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RESEARCH ARTICLE

Distractor objects affect fingers' angular distances but not fingers' shaping during grasping

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Abstract The aim of the present study was to determine whether and how hand shaping was affected by the presence of a distractor object adjacent to the to-be-grasped object. Twenty subjects were requested to reach towards and grasp a 'convex' or a 'concave' object in the presence or absence of a distractor object either of the same or different shape than the target object. Flexion/extension at the metacarpal-phalangeal (MCP) and proximal interphalangeal joints of all digits, and abduction angle between digits were measured by resistive sensors embedded in a glove. The results indicate robust interference effects at the level of reach duration and the extent of fingers' abduction angles together with changes at the level of a single joint for the thumb. No distractor effects on individual fingers' joints except for the MCP of the middle and little fingers were found. These findings suggest that the presence of distractor object affects hand shaping in terms of fingers' abduction angles, but not at the level of 'shape dependent' fingers' angular excursions. Furthermore, they support the importance of the thumb for the guidance of selective reach-to-grasp movements. We discuss these results in the context of current theories proposed to explain the object selection processes underlying the control of hand action.

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Introduction

From everyday experience, we intuitively know that we carry out many visually guided actions on the objects that surround us. For example, when choosing a piece of fruit from a bowl, many fruits are visible and within reach, but only the one that we would like to pick up governs the particular pattern and the direction of reaching movement. This implies that to avoid the undesired fruits and instead to act selectively towards the desired fruit, at some stage (or stages) in the information stream some objects are filtered out from processing. In this respect, little is known about the limits governing the brain's ability to process information presented in parallel for the control of overt action towards three-dimensional (3D) stimuli.

The mechanisms underlying the control of such behaviours have been studied by having people reach for, point to, and grasp objects when non-target (i.e. distractor) objects were introduced into the workspace (e.g. Castiello 1996; Deubel et al. 1998; Keulen et al. 2002; Pratt and Abrams 1994; Tipper et al. 1992, 1997). In the present article, we report an experiment that continues that tradition. Our interest is in the hand shape that people make while they grasp target objects in the presence of distractors. It is worth noting that much can also be learned about the underlying mechanisms by examining arm spatial trajectories and temporal aspects of the movement (e.g. Chang and Abrams 2004). Such an approach is taken by a number of researchers (e.g. Chang and Abrams 2004; Fischer and Adam 2001; Tipper et al. 1997). However, here we were specifically concerned with kinematics of hand shaping during reach to grasp movement.

In previous attempts to target specifically the grasping component during a reach to grasp movement towards a target in the presence of distractor objects (for a review see Castiello 1999) participants were requested to grasp a target presented in conjunction with a distractor of a different size, but similar in color and positioned roughly in the same position as the target (Bonfiglioli and Castiello 1998; Castiello 1996, 1998) It was found that the subjects' amplitude of peak grip aperture (i.e. the greatest angular distance between the thumb and the index finger) while en-route to the target was influenced by the size of the distractor. If the target was small, the amplitude of peak grip aperture was greater, when the distractor was large, than when no distractor was present. Conversely, the amplitude of peak grip aperture for the grasp of a large target was less, when the distractor was small, than when there was no distractor.

Common to these findings is the suggestion that if more than one grasping pattern is simultaneously kept active, this parallel activation triggers mutual interference. The proposal is that interference arose from the competition between the different types of grasp required by target and distractor having different size. Thus, parallel computations for different types of grasp, one for the target and one for the attended distractor, may have been at the origin of the changes found for the kinematics of the action directed towards the target when presented alone. In these terms, both of target and distractor evoke grasping representations which interact in a mutually suppressive or competitive way.

Research to date on this topic have focused on the relationship between the thumb and the index finger giving little attention to differences in the shape assumed by individual fingers when performing grasping movements to target objects in the presence of distractors. It is not known whether and how the presence of a distractor object affects hand shaping for a target object at the level of single fingers' posture. Recent methodological and theoretical developments in the study of grasping make this a particularly timely and tractable issue. Santello and colleagues (Santello and Soechting 1998; Santello et al. 2002) investigated hand shaping at the level of individual joints for all fingers for movements directed towards objects having different shapes. Results from these studies revealed a gradual modulation of hand posture during reaching, which was function of the object geometry. Therefore it may be reasonable to ask whether the presence of a distractor object affects hand kinematics only at the level of the thumb–index angular distance (as revealed by previous studies), or also at the level of hand shaping in terms of individual fingers' posture.

In the present experiment, we contrasted the evolution of hand shaping during a grasping task directed towards objects of different shapes in three conditions: a no-distractor condition in which a 'convex' or a 'concave' target object was presented in isolation, a congruent distractor condition in which the target object ('convex' or 'concave') was flanked by a distractor object of the same shape, and an incongruent distractor condition in which the target object was flanked by a distractor object of a different shape (e.g. either a 'convex' target with a 'concave' distractor or vice versa). Comparing the effects of distractor objects on the extent and timing of the abduction angles between fingers, with the extent and timing of kinematical parameters concerned with hand shaping at the level of single digits, may allow to ascertain if and at which level the distractor objects produce interference on the motor patterning for the target. If a distractor of a different shape than the target object is represented at a more generalized size level, then interference effects should be most evident at the level of abduction angles with particular reference to that involving the thumb and the index finger as previously demonstrated. In contrast, if the distractor representation is more fine-grained then it might be possible that the distractor being represented at the level of angular excursions of single fingers.

Our results indicate robust interference effects on reach duration on the extent of fingers' abduction angles and at level of a single joint for the thumb. In contrast, no distractor effects on the pattern of angular excursion for the joints, which were sensitive to object shape, were found.

Materials and methods

Subjects

Twenty right-handed subjects (males 10, females 10; mean age 19–34 years) participated in this experiment. They reported normal or corrected-to-normal vision and were naïve about the purpose of the experiment. The experimental procedures were approved by the Institutional Review Board at the University of Padova and were in accordance with the declaration of Helsinky.

Stimuli

In the present experiment, a convex and a concave wooden object served as targets and distractors (see Fig. 1a). The 'convex' object was characterized by a point at the top from which, two triangular protrusions ended up at the base (see Fig. 1a). It was 5 cm wide at the base and 10 cm wide at the point of maximum ‘convexity’ (i.e. the distance between the two vertices of triangular protrusions; see Fig. 1a). The ‘concave’ object was characterized by two triangular indentations extending from each of four corners to its center (see Fig. 1a). It was 10 cm wide at the base and 5 cm wide at the point of maximum ‘concavity’ (i.e. the distance between the two vertices of triangular indentations; see Fig. 1a). Both objects measured 3 cm in thickness, 9 cm in height and weighed ~100 g.

Apparatus

Subjects sat in a chair in front of a table and began each trial with the elbow and wrist resting on a flat surface, the forearm horizontal, and the arm oriented in the parasagittal plane passing through the shoulder. Each trial started with the subject’s right hand in a pre-set pronated position (i.e. initial hand posture; see Fig. 1b) pressing a starting switch embedded within the working surface (Fig. 1b). The surface of the starting position was designed with slight convexities dictating a natural posture of the fingers (see Fig. 1b). The subjects were instructed to maintain the initial hand position until they heard a tone signaling the start of the trial. Upon hearing this tone, subjects were instructed to reach towards, grasp and lift the target object, at a comfortable speed. The subjects naturally grasped the object opposing the thumb to the fingers as shown in Fig. 1a. The concave object was grasped by opposing the thumb with the other fingers around the area of maximum concavity (see Fig. 1a). In such circumstances, all fingers were near to each other. For the convex object the thumb/fingers opposition pattern was along the points of maximum convexity of the object (see Fig. 1a). In particular, the convex object was generally grasped with the index and the middle fingers above the point of maximum convexity and the ring and little fingers below this point; in some cases, also the ring finger was placed above the point of maximum convexity. The target object was placed at 30 cm from the hand start position along the subject’s midline (Fig. 1b) and it rested on a second pressure switch. When present, the distractor object was located at 30 cm from the hand start location, at ~30° either to the right or to the left side of the target object (Fig. 1b).

Visual availability of the stimuli was controlled with Plato spectacles (Plato Technologies Inc.). These were lightweight and were fitted with liquid crystal lenses. The opacity of the lenses was controlled by the starting switch, on which the hand rested when the hand was positioned on the switch, the lenses were opaque and cleared when the hand was lifted from the initial hand position. Once the subject re-placed his/her hand on the starting switch at the end of each trial, the LCD glasses were set to return in the opaque position.

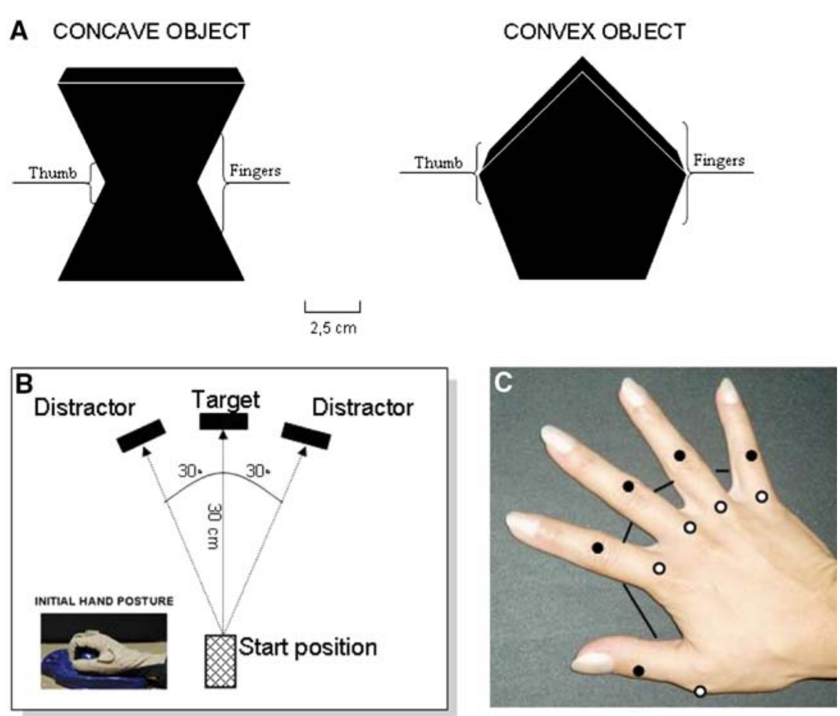

Fig. 1 **a** represents the objects used as targets and distractors in the present experiment. 2.5 cm refers to the drawing’s scale. *Parentheses* depict the thumb and fingers’ contact areas used by the subjects as to naturally grasp the objects. **b** shows the schematic representation of the workspace (*top view*) and the subject’s initial hand posture for the right hand. **c** shows a schematic view of *MCP* (*white dots*) and *PIP* joints (*black dots*), and distances between adjacent digits (*black segments*) from which angular excursions and abduction angles were recorded, respectively

Procedure

The main task of the subject was to reach towards and grasp the target object between the thumb and the four fingers on the vertical sides of the object, and briefly lift it from the working surface. The experimenter visually monitored the performance, during each trial, to ensure subject's compliance to these requirements. This main task was performed under three different conditions:

1. No-distractor condition: the target object was presented centrally and in isolation.
2. Congruent-distractor condition: the target object was centrally placed and flanked by an identical object (e.g. 'convex' target/'convex' distractor; 'concave' target/'concave' distractor).
3. Incongruent-distractor condition: the target object was centrally placed and flanked by an object of a different shape (e.g. 'convex' target/'concave' distractor; 'concave' target/'convex' distractor).

Subjects performed two blocks of 50 randomized trials over which all possible target/distractor combinations were presented (ten trials per each combination) and were given a rest at the end of the first block.

Recording techniques

Hand posture was measured by resistive sensors embedded in a glove (CyberGlove, Virtual Technologies, Palo Alto, CA) worn on the subjects' right hand. The sensor's linearity was 0.62% of maximum nonlinearity over the full range of hand motion. The sensor's resolution was 0.1°, which remained constant over the entire range of joint motion. Sensors' sampling occurred at 15-ms intervals. The movement's onset was signaled by the release of the pressure switch embedded in the hand starting position. The movement's end was taken as the time in which the switch underneath the target object was released by the object lifting.

Dependent measures

Movement duration was calculated as the time interval between the onset and the end of the movement. Movement duration was normalized such that a more informative comparison between subjects and conditions was allowed. Angular excursion was measured at the metacarpal-phalangeal (MCP) and proximal interphalangeal (PIP) joints of the thumb, index, middle, ring and little fingers (T, I, M, R, and L, respectively) (see Fig. 1c). Before starting the experiment we recorded the baseline hand posture, by asking subjects to position their right hand flat on the table and to maintain it in that position while MCP and PIP joint angles of all digits were recorded. The MCP and PIP joint angles were defined as 0° when all fingers were straight and in the palm plane ('baseline' hand posture). Flexion was assigned positive value. Furthermore, we measured the abduction angle between digits (thumb/index, index/middle, middle/ring, and ring/little fingers) (see Fig. 1c). The baseline abduction angle between digits was set as 0° when the hand was positioned flat on a pre-determined position ('baseline' hand posture) with pre-set abduction angles (thumb/index fingers 22°; index/middle fingers 32°; middle/ring fingers 45°; ring/little fingers 50°). Abduction angles' closure was assigned negative values.

Data analysis

It is evident in the literature that the hemispace location of the target relative to the distractor has differential effects for left versus right hand reaches (e.g. Howard and Tipper 1997; Jackson et al. 1995). However, preliminary analysis did not reveal differences due to the factor 'distractor location', consequently, trials for the left and right distractor's position were collapsed. To address the possible differences in absolute duration of reaching movements due to the manipulation of the distractor type condition and to the type of object to be grasped, we performed an ANOVA with 'distractor type' (no-distractor, distractor congruent, distractor incongruent) and 'type of target' ('convex', 'concave') as within-subjects factors. To assess the pattern of angular excursion depending on the distractor type condition we carried out repeated measures multivariate analyses of variance (MANOVAs), one for each digit for both MCP and PIP joints. In these MANOVAs, the main within-subjects factors were 'distractor type', 'type of target', and 'time' (from 10 to 100% of the normalized movement duration, at 10% interval). A MANOVA including the same main factors was carried out as to ascertain the effect of the distractor type condition and the type of object to be grasped on the abduction angle between fingers. Main effects were used to explore means of interest. Bonferroni's correction ($\alpha = 0.05$) was applied.

Results

This section will be organized in two parts. In the first part, we shall describe the differences between 'convex' versus 'concave' objects for the no-distractor condition for each of considered dependent measures (i.e. reach duration, fingers' angular excursion, and fingers' abduction angles). The determination of kinematical parameters, which are object-shape specific when no distractor object was present, allows us to address whether the presence of the distractor affected these parameters. In the second part, we shall describe the results concerned with the impact that the presence of a congruent or incongruent distractor had on hand shaping for the considered measures. In this section, we shall present the results for reach duration followed by the results concerned with the extent and timing of the patterns of fingers' angular excursion and abduction angle.

'Convex' versus 'concave' object: no-distractor condition

Reach duration was similar when comparing the 'convex' with the 'concave' object (1,339 vs. 1,328 ms, respectively). When looking at the patterns of angular excursion, the profile analysis revealed that from the beginning to 50% of reach duration no differences depending on the type of target object for any of the recorded joints were noticed (see Fig. 2). In contrast, after 50% of reach duration, the PIP joint of the middle finger and the MCP joint of the ring finger were more extended for the 'convex' than for the 'concave' object (see Fig. 2). Furthermore, after 50% of reach duration, the PIP joint of the index finger was more flexed for the 'convex' than for the 'concave' object (see Fig. 2). For the remaining joints the patterns of angular excursion were similar from the beginning up to the end of reach duration (see Fig. 2).

The type of hand configurations dictated by the type of target object also gave rise to some differences at the level of fingers' abduction angles. As shown in Fig. 3, middle/ring and ring/little fingers' abduction angles were similar from the beginning up to 50% of reach duration. However, after 50% of reach duration, these angles became larger for the 'convex' than for the 'concave' object (Fig. 3). In contrast, as revealed by the profile analysis, the thumb/index and index/middle fingers' abduction angle remained invariant with respect to the type of to-be-grasped object from the beginning to the end of the reaching movement (Fig. 3).

No-distractor versus congruent and incongruent distractor conditions

Reach duration

For reach duration, the main factor 'distractor type' was significant [$F_{(2,38)} = 4.374$, $P < 0.021$]. Post-hoc contrasts (Bonferroni's correction) revealed that reach duration was longer when the target was flanked by an incongruent distractor (1,364 ms), than when the target was presented alone (1,334 ms). The difference between the no-distractor and the congruent distractor (1,357 ms) conditions was almost significant ($P = 0.058$). The two-ways interaction between 'type of target' and 'distractor type' was not significant [$F_{(2,38)} = 0.728$, NS].

Patterns of angular excursion

The results obtained from the MANOVAs performed on the angular excursion for each finger separately (e.g. each for both of MCP and PIP joints, see Table 1) revealed that none of the joints which specifically modulated with respect to the shape of the target object ('convex' or 'concave') when presented in isolation (i.e. PIP joint of both index and middle fingers, and MCP joint of ring finger; see Fig. 2) were significantly affected by the distractor type condition. However, the distractor type condition significantly affected the PIP joint of the thumb, as revealed by the significance of the main factor 'distractor type' [$F_{(2,38)} = 8.066$, $P < 0.002$]. In particular, this joint was more extended when the target object was presented alone (5.579°) than when flanked by the congruent (6.466°) or the incongruent distractor (6.217°). As shown in Fig. 4, this pattern of over-extension was evident from 20 to 70% of movement time when the object to be grasped was 'concave', and from 40 to 80% when it was 'convex' (see Table 1; three-ways interaction between 'type of target', 'distractor type', and 'time' [$F_{(18,342)} = 2.496$, $P < 0.002$]). The interaction between 'distractor type' and 'time' was also significant for the MCP joint of both the middle and the little fingers ([$F_{(18,342)} = 1.692$, $P < 0.04$] and [$F_{(18,342)} = 1.730$, $P < 0.035$], respectively). Profile analyses for these two joints did not reveal a consistent pattern indicating the influence of the distractor's shape on the modulation of these joints during reaching (see Fig. 5). This latter observation might be ascribed to a generalized 'disturbance' effect due to the presence of the distractor or to the effect of experimental manipulation on fingers' abduction angles as explained below.

Fingers' abduction angles

Table 2 shows the results obtained from the MANOVA performed to address the effects of the experimental manipulation on the fingers' abduction angles. This analysis revealed a significant main effect of the factor 'distractor type' for the angular distance between thumb and index [$F_{(2,38)} = 4.665$, $P < 0.016$]. In

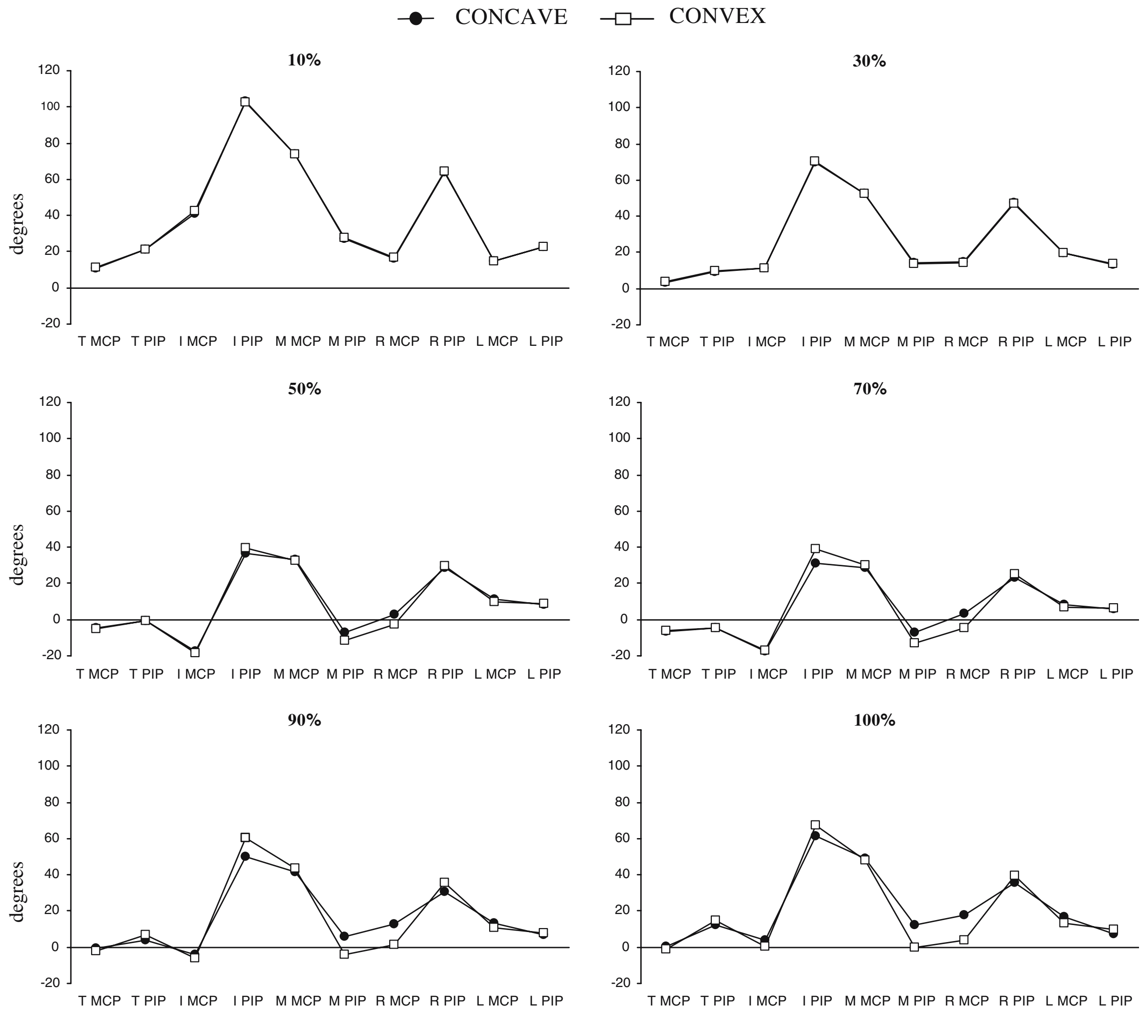

Fig. 2 Patterns of angular excursion for no-distractor trials at different epochs during reaching (10, 30, 50, 70, 90, and 100% of the movement time) for the concave (*filled circles*) and the convex (*empty squares*) objects. The represented angles correspond to the *MCP* and *PIP* joints for the thumb (*T*), index (*I*), middle (*M*), ring (*R*), and little fingers (*L*). Positive values correspond to fingers' flexion whereas negative values correspond to fingers' extension. Data are averaged across subjects and trials

particular, post-hoc contrasts revealed that this angle was smaller when the target object was presented alone (–61.600°) than when it was flanked by a congruent (–61.053°) or an incongruent (–61.200°) distractor. No significant differences were found when comparing the congruent and the incongruent distractor conditions. The interaction between 'distractor type' and 'time' was significant for the abduction angles between the middle/ring [$F_{(18,342)} = 1.645$, $P < 0.049$] and the ring/little fingers [$F_{(18,342)} = 1.616$, $P = 0.05$]. As revealed by the profile analysis, these angles were similar for each of the distractor type conditions at the very beginning of the movement (see Fig. 6), but became larger for the no-distractor than for the congruent and the incongruent distractor condition from 30–40% up to 60–70% of reach duration (Fig. 6). Further, from 60–70% up to 90% of reach duration the pattern inverted: these angles became smaller for the no-distractor than for the congruent and the incongruent conditions (Fig. 6). In particular, after 60–70% of reach duration when the distractor was incongruent these angles were larger than when the distractor was congruent. However, at object contact these angles were found to be similar for all distractor type conditions.

Discussion

The main goal of the present experiment was to observe, whether, hand shaping to a target of a particular shape was affected by the presence of a distractor object of a similar or a different shape. Our

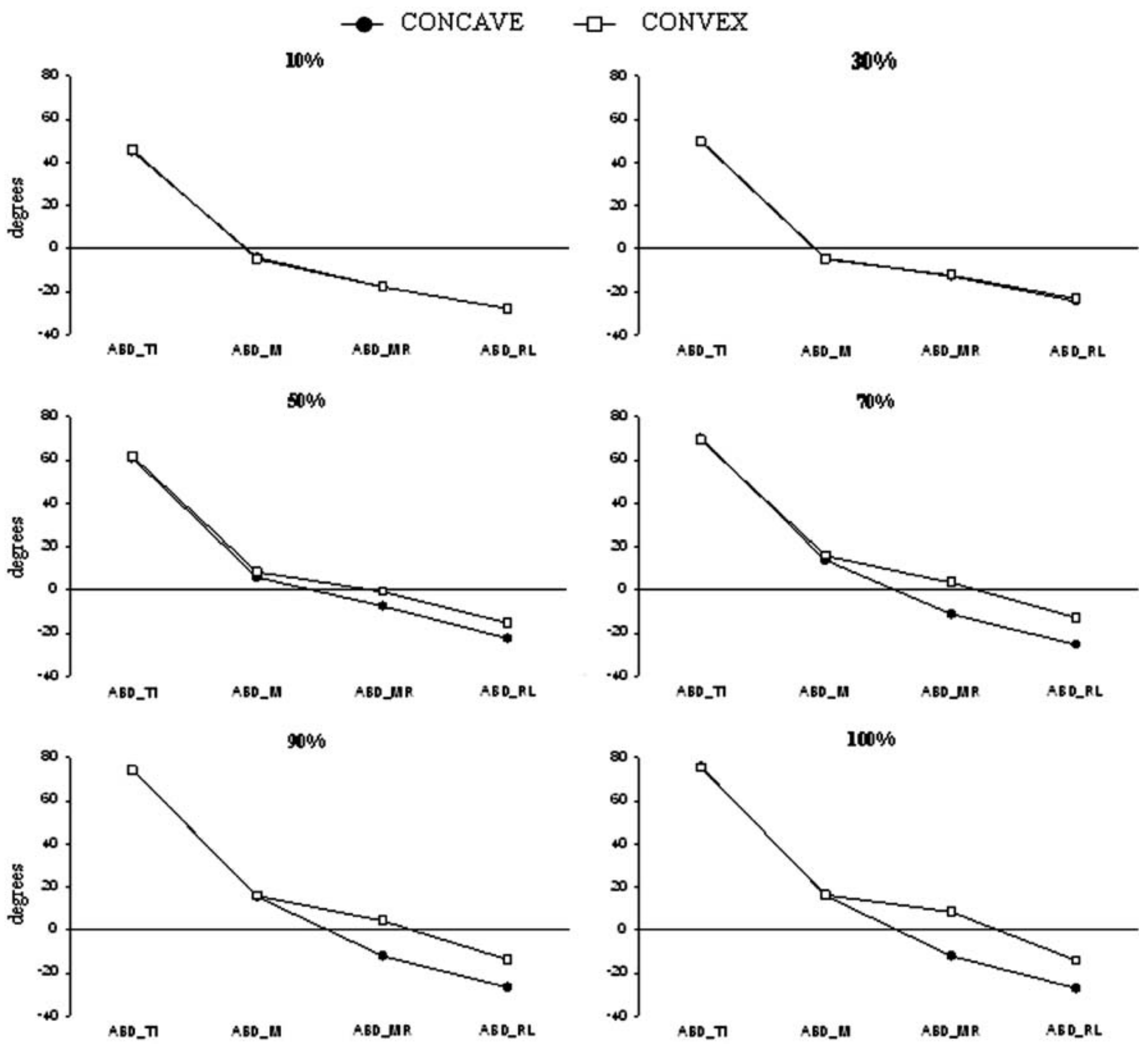

Fig. 3 Patterns of abduction angle between fingers for the no-distractor condition at different epochs during reaching (10, 30, 50, 70, 90, and 100% of the movement time) for the concave (*filled circles*) and the convex (*empty squares*) objects. The represented fingers' abduction angles (ABD) correspond to the angle between thumb and index (*TI*), index and middle (*IM*), middle and ring (*MR*), and ring and little fingers (*RL*). Negative values correspond to fingers' closure whereas positive values correspond to fingers' aperture. Data are averaged across subjects and trials

results indicate that the presence of the distractor object produced a significant increase in reach duration for the incongruent-distractor condition and, although not fully significant, also the presence of the congruent distractor elicited a lengthening of reach duration. Furthermore, the presence of the distractor object significantly affected kinematic parameterization of the thumb. Both angular excursion (i.e. PIP joint) and abduction-adduction angle showed an alteration of the stereotypical aperture-closure pattern found for the no-distractor condition. With respect to the pattern of fingers' angular excursion none of the joints sensitive to object shape, as identified for the no-distractor condition, were affected by the presence of the distractor. Conversely, the fingers' abduction angles which were related to the 'convex' or the 'concave' objects when grasped in isolation, were affected by the presence of the distractor independently from its shape.

This experiment has demonstrated that distractors can produce measurable interference effects in tasks requiring subjects to reach out and pick up an object. As previously demonstrated, the presence of the distractor increased the duration of the reach (e.g. Castiello 1996; Tipper et al. 1997; Meegan and Tipper 1998) indicating that the planning of reach duration has been altered by the presence of the distractor.

Of perhaps more interest, we have also observed that the presence of the distractor does not affect hand shaping at the level of shape-dependent fingers' joints, but in terms of the fingers' abduction angles. In

Table 1 Results of five MANOVAs performed on the patterns of angular excursion for all fingers (each for both of MCP and PIP joints)

Finger	Joint	Object	Distractor type	Time	Object × distractor type	Object × time	Distractor type × time	Object × distractor type× time
Thumb	MCP	$F = 1.271_{(1,19)}$, NS	$F = 0.111_{(2,38)}$, NS	$F = 46.841_{(9,171)}$, $P < 0.0001$	$F = 0.692_{(2,38)}$, NS	$F = 1.888_{(9,171)}$, NS	$F = 0.678_{(18,342)}$, NS	$F = 0.973_{(18,342)}$, NS
	PIP	$F = 3.014_{(1,19)}$, NS	$F = 8.066_{(2,38)}$, $P < 0.002$	$F = 42.704_{(9,171)}$, $P < 0.0001$	$F = 0.234_{(2,38)}$, NS	$F = 4.856_{(9,171)}$, $P < 0.0001$	$F = 1.004_{(18,342)}$, NS	$F = 2.496_{(18,342)}$, $P < 0.002$
Index	MCP	$F = 1.147_{(1,19)}$, NS	$F = 1.966_{(2,38)}$, NS	$F = 75.349_{(9,171)}$, $P < 0.0001$	$F = 0.598_{(2,38)}$, NS	$F = 1.557_{(9,171)}$, NS	$F = 0.837_{(18,342)}$, NS	$F = 0.532_{(18,342)}$, NS
	PIP	$F = 8.524_{(1,19)}$, $P < 0.01$	$F = 0.423_{(2,38)}$, NS	$F = 121.544_{(9,171)}$, $P < 0.0001$	$F = 0.361_{(2,38)}$, NS	$F = 5.934_{(9,171)}$, $P < 0.001$	$F = 0.499_{(18,342)}$, NS	$F = 2.049_{(18,342)}$, NS
Middle	MCP	$F = 0.181_{(1,19)}$, NS	$F = 0.821_{(2,38)}$, NS	$F = 112.430_{(9,171)}$, $P < 0.0001$	$F = 0.017_{(2,38)}$, NS	$F = 1.262_{(9,171)}$, NS	$F = 1.692_{(18,342)}$, $P < 0.04$	$F = 2.081_{(18,342)}$, $P < 0.007$
	PIP	$F = 15.478_{(1,19)}$, $P < 0.002$	$F = 0.958_{(2,38)}$, NS	$F = 78.363_{(9,171)}$, $P < 0.0001$	$F = 0.321_{(2,38)}$, NS	$F = 14.212_{(9,171)}$, $P < 0.0001$	$F = 1.005_{(18,342)}$, NS	$F = 0.262_{(18,342)}$, NS
Ring	MCP	$F = 42.182_{(1,19)}$, $P < 0.0001$	$F = 0.082_{(2,38)}$, NS	$F = 29.710_{(9,171)}$, $P < 0.0001$	$F = 0.610_{(2,38)}$, NS	$F = 20.526_{(9,171)}$, $P < 0.0001$	$F = 0.606_{(18,342)}$, NS	$F = 0.509_{(18,342)}$, NS
	PIP	$F = 3.550_{(1,19)}$, NS	$F = 0.087_{(2,38)}$, NS	$F = 107.454_{(9,171)}$, $P < 0.0001$	$F = 0.011_{(2,38)}$, NS	$F = 3.555_{(9,171)}$, $P < 0.0001$	$F = 1.192_{(18,342)}$, NS	$F = 1.546_{(18,342)}$, NS
Little	MCP	$F = 2.852_{(1,19)}$, NS	$F = 0.056_{(2,38)}$, NS	$F = 11.048_{(9,171)}$, $P < 0.0001$	$F = 1.165_{(2,38)}$, NS	$F = 1.698_{(9,171)}$, NS	$F = 1.730_{(18,342)}$, $P < 0.035$	$F = 0.551_{(18,342)}$, NS
	PIP	$F = 2.386_{(1,19)}$, NS	$F = 2.712_{(2,38)}$, NS	$F = 41.627_{(9,171)}$, $P < 0.0001$	$F = 0.698_{(2,38)}$, NS	$F = 5.100_{(9,171)}$, $P < 0.0001$	$F = 0.829_{(18,342)}$, NS	$F = 0.727_{(18,342)}$, NS

NS not significant

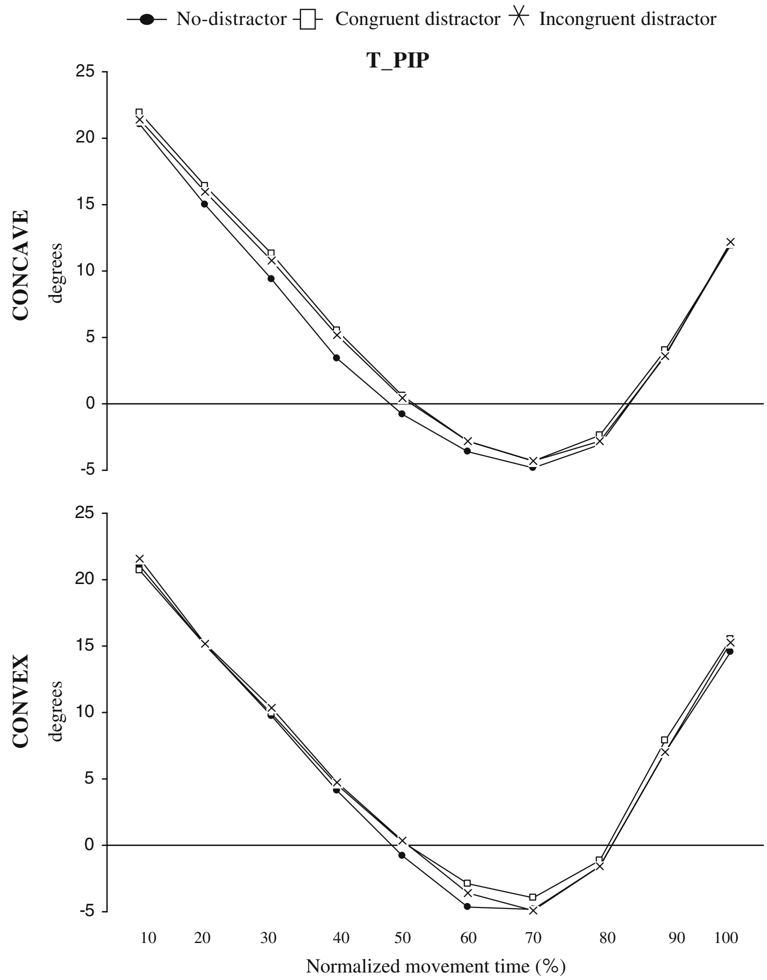

Fig. 4 Time course of angular excursion during reaching for the concave (*top panel*) and convex (*bottom panel*) objects in no-distractor (*filled circles*), congruent distractor (*empty squares*), and incongruent distractor (*asterisks*) conditions. The represented angular excursion refers to the *PIP* joint of the thumb (*T*). Data are averaged across subjects and trials

particular, these angles were similar for each of the distractor type conditions at the very beginning of the movement, but became larger for the no-distractor than for the congruent and the incongruent distractor conditions from 30 up to 70% of reach duration. Further, from 70 up to 90% of reach duration these angles became smaller for the no-distractor than for the congruent and the incongruent conditions. This would indicate that up to 30% target shape does not affect hand shape (as happens when no distractors are present), suggesting that hand shape is not selective for target shape and/or too noisy up to that point. Then selection of the distractor becomes necessary given that distractor shape is acknowledged and 'shape' interference has to be solved. This 'acknowledgment' phase starts from 30 up to 70%, a temporal window which is crucial for hand preshaping leading to maximum hand aperture. The fact that from 70% to the end of reaching the abduction angles' pattern returned at the same extent as found for the no-distractor condition signifies that the distractor-related movement plan has been possibly completed and totally filtered out by that moment. These findings give an estimate of the time period within which identifiable changes in kinematic patterning consequent to the presence of the distractor are noticed.

It is known that when humans manipulate irregularly shaped objects, they typically strive to select grasp points that result in a grasp axis that is normal to local surface curvatures at contact points. This suggests the use of a broader strategy to cope with such torsional loads to local surface curvatures at contact points (see Blake 1992; Goodale et al. 1994). Consequently it might be hypothesized that the presence of a distractor object produced a disturbance which in principle could have threaten grasp stability. In other words, by modulating the points in which the digits were placed, the applied forces would be more effective when the object had to be lifted. This modulation may bring to an amplification of the abduction angles. Furthermore, work by Jenmalm et al. (1998) seems to suggest that grip forces as to obtain grasp stability varies depending on surface curvature. In particular, the minimum grip forces required to prevent frictional slips were

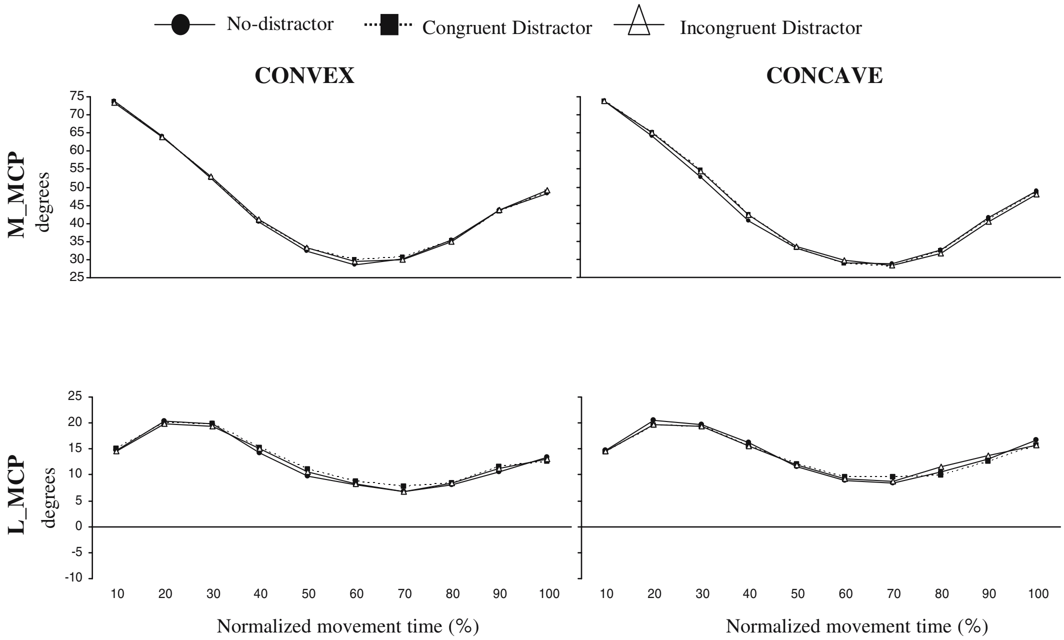

Fig. 5 Time course of angular excursion during reaching for the convex (*left column*) and concave (*right column*) objects in no-distractor (*filled circles*), congruent distractor (*filled squares*), and incongruent distractor (*empty triangles*) conditions. The represented angular excursion refers to the *MCP* joint of middle (*M*) (*top panels*) and little fingers (*L*) (*bottom panels*). Data are averaged across subjects and trials

Table 2 Results of MANOVA performed on the abduction angles between adjacent fingers

Fingers' abduction angle	Object	Distractor type	Time	Object × distractor type	Object × time	Distractor type × time	Object × distractor type × time
Thumb–index	$F = 0.056_{(1,19)}$, NS	$F = 4.665_{(2,38)}$, $P < 0.016$	$F = 154.551_{(9,171)}$, $P < 0.0001$	$F = 0.128_{(2,342)}$, NS	$F = 0.416_{(9,171)}$, NS	$F = 1.564_{(18,324)}$, NS	$F = 1.544_{(18,324)}$, NS
Index–middle	$F = 0.039_{(1,19)}$, NS	$F = 0.160_{(2,38)}$, NS	$F = 14.832_{(9,171)}$, $P < 0.0001$	$F = 0.205_{(2,342)}$, NS	$F = 0.099_{(9,171)}$, NS	$F = 1.225_{(18,324)}$, NS	$F = 0.476_{(18,324)}$, NS
Middle–ring	$F = 8.905_{(1,19)}$, $P < 0.009$	$F = 0.163_{(2,38)}$, NS	$F = 10.882_{(9,171)}$, $P < 0.0001$	$F = 0.050_{(2,342)}$, NS	$F = 7.624_{(9,171)}$, $P < 0.0001$	$F = 1.645_{(18,324)}$, $P < 0.049$	$F = 0.255_{(18,324)}$, NS
Ring–little	$F = 17.310_{(1,19)}$, $P < 0.002$	$F = 1.677_{(2,38)}$, NS	$F = 3.527_{(9,171)}$, $P < 0.0001$	$F = 0.497_{(2,342)}$, NS	$F = 10.451_{(9,171)}$, $P < 0.0001$	$F = 1.616_{(18,324)}$, $P = 0.054$	$F = 0.731_{(18,324)}$, NS

NS not significant

influenced by surface curvature, being higher for markedly convex and concave surfaces as those utilized in the present study. Therefore, the modulation of fingers' abduction angle along the object surface may be functional if grasp stability is considered in this wider context.

The thumb, in contrast to the other fingers, appears to be sensitive to the presence of the distractor at the level of single joints. This might be explained in terms of the role played by the thumb, an element of grasp, for the visual guidance of reaching. During normal reaching, as the object is approached, the thumb takes a relatively straight line of approach with most of the changes in grasp aperture resulting from the other fingers (Wing and Fraser 1983; Wing et al. 1986). Therefore the thumb sensitivity to the presence of the distractor might be dictated by the necessity to maintain a reference point for the conduction of reaching. In this respect, it is worth noting that the target and the distractor objects in this study were presented in different locations. Thus, it might be hypothesized that both of target and distractor objects triggered the planning of movements toward their respective locations. The parallel computation for the two different locations and the consequential interference then would be most evident at the level of the digit which acts as a point of reference for the target position, that is, the thumb.

Further, the specific effect of a distractor present (vs. no distractor) on thumb flexion may suggest a possible

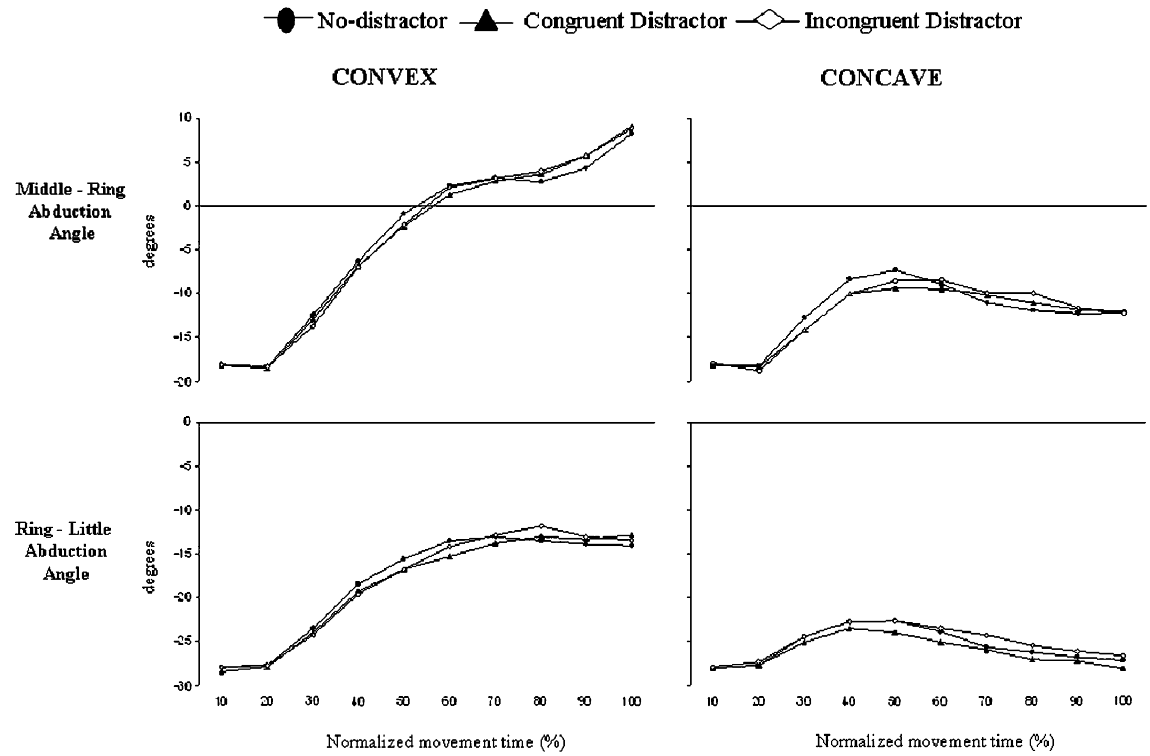

Fig. 6 Time course of abduction angle between fingers during reaching for the convex (*left column*) and concave (*right column*) objects in the no-distractor (*filled circles*), congruent distractor (*filled triangles*), and incongruent distractor (*empty diamonds*) conditions. Abduction angles between middle and ring fingers (*top panels*) and between ring and little fingers (*bottom panels*) are represented. Data are averaged across subjects and trials

obstacle explanation (Tresilian 1998; Biegstraaten et al. 2003). It might be hypothesized that subjects were constrained in thumb extension by the presence of the distractor. In this sense bumping into the distractor would indeed be a real concern. The longer movement duration for congruent and incongruent distractor conditions, consistent with a more careful approach of the object, together with the specific effect of a distractor present (vs. no distractor) on thumb flexion seem to support the obstacle explanation. However, given the distance between target and distractor (see Fig. 1b) and the lack of distractor location effects (which should have emerged for the thumb when the distractor was located to the left of the target) it might be unlikely that the physical presence of the distractor would be a real concern. The obstacle hypothesis, however, may become plausible when looking at the lack of difference between the congruent and incongruent distractor conditions for fingers' shaping regarding target's shape. In this respect, it can be hypothesized that the distractor is processed as an unspecific obstacle independently from its shape.

At the outset we hypothesized that how the hand responds to the presence of the distractor might be an index of the type of analysis performed on the distractor object. We suggested that if the analysis of the distractor would be concerned with the object general volumetric properties, then the maximum hand aperture should be chiefly affected. Alternatively, if the analysis of the distractor would be concerned in terms of a more holistic 'shape' type of processing then individual fingers' joint should be affected. Our findings suggest that the selection mechanisms mediating action seem to proceed using a more analytical type of processing considering object volume as the relevant dimension while partially ignoring a potential 'holistic' process, which would imply the coding of the distractor more fine-grained perceptual features. Support to this hypothesis comes from a recent study by Ganel and Goodale (2003), which demonstrated that in situations in which the elementary dimensions of an object's shape are perceived in a holistic manner, the same dimensions are treated analytically when a visually guided action is directed at the same object. The proposal here is that unlike visual perception, the visual mechanisms mediating action are able to process the most relevant dimension while ignoring irrelevant dimensions. We extend this notion to the implicit processing of objects which are potential target for action. That is, in order to minimize interference effects when distractor objects are presented the general volumetric properties, but not the specific perceptual features of the distractor object are considered.

In conclusion, a series of studies has demonstrated that hand shaping may be sensitive to the presence of distractor objects (for a review see Castiello 1999). However the majority of these studies focused only on the distance between thumb and index finger paying no attention to the configuration assumed by individual fingers and abduction angles between the other fingers. In this respect the present results extend this literature by looking at individual finger joints and at a more complete description of fingers' abduction angles. Looking at these measures adds a level of complexity to previous descriptions of interference effects in grasping demonstrating that task-irrelevant objects affect the expression of hand prehension at a level of coordination which involves all digits and goes above the thumb-index distance.

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