Exp Brain Res (2011) 211:145–160
DOI 10.1007/s00221-011-2659-2

RESEARCH ARTICLE

Discovering affordances that determine the spatial structure of reach-to-grasp movements

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Received: 4 December 2009 / Accepted: 25 March 2011 / Published online: 12 April 2011

Abstract Extensive research has identified the affordances used to guide actions, as originally conceived by Gibson (Perceiving, acting, and knowing: towards an ecological psychology. Erlbaum, Hillsdale, 1977; The ecological approach to visual perception. Erlbaum, Hillsdale, 1979/1986). We sought to discover the object affordance properties that determine the spatial structure of reach-to-grasp movements—movements that entail both collision avoidance and targeting. First, we constructed objects that presented a significant collision hazard and varied properties relevant to targeting, namely, object width and size of contact surface. Participants reached-to-grasp objects at three speeds (slow, normal, and fast). In Experiment 1, we explored a "stop" task where participants grasped the objects without moving them. In Experiment 2, we studied "fly-through" movements where the objects were lifted. We discovered the object affordance properties that produced covariance in the spatial structure of reaches-to-grasp. Maximum grasp aperture (MGA) reflected affordances determined by collision avoidance. Terminal grasp aperture (TGA)—when the hand stops moving but prior to finger contact—reflected affordances relevant to targeting accuracy. A model with a single free parameter predicted the prehensile spatial structure and provided a functional affordance-based account of that structure. In Experiment 3, we investigated a "slam" task where participants reached-to-grasp flat rectangular objects on a tabletop. The affordance structure of this task was found to eliminate the collision risk and thus reduced safety margins in MGA and TGA to zero for larger objects. The results emphasize the role of affordances in determining the structure and scaling of reach-to-grasp actions. Finally, we report evidence supporting the opposition vector as an appropriate unit of analysis in the study of grasping and a unit of action that maps directly to affordance properties.

Keywords Affordances · Reach-to-grasp · Perception/action · Mathematical model

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Introduction

Reach-to-grasp actions have been studied extensively to discover the functional relationships between the properties of graspable objects and the timing of the movements (e.g. Jeannerod 1984, 1988; Wing et al. 1996). The main object property that has been studied in this way is object size, that is, the width of the object to be spanned by the finger(s) and thumb. The main feature of the reach-to-grasp action that has been studied in this regard is the Maximum Grasp Aperture (MGA). This refers to the maximum size of the aperture between thumb and finger(s) which first opens and then begins to close as the hand approaches a target object in preparation for grasping. The relative timing of the MGA has been found to vary with object size, occurring proportionately later for larger objects.

Reaching-to-grasp is often described as a type of targeting task (Bootsma et al. 1994). The goal of the action is characterized as placing the fingers and thumb accurately on specific object surfaces. However, it has been noted in more recent studies that reaching-to-grasp is also a collision avoidance task (Rosenbaum et al. 1999). To grasp an object successfully without knocking, it over requires that the aperture between finger(s) and thumb be opened widely enough to avoid hitting the object with the fingers before they can encircle the object. Other variations in goals and constraints have been found to yield task-specific variations in the timing structure of reaches-to-grasp (e.g., Marteniuk et al. 1987). Accordingly, recent models of the organization of reaches-to-grasp have been formulated to flexibly handle such task specificity. For instance, Rosenbaum's posture-based exemplar model consists of a prioritized hierarchy of task-specific processes used to plan a reach-to-grasp (Rosenbaum et al. 2001). Such models, however, presume that the object properties used to determine the structure of reaches-to-grasp are known. The purpose of the present study was to investigate the object affordance properties that determine the spatial structure of reach-to-grasp movements.

Gibson formulated the notion of affordances in the 1970s and argued that the "objects of perception" cannot be found listed in the dictionary or named by standard variables used in physics or engineering (Gibson 1977, 1979/1986). Rather, Gibson was highlighting the fact that discovery of the objects of perception is itself a major scientific problem. Without concerted scientific investigation, the perceptible properties of the world remain unknown as does the information that allows those properties to be perceived. Logically, the investigation and discovery of affordance properties should precede investigations of the information that can be detected and used to allow perception.

Gibson was famous as a realist and described affordances as relational or dispositional properties that reflect potential relationships between an animal and the relevant aspects of objects and surfaces in the world. Affordances are real and continue to exist even when there is no one around to perceive them. Gibson was also a functionalist so he suggested that the relevant aspects of the world that should be perceived are those used in performing actions. The functional nature of affordances provides the means by which they can be investigated and discovered. The scientist investigates which object properties are relevant to specific actions such as walking or reaching-to-grasp. Gibson's argument was simple—the use of object properties in the organization and guidance of actions requires the actor to perceive those properties.

The first investigations of affordances involved the study of locomotion. Warren investigated affordances for stair climbing (Warren 1984) and for clear passage when walking or running over level ground (Warren and Whang 1987). Subsequently, affordances have been studied in the context of a number of different actions, including reaching and grasping. Affordance studies of reaching have investigated whether reachable distances of target objects can be perceived (e.g. Mark et al. 1997). Affordance studies of grasping have addressed two questions. First, what determines one versus two-handed grasps (e.g. Newell et al. 1989)? Second, how is the physical geometry of an object perceived and used to determine fingertip placement (Baud-Bovy and Soechting 2001a; Bingham and Muchisky 1993a, b, 1995; Goodale et al. 1994a; Iberall et al. 1986; Lederman and Wing 2003)? We tackle two related problems that remain to be addressed in the literature on reach-to-grasp actions. The extant work has focused on the temporal structure of reaches-to-grasp. We now pose the analogous question: What determines the spatial structure and scaling of reach-to-grasp movements? We also pose the related question: What are the relevant object affordance properties that contribute to determine reach-to-grasp structure? Object size has been presumed to be the relevant dimension with respect to which the MGA is controlled. However, this property was chosen for study without attention to the collision avoidance aspect of reaching-to-grasp. This problem needs to be revisited.

We conducted three experiments to investigate these issues. We designed objects to vary those properties relevant to both the targeting and obstacle avoidance goals of reaching-to-grasp. We made the objects easy to knock over as well as difficult to grip. We systematically varied both the size and separation between surfaces to be contacted by the fingers and thumb, keeping surface areas rather small and separation sometimes rather large. In the first two experiments, we investigated two different tasks. The first task emphasized collision avoidance where the object needed to be grasped without it moving. The second task tested the generality of the initial results by requiring the objects to be lifted. In both tasks, we also varied the speed of reaches from slow to very fast. We used the results of Experiment 1 to formulate and test a model that captures the spatial structure of reach-to-grasp movements with a single free parameter together with additional variables determined by the actor's hand size and relevant object properties. We examined the trajectories of the approaching hand and fingers relative to the objects to discover the relevant object properties. In particular, we considered a heretofore little studied aspect of the approach trajectory relevant both to aperture formation and determination of relevant affordance properties, namely, the orientation of the hand aperture. We tested the generality of the model in Experiments 2 and 3. The model reliably predicted the spatial structure of the reach-to-grasp movements and provides a functional affordance-based account of that structure. A third experiment was performed to investigate a task that eliminated collision risk (from the perspective of knocking the object over). Many previous studies of reaches-to-grasp have employed small flat (1–2 cm high) rectangular blocks sitting on a table surface. Such objects actually invite the use of collision to help bring the reach-to-grasp movement to a halt. In such a task, we predicted that the safety margins included in the grasp aperture of the approaching hand could well be eliminated. Nevertheless, we expected that the apertures would scale as a function of the relation between the maximum grip span and relevant object properties. We adapted our model to capture this relation.

Experiment 1: stop

We designed objects that would amplify both targeting and collision avoidance requirements and allow us to control and manipulate the affordances for reaching-to-grasp. As shown in Fig. 1, both object width (that is, the distance to be spanned by the grasp aperture) and the size of the contact surfaces for the fingers were varied. Contact surfaces were placed well above the tabletop, and the objects were configured so they could be easily knocked over if hit by a clumsy grasp. In Experiment 1, participants were asked to reach-to-grasp objects taking care not to lift or move them. This strongly increased the collision avoidance aspect of the task. Participants performed reaches at slow, medium, and fast speeds. We measured the grasp aperture at two points along the approach to the object. The

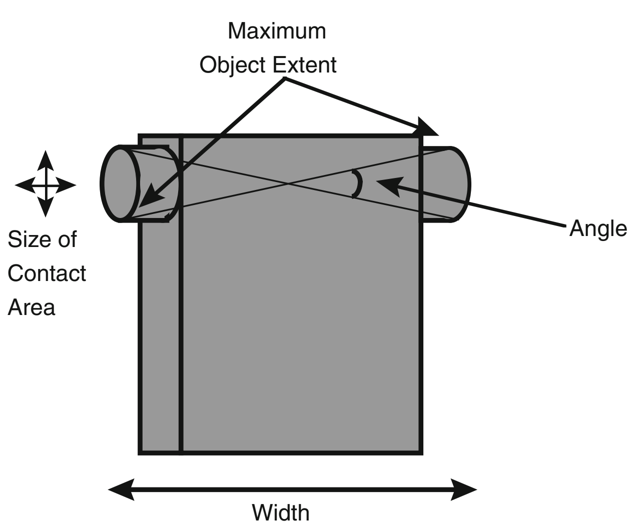

Fig. 1 Illustration of the objects used in Experiments 1 and 2, showing the ends of the dowel (which we call "buttons" to be contacted by the thumb and index finger), object width (the object dimension spanned by grasping), the grasp surface area at the end of the "buttons", the maximum object extent (MOE) (which is the object dimension that must be spanned if the grasp aperture is sufficiently tilted), and the angle formed by the button surfaces given their width and the object size. This angle determines how much the grasp aperture can be tilted whilst still allowing for the finger and thumb to make contact with the button surfaces

Maximum Grasp Aperture (MGA) occurs during the second half of the approach trajectory and is the widest opening between the fingers and thumb before they start to close down on the object. The Terminal Grasp Aperture (TGA) occurs at the terminus of the reach (hand or wrist speed equals zero) and when the fingers have enclosed the object but before they have contacted the object surfaces (Bingham et al. 2008; Coats et al. 2008; Lee et al. 2008). In this taxonomy, final contact of fingers and object yields the Final Grasp Aperture (FGA). We analyzed reaches-to-grasp to determine what object affordance properties determined the MGA and TGA and found that different properties were relevant in each case because these two features reflect different goals. The primary goal of the MGA is collision avoidance during approach, whereas the TGA goal is the targeting of the fingertips. Different object properties are relevant to these two goals.

The formation and control of an opposition vector was central to our affordance analysis (Iberall et al. 1986). This has been used extensively as the unit of analysis for grasping, and it corresponds to an axis running between the thumb and finger forming the aperture for the grasp. This unit of analysis was challenged recently by Smeets and Brenner (1999) who formulated an alternative account of the organization and control of grasping. We tested the alternative accounts by analyzing the distributions of thumb and finger positions and opposition vector positions in the final stage of the reach-to-grasp.

Methods

Participants

Six unpaid participants from the University of Aberdeen were recruited for the study (3 females and 3 males aged between 20 and 30, mean age 24 years). All participants had normal or corrected to normal vision, and none had any history of neurological deficit. The participants all reported a right-hand preference, and all wrote and threw a ball with their right hand. All participants provided their informed consent prior to their inclusion in the study. The study was approved by a University ethics committee and was performed in accordance with the ethical standards laid down in the Declaration of Helsinki.

Procedure

The experimental task required the participants to sit at a table and reach for one of nine objects. Participants started each trial with the right hand on a starting position located 10 cm from the edge of the table close to the participant. The objects were always placed with their front edge at 30 cm from the participant's starting location. The objects were constructed by inserting a dowel through a block of wood as shown in Fig. 1. All blocks were 9 cm in height and 4 cm in depth, and dowels were inserted 1 cm from the top. Participants grasped the object by contacting the ends of the dowel with index finger and thumb. Variation of the dowel diameter altered the grip area available for contacting the object with finger and thumb (0.8, 1.8, 3.4 cm). Smaller grip area was harder (in Fitts' (1954) sense of requiring more visually guided corrections). Variation of dowel and block width altered the width of the targets (3.0, 5.4, 8.0 cm, block width was 1 cm less in each case). Wider targets presented a larger collision hazard (Rosenbaum et al. 1999, 2001) and thus were harder in Fitts' sense. The three grip surfaces and three object widths gave nine different objects. We asked participants to move at one of three speeds: their normal speed, slower than normal or faster than normal. Participants determined these respective speeds but then were highly reliable in producing their respective slow, medium, and fast speed. The different factors (grasp surface size, width, and speed) were presented in a randomized order. An IRED was positioned on the top of the objects. To ensure that the objects were not moved, we differentiated the positional data provided by the IRED over the course of the trial and checked that its speed never exceeded 5 cm/s.

Participants performed 10 test trials in each of the 27 different conditions, but first, participants performed ten practice trials. Following this, the 270 test trials were completed. The entire session, including practice trials, lasted approximately two hours. Participants were informed that they should grasp the objects as accurately as possible between the pads of the forefinger and thumb and that they should not lift the object off the table or move it.

Analysis

Data acquisition was initiated approximately one second before the experimenter's verbal start command. Infra red emitting diodes (IREDs) were attached to the reaching hand at the index finger (distal medial corner of the finger), the thumb (distal lateral corner of the thumb), and the styloid process of the wrist. The first two were to measure grasp apertures, and the third was to measure wrist movement. The positions of the IREDs were recorded by an Optotrak movement recording system, factory precalibrated to a static positional resolution of better than 0.2 mm at 250 Hz. Data were collected for 3 s at 100 Hz and stored for subsequent offline analysis and filtered using a dual-pass Butterworth second-order filter with a cut-off frequency of 16 Hz (equivalent to a fourth-order zero phase lag filter of 10 Hz). The distance between the thumb and index finger IREDs was then computed (the aperture). Following this operation, the speed of the wrist IRED and the aperture was computed, and the onset and offset of movement was estimated using a standard algorithm (threshold for movement onset and offset was 5 cm/s). Custom analysis routines were used to compute the dependent variables of interest in this study. The criterion for onset of a reach was wrist velocity exceeding 5 cm/s. The criterion for cessation of reach movement was wrist velocity falling below 5 cm/s. The criterion for termination of the grasp closure was when finger speed dropped below 5 cm/s.

Results and discussion

The task was designed to heighten the collision avoidance requirements of the reaches-to-grasp while also controlling the targeting requirements. As the hand approaches an object targeted for a precision grasp, the index finger and thumb open to form an aperture to be used to enclose the object and place a vector through the object between the enclosing finger and thumb. The orientation of this vector as the hand approaches the object contributes to a determination of the size of the MGA required for avoiding inappropriate collision with the object. Thus, object width is not the relevant property for control of the MGA. As shown in Fig. 1, we computed the Maximum Object Extent (MOE) as the relevant affordance property. This was computed simply as the Pythagorean of width and grasp surface size (radius of the contact area) resulting in values as follows: 3.10, 3.50, 4.53, 5.46, 5.69, 6.38, 8.04, 8.20, 8.67 cm. This property has been described and investigated previously in studies of shape perception for the control of reaches to grasp (Lee et al. 2008; Lee and Bingham 2010).

A second consideration in the context of both collision avoidance and targeting is potential uncontrolled variation in the orientation of the opposition vector. With this in mind, we computed a second object affordance property, namely, the angle illustrated in Fig. 1. This angle determines the variation in orientation of the opposition axis that will still allow successful grasping. This angle decreased as grasp surface size decreased and as width increased with values that varied with the MGA values reported above as follows: 29.86, 61.93, 97.15, 16.85, 36.87, 64.39, 11.42, 25.36, 46.05 degrees. A small grasp surface size provided less area to be contacted by the fingers. A large width provided less leeway relative to the maximum grip span of the hand. Therefore, as this angle got small, the fit of the hand aperture to the target object became more constrained and more difficult.

All four dimensions, Grasp Surface Size (3 levels), Width (3 levels), MOE (9 levels), and Angle (9 levels), were used in analyses in addition to Speed (Slow, Medium, and Fast), and Repetition (1-10). For each of the measures that we analyzed, we first computed within cell means for each participant, averaging across the 10 repetitions performed in each Speed by Grasp Surface Size by Width cell. Each of the remaining factors was continuous with the exception of Speed. Speed levels were coded as –1, 0, +1. We performed regressions using either (1) MOE, Angle, Speed, MOE x Speed, Angle x Speed, and MOE x Angle or (2) Grasp Surface Size, Width, Speed, and Grasp Surface Size x Speed, Width x Speed, and Grasp Surface Size x Width to determine which analysis would account for the largest proportion of the variance with the fewest factors. We compared the predictive value of the alternative set of factors by performing multiple regressions, and in each case, progressively removing non-significant factors until only significant factors remained (Pedhazur 1982). Finally, we also ran all the variables from both sets together in stepwise regressions to let them compete directly. However, we ultimately did not want to allow these variables to mix. So, we preferentially used the indirect comparisons. Generally, the results using either of these methods were the same.

First, we examined the orientation of the grasp aperture at TGA. Grasp orientation was tilted by about 12 degrees for the smallest objects and then approached the horizontal as the MOE increased (Fig. 2). We performed regressions on grasp orientation. The only significant factor was MOE which yielded an r^2 of 0.16, $F(1, 160) = 30.4$. A simple regression on the overall means (computed across all three speeds) yielded the following relation between MOE and Grasp Orientation (GO):

$$\text{GO} = 1.39 \times \text{MOE} - 15.8, \quad r^2 = .97.$$

Thus, the mean grasp orientation reached the horizontal (that is, GO = 0°) at an MOE of 11.4 cm. However, the variability of the orientation increased as did the orientation itself, as shown by the standard error bars in Fig. 2. In fact, the standard deviations of the orientation were nearly equal in magnitude to the means. A linear regression of orientation means on standard deviations yielded a slope of 0.80 and an intercept ≈ 0, $r^2 = .85$. Thus, for the smallest MOE, hand orientation could vary over 36° (±2SD). On average, the variation exhibited by a given participant (that is, computing the mean of the within cell standard deviations) was 70° (±2SD)! Clearly, the orientation of the approaching hand is part of the problem in sizing the grasp aperture appropriately.

Next, we analyzed the MGA. The means are shown in Fig. 3 plotted against MOE separately for each Speed. MGA was found to vary with the MOE as would be expected given the problem created by the varying orientation of the grasp aperture. MGA increased with increasing MOE and also with increasing Speed. Finally, the slope of the relation between MOE and MGA decreased with increasing Speed. The regression on MGA was significant ($F(3, 158) = 162.1$, $P < .001$, $r^2 = .76$). The significant factors were Speed (partial $F = 28.3$, $P < .001$), MOE (partial $F = 376.3$, $P < .001$), and Speed x MOE (partial $F = 5.2$, $P < .03$). Both analyses (MOE or Width and Grasp Surface Size) accounted for 76% of the total variance. However, the former analysis required three factors and the analysis using Width and Grasp Surface Size required four (namely, Speed, Width, Grasp Surface Size, and Speed x Width). Furthermore and most pointedly, as shown in Fig. 3, the data were ordered by MOE, and thus, the analysis using MOE was more correct as well as more parsimonious. A simple regression of MOE on these means

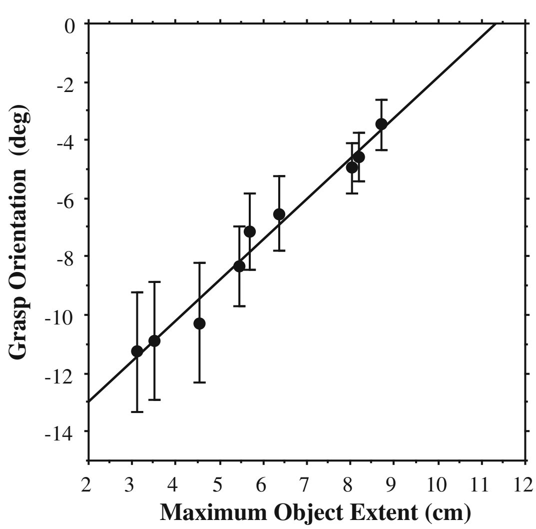

Fig. 2 Experiment 1: mean angle of the grasp aperture (with *standard error bars*) for each of the nine objects plotted as a function of maximum object extent. A *line* was fitted to the means by least square regression. See the text for details

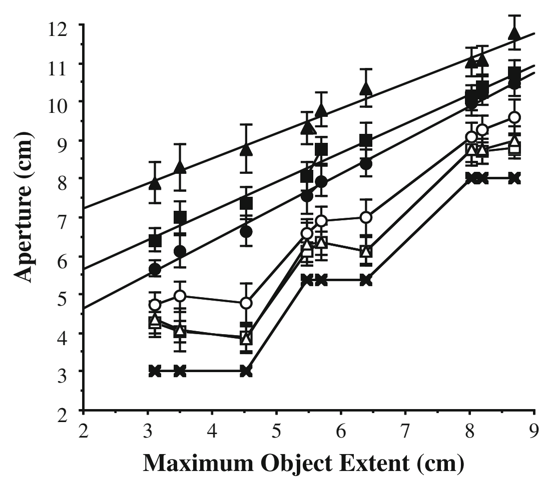

Fig. 3 Experiment 1: mean MGA and TGA (with standard error bars) for the nine objects plotted as a function of maximum object extent and reach speeds for the nine objects: slow (*circles*); medium (*squares*); fast (*triangles*); MGA (*filled symbols*); TGA (*open symbols*). MGA means for each reach speed were fitted with a *line* by least squares regression. TGA means for each reach speed are simply connected by a *line*. Also shown for the nine objects are the three object widths plotted as *crosses* (note: maximum object extent also varies with the button grasp surface size)

yielded a relation between MOE and MGA for each Speed as follows:

$$\begin{aligned} &\text{Slow}: \text{MGA} = .87\,\text{MOE} + 2.9, \quad r^2 = .99 \\ &\text{Medium}: \text{MGA} = .76\,\text{MOE} + 4.1, \quad r^2 = .99 \\ &\text{Fast}: \text{MGA} = .65\,\text{MOE} + 5.9, \quad r^2 = .98 \end{aligned} \tag{1}$$

Next, we analyzed TGA and, as shown in Fig. 3, we found that TGA varied with Object Width. TGA also varied with Speed, but in a way opposite to the MGA, that is, TGA was smaller as speed increased. The regressions on TGA were significant, ($F(2, 159) = 359.0$, $P < .001$, $r^2 = .82$). The significant factors were Width (partial $F = 705.2$, $P < .001$) and Speed x Grasp Surface Size (partial $F = 12.8$, $P < .001$). The alternative factor set accounted for less of the variance.

We sought to model and thus predict MGAs and TGAs. To provide insight about the models, we first describe how we developed the model for MGA. To do this, we started with Eq. (1). These indicated that mean MGAs were sized relative to the MOE providing a margin of safety appropriate to the speed of reaching. We computed the actual safety margins (SM) as follows: SM = MGA – MOE. Next, we estimated a mean maximum grip span (M) of 16 cm (by measuring hands).[1] 16 – MOE yielded the remaining grip span available (Available Span or AS) for each object. This set a limit on the maximum size of a possible safety margin. For each speed, we regressed AS on SM to obtain slopes. We found that slow speed reaches exhibited safety margins that were 13% of the available spans, medium speed reaches exhibited safety margins that were 24% of available spans, and fast speed reaches exhibited safety margins that were 35% of available spans. Using 16 cm for maximum grip span yielded intercepts ≈ 0 in these regressions. We then computed predictions of mean MGAs using these percentages:

$$\text{Safety margin} = (16 - \text{MOE}) \times \text{speed}\,\% \tag{2}$$

$$\text{Predicted MGA} = \text{Safety margin} + \text{MOE} \tag{3}$$

In Fig. 4, mean MGAs are shown plotted against the MGA prediction for each speed. In each case, simple regression of MGA prediction on MGA means yielded a slope of 1.0 and an intercept near zero with an $r^2 = .99$ reflecting good fit. These results show that the safety margin simply increased by 11% of the available grip span with each increment in speed.

[1] M was subsequently derived in the final models by fitting the data with M as a free parameter. The values returned were slightly different (≈ 17 cm) from those originally estimated. Measuring M independently of the grasping task itself yields only an approximation. The model fits actually provide the best measures of this 'effectivity' (Turvey et al. 1981).

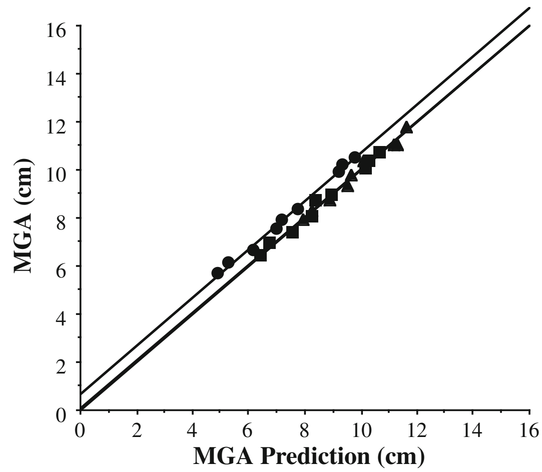

Fig. 4 Experiment 1: mean MGA plotted as a function of the MGA prediction for all nine objects and three reach speeds: slow (*circles*); medium (*squares*); fast (*triangles*). See text for details

Because TGAs were sized to object width while MGAs were scaled to MOE, we analyzed and modeled TGA/Width and MGA/MOE ratios, respectively. We used these ratios because they reflected an important feature of the functional relation between hand and object. Each ratio must reach a value of 1 when Width and MOE reached values equal to the maximum grasp span allowed by the hand. This shows that the space is bounded by this perceiver/actor property, M. The model equation for MGA/MOE was derived by substituting Eq. 2 into Eq. 3 and dividing by MOE. We modeled the ratios as follows:

$$\text{TGA/Width} = \mathbf{P_{TGA}}(\mathbf{s}) * [\mathbf{M}/\text{Width} - 1] + 1$$

$$\text{MGA/MOE} = \mathbf{P_{MGA}}(\mathbf{s}) * [\mathbf{M}/\text{MOE} - 1] + 1$$

where **M** was maximum grasp span and $\mathbf{P_{TGA}(s)}$ and $\mathbf{P_{MGA}(s)}$ were speed-specific safety margins for TGA and MGA, respectively. The grasp aperture was thus modeled as equal to the relevant object dimension plus a safety margin determined as a percentage of the remaining grasp span. The functions were all predicted to intersect at the point (**M**, 1). These functions reflect the affordances that determine the spatial structuring of the grasping component of reaches-to-grasp.

Using Quasi-Newton estimation in Systat, we fitted these two parameter models to data for each speed of reach ($df = 2, 52$) with results as follows:

Speed	$P_{TGA}(s)$	M	r^2	$P_{MGA}(s)$	M	r^2
Slow	.13	17.7	.98	.17	17.5	.99
Medium	.07	18.0	.96	.24	16.8	.99
Fast	.07	18.7	.96	.34	17.0	.98

The resulting fits are shown in Fig. 5 where we plotted each function together with means computed for each of the three object widths. Mean TGA/Width is plotted against Widths and mean MGA/MOE is plotted against MOE. The functions all reach one and intersect at an estimated maximum grasp span for the hand of about 17 cm. The safety margins for MGA of 17, 24 and 34% for slow, medium, and fast reaches compare well with the previous estimates of 13, 24, and 35%. Estimated margins for TGA were 13, 7, and 7%.

Opposition vector or independent control of fingers?

The analyses of MGA, TGA, and grasp orientation essentially entail the assumption that the grasp aperture (or the opposition vector) is a unit of coordination that is targeted and controlled in a reach to grasp. However, Smeets and Brenner (1999) have suggested that there is no such unit and that grasping is performed by targeting the thumb and index finger independently to locations on either side of an object to be grasped. To evaluate these alternative hypotheses, we analyzed the distributions of horizontal (Y) locations of the thumb and finger at the end of reaches (that is, at the moment of TGA). Smeets and Brenner effectively hypothesized that the distribution of Y locations of the thumb and the distribution of Y locations of the index finger should be independent. We simply tested whether these two distributions were, in fact, independent or instead, covaried. First, we performed two multiple regressions, one on thumb Y values and one on index Y values. On each, we regressed Speed (coded as -1, 0, and $+1$), Width, and Grasp Surface Size together with the three two-way and one three-way interactions. The results in both cases were significant, $P < 0.001$: for thumb, $F(7, 159) = 102.5$, $r^2 = 0.82$ and for index, $F(7, 159) = 81.5$, $r^2 = 0.79$. The factors accounted for about 80% of the variance in each case. We derived the residuals from each of the two analyses, that is, the variance occurring independently of our factors. We then regressed the index Y residuals on those for the thumb. Smeets and Brenner would predict these to be unrelated. If, however, reaches-to-grasp are controlled by targeting an opposition axis on the object to be grasped, then we would expect variations in thumb position to be compensated by variations in index position to preserve the position of the midpoint between the two. This expectation was supported by the results of the simple regression which was significant, $P < 0.001$, $F(1, 160) = 151.5$, $r^2 = 0.49$, with a slope of –0.84 (close to –1) and intercept 0. Both distributions ranged between ± 1.25 cm. This type of negatively correlated covariance is classic evidence for a coordinative structure (Kelso et al. 1984). The analysis solidly supported the opposition vector as the relevant unit of analysis for organization and control of grasping.

Van de Kamp and Zaal (2007) also investigated the Smeets and Brenner hypothesis that the thumb and index finger act independently during a reach-to-grasp. They perturbed the target for the thumb and found effects on both thumb and index finger trajectories. Likewise, they perturbed the target for the finger and found effects on both finger and thumb trajectories. Accordingly, Van de Kamp and Zaal also concluded that the finger and thumb are controlled together as a coordinated unit of action in grasping.

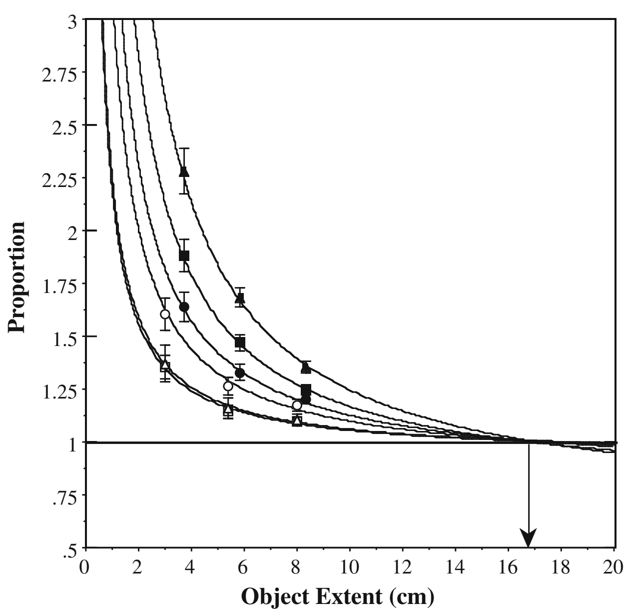

Fig. 5 Experiment 1: mean MGA/MOE (with standard *error bars*) plotted as a function of MOE: *Filled symbols*. Mean TGA/Width (with standard *error bars*) plotted as a function of width: *open symbols*. Each is plotted separately for each reach speed: slow (*circles*); medium (*squares*); and fast (*triangles*). Means are fitted by the model as described in the text. The functions all intersect one another and a value of 1 at an object extent of about 17 cm. This estimates the maximum grasp span allowed by the hand on average for these participants

Experiment 2: fly-through

This experiment was performed to test the extent to which the findings of Experiment 1 would generalize to a task in which participants reached-to-grasp and lift target objects. Participants reached-to-grasp and lift the same objects as tested in Experiment 1. Once more, participants were to avoid knocking the objects over, but of course, there was no prohibition on moving the objects. Reaches-to-grasp were performed at three speeds: slow, medium, and fast. No other instruction as to how the grasps were to be performed was given other than the use of the thumb and index finger to grip the dowel. In advance, we had no particular expectations as to whether or when participants might stop and grasp, as they did reliably in Experiment 1, or simply grab the object on the fly.

Methods

Participants

Six unpaid participants from the University of Aberdeen were recruited for the study (3 females and 3 males aged between 19 and 22, mean age 21 years). All participants had normal or corrected to normal vision, and none had any history of neurological deficit. The participants all reported a right-hand preference, and all wrote and threw a ball with their right hand. All participants provided their informed consent prior to their inclusion in the study. The study was approved by a University ethics committee and was performed in accordance with the ethical standards laid down in the Declaration of Helsinki.

Procedure

The experimental procedure was identical in every respect to Experiment 1, but participants were instructed to lift the target objects off the tabletop. An IRED was positioned on the top of the objects, and the object's "time-to-lift" was designated at the point when this IRED's speed exceeded 5 cm/s.

Results and discussion

The design and analysis of Experiment 2 was the same as Experiment 1 with one major exception. In Experiment 2, participants were instructed to grasp and lift the target objects, whereas in Experiment 1, they only grasped and did not lift the objects. As a consequence of the "lift" instruction, the movements spontaneously varied. Some trials appeared exactly the same as trials in Experiment 1, that is, the wrist came to a stop with the fingers poised around the object and then the object was grasped and lifted. However, in other trials, the wrist did not stop in advance of contact between hand and object. Instead, the object was grasped on the fly. We recorded the time at which the object first moved (Time of Lift or TOL), and in Fly-Though trials, the TOL was less than the time at which the hand and/or wrist stopped moving (MTw). So, MTw < TOL vs. MTw > TOL was used to categorize trials as Stop or Fly-Through, respectively. The proportions of these trials varied systematically as a function of Speed and Angle. (Angle was shown in Fig. 1 and described in Experiment 1.) The relation between Angle and the proportion of Fly-Throughs is plotted in Fig. 6

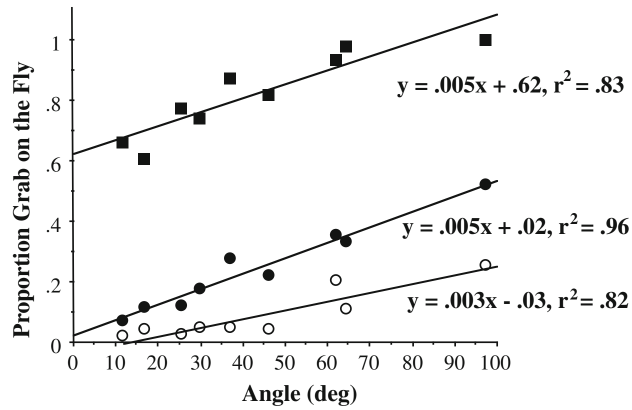

Fig. 6 Experiment 2: proportion of trials with grab on the fly for each of the nine objects plotted as a function of the angle formed by the buttons (given the object width and grasp surface size of contact area) and the reach speed: slow (*open circles*); medium (*filled circles*); and fast (*filled squares*). *Lines* were fitted to each set of points by least squares regressions

separately for each Speed. The slopes of the relations were the same for medium and fast speed reaches. Only the intercept changed as a function of Speed. More Fly-Throughs were performed with larger angles and faster reaches-to-grasp. The fast reaches to the objects with the largest angles were all Fly-Throughs while the medium and slow reaches to the objects with the smallest angles were all Stops. Angle was an affordance property of these objects that, together with the speed of the reaches, determined the difficulty of the task and thus, how it was to be performed.

We analyzed Stop data alone to determine whether the patterns found in Experiment 1 were replicated under the new task conditions. First, as before, we began with analysis of the orientation of the grasp aperture at TGA. Regression analysis yielded only a relation between MOE and grasp orientation ($F(1, 160) = 437.5$, $P < .001$, $r^2 = .73$). As shown in Fig. 7, grasp orientation was again tilted by about 12 degrees for the smallest objects and then continuously approached the horizontal as MOE increased. A simple regression on the overall means (computed across all three speeds) yielded the following relation between MOE and grasp orientation (GO):

$$GO = 1.75 \times MOE - 16.0, \quad r^2 = .99.$$

Thus, grasp orientation reached the horizontal at an MOE of 9.1 cm as compared with 11.4 cm in Experiment 1. So, as we found in Experiment 1, variations in the grasp orientation away from the horizontal are relevant to the control of the approaching grasp aperture.

As shown in Fig. 8, MGA varied with MOE and Speed just as in Experiment 1. As in Experiment 1, we computed means across the 10 repeated trials within cells for each participant and performed analysis on these means. We

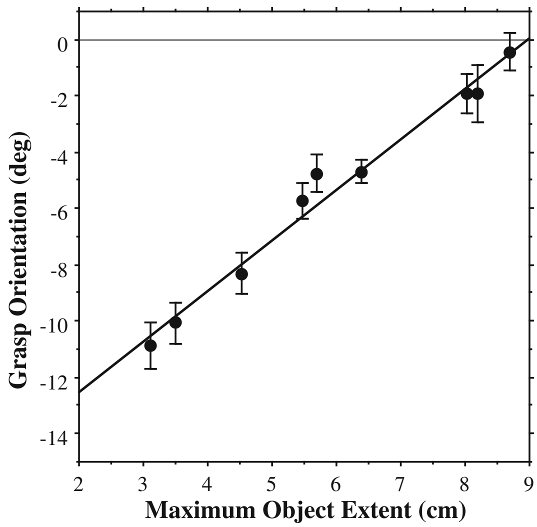

Fig. 7 Experiment 2: mean angle of the grasp aperture (with *standard error bars*) for each of the nine objects plotted as a function of maximum object extent. A *line* was fitted to the means by least square regression. See the text for details

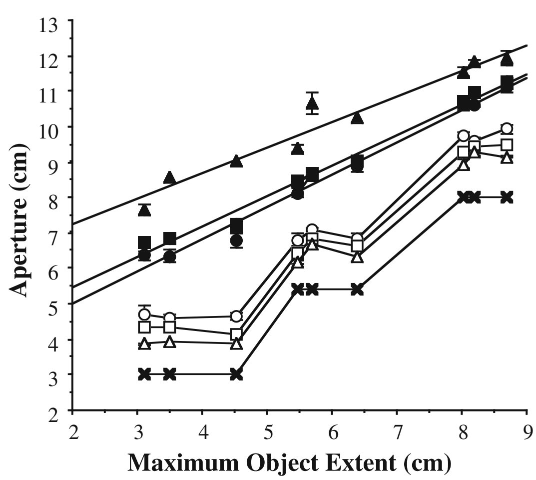

Fig. 8 Experiment 2: mean MGA and TGA (with *standard error bars*) for the nine objects plotted as a function of maximum object extent and reach speeds for the nine objects: slow (*circles*); medium (*squares*); fast (*triangles*); MGA (*filled symbols*); TGA (*open symbols*). MGA means for each reach speed were fitted with a *line* by least squares regression. TGA means for each reach speed are simply connected by a *line*. Also shown for the nine objects are the three object widths plotted as *crosses* (note: maximum object extent also varies with the button grasp surface size)

regressed Speed (coded as -1, 0, 1), MOE, and a Speed x MOE vector on MGA. The result was significant ($F(3, 158) = 653.1$, $P < .001$) and accounted for 92% of the variance. MOE was significant (partial $F = 1703.7$, $P < .001$), as was Speed (partial $F = 69.0$, $P < .001$) and the interaction (partial $F = 13.6$, $P < .001$). A simple regression of MOE on these means yielded a relation between MOE and MGA for each Speed as follows:

$$\text{Slow}: \text{MGA} = .91 \times \text{MOE} + 3.2, \quad r^2 = .98;$$
$$\text{Medium}: \text{MGA} = .86 \times \text{MOE} + 3.8, \quad r^2 = .98;$$
$$\text{Fast}: \text{MGA} = .73 \times \text{MOE} + 5.8, \quad r^2 = .95.$$

The pattern of decreasing slope and increasing intercept with increasing reach speed was the same as found in Experiment 1.

We computed a Predicted MGA just as described in Experiment 1. The results were identical to those in Experiment 1 in respect to the safety margin percentages at each speed using a maximum grasp span of 16 cm. Again, the intercepts were all $\approx$ 0.

$$\text{Slow}: 13\%$$
$$\text{Medium}: 24\%$$
$$\text{Fast}: 35\%$$

We used these percentages to compute predicted MGA as before. In Fig. 9, mean MGAs are shown plotted against the MGA prediction for each speed. In each case, simple regression of MGA prediction on MGA means yielded a slope $\approx$ 1.0 and an intercept near 0 with an $r^2 = .98$ reflecting a nearly perfect fit. (Slow reaches were an exception in respect to the intercept = 1.2 in this case.) These results show again that the safety margin simply increased by 11% of the available grip span with each increment in speed.

As shown in Fig. 8, TGA varied with Width and Speed just as in Experiment 1. Faster reaches again yielded smaller TGA with the fingers closer to the target objects. Figure 8 replicated Fig. 3 in Experiment 1. The regression was significant ($F(2, 159) = 5009.6$, $P < .001$, $r^2 = .98$), and only Speed (partial $F = 151.7$, $P < .001$) and Width (partial $F = 9867.5$, $P < .001$) were significant factors.

We modeled the TGA/Width and MGA/MOE ratios as before, and using Quasi-Newton estimation in Systat, we fitted the two parameter models to data for each speed of reach as follows:

Speed	$P_{TGA}(s)$	M	r^2	$P_{MGA}(s)$	M	r^2
Slow	.13	17.0	.99	.20	18.9	.99
Medium	.10	17.0	.99	.22	18.8	.99
Fast	.07	17.0	.99	.35	17.5	.99

The resulting fits are shown in Fig. 10 where we plotted each function together with means computed for each of the three object widths. Mean TGA/Width is plotted against Widths and mean MGA/MOE is plotted against MOE. The functions all reached one and intersected at an

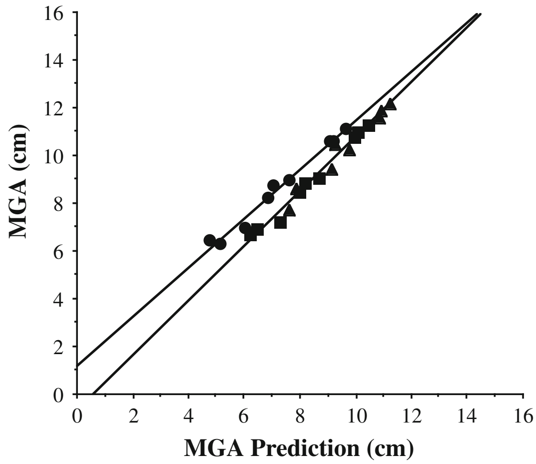

Fig. 9 Experiment 2: mean MGA plotted as a function of the MGA prediction for all nine objects and three reach speeds: Slow (*circles*); medium (*squares*); fast (*triangles*). See text for details

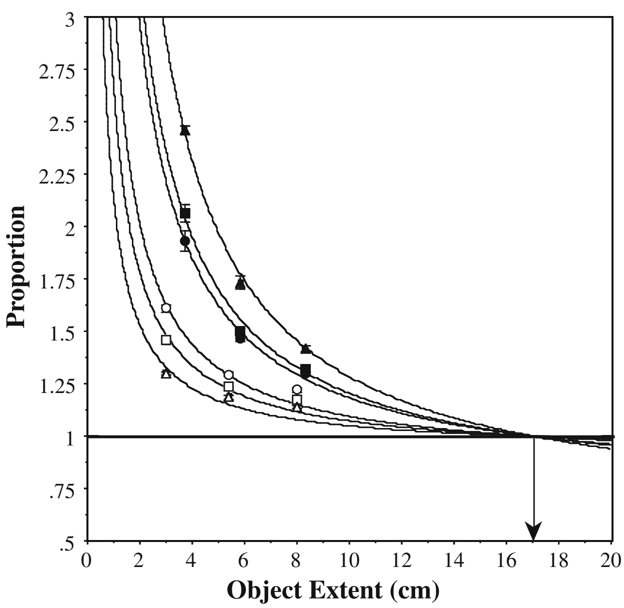

Fig. 10 Experiment 2: Mean MGA/MOE (with *standard error bars*) plotted as a function of MOE: *Filled symbols*. Mean TGA/width (with *standard error bars*) plotted as a function of width: *Open symbols*. Each is plotted separately for each reach speed: slow (*circles*); medium (*squares*); and fast (*triangles*). Means are fitted by the model as described in the text. The functions all intersect one another and a value of 1 at an object extent of about 17 cm. The estimates the maximum grasp span allowed by the hand on average for these participants

estimated maximum grasp span for the hand of about 17 cm for TGA and 18 cm for MGA. This is close to the estimate of 16 cm from the analysis reported above. The safety margins for MGA of 20%, 22% and 35% for slow, medium, and fast reaches, respectively, also compare reasonably well with the previous estimates of 13%, 24%, and 35%. Estimated margins for TGA were 13%, 10%, and 7% which is also comparable to the results of Experiment 1.

In Experiments 1 and 2, we found similar percentages for MGA safety margins at each of the three speeds: slow ≈ 13% (20% in Experiment 2), medium ≈ 24%, and fast ≈ 35%. For TGA, we found: slow ≈ 13%, medium ≈ 10% (7% in Experiment 1), and fast ≈ 7%. We next investigated the potential scaling relation between these percentages and the movement times for the reaches. As shown in Fig. 11, simple linear regression of mean movement time for each reach speed on safety margin percentages yielded excellent fits. Somewhat different MGA functions were found for the two Experiments, but both functions converged to a common maximum percentage at limit for the fastest reaches, namely, 50%. Thus, although there appear to be either individual differences or task specificity in the scaling between movement time and percentages for safety margins, use of a maximum margin of 50% was invariant. Furthermore, the degrees of freedom in our model for predicting MGA and TGA values can now be reduced as follows:

$$\mathbf{P_{MGA}}(\mathbf{s}) = -\mathbf{g} \times \mathrm{MT} + 50$$
$$\mathbf{P_{TGA}}(\mathbf{s}) = \mathbf{h} \times \mathrm{MT}$$

where MT is intended movement time, and **g** and **h** are task-specific parameters. However, we also reliably found

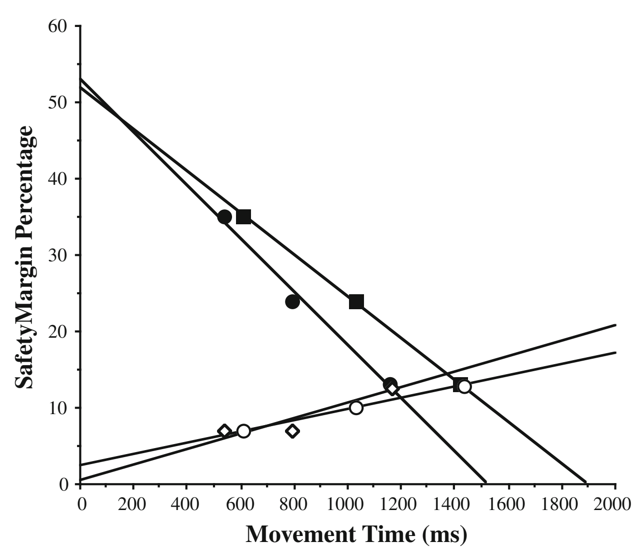

Fig. 11 Experiments 1 and 2: Derived safety margin percentages at each reach speed plotted against mean movement times for each reach speed. Experiment 1 MGA: *filled circles*. Experiment 2 MGA: *filled squares*. Experiment 1 TGA: *open circles*. Experiment 2 TGA: *open diamonds*. Each set of percentages was fitted by a *line* using simple regression. The corresponding functions and fits were as follows. Experiment 1 MGA: $P = -.035 * \mathrm{MT} + 53.1$, $r^2 = .99$. Experiment 2 MGA: $P = -.027 * \mathrm{MT} + 51.9$, $r^2 = .99$. Experiment 1 TGA: $P = .010 * \mathrm{MT} + 0.6$, $r^2 = .84$. Experiment 2 TGA: $P = .007 * \mathrm{MT} + 2.4$, $r^2 = .99$

that $\mathbf{P_{MGA}}$ **(slow) =** $\mathbf{P_{TGA}}$ **(slow).** Given this constraint, $\mathbf{g = 50/MT_{slow} - h}$**.** The degrees of freedom can be reduced to one.

Stop versus fly-through

Finally, we compared Stop and Fly-Through using the available measures for doing so, namely, grasp orientation (at MGA) and MGA itself. We also analyzed the total movement time (that is, the time from initiation of the reach to the lifting of the object) to investigate potential differences in MT between Stops and Fly-Throughs. We only used the Medium Speed data because it included comparable numbers of trials of each type. We replaced missing data with cell means. We performed regressions with Trial Type (Stop or Fly-through) coded (−1, +1) as a categorical factor.

The regression on grasp orientation at MGA yielded only a main effect for MOE ($F(1, 106) = 94.8$, $P < .001$) and accounted for 47% of the variance. The analysis showed that grasp orientation results were the same for Stops and Fly-Throughs, and the relation between MOE and grasp orientation at MGA (GO_{MGA}) was as follows:

$$GO_{MGA} = 1.2 \times MOE - 11.9°.$$

This was comparable to the relation found between GO and MOE at TGA for Stops. Grasp orientation varied systematically from the horizontal, again motivating analysis of MGA in terms of MOE.

The regressions on MGA yielded main effects only for MOE (partial $F = 1170.0$, $P < .001$) and Angle (partial $F = 11.9$, $P < .001$). The regression was significant ($F(2, 105) = 725.1$), $P < .001$) and accounted for 93% of the variance. When Angle was removed, it was found to account for only 0.7% of the variance. The analysis showed that the MGA results were identical for Stops and Fly-Throughs.

The regressions on MT yielded a main effect only of Trial Type ($F(1, 106) = 75.8$, $P < .001$) and accounted for 42% of the variance. The mean time for Stops was 1140.7 ms, and for Fly-Throughs, it was 969.5. Fly-Throughs were 171 ms faster (about 15%).

Overall, where the results could be compared between Stops and Fly-Throughs, the results were the same except that the Fly-Throughs were 15% faster.

Experiment 3: slam

A task that has been used frequently to study the form and timing of reaches-to-grasp is to have participants reach-to-grasp small flat rectangular objects placed on a table (e.g. Bootsma et al. 1994; Servos et al. 1992; Goodale et al. 1991; 1994b, Loftus et al. 2004; Marteniuk et al. 1987; Mon-Williams and Dijkerman 1999; Whitwell and Goodale 2009) as shown in Fig. 12. The focus of these studies has been on the properties of the target objects to be grasped (e.g. object size) and the ways that timing might vary with these properties. The potential role of the table surface in determining the form and timing of these movements has not been previously considered nor has the fact that the objects present little collision hazard. They cannot be knocked over. Given the shallow height of the target objects, the table surface could afford a means to help stop the reach-to-grasp movement. If it is used in this way, then the scaling of the reaches-to-grasp could be affected significantly. In particular, the safety margins could disappear. We asked participants to reach-to-grasp small flat rectangular objects placed on a table. As in the previous studies, we simply instructed them to reach to grasp the target objects. Although this task might have allowed participants to use the table surface to assist in stopping their hand movement, we did not tell them explicitly to do this. The question was whether they would spontaneously use this affordance. We asked participants to perform reaches at slow, medium, and fast speeds. We expected that the use of collision to stop hand movement would occur more often with faster movements.

Methods

Participants

Ten unpaid participants from the University of Aberdeen were recruited for the study (5 females and 5 males aged between 20 and 30, mean age 24 years). All participants had normal or corrected to normal vision, and none had any history of neurological deficit. The participants all reported a right-hand preference, and all wrote and threw a ball with their right hand. All participants provided their informed consent prior to their inclusion in the study. The study was approved by a University ethics committee and was

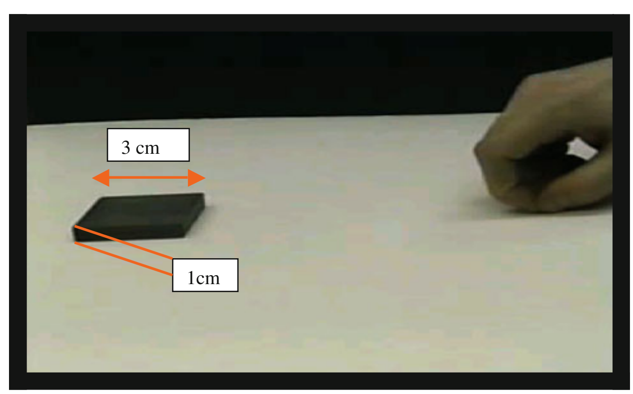

Fig. 12 Illustration of the target objects in Experiment 3

performed in accordance with the ethical standards laid down in the Declaration of Helsinki.

Procedure

The experimental task required the participants to sit at a table and reach for one of five objects. A starting position was located 10 cm from the edge of the table closest to the participant. Participants started each trial with the right hand on the starting position. Participants were asked to reach-to-grasp five different objects. The objects were flat blocks all with a height of 1 cm similar to that shown in Fig. 12. The objects had a constant width (aligned with the participant's fronto-parallel plane) of 3 cm but varied in length (aligned with the participant's sagittal plane). Five different lengths were used: 1.5 cm, 3 cm, 5 cm, 7 cm, and 8.5 cm. The objects were always placed with their front edge at 30 cm from the participant's starting location. The objects were grasped along their length (i.e. along the sagittal plane). We asked participants to move at one of three speeds: their normal speed, slower than normal or faster than normal. The different factors (object, distance, and speed) were presented in a randomized order across and between the participants.

Participants performed eight test trials in each of the 15 different conditions but first participants performed ten practice trials. Following this, the 120 test trials were completed. The entire session, including practice trials, lasted approximately one hour. Participants were informed that they should grasp the objects at the assigned speed and accurately as possible between the pads of the forefinger and thumb and that they should not lift the object off the table.

Results and discussion

The question in this study was whether and how the change in affordance properties would alter the form of the reach-to-grasp. Collision avoidance was eliminated in this task. In fact, we expected participants might actually use collision to help decelerate and stop their reach-to-grasp movement. In view of this, we also expected both that only OS (not MOE) would be the relevant object dimension and that the safety margins exhibited in the MGA and TGA of the previous experiments might change and perhaps disappear altogether.

The design included three repeated measures factors: Speed (Slow, Medium, and Fast), Object Size (1-5), and Repetition (1–10). For each of the measures that we analyzed, we first computed within cell means for each participant, averaging across the 10 repetitions performed in each Speed by Object Size cell. We then performed repeated measures Analysis of Variance (ANOVA) on these means with Speed and Object Size as factors.

First, we performed an analysis on MGA. As shown in Fig. 13, MGA increased with increasing object size as well as with reach speed. We obtained main effects of Object Size ($F(4, 36) = 1015.1$, $P < .001$) and Speed ($F(2, 18) = 5.9$, $P < .02$). Separate simple regressions of object size on MGA means for each speed yielded the following relations between object size and MGA:

$$\text{Slow : MGA} = .82\,\text{OS} + 15.5, \quad r^2 = .1.0;$$
$$\text{Medium : MGA} = .78\,\text{OS} + 18.4, \quad r^2 = 1.0$$
$$\text{Fast : MGA} = .79\,OS + 20.8, \quad r^2 = .99.$$

(In simple linear regressions using MOE, the r^2 were lower and the data exhibited a curved relation.)

For reaches at all speeds, MGAs were about 1.3–1.8 cm larger than object size for smaller objects, but for large objects, MGAs were equal to object size. This result (which was for MGA, not TGA!) shows clearly that collision avoidance was not a feature of this particular task.

Next, we performed the analysis on TGA. As shown in Fig. 13, TGA increased with Object Size and shrank with increasing reach speed rather than the reverse (as we had found previously in Experiments 1 and 2). The ANOVA again yielded main effects of both Speed ($F(2, 18) = 20.4$, $P < .001$) and Object Size ($F(4,36) = 1277.0$, $P < .001$). Separate simple regressions for each Speed yielded functions with larger slopes than for MGA:

$$\text{Slow : TGA} = .89\,\text{OS} + 8.3, \quad r^2 = 1.0;$$
$$\text{Medium : TGA} = .89\,\text{OS} + 5.6, \quad r^2 = 1.0;$$
$$\text{Fast : TGA} = .90\,\text{OS} + 1.7, \quad r^2 = 1.0.$$

For objects of all sizes, TGAs were about 0.5 cm larger than object size for slow reaches, but for fast reaches,

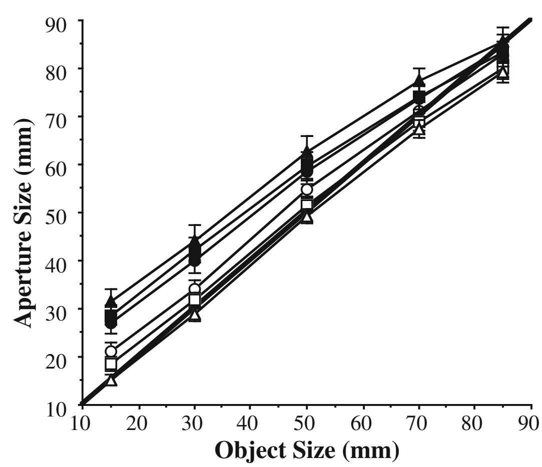

Fig. 13 Experiment 3: Mean MGA and TGA (with *standard error bars*) for the five objects plotted as a function of object size and the speed of reaches: slow (*circles*); medium (*squares*); fast (*triangles*); MGA (*filled symbols*); TGA (*open symbols*)

TGAs were again equal to object size or even slightly smaller (by $\approx$ 0.3 cm). In this latter case, the pads of the thumb and finger were typically resting on the edges and wrapped around the ends of the object. This and the fact that MGAs and TGAs were often equivalent meant that participants were often opening their fingers and hitting the object without closing the grasp aperture. That is, they were simply allowing collision with the object to end the reach-to-grasp.

Because safety margins were often at zero (or less) for TGA, our model could not be fit to that data. However, we were able to perform fits to MGA data for each reach speed as before (but using OS, not MOE) using Quasi-Newton nonlinear fitting in Systat with two free parameters, **M** and $\mathbf{P}_{\mathrm{MGA}}$, where **M** estimated the maximum grip span. The data for all three speeds were fit with $r^2 = .99$ yielding parameter values as follows:

Speed	P_{MGA}	M	r^2
Slow	.15	10.0	.99
Medium	.16	10.0	.99
Fast	.17	11.1	.99

The proportions for safety margins behaved differently than in the previous experiments. Rather than increasing with speed of reaching, they remained constant at a value comparable to that for slow speed reaches in Experiments 1 and 2, that is, $\approx$16% vs. 13%. The functions fit the data well and the three functions all equaled one, and thus intersected one another, at an object size of about 10 cm. According to the model, this should approximate the mean maximum grip span for the participants.

This latter modeling result was a bit surprising. We did expect a change in safety margins because obstacle avoidance was no longer part of the task, but we had not anticipated a change in the parameter estimate of maximum hand span. Nevertheless, we should have because attempts to measure maximum hand span yield different results depending on how the measurement is performed. We tested this by constructing a set of 15 dowels of 1 cm diameter (that is, the height of the objects in Experiment 3) and lengths that increased by 1 cm intervals from 8 cm to 22 cm. The ten participants were asked to grasp the dowels by spanning the length using the thumb and index finger. Reaching-to-grasp at natural speeds, they successively attempted to get a hold of increasingly longer dowels until they failed at a given size in three attempts. They did this first by reaching downwards to grasp the dowels lying on a table surface. Next, the experimenter held each dowel by its center in the air before the participant to be grasped. The mean maximum length dowel grasped in these two cases differed by 3.1 cm. The mean (and SD) in the air was 15.7 cm (1.2 cm) while on the table, it was 12.6 cm (1.3 cm). Necessarily, the hand was used differently in the two cases. The table only allowed the very tips of the index finger and thumb to contact the dowel while the other task allowed the entire finger and thumb pads to be used, thus making the task easier and allowing a larger effective maximum grasp span. The model estimate of 10-11 cm was comparable with the 12.6 cm mean found using the appropriate measure for the task in Experiment 3. In fact, model fits with a fixed value for **M** of 12 cm were essentially the same as reported above with $r^2 = .99$ and values for $\mathbf{P}_{\mathrm{MGA}} \approx 13\%$.

With a final analysis, we investigated whether indeed collision with the table was used to stop hand motion. We recorded when the fingers stopped moving and subtracted movement time to wrist cessation from movement time to finger cessation. If the fingers stopped moving before the wrist, then we would expect these difference values to be positive, whereas if the wrist stopped before the fingers closed, then the values would be negative. The means (and SD) for slow, medium, and fast reaches were as follows: –0.95 ms (5.48 ms), 23.01 ms (5.33 ms), and 32.58 ms (9.21 ms), respectively. The implication was that participants simply slammed their fingers onto the object or table surface allowing the surface to stop their motion and the wrist came to a stop shortly thereafter. An ANOVA on the difference times yielded a main effect only for Speed ($F(2, 18) = 4.2$, $P < .05$). The wrist stopped about 30 ms after the fingers in fast reaches but at about the same time in slow reaches. Clearly, the affordance made available by the flat objects and table surface was used in the organization of these reaches-to-grasp.

General discussion

Affordance analysis is an essential component of motor task investigation because it is affordances that determine the structure of the resulting actions. The current experiments illustrate this point well. Manipulation of the affordances made available within a task caused changes in the landmark features of the reach-to-grasp structure. In Experiment 1, we introduced a salient collision hazard, an affordance for ill. As a result, we discovered that a single feature, the grasp aperture at the end of the reach-to-grasp (as found in Experment 3, for instance), bifurcated into a terminal grasp aperture at the end of a reach and a final grasp aperture occurring when the fingers made contact with the target object. In Experiment 2, we found that these features changed within the context of a single task depending on the affordance properties of the target object and on the speed at which the reach-to-grasp was performed. Once more, the overall form of the action evolved as careful stop and grasp movements were exchanged in favor of more risky grasping on the fly. Finally, in Experiment 3, we introduced a collision affordance that could be used to stop the reach-to-grasp movement. We then found that two distinct features, namely, the maximum and terminal grasp apertures, often became one and the same.

Affordances are dispositional properties meaning that they exist in relation to corresponding properties of the actor from the perspective of the relevant action, effectivities (Turvey et al. 1981). In the context of reach-to-grasp actions, the relevant property of the actor is the opposition axis or vector. Iberall et al. (1986) introduced the "opposition axis" as a unit of analysis for reach-to-grasp actions. The axis extends between the opposing thumb and finger(s) and is placed through an object relative to its center of mass so as to yield stable grasping. Following Iberall et al. (1986), the opposition axis was widely used in investigations of visually guided reach-to-grasp actions (e.g. Anquetil and Jeannerod 2007; Baud-Bovy and Soechting 2001b; Frak et al. 2001; Harvey et al. 2002; Jeannerod 1997, 1999; Paulignan and Jeannerod 1996; Rand and Stelmach 2005; Roy et al. 2002; Steenbergen and van der Kamp 2004; Tucker and Ellis 1998, 2001; Oztop and Arbib 2001, 2002; Paulignan et al. 1997; Santello and Soechting 1997). The opposition axis is not only a unit for analysis, but it is also hypothesized as a unit of action that is controlled in the course of a reach-to-grasp. It is a "coordinative structure" (Bingham 1988; Tuller et al. 1982) that constrains the many degrees of freedom of the hand ($\approx$ 26 *df*) to perform in a coordinated fashion as a higher order unit with a reduced number of degrees of freedom to be controlled. An opposition axis varies in length (1 *df*), position (3 *df*), and orientation (2 *df*) for a total of 6 degrees of freedom to be controlled (the same number as a rigid body). Van Bergen et al. (2007) revised the "opposition axis" to make it an "opposition vector." Specification of orientation over 360° is required to describe the control of grasp apertures, and this entails a directed line segment, that is, a vector (but the concept is otherwise identical to the notion of an opposition axis).

Smeets and Brenner (1999) challenged this hypothesis by proposing that grasping is achieved by controlling the trajectories of the thumb and finger(s) independently of one another. They effectively suggested that twice as many degrees of freedom are actively controlled in performing a reach-to-grasp, namely, the 12 degrees of freedom entailed by the separate positions (2×3 *df*) and orientations (2×3 *df*) of the thumb and finger(s). This implies that a high dimensional space would be required to capture the variability, and in particular, it implies that the positional variability of the thumb and finger are independent. We tested this assumption using our data from Experiment 1 and found that Smeets and Brenner's theory was not supported. In fact, the results clearly showed that the relevant unit of action (and therefore, of scientific analysis) was the opposition axis.

Thus, a reach-to-grasp action entails orienting of an opposition vector relative to a target object as well as positioning and sizing the magnitude of the vector. With recognition that reaches-to-grasp entail collision avoidance as much as targeting (Rosenbaum et al. 1999), we realized that the need to control the orientation of the approaching opposition axis during a reach-to-grasp task suggests that mere object size or width might not be the relevant affordance property for the control of reaches-to-grasp. In both Experiments 1 and 2, we found that the orientation of the opposition axis varied systematically and quite significantly ($\approx 35°$) from the horizontal, and this persisted up to the point when the axis was actually positioned by the target object (that is, with the thumb and fingers spanning the object to form the TGA). This led us to hypothesize that the MOE or the Angle (as shown in Fig. 1) might be the more relevant affordance properties of objects targeted for grasping. We tested this hypothesis in Experiments 1 and 2 and found that indeed many features of the reach-to-grasps co-varied with either the MOE or the Angle.

We discovered that the orientation of the opposition axis varied systematically with MOE and that MGA varied with MOE. On the other hand, we found that TGA varied with object width. MGA also varied with the speed of the reaches, increasing in size as speed increased. We found that TGA varied with reach speed but decreased in size as speed increased. Experiment 1 results were replicated under the different task conditions of Experiment 2. In Experiment 2, we found that participants performed reaching-to-grasp-and-lift in two different ways, either in the same way as the simple grasps in Experiment 1, that is, "stops" or instead, grasping the objects on the fly. The respective proportions of these two different types of reach-to-grasp co-varied with the Angle affordance property, a property that determines the difficulty of targeting objects given noisy control of the orientation and position of the approaching opposition axis. (This property might also be called the "Grasp Orientation Range" or GOR, but we have called it simply Angle for brevity and to avoid yet another acromyn.)

We investigated the specific scaling of the spatial structure of the reaches-to-grasp: the MGA and TGA. Given the collision avoidance goals of the tasks, we realized that the problem was similar to that studied by Warren and Whang (1987), who investigated the scaling of passable apertures for walking, and by Snapp-Childs and Bingham (2009), who studied the scaling of foot clearance when participants stepped over obstacles. In the former, participants exhibited safety margins that were scaled to their relevant body dimension, namely, shoulder width. In the latter, participants exhibited safety margins that were scaled to the relevant motor variability, namely, foot position midway through a step. In the present case, we expected safety margins scaled to the relevant body dimension and motor variability. Hand size and the maximum grasp span that it allows must be involved as the relevant body dimension because this determines the available aperture size to be used in a safety margin. On the other hand, with increases in the speed of reaching, increases in the variability of the sizing, positioning and/or orienting of the opposition axis must be expected. Indeed, standard deviations for the MGA increased with speed. Thus, the safety margin was expected to scale both as a function of the relation between maximum hand span and the relevant object dimension (MOE for MGA) and as a function of speed. These relations were successfully represented in a model that captured the data and provided an estimate of maximum hand spans. The model is extremely efficient because it only requires a single free parameter (hypothesized to be task specific) to predict the size of MGAs and TGAs for all graspable objects and reach speeds for an actor of a given size. This is important because it reveals how the data reflect the relevant effectivity, the opposition axis, scale of the actor with respect to this effectivity, maximum grip span, and the goal determined relation between actor and object scale, that is, the affordances.

Finally, we note that the MOE affordance property has been applied as a relevant and uniquely effective unit of analysis in previous work on shape perception and guidance of reaches-to-grasp (Lee et al. 2008; Lee and Bingham 2010).

References

Anquetil T, Jeannerod M (2007) Simulated actions in the first and in the third person perspectives share common representations. Behav Brain Res 1130:125–129. doi:10.1016/j.brainres.2006.10.091

Baud-Bovy G, Soechting JF (2001a) Visual localization of the center of mass of compact, asymmetric, two-dimensional shapes. J Exp Psychol Hum Percept Perform 27:692–706. doi:10.1037/0096-1523.27.3.692

Baud-Bovy G, Soechting JF (2001b) Two virtual fingers in the control of the tripod grasp. J Neurophysiol 86:604–615. doi:10.1007/s00221-002-1359-3

Bingham GP (1988) Task specific devices and the perceptual bottleneck. J Hum Mov Sci 7:225–264. doi:10.1016/0167-9457(88)90013-9

Bingham GP, Muchisky MM (1993a) Center of mass perception and inertial frames of reference. Percept Psychophys 54:617–632. doi:10.1016/j.cub.2010.01.054

Bingham GP, Muchisky MM (1993b) Center of mass perception: perturbation of symmetry. Percept Psychophys 54:633–639

Bingham GP, Muchisky MM (1995) "Center of mass perception": affordances as dispositions determined by dynamics. In: Flach JM, Hancock P, Caird J, Vicente K (eds) Global perspectives on the ecology of human-machine systems, vol 1. Erlbaum, Hillsdale

Bingham GP, Hughes K, Mon-Williams M (2008) The coordination pattern observed when two hands reach-to-grasp. Behav Brian Res 184:283–293. doi:10.1007/s00221-007-1107-9

Bootsma RJ, Marteniuk RG, MacKenzie CL, Zaal FTJM (1994) The speed-accuracy trade-off in manual prehension: effects of movement amplitude, object size, and object width on kinematic characteristics. Behav Brain Res 98:535–541. doi:10.1007/BF00233990

Coats R, Bingham GP, Mon-Williams M (2008) Calibrating grasp size and reach distance: interactions reveal integral organization of reaching-to-grasp movements. Exp Brain Res 189:211–220. doi:10.1007/s00221-008-1418-5

Frak V, Paulignan Y, Jeannerod M (2001) Orientation of the opposition axis in mentally simulated grasping. Exp Brain Res 136:120–127. doi:10.1007/s002210000583

Gibson JJ (1977) The theory of affordances. In: Shaw R, Bransford J (eds) Perceiving, acting, and knowing: towards an ecological psychology. Hillsdale NJ, Erlbaum

Gibson JJ (1979/1986) The ecological approach to visual perception. Hillsdale NJ, Erlbaum

Goodale MA, Milner AD, Jakobson LS, Carey DP (1991) A neurological dissociation between perceiving objects and grasping them. Nature 349:154–156. doi:10.1038/349154a0

Goodale MA, Meenan JP, Bülthoff HH, Nicolle DA, Murphy KS, Racicot CI (1994a) Separate neural pathways for visual analysis of object shape in perception and prehension. Curr Biol 4:604–610. doi:10.1016/S0960-9822(00)00132-9

Goodale MA, Jakobsen LS, Keillor JM (1994b) Differences in the visual control of pantomimed and natural grasping movements. Neuropsychology 32:1159–1178. doi:10.1016/0028-3932(94)90100-7

Harvey M, Jackson SR, Newport R, Krämer T, Morris DL, Dow L (2002) Is grasping impaired in hemispatial neglect? Behav Neurol 13:17–28

Iberall T, Bingham GP, Arbib MA (1986) Opposition space as a structuring concept for the analysis of skilled hand movements. In: Heuer H, From C (eds) Experimental brain research series 15. Springer, Berlin, pp 158–173

Jeannerod M (1984) The timing of natural prehension movements. J Motor Behav 16:235–254

Jeannerod M (1988) The neural and behavioural organization of goal-directed movements. Oxford University Press, Oxford

Jeannerod M (1997) The cognitive neuroscience of action. Blackwell, Oxford

Jeannerod M (1999) Visuomotor channels: their integration in goal-directed prehension. Hum Mov Sci 18:201–218. doi:10.1016/S0167-9457(99)00008-1

Kelso JAS, Tuller B, Vatikiotis-Bateson E, Fowler CA (1984) Functionally specific articulatory cooperation following jaw perturbation during speech: evidence for coordinative structures. J Exp Psychol Hum Percept Perform 10:812–832. doi:10.1037//0096-1523.10.6.812

Lederman SJ, Wing AM (2003) Perceptual judgment, grasp point selection and object symmetry. Exp Brain Res 152:156–165. doi:10.1007/s00221-003-1522-5

Lee YL, Bingham GP (2010) Large perspective changes yield perception of metric shape that allows accurate feedforward reaches-to-grasp and it persists after the optic flow has stopped!. Exp Brain Res 204:559–573. doi:10.1007/s00221-010-2323-2

Lee YL, Crabtree CE, Norman JF, Bingham GP (2008) Poor shape perception is the reason reaches-to-grasp are visually guided online. Percept Psychophys 70(6):1032–1046. doi:10.3758/PP.70.6.1032

Loftus A, Goodale MA, Servos P, Mon-Williams M (2004) When two eyes are better than one in prehension: prehension, end-point variance and monocular viewing. Exp Brain Res 158:317–327. doi:10.1007/s00221-004-1905-2

Mark LS, Nemeth K, Gardner D, Dainoff MJ, Paasche J, Duffy M, Grandt K (1997) Postural dynamics and the preferred critical boundary for visually guided reaching. J Exp Psychol Hum Percept Perform 23:1365–1379. doi:10.1037/0096-1523.23.5.1365

Marteniuk RG, MacKenzie CL, Jeannnerod M, Athenes S, Dugas C (1987) Constraints on human arm movement trajectories. Can J Psychol 41:365. doi:10.1037/h0084157

Mon-Williams M, Dijkerman HC (1999) The use of vergence information in the programming of prehension. Exp Brain Res 128:578–582. doi:10.1007/s002210050885

Newell KM, Scully DM, Tenenbaum F, Hardiman S (1989) Body scale and the development of prehension. Dev Psychobiol 22:1–13. doi:10.1002/dev.420220102

Oztop E, Arbib MA (2001) A biologically inspired learning to grasp system. Proceedings of the 23rd annual international conference of the IEEE. Eng Med Biol Soc 1:857–860. doi: 10.1109/IEMBS.2001.1019077

Oztop E, Arbib MA (2002) Schema design and implementation of the grasp-related mirror neuron system. Biol Cybern 87:116–140. doi:10.1007/s00422-002-0318-1

Paulignan Y, Jeannerod M (1996) Prehension movements: the visuomotor hypothesis revisited. In: Wing AM, Haggard P, Flanagan JR (eds) Hand and brain: the neurophysiology and psychology of hand movements. Academic Press, San Diego

Paulignan Y, Frak VG, Ton I, Jeannerod M (1997) Influence of object position and size on human prehension movements. Exp Brain Res 114:226–234. doi:10.1007/PL00005631

Pedhazur EJ (1982) Multiple regression in behavioral research. Harcourt Brace, Fort Worth

Rand MK, Stelmach GE (2005) Effect of orienting the finger opposition space in the control of reach-to-grasp movements. J Motor Behav 37:65–78. doi:10.3200/JMBR.37.1.65-78

Rosenbaum DA, Meulenbroek RGJ, Vaughan J, Jansen C (1999) Coordination of reaching and grasping by capitalizing on obstacle avoidance and other constraints. Exp Brain Res 128:92–100. doi:10.1007/s002210050823

Rosenbaum DA, Meulenbroek RGJ, Vaughan J, Jansen C (2001) Posture-based motion planning: applications to grasping. Psychol Rev 108:709–734. doi:10.1037//0033-295X.108.4.709

Roy AC, Paulignan Y, Meunier M, Boussaoud D (2002) Prehension movements in the macaque monkey: effects of object size and location. J Neurophysiol 88:1491–1499. doi: 10.1007/s00221-005-0133-8

Santello M, Soechting JF (1997) Matching object size by controlling finger span and hand shape. Somatosens Motor Res 14:203–212

Servos P, Goodale MA, Jakobson LS (1992) The role of binocular vision in prehension: a kinematic analysis. Vision Res 32:1513–1521. doi:10.1016/0042-6989(92)90207-Y

Smeets JBJ, Brenner E (1999) A new view on grasping. Mot Control 3:237–271

Snapp-Childs W, Bingham GP (2009) The affordance of barrier crossing in young children exhibits dynamic, not geometric similarity. Exp Brain Res 198:527–533. doi:10.1007/s00221-09-1944-9

Steenbergen B, van der Kamp J (2004) Control of prehension in hemiparetic cerebral palsy: similarities and differences between the ipsi- and contra-lesional sides of the body. Dev Med Child Neurol 46:325–332. doi:10.1017/S0012162204000532

Tucker M, Ellis R (1998) On the relations between seen objects and components of potential actions. J Exp Psychol Hum Percept Perform 24:830–846. doi:10.1037//0096-1523.24.3.830

Tucker M, Ellis R (2001) The potentiation of grasp types during visual object categorization. Vis Cogn 8:769–800. doi:10.1080/13506280042000144

Tuller B, Fitch HL, Turvey MT (1982) The Bernstein perspective: II. The concept of muscle linkage or coordinative structure. In: Kelso JAS (ed) Human motor behavior: an introduction. Erlbaum, Hillsdale

Turvey MT, Reed ES, Shaw RE, Mace M (1981) Ecological laws of perceiving and acting: in reply to Fodor and Pylyshyn. Cognition 9:237–304. doi:10.1016/0010-0277(81)900002-0

Van Bergen E, Van Swieten LM, Williams JHG, Mon-Williams M (2007) The effect of orientation on prehension movement time. Exp Brain Res 178:190–193. doi:10.1007/s00221-006-0722-1

Van de Kamp C, Zaal FTJM (2007) Prehension is really reaching and grasping. Exp Brain Res 182:27–34. doi:10.1007/s00221-007-0968-2

Warren WH (1984) Perceiving affordances: visual guidance of stair climbing. J Exp Psychol Hum Percept Perform 10:683–703. doi:10.1037//0096-1523.10.5.683

Warren W, Whang S (1987) Visual guidance of walking through apertures: body-scaled information for affordances. J Exp Psychol Hum Percept Perform 13(3):371–383. doi:10.1037/0096-1523.13.3.371

Whitwell RL, Goodale MA (2009) Updating the programming of a precision grip is a function of recent history of available feedback. Exp Brain Res 194:619–629. doi:10.1007/s00221-009-1737-1

Wing AM, Haggard P, Flanagan JR (1996) Hand and brain: the neurophysiology and psychology of hand movements. Academic Press, San Diego