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RESEARCH ARTICLE

Change in effectivity yields recalibration of affordance geometry to preserve functional dynamics

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Abstract

Mon-Williams and Bingham (Exp Brain Res 211(1):145–160, 2011) developed a geometrical affordance model for reaches-to-grasp, and identified a constant scaling relationship, *P*, between safety margins (SM) and available apertures (SM) that are determined by the sizes of the objects and the individual hands. Bingham et al. (J Exp Psychol Hum Percept Perform 40(4):1542–1550, 2014) extended the model by introducing a dynamical component that scales the geometrical relationship to the stability of the reaching-to-grasp. The goal of the current study was to explore whether and how quickly change in the relevant effectivity (functionally determined hand size = maximum grip) would affect the geometrical and dynamical scaling relationships. The maximum grip of large-handed males was progressively restricted. Participants responded to this restriction by using progressively smaller safety margins, but progressively larger *P* (= SM/AA) values that preserved an invariant dynamical scaling relationship. The recalibration was relatively fast, occurring over five trials or less, presumably a number required to detect the variability or stability of performance. The results supported the affordance model for reaches-to-grasp in which the invariance is determined by the dynamical component, because it serves the goal of not colliding with the object before successful grasping can be achieved. The findings were also consistent with those of Snapp-Childs and Bingham (Exp Brain Res 198(4):527–533, 2009) who found changes in age-specific geometric scaling for stepping affordances as a function of changes in effectivities over the life span where those changes preserved a dynamic scaling constant similar to that in the current study.

Keywords Reach-to-grasp · Affordance · Perception/action · Calibration · Body size

Introduction

> The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. The verb to afford is found in the dictionary, but the noun affordance is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment.
> James J. Gibson (1986, p. 127)

Ever since James Gibson proposed the revolutionary idea of affordances in his *Ecological Approach to Visual Perception*, there has been much development in the field. As explicitly stated in the quote above, affordances are about a relationship between the organism and the environment. Turvey et al. (1981) formalized Gibson's theories about affordances. They argued that there are two properties one can use to depict the relationship, namely affordances and effectivities. The former refers to properties of an object in relation to the action abilities of an animal that enable specific actions for that animal, whereas the latter refers to action-relevant properties of the animal that allow the animal to perform the action using the object. Thus, affordances are object properties while effectivities are properties of the organism, and in both cases, they are action relevant properties. To empirically investigate affordance theory, one needs to identify invariants that capture the relationship between the complementary properties of the organism and the environment for a specific task across different individuals. Specifically, one can characterize such invariant relationships through geometrical and dynamical scaling.

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Geometrical scaling corresponds to the invariant relationship between geometrical scale of the organism in relation to the environment, whereas dynamical scaling corresponds to the invariant relationship between an actor's error tolerance and variability or stability of the action (Snapp-Childs and Bingham 2009). Subsequently, we will illustrate each form of scaling and discuss their specific roles in the context of reaches-to-grasp.

Warren (1984) applied the ideas of affordances to investigate stair climbing, characterizing the relationship between actor and environment in geometric terms relating the actor's leg length to the riser height of a stair. His results suggested that there is an invariant scaling relationship between the two for people with different leg lengths, which marked the action boundary for climbing stairs, i.e., the height of stairs that required the actor to use both hands and legs to climb, instead of just using their legs. He also measured the actor's energy consumption during stair climbing and found that the ratio between stair height and leg length was invariant for people with different leg lengths when they were climbing the stairs that yielded minimum energy consumption. Similarly, when studying the action of passing through an aperture, e.g., a doorway, Warren and Whang (1987) found that there was a constant ratio between the size of actors' shoulder width and the aperture's width that marked the point when they began to turn their shoulders to avoid running into the aperture. Both studies focused on the geometrical scaling relationship between features of the organism, such as leg length or shoulder width, and properties of the environment, such as riser height or aperture width, for a specific action, such as stair climbing or passing through an aperture. Following these inaugural studies, most research on affordances has focused on identifying invariant geometrical scaling relationships [e.g., Cesari and Newell 1999; Choi and Mark 2004; Stefanucci and Geuss 2010; see Challis (2018) for a review].

Snapp-Childs and Bingham (2009) attempted to apply this approach to a study of the action of stepping onto or over a barrier performed by children of different ages and adults. The problem found in previous studies was that invariant scaling did not exist across ages. Specifically, as age increased, the relative amount of toe clearance (the distance between the toe and the obstacle, both scaled by leg length) decreased. This circumstance led the investigators to analyze the problem functionally. The toe clearance functioned as a safety margin to ensure that the actor would not trip before the stepping. It is the reliability of stepping and toe clearance over various occasions that determines the likelihood of tripping on any particular occasion. The stability of the performance reflects not just the geometry, but, in addition, the control dynamics. They investigated the variation in the variability of the toe clearance as a function of age and found that indeed, the variability decreased with increasing age. Furthermore, they found a constant scaling relationship between leg-length-scaled toe clearance and toe clearance variability, where the safety margin was twice the variability. This phenomenon was what they identified as a dynamical scaling relationship, which captures the scaling between an action relative to an object and the variability of that action, a reflection of one's own action capabilities [or effectivity, as described by Turvey et al. (1981)]. This study revealed the fact that affordances do not solely reflect an invariant geometrical relationship between organisms and the environment, but also invariance found in the dynamics of the perception and action system, the stability of the action itself, an effectivity.

While Snapp-Childs and Bingham (2009) studied the change of effectivities over the lifespan, others have investigated changes that occur over a short period of time, where the organism's behavior would exhibit adaptation or recalibration. Mark (1987) altered leg length by having participants wear 10 cm blocks or stilts to study how it would affect their visual judgments of maximum seat height. He found that participants exhibited gradual recalibration in perceptual judgments over trials, where they were not allowed to actually sit. Fajen (2005, 2007a) later developed an affordance-based control model that took into consideration what he called the problem of action boundaries (Fajen 2005), which was essentially the constraints imposed by an actor's effectivity. Fajen (2005) showed that to act within one's action capability, specifically one's braking capability, the actor needs to calibrate, meaning to map the information that guides the specific action to the action itself. In this experiment, he manipulated brake strength and found that for participants with different braking capability, that is, maximum decelerations, the ratio between the ideal deceleration at onset and maximum deceleration was constant (where the ideal is the constant deceleration that yields a stop at a target). Furthermore, in a later study, Fajen (2007b) found that in the face of ongoing change in action capability, the actor would continuously use the perceptual information to produce ongoing adjustments during a trial, demonstrating a rapid recalibration without knowledge of results of the task. Comparing Fajen's results to the recalibration found in Mark (1987) and other subsequent studies (e.g., Bingham and Mon-Williams 2013), the rate at which recalibration occurred was different. According to Fajen (2007a), this reflected the fact that braking is an action-scaled affordance, that is, continuously altered throughout the course of the action based on perceptual feedback about the movement itself, whereas sitting is a body-scaled affordance that does not require constant perceptual feedback to execute.

Given this context, we investigated the recalibration of reaches-to-grasp in response to changes in the grasping effectivity. Reaching-to-grasp entails two separate goals, namely collision avoidance and targeting (Bootsma et al.

1994; Rosenbaum et al. 1999; Mon-Williams and Bingham 2011; Bingham et al. 2014). Collision avoidance requires the span of the grasp aperture between the fingers and thumb as the hand approaches a target object to be wide enough to avoid hitting the object before being able to grasp it. The goal of targeting is to place the fingers and thumb on opposing surface locations on the object, where the locations are typically selected to place an axis between the contact points through the object relative to its center of mass (Iberall et al. 1986; Mon-Williams and Bingham 2011). Reaching-to-grasp has been studied extensively, primarily with a focus on the temporal structure of the action (e.g., Jeannerod 1984; Hoff and Arbib 1993; Parsons 1994; Ansuini et al. 2015). For instance, Jeannerod (1984) studied the relative timing of different features of the movement, where he found that the peak velocity of the reach was correlated with when the thumb and index finger were at maximum distance (i.e., the maximum grasp aperture or MGA), whereas the low-velocity phase was correlated with when the thumb and index finger began to close in on the object.

Mon-Williams and Bingham (2011) investigated reaches-to-grasp from an affordance perspective to identify the scaling of the spatial structure relative to the collision avoidance and targeting goals. They found that the maximum grasp aperture (MGA) (the widest opening between the fingers and thumb before they start to close down on the object) reflects the collision avoidance goal, whereas the terminal grasp aperture (TGA) (when the hand stops moving but prior to fingers closing on the object) reflected the targeting goal (see also Bingham et al. 2008; Coats et al. 2008; Lee and Bingham 2010). They also found that the relevant property of the object for collision avoidance was the maximum diagonal distance through the object across which the participants grasped, called the maximum object extent (MOE), while the relevant object property for the targeting goal is the object's width.

Based on their results, Mon-Williams and Bingham formulated a geometrical affordance model, incorporating the object scale (MOE), the actor scale [effective hand size or maximum grip (MG)], and the task goals. They defined the safety margin (SM) as the difference between the MGA and the MOE (SM = MGA − MOE), and the available aperture (AA) as the difference between MG and MOE (AA = MG − MOE). They found that there is an invariant scaling (P) between the safety margin and the available aperture ($\mathrm{SM} = P \times \mathrm{AA}$). Additionally, they also found that P varied as a function of reach speed (smaller for medium or normal speed reaching and greater for high speed reaching). This model simply means that when the collision avoidance goal was more difficult to attain (reaching at a higher speed), the actor would resort to a more conservative grasp strategy, using a larger proportion of their available aperture in the safety margin to avoid collision during the reach. The proportional nature of these relationships simply reflects the absolute limit on the range of variation, that is, the maximum grip size.

In a subsequent study, Bingham et al. (2014) introduced a dynamical component to the original geometrical affordance model, namely, a stability component just as in the previous study of stepping (Snapp-Childs and Bingham 2009). For reaches-to-grasp, they noted that two components of variability would be relevant: variability of the safety margin (measured as SM SD, reflecting the stability in grasping performance relative to the collision avoidance goal) and variability of the lateral position of the MGA (MGA POS SD, reflecting the stability in reaching performance relative to the targeting goal). They defined the MGA POS as the lateral distance between the midpoint of the MGA relative to the center of the object [measured as the midpoint of the final grasp aperture (FGA)]. The total variability (TV) is simply the sum of the two components (TV = SM SD + MGA POS SD). Finally, according to Mon-Williams and Bingham (2011), because the safety margin varied as a function of the available aperture, the total variability should be similarly scaled. This was a task and object-dependent measure for every participant. Over four groups of participants, large- and small-handed men and women, respectively, all reaching at normal and fast speeds, they found a constant dynamical scaling relationship between P (= SM/AA) and variability, that is, $P = \delta \times \mathrm{TV/AA}$, where δ scales the geometrical invariant to the dynamical invariant. The direct interpretation of δ is as a measure of risk tolerance, that is, the proportion of the safety margin the actor employs to guard against the variability of movement. Based on this interpretation, they found that males had a smaller δ than females, suggesting that the men were more risk tolerant than the women.

In the current study, we tested a group of large-handed males to investigate whether reaches-to-grasp would adapt to changes in effective hand size and if so, whether the invariance of the dynamical scaling would be preserved. We used a device to constrain and reduce the maximum grip size, thus, functionally shrinking the hand size. The goals of the current experiment were twofold. First, we further tested the geometrical and dynamical affordance model developed by Mon-Williams and Bingham (2011) and Bingham et al. (2014), with a focus on the dynamical invariant. Would it be preserved? Second, we perturbed the effectivity (or action capability) relevant to reaches-to-grasp. Based on Fajen's affordance-based control model (Fajen 2007a), we expected recalibration of the geometric scaling to occur.

Method

Participants

Ten male participants took part in the experiment and were paid $10/h for their participation. All participants had normal or corrected to normal vision and normal motor abilities. All participants were right handed with large hand size, whose selection criteria would be discussed in "Apparatus and procedure". All participants gave their informed consent approved by the Indiana University IRB prior to the beginning of the study.

Apparatus and procedure

We used large-handed males as our participants, since their large hand size provided plenty of room for restriction. We recruited our participants using the method similar to that in Bingham et al. (2014) by recruiting tall adult males (height > 180 cm). After providing their informed consent, participants were seated at the testing table. We first determined participants' maximum grip (MG). Bingham et al. (2014) found that MG has to be determined functionally, rather than anatomically. Instead of measuring the maximum distance between the tips of participants' thumb and index finger, we asked participants to try to lift each of a series of wooden dowels varying in length to find the longest that they could grasp and hold by spanning the length with their thumb and index finger contacting the ends. The dowels incremented by 1 cm in length, ranging from 10 to 22 cm. Participants began with the shortest and tried to hold the grasp for at least 5 s. If they consistently failed to hold the grasp, then the length of the previous dowel was considered as the participants' MG. The resulting range and mean maximum grips were $\mathrm{MG}_{\min} = 17$ cm, $\mathrm{MG}_{\max} = 19$ cm, mean = 17.50 cm. The minimum MG in the current study was in accordance with that for large-handed males in Bingham et al. (2014).

To alter participants' MG, we devised a prosthesis for restricting the MG (Fig. 1). We used the Mini-Bird motion capture system (Ascension Technology Corporation) to record the kinematic data. We attached the system's sensors to the center of the finger nails of the participants' thumb and index finger. A third sensor was also attached to the participant's pisiform bone (wrist). Each sensor generated a series of real-time recording of its position on the x, y, and z coordinates. The x axis was parallel to the direction of the reach, the y axis was perpendicular to the direction of the reach in the plane parallel to the table surface (egocentric left and right), and the z axis was perpendicular to the table surface. Data recording was initiated 0.5–1.0 s prior to experimenter's verbal start command and was terminated 0.5–1.0 s after the participant had successfully grasped the object. Data were recorded at a sampling frequency of 103 Hz. One participant's data had to be discarded due to technical malfunctions of the recording device during the experiment.

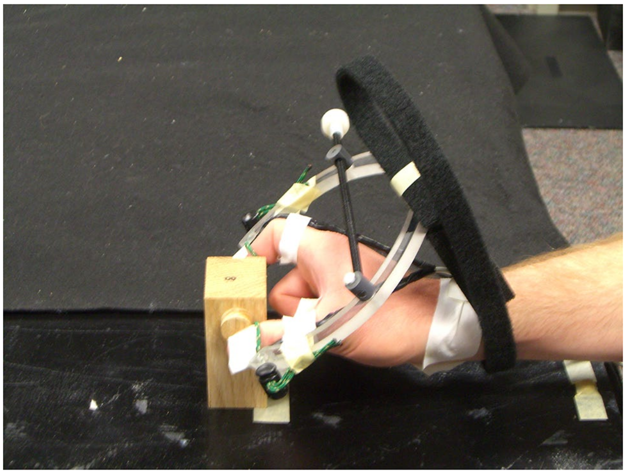


Fig. 1 Restriction prosthesis used for the experiment

During the experiment, participants were asked to reach-to-grasp each of the nine wooden objects using thumb and index finger at a fast speed. We used the same objects as used in Bingham et al. (2014). They had equal height (9 cm) and depth (4 cm), and varied in width (3 cm, 4.7 cm, and 7.1 cm) and circular grasp area (diameters 1 cm, 2 cm, and 3.2 cm). Consequently, these width and grasp area combinations yielded unique objects with different maximum object extent (MOE): 3.18 cm, 3.65 cm, 4.50 cm, 4.88 cm, 5.18 cm, 5.81 cm, 7.07 cm, 7.30 cm, and 7.75 cm. Figure 2a shows the schematic illustration of the object dimensions, and Fig. 2b shows the actual objects used in this experiment. They could readily be knocked over if collision avoidance failed.

Within each trial, we asked participants to flex and extend their fingers and hand to ensure free movement after markers were placed on their corresponding positions. Participants began reach-to-grasp after the verbal command "start", and, upon the completion of reach-to-grasp, they kept their final hand and finger positions until given a verbal "stop" command. Data acquisition was initiated approximately one second prior to the start command and was terminated approximately one second after the stop command. The starting position was marked at the edge of the table, and the distances between the participants and the object, and the reach start position and the object were constant relative to participants' arm lengths. The distance between the edge of the object that faced the participants and the participants was 70% of the participants' arm length, while the distance between that edge and the reach start position was 30% of the arm lengths.

Participants each performed 16 blocks of the reach-to-grasp task. Each block consisted of nine randomized trials of reaches-to-grasp the nine different target objects for a total of 144 trials for each participant. The 16 blocks were divided

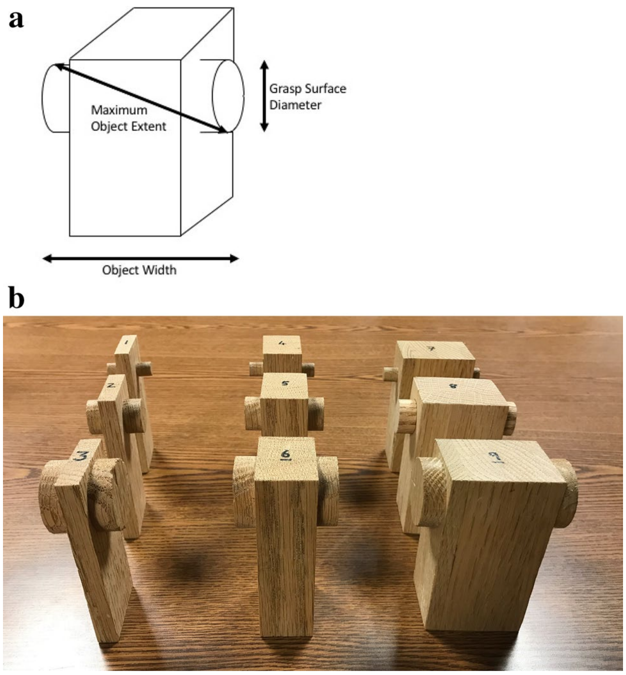


Fig. 2 Objects used in the experiment. **a** A schematic of the objects. Different objects varied in width (3 cm, 4.7 cm, and 7.1 cm), and grasp surface diameter (diameters 1 cm, 2 cm, and 3.2 cm). Fully crossing the object width and diameter produced nine objects, each with different MOE, 3.18 cm, 3.65 cm, 4.50 cm, 4.88 cm, 5.18 cm, 5.81 cm, 7.07 cm, 7.30 cm, and 7.75 cm. **b** The actual objects

into four different conditions, in which we varied the effectivity. For the first 3 blocks of the experiment, participants reached-to-grasp target objects with their bare hands (condition 1: no perturbation). In the following 3 blocks, participants wore the device that would restrict their MG, but with a setting that did not alter the MG (condition 2: device with normal span). This step was to allow participants to become familiar with the device and to measure any resulting perturbing effect. Next, participants performed 5 blocks of trials in which a 20% perturbation was applied to the MG (condition 3: 20% perturbation). In the last five blocks, we applied a 35% perturbation (condition 4: 35% perturbation).

Data analysis

The first step in processing the recorded data was to filter them using a dual-pass Butterworth filter with a cutoff frequency of 10 Hz. Then, we used a central difference method to calculate the velocity, which was filtered using the same filter. We adopted the same custom analysis routines as in Bingham et al. (2014) to determine the movement onset and offset, and a series of dependent variables pertinent to the analysis of the results. Reach initiation was defined as when the wrist velocity exceeded 5 cm/s, while reach termination was defined as when the wrist velocity fell below 5 cm/s after reach initiation. The grasp initiation and termination were defined as when the velocity of the index finger went above and fell below 3 cm/s, respectively.

We subsequently computed various geometrical components. We derived the available aperture (AA) by subtracting MOE from MG. The maximum grasp aperture (MGA) was the maximum three-dimensional distance between the thumb and index finger during the reach. The terminal grasp aperture (TGA) was the 3D distance between thumb and index finger at reach termination, while the final grasp aperture (FGA) was the distance at grasp termination, fingers in contact with the target object. Safety margin (SM) was computed by subtracting MOE from MGA. We also computed the relative lateral (y) position of the midpoint between thumb and index at MGA and center of the object determined at the midpoint between thumb and index at FGA (MGA POS). We derived the distance to the center of the object as the distance between the midpoint between the thumb and index at FGA and at the reach starting position. The P values were computed as the ratio of SM and AA ($P = \mathrm{SM/AA}$). Moreover, to capture variabilities of the targeting and collision avoidance goals, we computed the standard deviations of MGA POS (MGA POS SD) and SM (SM SD) for a given object for each condition for each participant. Total variability (TV) was the sum of MGA POS SD and SM SD. Finally, we computed the scaling factor, δ, between the relative variability, TV/AA, and P ($P = \delta \times \mathrm{TV/AA}$). See Glossary for a complete list of the terms and their corresponding operational definitions.

Statistical power analysis

We used repeated-measure analysis of variance (ANOVA) to evaluate the effects of conditions on various geometrical and dynamical components of reaches-to-grasp. There was a total of 4 levels of the within-subject perturbation condition (i.e., no perturbation, with device, 20% restriction, and 35% restriction). Within the first two conditions, there was a total of 3 blocks, consisting of 9 trials per block, resulting in a total of 27 trials per condition. The latter two conditions had 5 blocks, resulting a total of 45 trials per condition. To determine the appropriate sample size, we performed a power analysis using G*Power Version 3.1.9.3 (Faul et al. 2007, 2009). We used $\alpha = 0.05$ and a desired power of 0.95. Based on Bingham et al. (2014), the approximate effect size for the model is 0.40. Power analysis showed that 8 participants would be sufficient to achieve a power of 0.95. Combining the above power analysis with the fact that a similar number of participants was used in the previous study with a similar experimental paradigm [i.e., 10 participants for each gender group in Bingham et al. (2014)], we concluded that the use of ten minus one participants would be appropriate in our current experiment.

Results

We analyzed first the geometrical and then the dynamical components of the affordance model.

Analysis of the geometrical component

First, we analyzed the safety margin. Figure 3 shows the mean safety margin as a function of trial number over the successive conditions. As expected, there was no change simply in response to application of the device with no restriction on the MG. However, with a 20% restriction of the MG, SM abruptly dropped, and then dropped farther with 35% restriction.

We ran a repeated-measures analysis of variance (ANOVA) on safety margin with condition as the within-subject factor (Fig. 4). For each condition, we computed the mean safety margin for each participant excluding the first block due to the initial jump. Mauchly's test of sphericity showed the sphericity assumption was violated ($\chi^2(5) = 22.94$, $P < 0.001$). With Greenhouse–Geisser correction, there was a significant effect of condition ($F(1.37, 10.92) = 10.86$, $P < 0.01$, $\eta_p^2 = 0.58$). Post hoc analysis with LSD correction showed that condition 1 had a significantly larger safety margin than all other conditions ($P < 0.05$).

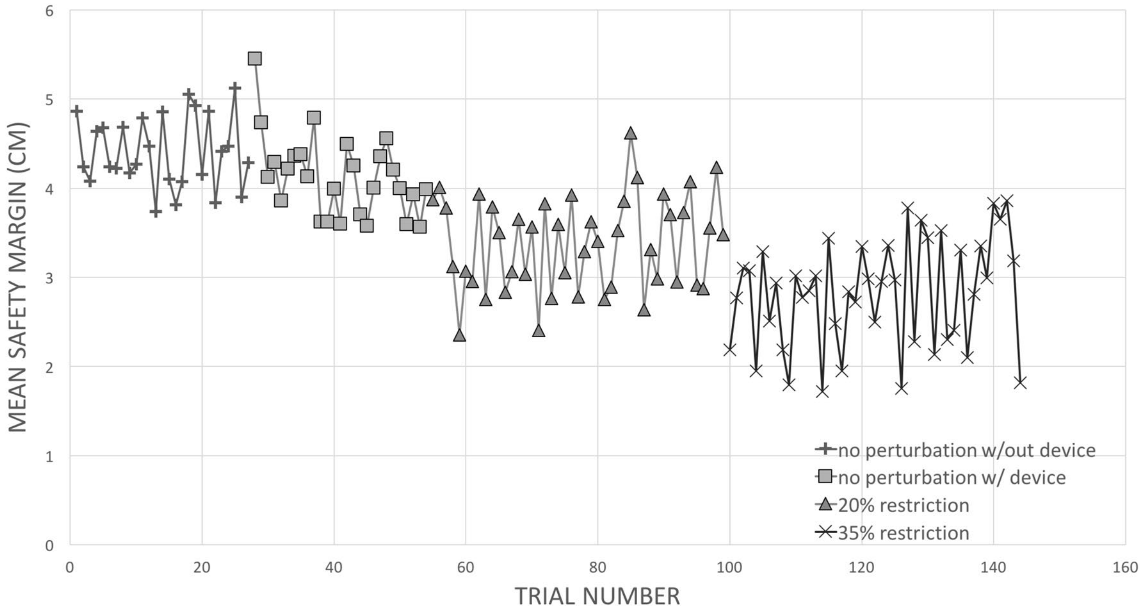
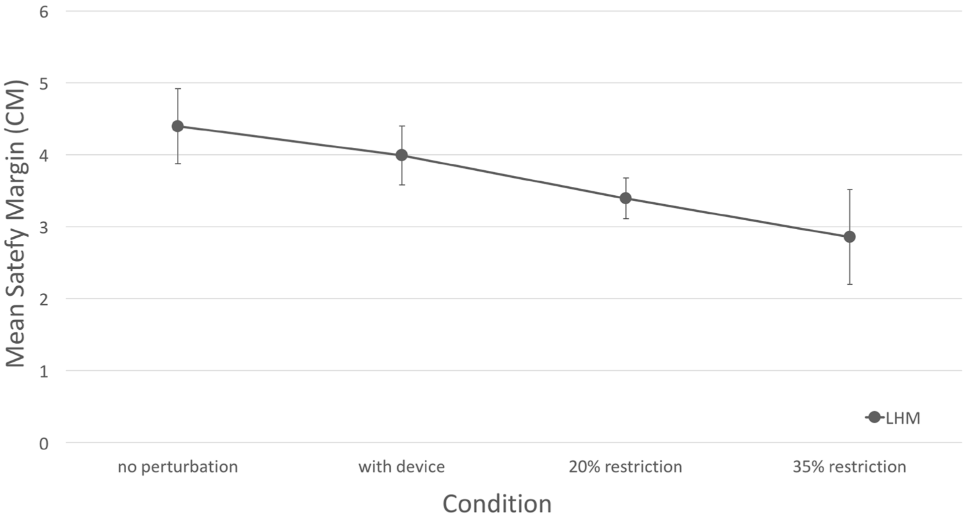


Fig. 3 Mean safety margin (SM) for each trial

Fig. 4 Mean safety margin (SM) for four different conditions. Error bars represent 95% confidence intervals around the mean, calculated for repeated-measures designs (Cousineau 2005; with correction by; Morey 2008)



Condition 2 had a significantly larger safety margin than conditions 3 and 4. Condition 3 had a significantly greater safety margin than condition 4 ($P < 0.05$). Thus, as the effective hand size decreased, so did the safety margins.

Next, we analyzed P, the geometric scaling in the original affordance model. P is the ratio of the Safety margin and the available aperture and represents the proportion of the difference between hand size (MG) and the object size used for the safety margin. The mean P trajectories can be seen in Fig. 5. As shown in the plot, participants started in the unperturbed condition at a P value ≈ 0.35, a value observed in previous studies. However, P changed, growing in size, with increasing change in MG that progressively reduced effective hand size. A sudden increase in P occurred in the initial trials of each successive condition.

We ran a repeated-measures ANOVA on P values with condition as the within-subjects factor. Means are shown in Fig. 6. Mauchly's test of sphericity again showed the sphericity assumption was violated ($\chi^2(5) = 23.81$, $P < 0.001$). With Greenhouse–Geisser correction, there was a significant effect of condition ($F(1.37, 10.95) = 9.69$, $P < 0.01$, $\eta_p^2 = 0.55$). Post hoc analysis with LSD correction showed that restricting MG yielded significantly increasing P values, where conditions 3 ($P < 0.05$) and 4 had significantly larger P values than did condition 2 ($P < 0.05$).

Thus, the geometrical analysis of the reaches-to-grasp showed that, as the MG or effective hand size was restricted, participants recalibrated, increasing the geometric scaling constant, P, of the affordance model. Even though the safety margins themselves actually shrank with the shrinking hand size, the proportion of the resulting available apertures used for the safety margins increased.

Analysis of the dynamical component

We computed two variability measures, the variability of the hand position during the reach and, at the same time,

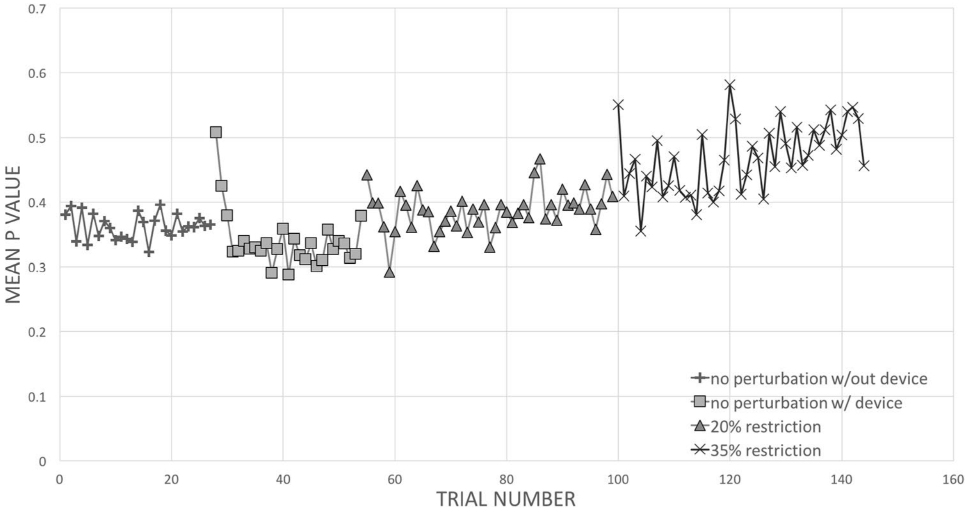


Fig. 5 Mean P values for each trial

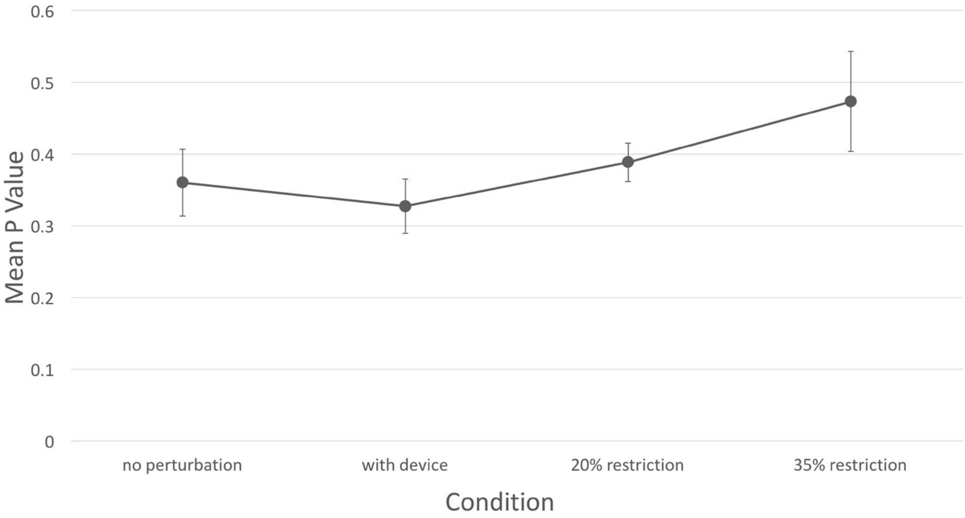


Fig. 6 Mean P values for four different conditions. Error bars represent 95% confidence intervals around the mean, calculated for repeated-measures designs (Cousineau 2005; with correction by; Morey 2008)

the variability in the size of the grasp aperture, that is, the variability of the midpoint of MGA relative to the center of the object (MGA POS SD) and the variability of the safety margin (SM SD). Their sum is the total variability (TV), that is, the variability that could yield collision of the fingers with the object before it could be grasped. We examined the effects of condition on the relative variability, TV normed by AA. Figure 7 shows the mean relative variability, TV/AA, for each condition. An ANOVA performed on TV/AA showed that there was a significant effect of condition ($F(3,24) = 22.57$, $P < 0.001$, $\eta_p^2 = 0.74$). Post hoc tests with LSD correction showed that there was no significant difference in relative variability between the first two conditions ($P > 0.4$). Relative variability in conditions 3 and 4 was significantly greater than in conditions 1 and 2 ($P < 0.05$) and condition 4 was larger variability than condition 3 ($P < 0.01$). So, applying the device without restriction of MG did not affect the relative variability, but then, the relative variability increased as MG was progressively restricted.

Subsequently, we looked at the scaling relationship between P (the geometry) and variability (the dynamics). Figure 8 shows the relationship between P and TV/AA within and across conditions. Participants responded to the progressive increase in the relative variability in the approaching grasp by increasing the relative size of the safety margin, P. TV/AA accounted for 65% of the variation in P ($R^2 = 0.65$, $F(1,34) = 62.83$, $P < 0.001$). TV/AA was significant as a predictor ($\beta = 2.15$, $t = 7.93$, $P < 0.001$), as was the constant ($\beta = 0.26$, $t = 14.61$, $P < 0.001$). The fitted linear model was:

$$P = 2.15 \times \frac{\text{TV}}{\text{AA}} + 0.26.$$

The coefficient (≈ 2) matched that found in Bingham et al. (2014) for large-handed males. This is the dynamic scaling

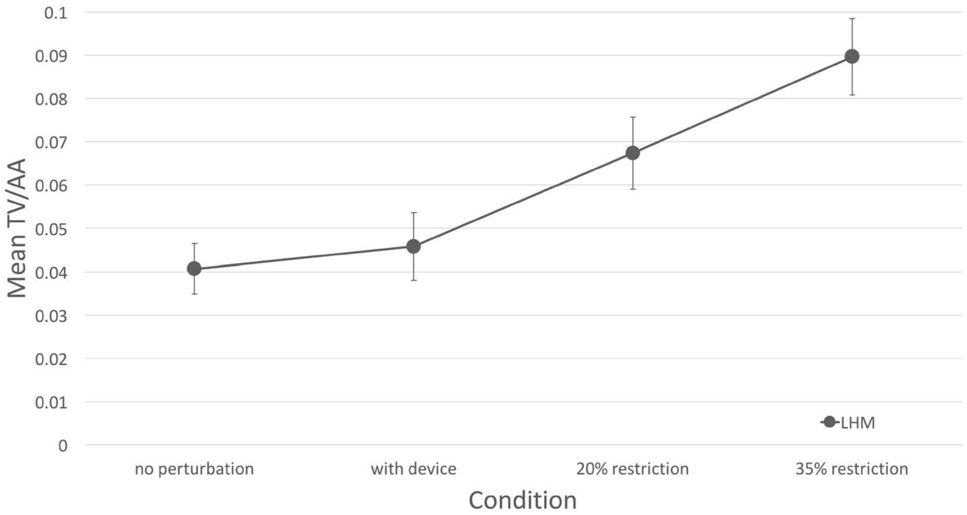


Fig. 7 Mean TV/AA for four different conditions. Error bars represent 95% confidence intervals around the mean, calculated for repeated-measures designs (Cousineau 2005; with correction by; Morey 2008)

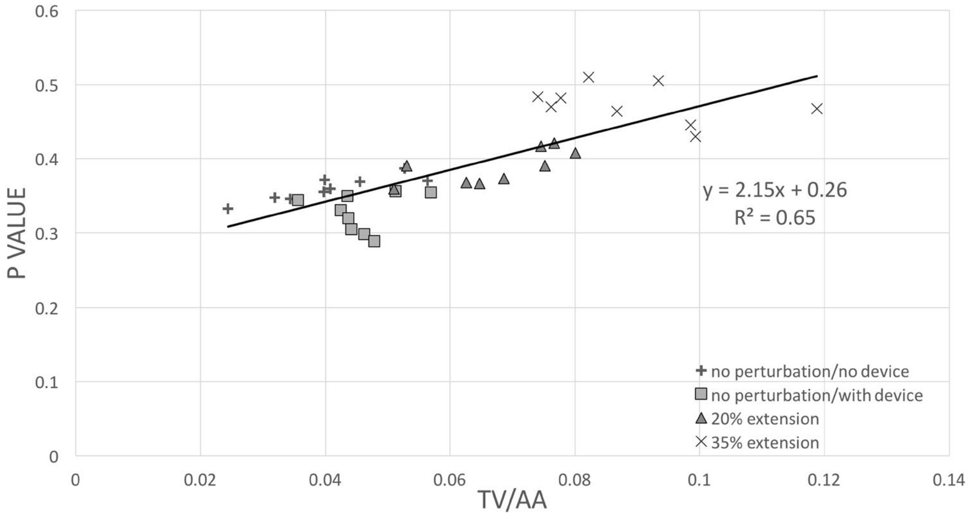


Fig. 8 Mean P values plotted as a function of the relative variability (TV/AA) for conditions 1–4 together with the scaling relation revealed by a line fitted using linear regression

invariant in the affordance model. As shown in Fig. 8, it reflects the stable relationship that was maintained between safety margin and the variability, each relative to the relevant actor effectivity, MG, as it changed.

General discussion

In the current study, we investigated the effect on the geometrical and dynamical scaling of the reach-to-grasp affordance as we changed the effectivity, maximum grip size. Three notable results were reported in this study. First, with progressively greater restriction of the maximum grip or effective hand size, we observed that participants used a progressively larger proportion of their available aperture for the safety margin. Second, results from the present study confirmed the invariant dynamical scaling of the action found in Bingham et al. (2014). Participants rescaled their safety margins as the relative variability increased due to the effective decrease in hand size. We found a significant linear relationship between the relative variability and the relative size of the safety margins, and the coefficient (≈ 2) for this relationship was comparable to the one found in Bingham et al. (2014) for similar participants, large-handed males. Participants scaled the relative size of their safety margin to be approximately twice as large as the relative variability of their reach-to-grasp action. Finally, we found that when we changed the effectivity for reaches-to-grasp, recalibration occurred within a few trials immediately after the change, a time scale of change likely determined by the availability of information used for calibration.

Mon-Williams and Bingham (2011) studied the geometrical scaling of this affordance, identifying an invariant scaling between the safety margin (SM) and the available aperture (AA). Bingham et al. (2014) extended this geometric affordance model by incorporating a dynamical component composed of a scaling relationship between the relative variability of the reach-to-grasp action and the geometric scaling. As also found in the current study, large-handed male participants used 2 times the relative variability to determine the safety margin as a proportion of the available aperture. This dynamical scaling relationship reflects the level of risk tolerance in the task. In the previous study, men used a scaling factor of 2 and women, 3, suggesting that the women were more conservative. Note that this is 2 or 3 times the standard deviation in finger positions relative to the target object during approach of the hand to grasp it. So, the difference is a 5% versus a 0.3% risk factor. The current study applied both the geometrical and dynamical aspects of the reach-to-grasp affordance model to explore how change in one's effective hand size would affect these relationships with the expectation that the geometrical scaling relation would distort (or recalibrate) to preserve the more functionally relevant dynamical scaling. The relative variability or stability of the reaches-to-grasp determines the likelihood that the fingers might collide with a target object before grasping can be accomplished.

A second goal of the current study was to determine the time scale over which recalibration would occur. We changed the effective hand size for males with large hands by restricting their maximum grip (MG). Fajen (2005, 2007a) argued that perturbing one's action capabilities, or effectivities, necessitates recalibration of one's action to preserve the ability to achieve the given task goal. He found that such recalibration was fast, occurring within a trial during the execution of an action. He was studying such recalibration in the context of braking behavior in locomotion. Mark (1987) found relatively slower recalibration that occurred across trials in the context of perceived maximum sitting height. He also found that the recalibration occurred without actually performing the action, but that this required free standing posture that would necessarily and normally result in postural sway. When participants leaned on a wall, eliminating postural sway, recalibration did not occur. Fajen (2007a) argued that the fast recalibration would occur for action-scaled affordances, whereas the slow recalibration is associated with body-scaled affordances. In Fajen's studies, the action-scaled affordance was the relative ability to decelerate, that is, it was active braking ability. In the current study, we changed a body-scaled affordance, altering the relevant effectivity, namely, maximum grip size in grasping. However, like Fajen, we used relevant action measures rather than judgments as had been used by Mark and thus, we observed recalibration in the context of the performance of reach-to-grasp actions. So, first, if recalibration occurred, we wondered whether would it be fast or slow? Second, would it be expressed as a change in the geometric scaling so as to preserve the dynamic scaling? Because dynamic scaling entails the variability of the behavior, the latter question was relevant to the first. If the variability of reaches-to-grasp changed, then it would presumably require a few trials to detect this change and recalibrate accordingly in a way that preserved the dynamic scaling. Indeed, this is what we found. So, the change was relatively fast, but did not occur within the course of a single reach-to-grasp trial. Instead, it seemed to occur over half a dozen trials, enough to assess the relative variability that determined the invariant dynamic scaling. Thus, the time scale of recalibration would seem to be a function of the availability of the information required.

Finally, the current study further confirmed the importance of considering both the geometrical and dynamical aspects of the affordance relationship. Snapp-Childs and Bingham (2009) found that change in effectivity across the lifespan affected the geometrical scaling of a stepping affordance because it was accompanied by change in the stability of stepping, but the change in the geometrical scaling preserved a constant dynamical scaling relation. Room for errors, as measured by the safety margin relative to the leg length, varied systematically as an invariant function of the variability of stepping. To preserve the dynamical scaling, the geometrical scaling distorted or recalibrated. The same set of relationships was found in the current study although the timescale for the change in the relevant effectivity was much shorter, that is, changing over the experimental session rather than over development. It is the functionally relevant dynamics that run the show at a timescale for the resulting recalibration that is determined by the availability of the information used to recalibrate.

One potential extension of the current study would be to investigate the evolution of geometrical and dynamical scaling relationships in the face of an increase in maximum grip. In this study, we restricted participants' maximum grip while preserving their ability to use their own fingers to perform the grasping task. However, when increasing maximum grip, the grasping action would have to be performed with a device that extends their maximum grip and not their own fingers. Consequently, this manipulation would introduce tool use and motor learning of tool use. A study explicitly of tool use by Golenia et al. (2014) was of this sort. They used pliers that could expand, maintain, or restrict participants' grasp aperture. However, they only reported effects of differences in tools in terms of apertures and learning curves. Additionally, theories in the tool use literature have also suggested that the goals intended for tools could have an impact on the geometrical structure of an action [see Osiurk et al. (2010), and Osiurak and Badets (2016) for reviews]. Therefore, the manipulation would yield an investigation of tool use, rather than of normal reaches-to-grasp.

Compliance with ethical standards

Ethical approval Procedures in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and the Declaration of Helsinki.

Conflict of interest The authors declare that they have no conflicts of interest.

Glossary

Available aperture, AA	The difference between MG and MOE (AA = MG − MOE)
Final grasp aperture, FGA	Occurs when the fingers, i.e., thumb and index finger, actually contact the object in the grasp. Temporally, FGA occurs after TGA. FGA is operationally defined as the distance between the fingers when the velocity of the index finger falls below 3 cm/s
Lateral position of MGA, MGA POS	The difference between the center of the object and the center of MGA. This is a measure of the accuracy of the targeting portion of reach-to-grasp. MGA POS is operationally defined as the distance from the center of MGA to the vertical plane formed between the midpoints of grasp aperture at the initiation of the reach and that at FGA
Maximum grasp aperture, MGA	Occurs during the approach of the hand to the target object when the grasp aperture is the maximum
Maximum grip, MG	Reflects the effective size of the actor's hand. MG is operationally determined by having the actors to grasp and hold the longest rod they can using their thumb and index finger
Maximum object extent, MOE	The maximum length diagonal through the object. This is operationally defined as the Pythagorean of the object width and the length of the grasp surface.
Safety margin, SM	The difference between the MGA and MOE (SM = MGA − MOE)
Safety margin's variability, SM SD	Reflects the variability of the grasping movement. SM SD is operationally defined as the standard deviation of SM for a given object
Terminal grasp aperture, TGA	Occurs when the hand velocity drops to zero with the hand at the target object but prior to the fingers closing on the object. Temporally, TGA occurs before FGA. TGA is operationally defined as the distance between the fingers

	when the velocity of the wrist drops below 5 cm/s
Total variability, TV	Sum of SM SD and MGA POS SD

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