster with their dominant hand drilled and tightened bolts at the same speed with either hand (Salazar & Knapp, 1996). Moreover, their aim was just as accurate while drilling with their non-dominant hand. Similarly, partici-

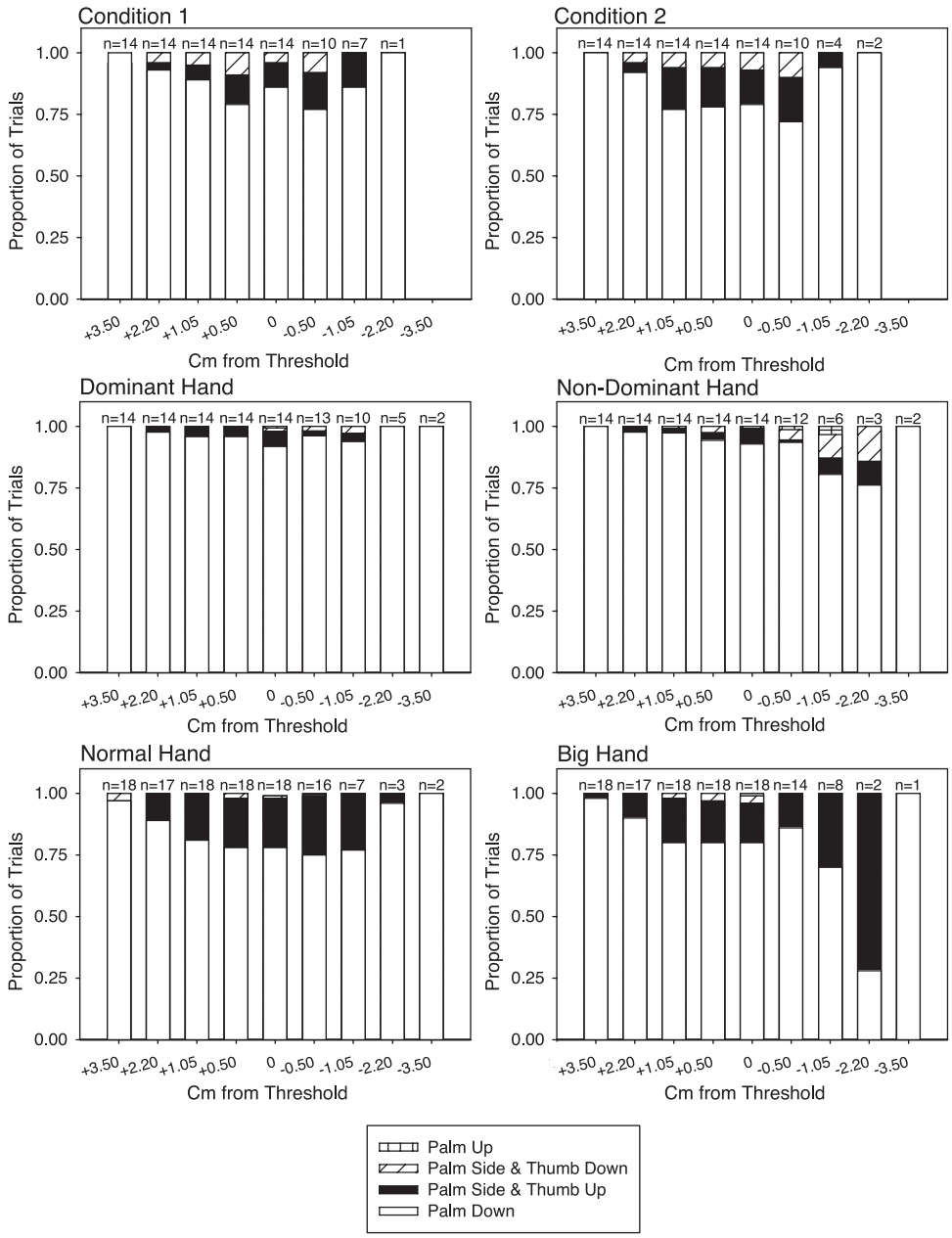

Figure 5. The distribution of hand orientations within each aperture group for Experiment 1 (top row), Experiment 2 (middle row), and Experiment 3 (bottom row). The number of participants contributing data to each aperture group is given above each bar.

pants showed no intermanual differences when estimating how far they could reach for targets in space (Fischer, 2005) or while copying complex designs on the Rey Complex Figure Test (Bush & Martin, 2004).

Method

Participants and procedure. Fourteen adults (7 women, 7 men) were recruited and compensated as in Experiment 1. Their mean age was 20.10 years (range = 19.19 to 21.46), and they reported their race as White ($n = 9$), Asian ($n = 4$), and Hispanic ($n = 1$). Only one participant was left-handed. Two additional participants were tested but their data were excluded due to experimenter error.

The experimental procedure and data coding were identical to Experiment 1. Dominant and non-dominant hand conditions were blocked and counterbalanced; 3 of the men and 3 of the women reached first with their dominant hand. Agreement between the primary and secondary coder was high for trial outcome (98.1%, $\kappa = .97$, $p < .001$), reaching strategy (97.9%, $\kappa = .96$, $p < .001$), and orientation (99.0%, $\kappa = .96$, $p < .001$).

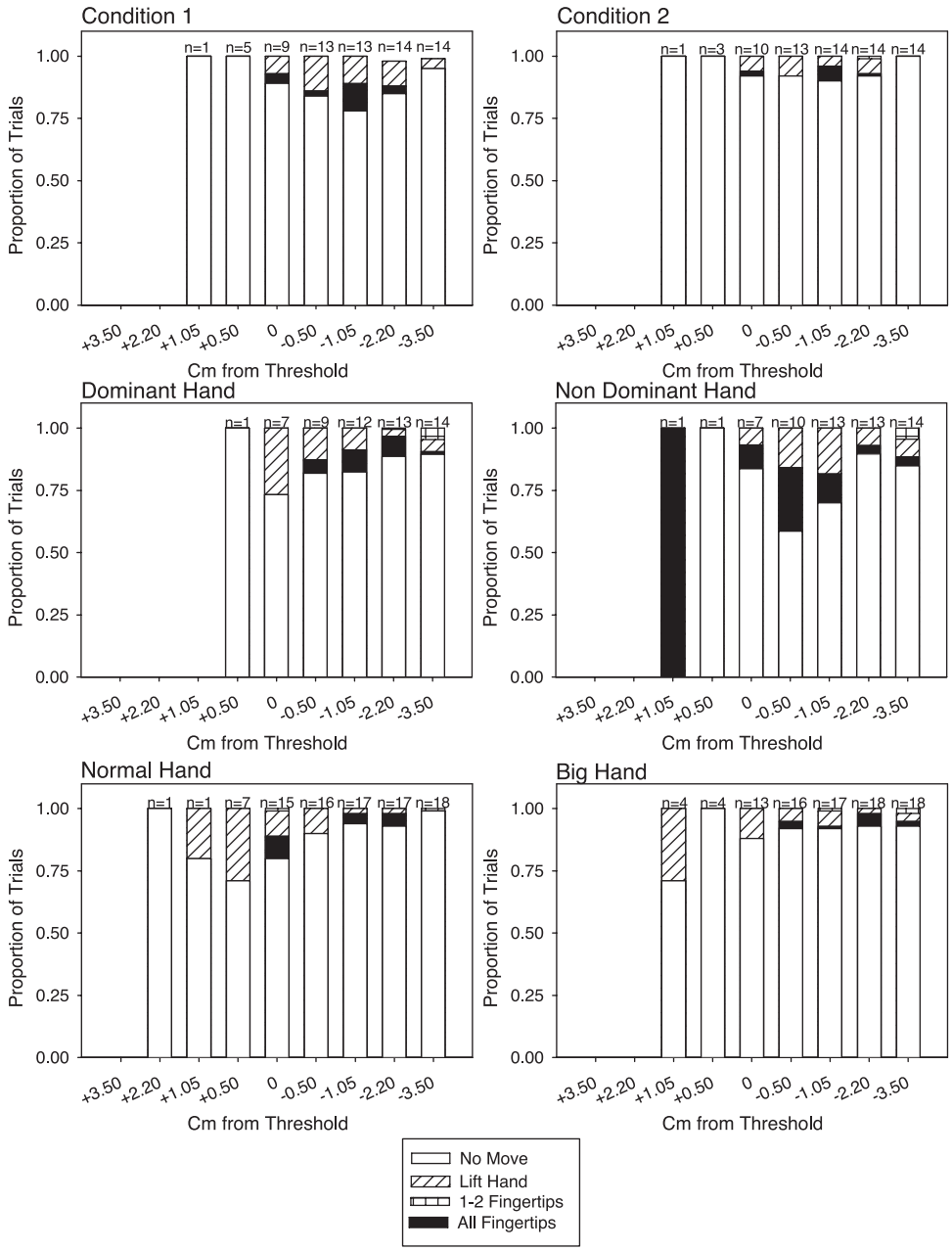

Figure 6. The distribution of participants' exploratory behaviors on refusal trials within each aperture group for Experiment 1 (top row), Experiment 2 (middle row), and Experiment 3 (bottom row). Solid white bars indicate participants saying "no" without moving their hands. Diagonal stripes indicate lifting the hand to the aperture but withdrawing the arm without attempting to reach. Vertical stripes indicate inserting one or two fingertips into the aperture before retracting the arm. Solid black indicates inserting all fingertips into the aperture before retracting the arm. The number of participants contributing data to each aperture group is given above each bar.

Results and Discussion

Affordance thresholds. As in Experiment 1, the slope of the affordance function was relatively steep. The distance under the inflection of the affordance function was small for both hands (M_{dominant} = 0.60 cm and $M_{\text{non-dominant}}$ = 0.41 cm), $t(15) = -0.07$, $p > .10$, meaning that possibilities for manual navigation transitioned sharply from possible to impossible around the affordance threshold. As shown in Figure 3B, affordance thresholds were similar for both hands ($M_{\text{non-dominant}}$ = 5.89 cm; M_{dominant} = 5.86 cm), $t(13) = -0.35$, $p > .05$, and affordance thresholds were correlated across conditions, $r(14) = .86$, $p = .001$. As shown in

the middle panel of Table 1, dominant hand width was 0.28 cm larger for the dominant hand compared with the non-dominant hand, $t(12) = 3.52$, $p = .004$. Scrunched hand width was correlated with affordance thresholds, $r_{\text{dominant}}(13) = .70$, $p = .008$, and $r_{\text{non-dominant}}(13) = .68$, $p = .01$.

Motor decisions. The slope of the motor decision function was relatively steep for some participants but shallow for others. The distance covered under the inflection of the motor decision function (between .999 and .001) for the dominant hand was similar to that of the non-dominant hand ($M = 2.62$ cm and $M = 2.69$ cm, respectively), $t(13) = -0.09$, $p > .10$. Two participants were particularly inconsistent; the distance covered under the inflection of the decision function was 8.30 cm for 1 participant in the dominant hand condition and 11.29 cm for 1 participant in the non-dominant condition. As in Experiment 1, the distance covered by the inflection of the motor decision function was larger than the distance covered by the inflection of the affordance function for both conditions [dominant: $t(13) = -3.68$, $p = .003$; non-dominant: $t(13) = -2.86$, $p = .01$], indicating that motor decisions were more variable than actual affordances.

The central question of interest was whether participants' motor decisions were similar when reaching with their dominant and non-dominant hands. Inspection of individual and group data (Figure 4B) revealed that participants responded similarly with both hands. A 2 (gender) $\times$ 2 (hand condition) $\times$ 9 (aperture group) repeated measures ANOVA on attempts revealed only a main effect for aperture group, $F(8, 96) = 71.11$, $p = .001$, partial $\eta^2 = .86$. Trend analyses on aperture groups revealed linear, $F(1, 12) = 176.89$, $p = .001$, partial $\eta^2 = .94$, and quadratic trends, $F(1, 12) = 47.28$, $p = .001$, partial $\eta^2 = .80$, confirming that participants' motor decisions decreased with the decreasing likelihood of fitting through the aperture.

Figure 5, middle row, shows participants' hand orientation on trials in which they attempted to reach (hand position just before the tip of their fingers entered the aperture). As in Experiment 1, participants (10/14) approached the aperture with their hand palm down on every trial, whereas the others occasionally used palm sideways and palm-up strategies. On trials where participants refused, they showed the same array of information-gathering behaviors as in the earlier experiment (Figure 6, middle row), primarily visual exploration, but occasionally lifting the hand or inserting fingers into the opening.

Summary. As in Experiment 1, participants scaled their motor decisions to their hand size relative to aperture size, but they slightly misjudged their ability by attempting to fit their hand through impossibly small apertures. Moreover, the findings from Experiment 2 suggest that habitual practice in specific activities (i.e., tasks that involve use of the dominant hand) does not influence participants' accuracy in the current task of reaching through apertures. Affordance thresholds were similar in both conditions, and most participants maintained the same level of accuracy across hands. Possibly, gauging affordances for reaching may be so well learned with both hands that hand dominance had no effect.

Experiment 3: Varying Hand Width

In Experiment 3, we examined whether participants could adjust their motor decisions to take changes in their hand dimensions into account. Changes in body dimensions alter affordances for action. Thus, we compared participants' motor decisions as they reached with their dominant hand in two blocked conditions following the procedure outlined in Experiment 1. In the big hand condition, participants wore a padded prosthesis that increased the width of their hand by approximately 1 cm. In the normal hand control condition, participants wore an unpadded prosthesis. Because participants did not show any differences when tested in identical conditions in Experiment 1, any differences between the two conditions could be attributed to increasing the width of the hand.

Given the seemingly straightforward effects of the prosthesis, we anticipated larger affordance thresholds in the big hand condition. The central question was whether participants would update their motor decisions to take their new hand dimensions into consideration. If so, then their motor decisions should appear similar across conditions once normalized to the respective affordance thresholds for each condition. That is, participants should treat the same absolute aperture size as passable while wearing the normal prosthesis but impassable while wearing the big prosthesis, but treat relative hand size equivalently in both conditions.

To date, only one study has examined whether adults can accurately modify their actions in accordance with altered body dimensions when fitting through apertures (Higuchi, Cinelli, Greig, & Patla, 2006). Previous research has shown that adults are sensitive to changes in their own body dimensions when performing actions such as pointing, sitting, and walking. They are able to quickly adjust given only a few minutes of familiarization. College students appropriately adjusted the height of a bar to step over when wearing shoes that increased their height by 10 cm (Hirose & Nishio, 2001). They also correctly choose higher chairs to sit on when wearing platform shoes compared with their normal height. Likewise, infants descending slopes adjusted their decisions for walking when loaded with 15% of their body weight. While loaded with "feather weights," they attempted to walk down steeper slopes than while loaded with lead weights (Adolph & Avolio, 2000).

Method

Participants. Eighteen adults (9 women, 9 men) were recruited and compensated as before. The average age of the participants was 22.56 years (range = 18.53 to 38.13). Participants reported their race as White ($n = 8$), Asian ($n = 6$), Black ($n = 1$), Hispanic ($n = 1$), and other ($n = 2$). Sixteen participants were right-handed and 2 were left-handed. Two participants were excluded due to equipment failure.

Neoprene prostheses. We constructed two fitted prostheses to be worn on participants' dominant hand. The normal hand prosthesis (Figure 7A) fit flat against the hand, adding only a negligible increase in hand width (.30 cm). The big hand prosthesis (Figure 7B) enlarged the ulnar edge of participants' hands from the base of the pinky finger to the wrist by 1 cm. The components of the prostheses were constructed out of a lightweight, flexible Neoprene material. A finger-sized loop of material was sewn onto one end of a strip of fabric (5 cm $\times$ 3.5 cm) and a Velcro strap was attached to the opposite end of the strip. Participants first slid their pinky finger into the loop, then fastened the strap around their wrist. Another Velcro strap around the palm prevented the prosthesis from shifting during the session. On the big hand prosthesis, 1-cm thick Neoprene padding was sewn into the part of the

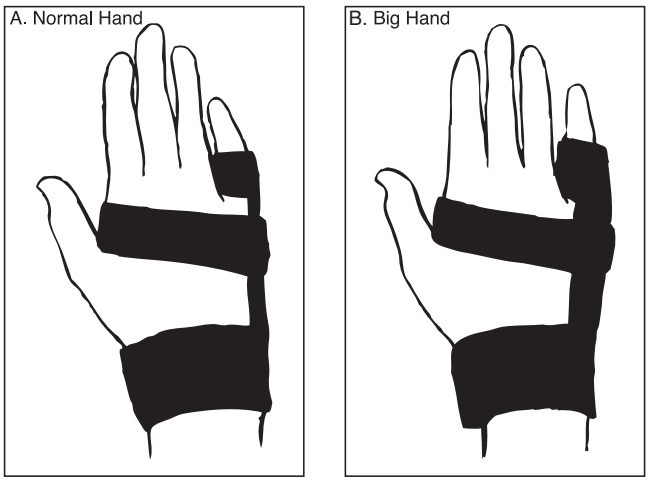

Figure 7. Neoprene prostheses worn in Experiment 3. Velcro straps across the palm and wrist secured the prosthesis to the hand. (A) Unpadded prosthesis for normal hand condition. (B) Padded prosthesis for big hand condition.

prosthesis covering the pinky side of the hand. Pilot testing showed that participants could easily flex and contort their hands while wearing either prosthesis. Because the padding could be compressed to different extents depending on the pressure, we expected that affordance thresholds might not increase by exactly 1 cm for each participant. The normal hand prosthesis was identical but unpadded. We built three pairs of prostheses to accommodate small, medium, and large hands.

Procedure and data coding. As in Experiment 1, participants were encouraged to reach through the aperture apparatus using their dominant hand in two conditions: big hand and normal hand. Condition order and gender were counterbalanced (4 men and 5 women reached with the big hand first). Participants put on the appropriate prosthesis just before the start of the condition. They were given approximately 30 s to flex their hand to ensure that the prosthesis did not hinder their ability to move their hand. Participants' hands were not hidden from view during any part of the session, so they could (and sometimes did) look at their big hand between trials while their back was to the aperture. We used the same experimental and data coding procedure as before. Two participants never failed, one in the normal hand condition and one in the big hand condition. The experimenter asked them to produce failures in order to establish affordance thresholds. However, these trials were not included in analyses of motor decision. Scrunched hand widths were measured at the end of the session while participants wore the prostheses. Agreement between primary and secondary coders was the same for trial outcome and reaching strategy (both variables agreement = 98.7%, $\kappa = .98$, $p < .001$). For orientation, interrater agreement was 98.2% ($\kappa = .92$, $p < .001$).

Results and Discussion

Affordance thresholds. As shown in Table 1, the big hand manipulation effectively enlarged the width of participants' hands compared with the normal hand condition, $t(14) = -9.00$, $p = .001$. Several participants also commented that their hand "felt big" when wearing the big hand prosthesis. Figure 3C shows affordance thresholds for both conditions. Larger hand widths with the padded prosthesis resulted in larger affordance thresholds in the big hand condition ($M = 6.88$ cm) compared with the normal hand condition ($M = 6.35$ cm), $t(17) = -7.23$, $p = .001$. Although the difference between the size of the prostheses was 0.70 cm, the average difference in affordance thresholds between conditions was only 0.53 cm. One reason for the smaller change in thresholds is that the flexible Neoprene material was compressed as participants pressed their hands through the aperture. Affordance thresholds were correlated with hand width for both conditions, $r_{normal}(16) = .61$, $p = .02$, and $r_{big}(16) = .66$, $p = .008$.

Although the big hand prosthesis affected affordance thresholds, it did not affect the shape of the psychometric function underlying motor performance. The distance under the inflection of the affordance function (from .999 to .001) was similar across conditions ($M_{big} = 1.53$ cm, $SD = 0.91$; $M_{normal} = 1.34$ cm, $SD = 1.29$), $t(17) = -0.51$, $p > .10$. Thus, if motor decisions were updated in accordance with altered body dimensions, participants should displace their judgments by the size of the discrepancy between thresholds.

Motor decisions. The slope of the motor decision function ranged from relatively steep to shallow across participants. Participants showed similar variability between conditions; the distance covered by the inflection of the motor decision function did not differ across conditions ($M_{big} = 2.63$ cm, $SD = 1.91$; $M_{normal} = 2.71$ cm, $SD = 2.08$), $t(17) = 0.15$, $p > .50$. Additionally, participants' motor decision functions revealed more variability than their affordance functions; the distance under the inflection of the motor decision function tended to be greater than the affordance function [big hand: $t(17) = -2.45$, $p = .02$; normal hand: $t(17) = -2.06$, $p = .06$].

Figure 4C shows the average proportion of trials at which participants attempted to reach at aperture sizes normalized to their affordance thresholds in each condition. As in Experiments 1 and 2, attempts were high on apertures larger than the affordance threshold (e.g., $M = 0.99$ at the +1.05-cm aperture) and steadily decreased on apertures smaller than the affordance threshold (e.g., $M = 0.13$ at the −1.05-cm aperture). Most important for understanding participants' ability to recalibrate motor decisions to altered body dimensions, the motor decision curves were overlapping at each relative aperture size. A 2 (gender) × 2 (prosthesis condition) × 9 (aperture group) repeated measures ANOVA on attempts confirmed a main effect only for aperture group, $F(8, 104) = 202.67$, $p = .001$, partial $\eta^2 = .94$. Trend analysis revealed significant linear, $F(1, 13) = 3{,}574.42$, $p = .001$, partial $\eta^2 = .99$, and quadratic effects, $F(1, 12) = 17.94$, $p = .001$, partial $\eta^2 = .58$, confirming that attempts decreased on smaller apertures.

Figure 8 shows participants' attempts for each condition by absolute aperture size. At each aperture size between 4 cm and 8 cm, attempt rates were higher in the normal hand condition compared with the big hand condition, indicating that participants appropriately perceived altered affordances while wearing the big hand prosthesis. We also analyzed participants' attempts for each condition at the same absolute aperture size. The only aperture sizes where all participants contributed data were at the normal and big hand thresholds. Figure 9 shows participants' attempts at the affordance threshold for each condition. Participants were more

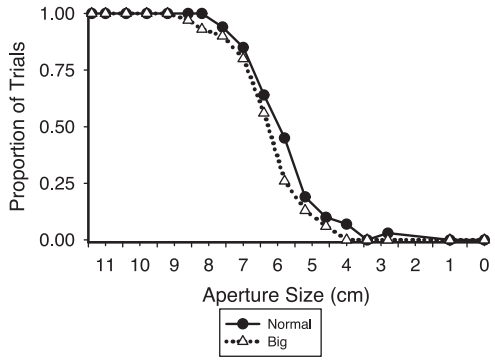

Figure 8. Overall average proportion of attempts by absolute aperture size for the normal and big hand conditions for Experiment 3.

likely to attempt to fit their hand through the aperture at their big hand threshold than their normal hand threshold. Additionally, attempt rates were higher in the normal hand condition than the big hand condition at both aperture sizes. A repeated measures ANOVA verified the effect of threshold size, $F(1, 17) = 24.57$, $p = .001$, partial $\eta^2 = .59$, and condition, $F(1, 17) = 8.60$, $p = .009$, partial $\eta^2 = .34$.

Figure 5, bottom row, shows the orientation of participants' hand as they attempted to fit it through the aperture. Similar to Experiments 1 and 2, many participants (9/18) only approached the aperture with their hand oriented palm downwards in both conditions. On normal hand trials some participants turned their hand sideways with thumb pointing upwards on trials surrounding their affordance threshold. However, on big hand trials participants gradually shifted from orienting their palm down to turning their palm sideways and thumb pointing upwards. Three subjects used three different orientation strategies over the course of their test session. Participants displayed the same range of refusal strategies as in Experiments 1 and 2 (Figure 6, bottom row). Participants most often turned to face the aperture and said "no" without lifting their hand from their lap. On apertures slightly larger than their affordance threshold, participants lifted their hand and brought it in front of the aperture before refusing. Some participants also used the time between trials to examine their new hand size: They held their padded hand in front of their face while scrunching and extending their fingers.

Summary. Experiment 3 showed that experimental manipulation of hand size with the prosthesis increased affordance thresholds, and participants adjusted their motor decisions accordingly: They attempted smaller apertures in the normal hand condition than in the big hand condition. It seems unlikely that participants were using memorized dimensions of their normal hand to guide their actions. With a static representation of their normal hand size as a guide, motor decisions should not have shifted in line with shifts in affordance thresholds in the big hand condition. However, as in the previous experiments, participants were likely to attempt to fit their hand through apertures that were smaller than their affordance threshold in both conditions.

General Discussion

On a daily basis, many animals navigate through large and small openings. Fitting through apertures is a complex process that involves steering the relevant body parts toward the opening, reshaping the body to minimize the largest dimensions, and orienting the direction of the body to align its largest dimensions to the largest dimensions of the opening. Hence, there is ample opportunity for errors that can result in entrapment and injury. Safely moving through apertures involves perceiving the relationship between the size of the opening and the dynamics of one's own body. In the current studies, we examined manual navigation through apertures to understand how people cope with this challenge. In Experiment 1, participants reached with their dominant hand in two identical conditions. In Experiment 2, participants reached with their dominant and nondominant hands. In Experiment 3, their dominant hand was artificially enlarged.

In contrast to previous research (e.g., Higuchi et al., 2004; Wagman & Taylor, 2005), we used a psychophysical method to determine the actual affordance for fitting through apertures by indexing participants' success while performing the task rather than estimating affordances based on static measures of body dimensions. We measured participants' scrunched hand size to determine the relationship between affordance thresholds and dynamic body dimensions. Affordance thresholds and hand width were only moderately correlated. Participants with similar hand widths might have had different affordance thresholds due to differing ability to scrunch their fingers together and compress their soft tissue while fitting through the apertures. These findings suggest that dynamic properties, such as flexibility and compressibility, rather than solely static dimensions are related to the affordance threshold (e.g., Konczak, Meeuwson, & Cress, 1992). Furthermore, we did not instruct participants how to reach through the apertures; affordance thresholds may have been influenced by strategies too subtle to discern from video recordings. In addition, we indexed motor decisions on the basis of participants' attempts to fit through the apertures rather than based on verbal judgments as was used in previous work (Gordon & Rosenblum, 2004; Higuchi et al., 2004; Wagman & Taylor, 2005).

Perceiving Affordances

In all three experiments, participants showed evidence of detecting affordances for guiding action adaptively. Their attempts to

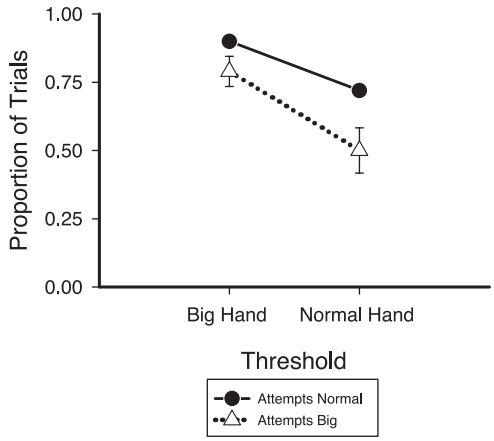

Figure 9. Overall average proportion of attempts at the normal and big hand thresholds in the normal and big hand conditions in Experiment 3.

reach decreased on apertures smaller than their affordance threshold. Moreover, participants scaled their motor decisions to their individual hand size. That is, people with smaller hands treated smaller apertures as more passable than people with larger hands. Additionally, many of the participants' motor decisions showed a high level of sensitivity to the difference between aperture increments. They showed impressive precision in their decisions, consistently switching between attempts and refusals within a few millimeter variations in aperture size. For instance, one participant consistently attempted to fit her hand through the 6.00-cm aperture but refused the 5.80-cm aperture on repeated trials.

However, consistent with previous findings, most participants did not maintain a consistent safety margin (i.e., by undershooting the affordance threshold) but rather attempted tight fits on many trials (Wagman & Taylor, 2005). Many participants attempted to fit their hand through apertures that were 0.50 cm smaller than their affordance threshold or about 7% of their own hand size. Indeed, on those trials, participants determined affordances based on whether they could press their hand through the aperture by force and swiveling motions.

We offer several possible explanations for participants' willingness to err by attempting to reach through too-small apertures. First, participants felt motivated to attain the payoff; they commented that they tried to fit through small apertures because they really wanted to retrieve the candy. Second, putting the hand into the aperture was extremely compelling. Indeed, on many trials participants saw the aperture and said "no" but still attempted to fit their hand in the opening. Third, errors in motor decisions resulted in only a small penalty: The hand became briefly entrapped in the aperture before the experimenter released it to end the trial. Fourth, although participants could use visual information to detect their hand size as it approached the aperture, they may have required more information gained from haptic exploration by touching the aperture or attempting to fit fingers or hands through the opening. Additionally, participants were not tracking the exact size of the opening; they were unaware of how many different-sized apertures they received. Most participants responded that they had received only 5 to 10 different-sized apertures, but in reality, they averaged 30 different-sized apertures. Finally, previous research has suggested that participants' emotional state is related to the perception of affordances when reaching across a distance (Pijpers, Oudejans, Bakker, & Beek, 2006). Participants with lower levels of anxiety expect to perform better than participants with higher levels of anxiety, and do indeed reach across greater distances. Although we did not directly assess participants' emotional state, none of them appeared anxious, and low-anxiety levels may have led them to overestimate their ability to fit through small apertures.

Exploring Affordances

The range of reaching strategies displayed in the current experiments mirrors the range of strategies people use to perform similar tasks in everyday situations. Moreover, participants' systematic use of alternative hand orientations is also evidence for their sensitivity to affordances. None of the participants asked if they had to insert their hand through the apertures in a specific way. They seemed to interpret the instructions to mean that they could put their hand into the aperture in any orientation, and they correctly perceived that they could twist their hand into several different positions to fit through. The high frequency of palm-down reaches across experiments was likely driven by the small target size and the goal of grasping it from the end of the stick. They were more likely to use orientations other than palm down on apertures smaller than the affordance threshold, and they exhibited prospective control by orienting their hand before it arrived at the aperture. Participants probably thought that turning the hand sideways, particularly while wearing the big hand prosthesis, would be an adaptive strategy. Although vertical and horizontal hand orientations would have the same result in this task because the aperture was a diamond, in most situations the dimensions of the hand are minimized when the hand is held sideways.

How might people have detected the relation between their dynamic hand size and the changing size of the aperture? What perceptual information may have supported their motor decisions? At the extreme tails of the affordance function, participants may have relied on prior knowledge. They immediately reached through the largest apertures and said "no" when faced with the smallest apertures. However, if participants had only fixed, rigid representations of their hand size vis-à-vis aperture size, then they would not have sought additional perceptual information when deciding whether to reach through intermediate-sized apertures. On aperture sizes around their affordance thresholds, participants displayed an array of spontaneous, information-generating, exploratory behaviors. Reaching toward a target at eye level naturally brings the hand into the line of sight. Accordingly, on some trials, participants lifted their hand toward the aperture and then retracted their arm. They inserted one, two, or all of their fingertips into the edge of the aperture before retracting their hand. Thus, the combination of visual and mechanical stimulation provides a wealth of information about the size of the hand relative to the size of the aperture. According to Gibson (1979), actors use information gleaned from such exploratory behavior to determine affordances for action.

Conclusion

The results of three experiments suggest that people are highly sensitive to affordances for fitting through apertures—they notice millimeter changes in the size of the opening and the size of their hand—and they quickly and spontaneously modify their motor decisions to take changes in the affordance relationship into account. Visual and proprioceptive information from exploratory movements appear to be the critical key for recalibration. Overestimation in motor decisions appears to result from a low penalty for errors, rather than a lack of sensitivity to the information for the affordance.

References

Adolph, K. E., & Avolio, A. M. (2000). Walking infants adapt locomotion to changing body dimensions. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1148–1166.

Adolph, K. E., & Berger, S. A. (2006). Motor development. In D. Kuhn & R. S. Siegler (Eds.), *Handbook of child psychology: Vol. 2. Cognition, Perception, and Language* (6th ed., pp. 161–213). New York: Wiley.

Berger, J. O. (1985). *Statistical decision theory and Bayesian analysis.* New York: Springer.

Buekers, M., Montagne, G., de Rugy, A., & Laurent, M. (1999). The

regulation of externally paced human locomotion in virtual reality. *Neuroscience Letters, 275,* 171–174.

Bush, S., & Martin, T. A. (2004). Intermanual differences on the Rey Complex Figure Test. *Rehabilitation Psychology, 49,* 76–78.

Efron, B., & Tibshirani, R. J. (1993). *An introduction to the bootstrap.* New York: Chapman Hall.

Fischer, M. H. (2005). Perceived reachability: The roles of handedness and hemifield. *Experimental Brain Research, 160,* 283–289.

Flascher, O. M., Shaw, R. E., Kader, E. E., & Aromin, T. A. (1995). Intentional perceptual scaling means $\pi = 1$. In B. G. Bardy, R. J. Bootsma, & Y. Guiard (Eds.), *Studies in perception and action III* (pp. 133–136). Mahwah, NJ: Erlbaum.

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

Gordon, M. S., & Rosenblum, L. D. (2004). Perception of sound-obstructing surfaces using body-scaled judgments. *Ecological Psychology, 16,* 87–113.

Higuchi, T., Cinelli, M. E., Greig, M. A., & Patla, A. E. (2006). Locomotion through apertures when wider space for locomotion is necessary: Adaptation to artificially altered bodily states. *Experimental Brain Research, 175,* 50–59.

Higuchi, T., Takada, H., Matsuura, Y., & Imanaka, K. (2004). Visual estimation of spatial requirements for locomotion in novice wheelchair users. *Journal of Experimental Psychology: Applied, 10,* 55–66.

Hirose, N., & Nishio, A. (2001). The process of adaptation to perceiving new action capabilities. *Ecological Psychology, 13,* 49–69.

Ingle, D., & Cook, J. (1977). The effect of viewing distance upon size preference of frogs for prey. *Vision Research, 17,* 1009–1013.

Konczak, K., Meeuwson, H. J., & Cress, E. M. (1992). Changing affordances in stair climbing: The perception of maximum climbability in young and older adults. *Journal of Experimental Psychology: Human Perception and Performance, 3,* 691–697.

Lock, A., & Collett, T. (1980). The three-dimensional world of a toad. *Proceedings of the Royal Society of London. Series B, Biological Sciences, 206*(1165), 481–487.

Maloney, L. T. (1990). Confidence intervals for the parameters of psychometric functions. *Perception & Psychophysics, 47,* 127–134.

Montagne, G., Buekers, M., de Rugy, A., Camachon, C., & Laurent, M. (2002). Control of human locomotion under various task constraints. *Experimental Brain Research, 143,* 133–136.

Pijpers, J. R., Oudejans, R. R. D., Bakker, F. C., & Beek, P. J. (2006). The role of anxiety in perceiving and realizing affordances. *Ecological Psychology, 18,* 131–161.

Salazar, P. S., & Knapp, R. K. (1996). Preferred and nonpreferred hand skill in performing four industrial tasks. *Human Performance, 9,* 65–75.

Sanderson, P. M., Scott, J. J. P., Johnston, T., Mainzer, J., Wantanbe, L. M., & James, J. M. (1994). MacSHAPA and the enterprise of Exploratory Sequential Data Analysis (ESDA). *International Journal of Human-Computer Studies, 41,* 633–681.

Tinsworth, D. K., & McDonald, J. E. (2001). *Special study: Injuries and deaths associated with children's playground equipment.* Washington, DC: Consumer Product Safety Commission.

Wagman, J. B., & Taylor, K. R. (2005). Perceiving affordances for aperture crossing for the person-plus-object system. *Ecological Psychology, 17,* 105–130.

Warren, W. H. (1984). Perceiving affordances: Visual guidance of stair climbing. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 683–703.

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

Wichmann, F. A., & Hill, N. J. (2001a). The psychometric function: I. Fitting, sampling, and goodness of fit. *Perception & Psychophysics, 63,* 1293–1313.

Wichmann, F. A., & Hill, N. J. (2001b). The psychometric function: II. Bootstrap-based confidence intervals and sampling. *Perception & Psychophysics, 63,* 1314–1329.

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