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A Geometric and Dynamic Affordance Model of Reaches-To-Grasp: Men Take Greater Risks Than Women

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Mon-Williams and Bingham (2011) developed an affordance model of the spatial structure of reaches-to-grasp. With a single free parameter (P), the model predicted the safety margins (SMs) exhibited in maximum grasp apertures (MGAs), during the approach of a hand to a target object, as a function of an affordance measure of object size and a functional measure of hand size. An affordance analysis revealed that object size is determined by a diagonal through the object, called the maximum object extent. Mon-Williams and Bingham provided no theoretical account for the empirically determined values of P. We now address this question. Snapp-Childs and Bingham (2009) augmented Warren's (1984) geometric affordance scaling model with a dynamical component determined by the stability of the motor performance. Because P was found to vary with the speeds of reaches, we incorporated a measure of the variability of performance into the model to yield predictions of P. We also found that P varied with gender. In respect to the size of safety margins, women were more conservative in taking risks then men. Finally, following Warren (1984), the classic paradigm for testing affordance models is to test the scaling relations with both small and large participants. We tested small- and large-handed men and small- and large-handed women and found that the new parameter free model successfully accounted for the spatial structure of reaches-to-grasp.

Keywords: reach-to-grasp, affordance, perception/action, Fitts' Law

Perception/action studies have focused primarily on fundamental human actions like locomotion (e.g., Warren & Fajen, 2004), upright posture (e.g., Haddad, Van Emmerik, Wheat & Hamill, 2008), speech (e.g., Pisoni & Remez, 2007), throwing (e.g., Bingham, Schmidt & Rosenblum, 1989; Zhu & Bingham, 2010, 2011), and reaches-to-grasp (e.g., Jeannerod, 1984; Wing, Haggard, & Flannagan, 1996). The emphasis of research in this latter case has been predominantly on the temporal structure of reaches-to-grasp. The earlier studies by Jeannerod (1984), for instance, focused on the timing of features of the grasping movement (e.g., the maximum grasp aperture or MGA) relative to features of the reaching movement (e.g., peak velocity). The MGA is the widest opening of the grasp during the reach in preparation for closing the grasp down on the object. Initially, it was hypothesized that the MGA occurred at 70% of the reach duration just after the peak velocity of the reach, but subsequent studies revealed that the relative timing varied depending on other features of the reaching like the amount of hand opening at the beginning and end of the reach (Mon-Williams & Tresilian, 2001) or the speed of the reach (Wing, Turton & Fraser, 1986). The spatial structure of reaches-to-grasp has been investigated in two types of previous studies, namely, studies investigating finger placement relative to the center of mass of an object (Goodale et al., 1993; Lederman & Wing, 2003) and studies developing process models of reaches-to-grasp (e.g., Hoff & Arbib, 1993; Ulloa & Bullock, 2003; Verheij, Brenner, & Smeets, 2012). The process models have provided only qualitative approximations to reach-to-grasp spatial structure that was assumed to vary only in two dimensions (that is, a strictly horizontal orientation of the MGA). The size of the MGA is known to covary systematically with the object size, but the specific scaling relation remained unknown until Mon-Williams and Bingham (2011) set out to discover the relevant object affordance properties and then, model the scaling of the MGA and the terminal grasp aperture (TGA).[1]

Reaches-to-grasp entail two essential goals: targeting and collision avoidance. The targeting goal is to place hand surfaces (typically the finger(s) and thumb) on opposite sides of an object so as to position the "opposition axis" (Iberall, Bingham, & Arbib, 1986) relative to the object center of mass. The collision avoidance

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[1] Bingham, Hughes, and Mon-Williams (2008) distinguished the maximum grasp aperture (MGA), the terminal grasp aperture (TGA), and the final grasp aperture (FGA). MGA occurs during the approach of the hand to the target object. TGA occurs in many reaches-to-grasp when the hand velocity drops to zero with the hand at the target object, while the fingers remain poised around the object without yet contacting it. The FGA occurs when the fingers have finally closed on the object.

goal is to avoid hitting the object with the fingers before they can span the object and effect the grasp. This requires the grasp aperture between thumb and index, for instance, to be opened wide enough and centered on the object during the approach of the hand. Mon-Williams and Bingham (2011) found that the TGA, occurring at the end of a reach, reflected the targeting goal while the MGA, occurring roughly midway through a reach, reflected the collision avoidance goal. When considering formation of the MGA, Mon-Williams and Bingham realized that the hand and grasp aperture are not typically level or horizontal during the approach. They found systematic variations in this orientation as a function of the size of the object. In addition, they found considerable random variation in the orientation of the approaching grasp aperture at MGA. This meant that the relevant object affordance property for grasping was not object size or width, but instead was the maximum length diagonal through the object that they called the maximum object extent (or MOE). They showed that MGA varied as a function of MOE and TGA varied as a function of object width (see Figure 1 for illustration of the difference between MOE and width).

The MGA is formed to provide a safety margin for collision avoidance. The MGA, and thus the size of the safety margin, varies with the MOE. It also varies as a function of the size of the grasping hand. Mon-Williams and Bingham formulated a geometric affordance model of MGA formation. The model incorporated the roles of both object scale (that is, MOE) and actor scale (that is, effective hand size) in the context of the task goals (that is, obstacle avoidance). The model was formulated as follows. The safety margin (SM) is the difference between the MGA and the MOE: SM = MGA − MOE. The relevant functional measure of the actor's hand size is the maximum grip (MG). It is the largest aperture between thumb and index finger that can be used to grasp and pick up an object. The available aperture (AA) is the difference between the hand's maximum grip (MG) and the maximum object extent (MOE): AA = MG − MOE (see Figure 2 for illustration). Mon-Williams and Bingham found that the size of the SM was an invariant proportion (P) of the available aperture: SM = P × AA. However, they also found that the value of P varied as a function of the speed of the reach. For medium or normal speed reaches-to-grasp P ≈ .24. For maximally fast reaches P ≈ .35.

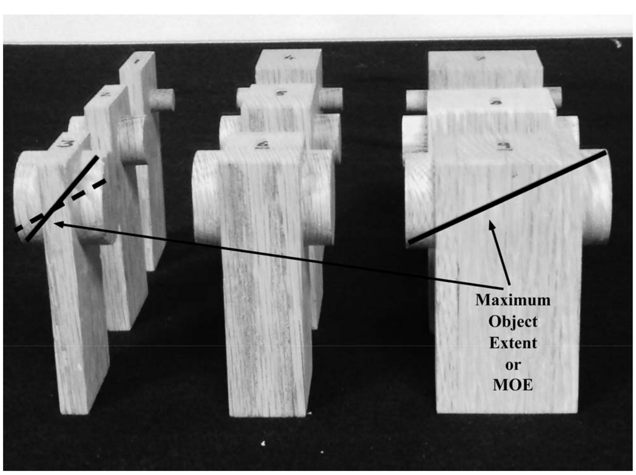

Figure 1. The nine objects used in the current study. Similar to those used by Mon-Williams and Bingham (2011), the objects vary in both width and contact surface area for grasping. There were three widths: small (Objects 1–3 on the left), medium (Objects 4–6 in the middle), and large (Objects 7–9 on the right). (Object numbers appear on the tops of the objects.) The maximum object extent (or MOE) is the largest diagonal through the object between the two contact surfaces. MOE = $[(\text{height of the contact surface area})^2 + (\text{width})^2]^{0.5}$. See the text for explanation of the dotted MOE diagonal on Object 3 at the left side of the figure.

Mon-Williams and Bingham did not provide an account for these specific values observed for P. This is the goal of current article. The solution that we propose entails an addition to the affordance theory originally developed and proposed by Warren (1984). Warren's theory was geometric. The relevant actor and environment properties that it related were lengths, for instance, leg length and step height. To this theory, we now add a dynamical component, namely, a measure of the dynamic stability of the controlled action. The fact that different values of P were found for reaches performed at different speeds, with a larger value for fast as compared with normal speed, provided us a hint as to how to account for P values. Fitts' Law tells us that positional variability increases with the speed of a reach. Such variability is exactly why a safety margin is required to avoid collision either when passing an object into a grasp aperture during a reach-to-grasp or when passing one's body through an aperture during locomotion (e.g., Warren & Whang, 1987). Likewise, a safety margin is used when stepping over an obstacle to avoid tripping. Snapp-Childs and Bingham (2009) noted that the geometric affordance theory of Warren (1984) failed to account fully for the scaling of such stepping behaviors across a range of ages from young children (4- and 6-year-olds) to adults in their 20s. They argued for the addition of a dynamical component to the original geometric affordance theory. The stability of the individual's performance of the relevant action should determine the scaling of the safety margin once that variability had been normalized by the performer's size (in that case, leg length). A combined geometric and dynamic affordance model successfully predicted stepping heights. Thus, we now propose that the addition of such a dynamical component to the original geometric affordance model of Mon-Williams and Bingham should yield prediction of the scaling of the MGA in reaches-to-grasp. We expect the positional variability of the fingers at MGA (see Figure 3), normed by the relevant actor dimension (namely, maximum grip) will determine the value of P to predict the size of the safety margins and thus, the size of the MGA. The positional variability of the fingers, relative to the target object, was measured by the variability in the size of the SM plus the variability in the lateral position of the MGA (MGA POS). If the model is successful, then a coefficient should scale these measures of variability (or inversely, stability) to yield predicted P values. These P values should, in turn, yield predicted safety margins that correlate well with actual measured safety margins.

Warren (1984) introduced what has become the classic paradigm for testing affordances. The paradigm is to test participants at the extremes of variations in size, that is, large and small people. Applying the intrinsic scaling of the geometric affordance model, the expectation is that the scaling should be invariant despite the variations in size. So, we now tested people with small and large MGs. With the addition of a dynamical component to the model, we now directly address factors underlying the formation of safety

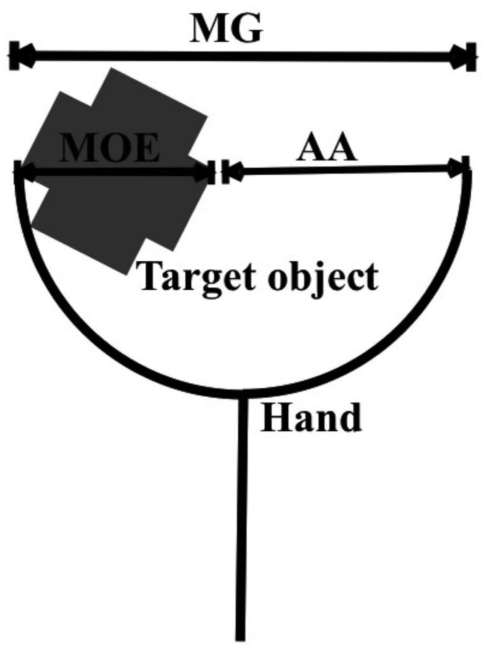

Figure 2. Illustration of the variables used in the geometric model. MG is the maximum grip, so the hand is shown maximally open. MOE is the maximum object extent, as shown in Figure 1. AA is the available aperture, which is the difference between the MG and the MOE. Note: if the hand were shown as in Figure 3 with the grip span or aperture only as large as a typical maximum grasp aperture for the given object, then the interval shown in the current figure as the AA would instead be the safety margin, obviously smaller than the AA.

margins. The size of a safety margin is also determined by assessment of potential risk. Using good classic design, we also tested both men and women. It has been well established that men and women exhibit systematic differences in risk assessment. Women are more risk adverse (see Harris, Jenkins, & Glaser, 2006 for a review.) Thus, we expected systematic gender differences in the way the dynamical component (e.g., variability) was scaled to determine P values. The variation of small and large handed women and small and large handed men yielded four groups. Each participant performed both normal and fast speed reaches to each of nine objects that varied in MOE.

Method

Participants

Twenty participants (half male) took part in the experiment and were remunerated at a rate of $10/hr for their time. All participants had normal or corrected to normal vision and normal motor abilities. Participants were selected on the basis of their evident hand size. All participants, save one male, were right-handed. All participants participated with informed (written) consent.

Apparatus and Procedure

After the participant had read and signed consent forms approved by the IRB at Indiana University, participants were seated in a chair that was adjusted in height so that they could comfortably sit at the testing table. First, we established participants' MG. We found that the MG could not be determined simply by applying calipers or a ruler to the hand to measure the maximum distance between distal segments of the thumb and index finger. Instead, this had to be measured functionally, because the MG is determined as much by coordinative abilities as by pure anatomical size. This was achieved using a series of dowels varying in length. Participants lifted the longest dowel they were able to lift by placing their thumb and index finger on opposite ends of the dowel. Often, someone with a somewhat smaller hand than another person was able to pick up a significantly longer dowel than the person with the larger hand. We used a series of wooden dowels that varied in length by 1 cm. The shortest dowel in the series was 10 cm in length and the longest was 22 cm in length. Participants grasped each dowel, in increasing order of size, between their thumb and index finger of their preferred hand and attempted to lift

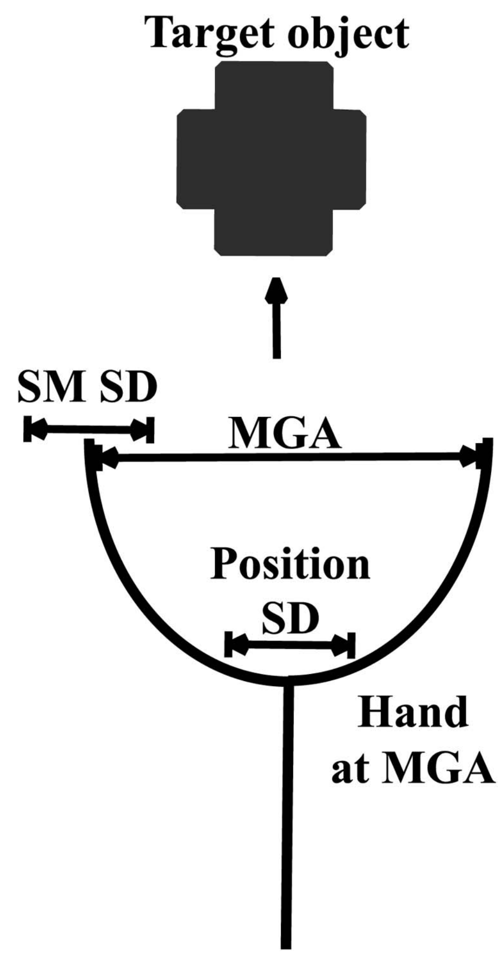

Figure 3. Illustration of the variables used in formulating the dynamic aspect of the affordance model. SM *SD* is the standard deviation of the safety margin (SM) where the SM is the difference between the maximum grasp aperture (MGA) and the maximum object extent (MOE): SM = MGA − MOE. Position *SD* is the standard deviation in the lateral (perpendicular to the direction of the reach) position of hand measured as the position of the midpoint of the grasp aperture.

it from a table top and hold it. If a participant could not maintain a grasp on the dowel for at least 5 s, the length of the previous dowel was considered to be their maximum grip span. Next we measured and recorded the length of the participants' arm from the center of pisiform bone (wrist) to the center of the glenohumeral joint (shoulder).

Participants were assigned to one of four groups based on their gender and hand size, five participants per group. Based upon anthropometrics for adult (male) hand size (Greiner, 1991), we determined that there should be a 3 cm difference in grip span between the 90th and 10th percentiles. We then sampled the grip spans of several tall adult males (height > 183 cm) and several short adult females (height < 157 cm) because hand size is generally related to stature and determined that the large handed males should have grip spans 17 cm or greater and small handed females should have grip spans 13 cm or smaller. Consequently, grip spans for small handed males should be 14 cm or smaller and grip spans for large handed females should be 16 cm or larger. In this study, MG for small handed females were 12 cm (three participants) and 13 cm (two participants). MG for small handed males was 14 cm. MGS for large handed females was 16 cm. MG for large handed males was 17 cm (two participants), 18 cm (two participants), and 20 cm.

During the experiment, each participant sat at a table and reached-to-grasp each of nine objects using the thumb and index finger. Participants started each trial with the thumb and index finger pinching a small mound which was mounted on the table and located ~10 cm from the edge of the table closest to the participant. Each object was placed with its front edge at a distance equal to 70% of the participant's arm length from the starting location. The objects were constructed from a solid piece of hardwood. The objects varied in both width (3 cm, 5 cm, 7 cm) and circular grip surface area (diameters 1 cm, 2 cm, 3 cm) and are shown in Figure 1. The MOEs were as follows: 3.18 cm, 3.65 cm, 4.50 cm (or 3.70 cm; see in the results for explanation of the two values for this object), 4.88 cm, 5.18 cm, 5.81 cm, 7.07 cm, 7.30 cm, 7.75 cm. These objects were designed to be similar to those used by Mon-Williams and Bingham (2011).

Participants performed a total of 90 reach-to-grasp movements. Half were normal speed reaches, half were maximally fast speed: The respective speeds were determined by the individual participants. The reaches were performed in blocks of nine. Within each block each objected was present once, but the order of objects and reach speed (regular or fast) was randomized. Participants were instructed to grasp the objects as accurately as possible between the pads of the thumb and index finger. They were told not lift or move the object. If an object was visibly moved or if a participant reached at the incorrect reach speed, the trial was repeated.

Data Recording and Analysis

The MOE for the nine target objects were measured using a ruler. The AA were computed for each participant and object by subtracting MOE from MG.

Mini-Bird sensors were attached to the center of the participant's fingernail on the index finger and thumb. A sensor was also attached to the participants' pisiform bone (wrist). The x, y, z coordinates of the sensors were recorded by a Mini-Bird motion capture system (Ascension Technology Corporation). z was parallel to the direction of the reach and y was parallel and x perpendicular to the table surface. The data acquisition was initiated approximately 0.5 s–1.0 s before the experimenter's verbal start command and was terminated 0.5 s–1.0 s after the participant successfully grasped the object. Data was collected at 103 Hz and stored for subsequent analyses.

First, the position data was filtered using a dual-pass Butterworth filter with a cutoff frequency of 10 Hz. Then, using a central difference method, velocity was calculated; the velocity data were then filtered using the same filter. Custom analysis routines were then used to determine movement onset and offset as well as the dependent variables for this study. The start of the reach was defined as when wrist velocity initially exceeded 5 cm/s. Reach termination was determined to be when the velocity of the wrist fell below 5 cm/s (after reach initiation). Grasp termination was when velocity of the index finger fell below 3 cm/s. The main dependent measure taken from the trajectories for this study was the MGA (the maximum three-dimensional distance between the thumb and index finger during the reach). Movement time, grasp aperture orientation at MGA, terminal (when hand velocity ≈ 0), and final (digits cease movement) grasp apertures (TGA and final grasp aperture, FGA), and peak velocities were also recorded and examined. The orientation of the grasp aperture at MGA was determined using the x and y coordinates of the index finger and thumb, respectively, and computing the angle with respect to the horizontal, that is, the *y*-axis. This placed the aperture (or the opposition axis) in the same plane as the MOE.

The SM were computed by subtracting the MOE from the MGA for each trial. Also, the y (or lateral) position of the midpoint of the MGA relative to the midpoint of the object was recorded (MGA POS). (The midpoint of the object was measured using the midpoint of the FGA.) Each participant performed five reaches to each of the nine targets at each of the two speeds. For the MGA, SM, and MGA POS, the mean and standard deviation for the five reaches-to-grasp were computed for each participant and each of the 18 [$= 9$ (objects) $\times$ 2 (speeds)] cells.

Analyses were performed using multiple regression. The independent variables used in the regressions were MOE, MG, speed (coded as +/–1), and the standard deviations of the SM and the MGA POS. MOE is the affordance property found by Mon-Williams and Bingham (2011) to determine the effective object size for reaches-to-grasp. MG is the relevant actor size. Speed is reach speed, normal and fast. The standard deviations measured the relevant dynamical stability, that is, the reliability of positioning of the grasp aperture and fingers relative to the target object during a reach. The dependent measures were SM (the safety margin) and P values. The P values were determined as safety margin/available aperture ($P = SM/AA$). The available aperture was the difference between the maximum grip and the maximum object extent ($AA = MG - MOE$). The expectations were that all four independent variables would be significant in analysis of SM, but that MOE would not be significant in analysis of P values. Finally, P values derived from the variability measures were expected to account for variations in actual P values as a function of speed and gender differences, with females exhibiting more conservative P values.

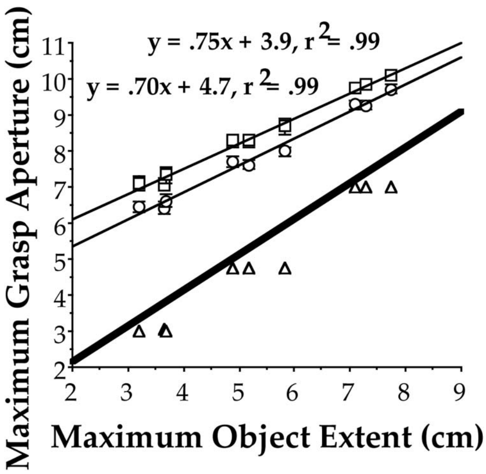

Figure 4. Mean maximum grasp apertures (MGAs) for the nine objects and the two reach speeds (normal and fast) plotted as a function of the maximum object extents (MOEs). Mean MGAs for each reach speed were fitted with a line using least squares regression. Also shown are the object widths and a dark line representing the MOEs. Normal speed reaches: open circles. Fast speed reaches: open squares. Object widths: open triangles. Error bars are standard errors.

Results

We computed the overall mean MGAs for each object and reach speed and plotted them as a function of the object MOEs as shown in Figure 4. Mon-Williams and Bingham (2011) had found similarly that MGAs covaried directly with the MOE. As MOE increased, so did MGAs at about 0.75 the rate of increase in MOE. In our current data, we found one apparent exception to this rule. The MGAs for Object 3 (see Figure 1) fell below the regression lines fitted to the means for both normal and fast speed reaches. As shown in Figure 1, Object 3 was different because the diagonal drawn from the top of the contact surface area on one side to the bottom of the contact surface area on the other side formed an exceptionally large angle ≈ 45° to the horizontal. None of the objects previously tested yielded such a large angle. This angle was large in relation to the range of hand aperture (MGA) orientations found both in the previous and current studies (see Mon-Williams & Bingham, 2011 for analysis of these orientations). The orientation or angle of the MOE determines its length given the object size or width. According the theory, the maximum relevant angle is determined by the variations in orientation of the approach hand aperture. If one reaches-to-grasp a pencil that is in an upright or vertical orientation, the angle formed by the diagonal from top to bottom would be almost 90° and the resulting length of the MOE would equal the length pencil. Obviously, these are both too large. So, what is the limit? We were able to use the data in this case to estimate the largest relevant angle for determining the MOE as the angle for object three that placed the length of the MOE on the regression line. The result is plotted in Figure 4 and illustrated in Figure 1 by the dotted line on Object 3. The MOE length that placed the means on the regression line was produced by a diagonal through the object at ≈ 35°. This was comparable with the largest hand aperture orientations observed at MGA.

Analysis for the Geometric Component of the Model

Safety margins were computed by subtracting MOEs from MGAs. As can be seen in Figure 5, where SM means were plotted as a function of the nine objects and reach speeds, the safety margins varied as a function of object size (or MOE), but inversely to the way MGAs varied with MOE. safety margins were larger for smaller objects. The goal of the original affordance/effectivity model formulated by Mon-Williams and Bingham was to provide an account for this variation in the size of the safety margins. We performed a multiple regression, regressing four factors on SM, namely, the MOE, the MG, the reach speed (normal and fast coded as +/−1), and the variability. First, we performed this analysis by entering two vectors into the analysis, both the SM *SD* and the MGA POS *SD*. However, we found that a single vector composed of the sum of the two standard deviations (total variability [TV] = SM *SD* + MGA POS *SD*) accounted for exactly the same proportion of the variance in safety margins. The result was significant, $F(4, 346) = 59.6$, $p < .001$ and accounted for 40% of the variance. MOE was significant ($t = 11.4$, $\beta = -0.47$, $p < .001$) with a coefficient (or slope) of −0.27. MG was significant ($t = 2.1$, $\beta = -0.09$, $p < .05$). Speed was significant ($t = 6.6$, $\beta = 0.28$, $p < .001$). TV was significant ($t = 5.6$, $\beta = 0.24$, $p < .001$). These results were as expected. The safety margins varied as a function of object size (MOE), grasper size (MG), speed and stability of the reaches.

Next, following the original model, we normed SM using the AA to derive P values (P = SM/AA), where the available spans reflected, in turn, both object size and grasper size). Mon-Williams and Bingham (2011) had found P values to be invariant across the nine objects and to vary with reach speeds: normal speed P = .24 and fast speed P = .35. We computed mean P values for each object, group, and reach speed as shown in Figure 6. We performed a multiple regression on P values, regressing the same four factors as in the previous analysis, except now the total variability was normed by the available aperture (TV/AA). In this analysis, MOE failed to approach significance ($p > .2$) as expected. We

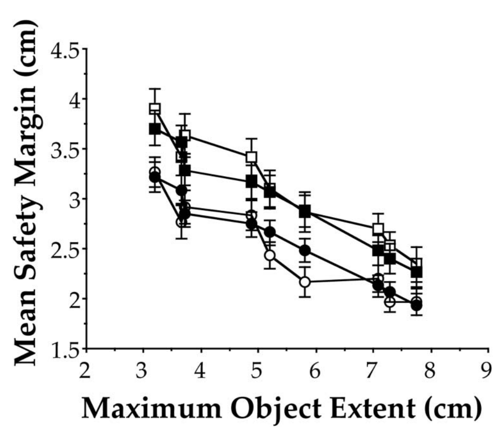

Figure 5. Mean safety margins for the nine objects and the two reach speeds (normal and fast) plotted together with model derived values as a function of maximum object extent. Means for normal speed reaches: open circles. Means for fast speed reaches: open squares. Model derived means for normal speed reaches: filled circles. Model derived means for fast speed reaches: filled squares. Error bars are standard errors.

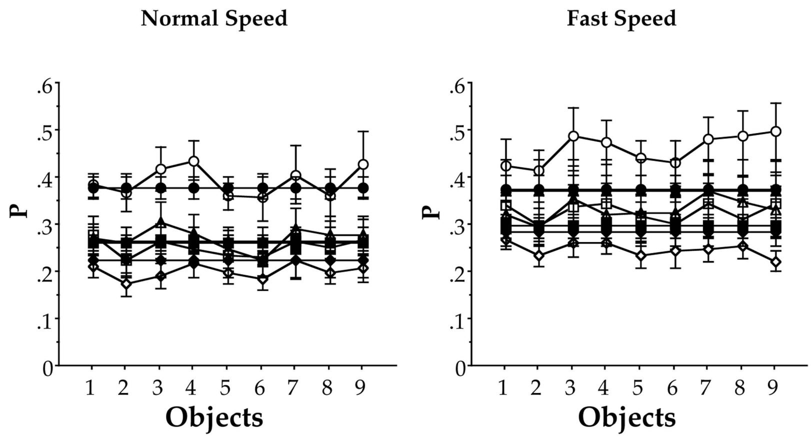

Figure 6. Mean P values plotted by object number for each of the nine objects and each of the four groups. Left panel is normal speed reaches and right panel is fast speed reaches. P = safety margin/available aperture = SM/AA: open symbols. P = 2.5 × Total Variability/Mean Available Aperture = 2.5 × TV/AA_m: filled symbols. Small handed females: circles. Large handed females: squares. Small handed males: triangles. Large handed males: diamonds. Error bars are standard errors.

repeated the analysis after removing the MOE factor. The result was significant, $F(3, 347) = 120.56$, $p < .001$ and accounted for 51% of the variance. MG was significant ($t = 13.8$, $\beta = -0.57$, $p < .001$). Speed was significant ($t = 6.6$, $\beta = 0.25$, $p < .001$). TV/AA was significant ($t = 4.4$, $\beta = 0.18$, $p < .001$). Again, as shown by this analysis and in Figure 6, the P values were invariant over different object sizes, but now varied both with reach speeds and hand size, thus, the groups.

Analysis for the Dynamic Component of the Model

Next, we computed means for each participant and reach speed of TV/AA and of P. We plotted the mean P as a function of the mean TV/AA and performed a simple regression as shown in Figure 7. The result was significant, $F(1, 38) = 35.1$, $p < .001$ and

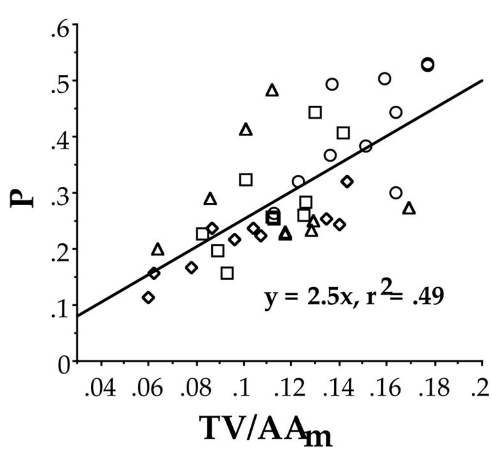

Figure 7. Mean P values plotted as a function of TV/AA_m. P = parameter; TV = total variability; AA_m = mean available aperture. Small handed females: circles. Large handed females: squares. Small handed males: triangles. Large handed males: diamonds. The data were fitted by a line using least-squares regression. The resulting intercept ≈ 0.

accounted for 49% of the variance. The resulting equation returned by the regression was $P = 2.5 \times TV/AA_m$, where AA_m is the mean available aperture for a participant and is, thus, a task and object relative measure of actor size. The intercept was $0.004 \approx 0$. This was similar to the result in Snapp-Childs and Bingham (2009) who found that 2 × Step Height Variability/Leg Length predicted the safety margins.

Using this result, we computed "dynamic" P values (P_D), for each participant and reach speed, predicted using the mean normed variability: $P_D = 2.5 \times TV/AA_m$. Returning to the data for each object, participant and speed, we multiplied participant and speed specific P_D values by object and participant specific AA values to derive predicted safety margins. We then performed the same multiple regression as performed on the actual safety margins. The result was significant, $F(4, 346) = 173.4$, $p < .001$ and accounted for 67% of the variance. MOE was significant ($t = 17.2$, $\beta = -0.54$, $p < .001$) with a coefficient (or slope) of −0.26. MG was significant ($t = 4.3$, $\beta = 0.14$, $p < .001$). Speed was significant ($t = 4.4$, $\beta = 0.14$, $p < .001$). TV was significant ($t = 15.0$, $\beta = 0.49$, $p < .001$). These results replicated those when the analysis was performed on the actual safety margins. We computed mean values of P_D and of P for each group (four), object (nine), and speed (two) cell yielding 72 values in each case. We regressed P_D on P. The result was significant, $F(1, 70) = 219.2$, $p < .001$ and accounted for 76% of the variance and the fitted linear relation was $P_D = 1.28 \times P - 0.08$. These values were plotted together in Figure 6 with corresponding *SE* bars. There it can be seen that the fit is modestly good, but did not well capture the behavior of the small-handed females relative to the large-handed males, especially with speed variations.

When we performed versions of the previous multiple regressions on SM, P, and P_D in which we now included all of the interaction vectors, we found in each case that the only significant ($p < .05$ or less) interactions involved MG and, in particular, it was MG × TV that was significant. MG indexes the different groups. We had anticipated that there might be a reliable difference in SM, and thus, P values as a function of gender. So, we performed a multiple regression regressing TV/AA_m, Gender (coded as +/–1), and the interaction vector on mean P values (reprising the analysis corresponding to Figure 7, but now including gender). The result was significant, $F(3, 36) = 17.6$, $p < .001$ and accounted for 60% of the variance. TV/AA_m was significant ($t = 5.4$, $\beta = 0.63$, $p < .001$). Gender was significant ($t = 2.1$, $\beta = 0.99$, $p < .05$). Gender $\times$ TV/AA_m was significant ($t = 2.7$, $\beta = -1.22$, $p < .02$). (When we ran this analysis including speed and all interactions, none of these factors reached significance at $p < .05$.) We computed coefficients relating TV/AA_m to P_D separately for each gender. Males: $P_D = 2.0 \times TV/AA_m$. Females: $P_D = 3.0 \times TV/AA_m$. The gender specific Model P_D values were plotted against actual P values in Figure 8, where the fit can be seen to be quite good. We regressed the gender-specific Model P_D values on P values and the result was significant, $F(1, 70) = 291.5$, $p < .001$ and accounted for 81% of the variance and the fitted linear relation was $P_D = 0.885 \times P + .04$.

Finally, we computed model safety margins (SM_{mod}) by multiplying AA for each object, participant and reach speed by the appropriate gender specific P_D. We computed means for each group, object and speed and then, regressed these model generated safety margins on the actual safety margins. The result was significant, $F(1, 70) = 223.2$, $p < .001$ and accounted for 76% of the variance and the fitted linear relation was $SM_{mod} = 0.99 \times SM + 0.02$. The fit was excellent, as shown in Figure 9, with slope ≈ 1.0 and intercept ≈ 0.

General Discussion

The goal of this study was to provide an account for the remaining free paramenter in an affordance model developed by

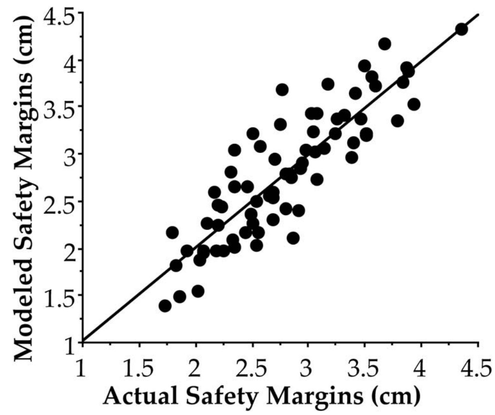

Figure 9. Modeled safety margins plotted as a function of actual safety margins. Means for each group, object, and speed. The data were fitted by a line using least-squares regression. See the text for details.

Mon-Williams and Bingham (2011) to predict the spatial structure of reaches-to-grasp. Formulating a geometric model in line with Warren's affordance scaling models (e.g., Warren, 1984; Warren & Whang, 1987), Mon-Williams and Bingham showed that MGA include a safety margin that is scaled as an invariant proportion, P, of the AA, that is, the difference between object size and the actor's maximum grip span. However, they also found that this proportion varied in size as a function of the speed of reaching with faster reaches exhibiting larger P values. Given the predictions of Fitts' Law, one would expect the positional variability for faster reaches to be greater. This, in turn, suggested that P values might be determined by the positional variability. Indeed, Snapp-

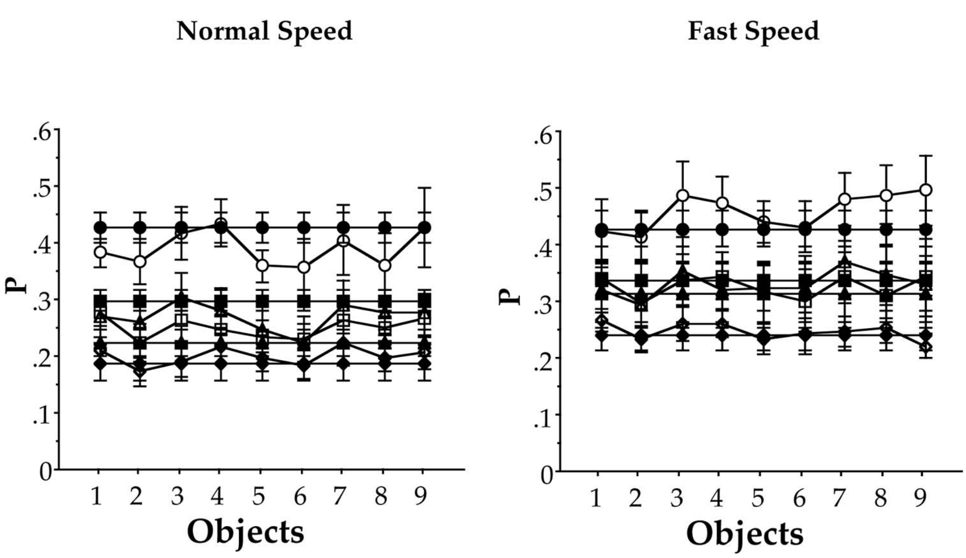

Figure 8. Mean parameter (P) values plotted by object for each of the nine objects and each of the four groups. Left panel is normal speed reaches and right panel is fast speed reaches. $P = (MGA - MOE)/AA = SM/AA$: open symbols. For males, $P = 2.0 \times$ Total Variability/Mean Available Aperture $= 2.0 \times TV/AA_m$ and for females, $P = 3.0 \times$ Total Variability/Mean Available Aperture $= 3.0 \times TV/AA_m$: filled symbols. Small handed females: circles. Large handed females: squares. Small handed males: triangles. Large handed males: diamonds. Error bars are standard errors.

Childs and Bingham (2009) had extended the geometric affordance model applied to stepping height by adding a dynamical component that scaled the safety margins in stepping as a function of the positional variability in stepping. They found that the safety margins scaled as a function of the variability normed by the appropriate linear dimension of the stepper, that is, safety margins were proportional to 2 × step height *SD*/leg length. Adding a dynamical component to on the actor side of the modeled affordance relation makes sense because the relevant task involves the dynamics of the control of the action. The stability of those dynamics are bound to be relevant to the scaling relation between the perceiver/actor and the environment captured by an affordance model.

A second goal of this study was to test the model using the standard paradigm for testing affordance models, that is, to test large and small people to determine whether the intrinsic scaling of the affordance model yields the predicted invariance. Hence, we tested participants with small and large maximum grips, each group falling within approximately the bottom and top 5% of the distribution. However, a problem emerged with this design, namely, all of the largest handed participants would be male and all of the smallest handed participants would be female. More to the point, the formation of safety margins entails risk assessment. The literature on decisions and risk assessment shows that there are reliable gender differences with females being more conservative than males. So, we added gender as another factor and tested small and large handed females and small and large handed males, where each group consisted of members falling approximately in the bottom or top 5% of hand size for the gender.

Three results were produced by the current study. First, Mon-Williams and Bingham (2011) had discovered that the affordance property of objects, corresponding to object size, was the so-called MOE. The MOE is the length of a diagonal through the object extending from the top of the grasp contact surface area on one side to the bottom of the grasp contact surface area on the other side. The reason for MOE being the object size affordance property was that hands do not "fly in" with the grasp aperture (or opposition axis) perpendicular to gravity. Instead, the orientation of the aperture varies both systematically (with object size) and randomly. Thus, the collision hazard presented by an object to be grasped is determined by the size of a diagonal extent through the object that corresponds to the maximum possible deviation in the orientation of the grasp aperture from the horizontal. Mon-Williams and Bingham (2011) did not specify what the maximum angle of deviation might be. That is, for instance, when reaching to grasp an upright pencil, should the MOE extend from the top to the bottom of the pencil or should the diagonal be at a smaller angle than this? We were able to use the data in the current study to estimate this maximum angle for the MOE as ≈35° from the horizontal. This was consistent with an estimate of the maximum deviations from horizontal of grasp apertures found in Mon-Williams and Bingham (2011).

Second, we found that P values did in fact vary as a function of the scaled positional variability of the fingers relative to the object at the moment of MGA during a reach-to-grasp. We normed the measure of this variability using the mean size of the available aperture for the participant. When we regressed these on the P values, we found a scaling relation similar to that found in Snapp-Childs and Bingham (2009). That scaling was then used to generate model "Dynamic" P values: $P_D = 2.5 \times TV/AA_m$. So, the stability of the reach dynamics in producing the position of the grasp aperture as it approached the target object, when scaled by a task specific measure of actor size, yielded a good prediction of the size of safety margins exhibited in reaches-to-grasp. However, we found that the prediction could be improved.

Because the distributions of hand sizes were gender specific and given known differences in risk assessment as a function of gender, we included gender as a factor in the study. We found that females were exhibiting P values that were larger than those characteristic of the males. When we entered gender into the regression of normed variability on P values, we discovered reliably different scaling as a function of gender. Females were more conservative than males, acting to incur less risk of collision. Females exhibited safety margins that were three times the normed positional standard deviation, that is, larger than 99% of the positional errors. In contrast, males produced safety margins only twice the normed positional standard deviation, that is, only larger than 95% of the positional errors. They risked the 4% that females would not.

So, we now have a parameter-free affordance model of the spatial structure of reaches-to-grasp. These results and the affordance model have implications for future process models of reaches-to-grasp. If such models are to capture the parametric scaling of the grasp formation as represented by the current affordance model, then five aspects of reaches-to-grasp that have not previously been considered in such models must be included. The first is the effective size of the actor's hand, that is, the functionally determined maximum grip. The second is the spatial variability in positioning of the fingers over the reach-to-grasp trajectory. The third is variations in the orientation of the grasp aperture as the hand approaches the target object. Mon-Williams and Bingham (2011) found those variations to be both random and systematic, varying as a function of the MOE. The variability in the orientation of the grasp aperture contributes to the variability in the spatial position of the fingers along the trajectory. Fourth, the level of risk tolerated by the actor in determining a safety margin is required to transform the scaled spatial variability to the size of grasp apertures. Finally, the relevant property of the target object that determines its size in respect to grasping is the MOE, that is, not the width or horizontal extent in a plane perpendicular to the direction from which the reach approaches the object, but instead, the maximum length diagonal in that plane through the object up to a deviation from the horizontal of about 35°.

The strongest constraints on future process models will likely derive from variations in orientation and positional variability of the grasp aperture. Mon-Williams and Bingham (2011) analyzed the structure of the positional variability at MGA and found a lack of independence of the variability in the positions of the index finger and thumb. The result supported the "opposition axis" (Iberall, Bingham & Arbib, 1986) as a higher order coordinative unit that is controlled in reaches-to-grasp and failed to support a process model that controls the index finger and thumb as independently targeted to locations on an object to be grasped (Verheij et al., 2012). As one might expect, Fitts' Law also appears to be reflected in the patterns of the reach-to-grasp positional variability. Thus, a process model that captured these patterns should also provide some understanding of the processes yielding Fitts' Law.

Thus, we suggest that the current results provide a good context for the next generation of process models.

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