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Modulation of reach-to-grasp parameters: semantic category, volumetric properties and distractor interference?

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Abstract In the two experiments of this study, we assessed the influence of target size and semantic category on the expression of reach-to-grasp kinematic parameters. Moreover, we investigated the influence of size and semantic category of distractors on reaches to the target. The experimental objects represented living and non-living categories and wide and narrow grasp sizes. Participants reached for and picked up mid-sagittally placed targets, which were either alone or flanked by distractors congruent or incongruent to semantic category and size of the target. In experiment 1, movement duration was faster to living objects. We could not replicate this, however, in experiment 2. Conversely, significant and reliable Category \times Size interactions for grasp were obtained in experiment 1 and replicated in experiment 2. The pattern of the means in these interactions coincided with the absolute volumetric properties of the stimuli, indicating that the size of the stimuli was the main determinant of the expression of kinematic parameters. We conclude that volumetric properties such as size, rather than semantic category, are the crucial features in the programming and execution of movement to targets. As regards the category and size of the distractor, interference effects were evident: both category and size exerted a comparable influence on reaches to the target. The direction of interference, however, was not systematic. The interference effects are discussed in the context of visual search models of attention.

Keywords Reach-to-grasp · Semantic category · Volumetric properties · Distractor interference

Introduction

In daily life, we reach for objects without stopping to consider their dimensions, or those of non-relevant objects (distractors). Yet the dimensions of both targets and distractors are important in reach-to-grasp programming to targets (for example, Howard and Tipper 1997; Kritikos et al. 2000). Moreover, recent work indicates that semantic category (living versus non-living) may also influence movement (Bennett et al. 1998; Castiello et al. 1995), suggesting a tight coupling between visuo-motor control, semantic and mnemonic systems (Bennett et al. 1998).

In experiment 1, we presented subjects with living and non-living targets, which were either wide or narrow. We presented these targets either alone or with distractors, which were congruent or incongruent to the target according to category and size. In experiment 2, the category of the target was either relevant or irrelevant to the goal of the action executed towards it. We show that the volumetric properties of the target and distractors influence kinematic parameters; there is little reliable evidence, however, for an influence of semantic category.

Warrington (1975) described patients in early stages of dementia who were able to provide superordinate category (“object” versus “animal”), but not fine details of object information. Warrington and others argued that categorical structure underpins knowledge representation (Hodges et al. 1994; McCarthy and Warrington 1994; Warrington 1975; Warrington and Shallice 1984). More than memory and language, however, categorical structure may impinge on kinematic parameterisation of reach-to-grasp movements (Bennett et al. 1998; Castiello et al. 1995). Specifically, Bennett et al. (1998) suggest that perception, action and information storage and retrieval may rely on a common set of mechanisms for which category is integral.

Castiello et al. (1995) presented a simultanagnosic patient with a subset of the Snodgrass and Vanderwart (1980) line drawings of objects, as well as cards with names of objects. When both drawings or names on the

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cards represented living objects (animals or fruit) or both non-living objects, the patient's movements were well co-ordinated in bringing the cards together and pulling them apart. When each drawing belonged to a different category, however (for example, lemon and bed), movements were reportedly uncoordinated and inefficient, with multiple peaks in the velocity profile. The authors postulated object information (categorical, functional and spatial) is integrated and subsequently provided to the motor system.

Subsequently, Bennett et al. (1998) maintained that the dissociation between living and non-living categories extends to healthy controls. They presented eight healthy participants with a subset of the Snodgrass and Vanderwart (1980) line drawings. Two drawings, each embedded in a clear Perspex trolley, were initially obscured with a screen. The experimenter lifted the screen, a start signal was then given and subjects reached to and grasped the handle of the trolley corresponding to each hand, pushing it to the centre. Reaches were bimanual to drawings of congruent or incongruent categories. The screen was then replaced by the experimenter, and subjects were asked to name the drawings on the two cards. The authors reported that movement duration was shorter, and peak velocity, peak acceleration, peak deceleration and peak grasp occurred earlier, for the living than for the non-living pairs and argued that depictions of objects are sufficient to activate the motor system (Bennett et al. 1998).

Interestingly, however, Bennett et al. (1998) required subjects to name the depicted objects after movement completion and after the screen was replaced. Thus, subjects performed two tasks concurrently, name generation and bimanually co-ordinated reaching. At this point, two issues need to be considered. First, naming is a more difficult task than categorisation, and it accentuates dissociations based on structural similarity between exemplars within a category (Humphreys et al. 1988; Lloyd-Jones and Humphreys 1997; Snodgrass and Vanderwart 1980). Specifically, objects within the living category look similar and have similar parts, whereas objects within the "non-living category" do not (Humphreys et al. 1988). If the task is naming, a target object from the living category will prime another object within the same category, leading to categorical differences more apparent than real in reaction times and accuracy (Humphreys et al. 1988; Tversky and Hemenway 1984). Second, Snodgrass and Vanderwart (1980) pointed out that exemplars across the entire range of their line drawings are not equivalent in terms of name agreement, familiarity and image complexity and, thus, visual and cognitive processing demands, a problem compounded when subsets are used. Moreover, in the factor analysis conducted by Snodgrass and Vanderwart (1980), a clear living versus "man-made" distinction is not evident. Thus, it is difficult to distinguish between the programming costs associated with bimanual reaches, the name generation required and the role of semantic category of the targets.

More recently, Jervis et al. (2001) asserted that the category of the distractor influences movement to the

target. Eight participants reached to a plastic apple presented either alone or flanked by an identical apple (compatible distractor) or a cardboard box (incompatible distractor). The temporal measures of the grasp (but not the reach) component of movement occurred significantly earlier in the presence of the incompatible distractor (box) than with the compatible distractor (apple). The same pattern was evident in the second experiment, in which the compatible distractor was a small apple and the incompatible distractor a small box. The authors concluded that implicit categorical processing of the distractor was evident in the motor output to the target.

While the pattern of results for the effect of a smaller distractor is consistent with other literature (Castiello 1996; Kritikos et al. 2000), three issues need to be addressed. First, the compatible and incompatible distractors were not of comparable diameter in either the first experiment (55 mm and 70 mm, respectively) or the second experiment (30 mm and 38 mm, respectively). Thus, the influence of size and semantic category of distractor cannot be dissociated. Second, volumetric properties other than size influence the visuomotor control of action, in particular, shape and orientation of grasp surfaces (Georgopoulos 1990; Shikata et al. 1996; Taira et al. 1990). Moreover, grasp size and orientation vary according to the optimum contact points of the target (Goodale and Humphrey 1998; Servos et al. 1998). Finally, clinical neuropsychological evidence suggests that successful grasp computation towards an object does not require correct identification (Goodale et al. 1991). Thus, the possibility those interference effects were due to the grasp affordance of the distractor, and not its semantic category, cannot be excluded.

In summary, although the concept of semantic category in language and memory processes is well-established, its role in motor control is equivocal. It is possible that targets and distractors in reach-to-grasp paradigms are processed in a category-specific manner, evoking category-specific motor programmes. Firm conclusions, however, cannot be drawn due to the presence of potential confounds such as the nature of the task, and object features such as complexity, familiarity and volumetric properties.

Using real objects, in this study, we aimed to clarify the issues raised above. First, to observe systematically the influence of volumetric properties of stimuli, we restricted grasp size to either wide or narrow. Second, to avoid the potential confound of visual complexity (Humphreys et al. 1988; Snodgrass and Vanderwart 1980), we used simple one-part stimuli. Third, to avoid the potential confounds of frequency and familiarity (Humphreys et al. 1988; Snodgrass and Vanderwart 1980), we presented only four exemplars, two from each category and grasp size. Fourth, to minimise conflicting processing demands (Humphreys et al. 1988; Lloyd-Jones and Humphreys 1997), the response was only reach-to-grasp, without naming. Fifth, to observe the effects of size and semantic category of distractors, we presented targets either alone or accompanied by a dis-

tractor that was congruent or incongruent to the target according to semantic category and grasp size.

We hypothesised that, if reach-to-grasp actions are influenced by semantic category, the temporal organisation of kinematic parameters should be consistently advanced, and amplitudes should be higher for reaches to living stimuli, averaged across grasp size. As regards distractor interference, if grasp is influenced by semantic category, then interference should be greater when the distractor is incongruent to the target for category rather than grasp size (Jervis et al. 2001). Conversely, if grasp is influenced by size, interference should be greater when the distractor is incongruent to the target for size rather than category (Goodale and Humphrey 1998).

Experiment 1

Materials and methods

Twenty first-year psychology students (13 women and seven men) were recruited from the Department of Psychology. They received course credit for their participation. Their mean age was 18.8 years ($SD=1.5$), they were right handed and had normal or corrected-to-normal vision.

Apparatus and materials

Participants sat at a table (50×90 cm). We presented targets mid-sagittally, 30 cm from the starting position of the hand, either alone or flanked by a distractor. We placed distractors 30 cm from the starting switch and 35° to the right or left of the target.

We used four objects, representing two semantic categories (living and non-living) and two grasp sizes (narrow and wide). The living objects were a plastic green apple (height 70 mm, diameter 77 mm) and a plastic contoured green bean (height 80 mm, diameter 10 mm at concavity and 12 mm at convexity). The non-living objects were a green styrofoam sphere (height 70 mm, diameter 73 mm) and a green cylinder (height 80 mm, diameter 12 mm). The apple and sphere represented the wide size, while the vertically oriented bean and the cylinder represented the narrow size.

Reaches were always performed with the right hand. We attached hemispherical passive reflective markers to the wrist (radial aspect of the distal styloid process of the radius), the index finger (radial side of the nail) and the thumb (ulnar side of the nail).

Procedure

Participants rested the ulnar side of their right hand on the starting pad, thus ensuring that the hand was positioned mid-sagittally in the frontal plane and 15 cm from the trunk. The pads of the right index finger and thumb were held in gentle opposition and the right shoulder was flexed 5–10°. The right elbow was also flexed, the right forearm semipronated and the right wrist extended 10–15°. We instructed participants to begin moving only on hearing the start signal (80 Hz, 100 ms), which was delivered at irregular intervals of between 5 and 10 s. Participants were instructed to reach for, grasp and lift the target, and then replace it on the table.

Design and data analysis

We conducted a 2×2×5 within-subject repeated measures design. The first within-group factor was semantic Category (living, non-living), the second within-group factor was grasp Size (wide, narrow)

and the third within-group factor Distractor (no distractor; category congruent and size congruent distractor; category congruent and size incongruent distractor; category incongruent and size congruent distractor; category and size incongruent distractor). Participants performed ten of each type of reach. Trials were completed in five blocks of 40 reaches each. Type of reach was randomised within each block.

Data processing and recording

We recorded movements with the ELITE system (Ferrigno and Pedotti 1985), using two infra-red cameras (sampling rate 100 Hz). The calibrated working space was a parallelepiped, from which the spatial error measured from stationary and moving stimuli was 0.4 mm. Co-ordinates of the markers were reconstructed with an accuracy of 1/3000 for the vertical (Y) axis and 1.4/3000 for the two horizontal (X and Z) axes.

The data were processed using a modified version of the Eli-grasp (B|T|S 1994) software package, which gave a three-dimensional reconstruction of the marker positions. The data were filtered with a FIR linear filter-transition band of 1 Hz (sharpening variable =2; D'Amico and Ferrigno 1990, 1992). X and Y marker displacements and the resultant velocity and acceleration profiles were determined.

Dependent variables

Calculation of reach parameters (movement duration, tangential peak velocity, time to peak velocity) was based on the wrist marker. Movement initiation was taken from the release of the starting switch; end of movement was taken as the time when the fingers closed on the target and there was no further change in the distance between the index finger and thumb. Movement duration was the time (in milliseconds) from movement initiation to the end of movement. The point during the course of the movement at which peak velocity occurred was calculated as a percentage of the movement duration. Grasp component parameters were based on the X- and Y-co-ordinate displacements of the thumb and index markers. Peak grasp aperture was the maximum distance between these two markers, and time to peak grasp was the point during the course of the movement at which peak grasp occurred as a percentage of the movement duration. Grasp opening velocity denotes the peak velocity with which the thumb and index markers moved apart.

Results and discussion

Table 1 shows the means, *F* values and significance levels for the kinematic parameters analysed in experiment 1.

Reach component

Category main effects. A significant Category main effect was obtained for movement duration. Averaged across Size and Distractor, and consistent with Bennett et al. (1998), movement duration was 10 ms shorter for reaches to living for those to non-living targets (see Table 1). Caution is required, however, in interpreting this pattern. As evident in Table 1, mean movement duration was shortest, in fact, for the non-living wide object (the cylinder), slowest for the non-living narrow object (the sphere), while means for the living objects fell between these extremes. Moreover, the strength of the effect was low ($\eta^2=0.385$), indicating that very little of the variance was accounted for by Category.

Size main effects. Significant Size main effects were also obtained (see Table 1). Averaged across Category and Distractor, peak velocity was attained significantly earlier, as a percentage of movement duration, for narrow targets than for wide targets. Although

Table 1 Means and significance levels for the Category, Size and Distractor main effects and Category \times Size interactions of experiment 1. SDs in brackets

	Living wide	Living narrow	Non-living wide	Non-living narrow	Category main effect $F(1,16)$	Size main effect $F(1,16)$	Distractor main effect $F(4,64)$	Category \times Size interaction $F(1,64)$
Movement duration (ms)	1023.43 (184.23)	1033.41 (198.18)	1015.80 (188.99)	1040.20 (171.04)	10.001** ($\eta^2=0.385$)	0.984 n.s.	0.471 n.s.	0.530 n.s.
Peak velocity (mm/s)	544.93 (91.15)	565.66 (83.43)	546.09 (97.93)	545.68 (76.08)	0.019 n.s.	4.270 n.s.	4.159 n.s.	4.159 n.s.
% Time to peak velocity	44.11 (4.72)	42.67 (4.69)	44.00 (4.49)	42.78 (4.46)	0.524 n.s.	6.779* ($\eta^2=0.298$)	0.773 n.s.	0.002 n.s.
Peak grasp (mm)	104.44 (8.52)	56.86 (7.55)	102.09 (8.26)	59.59 (5.38)	0.050 n.s.	522.716**** ($\eta^2=0.966$)	0.671 n.s.	25.382**** ($\eta^2=0.582$)
% Time to p peak Gras	66.83 (5.87)	54.57 (6.19)	66.97 (6.22)	56.13 (6.15)	3.743 n.s.	162.49**** ($\eta^2=0.910$)	0.569 n.s.	2.455 n.s.
Grasp opening velocity (mm/s)	422.92 (108.34)	253.65 (78.88)	415.90 (107.26)	256.45 (5.88)	0.000 n.s.	94.983**** ($\eta^2=0.856$)	0.391 n.s.	6.025* ($\eta^2=0.279$)

* $P<0.05$, ** $P<0.01$, *** $P<0.001$, **** $P<0.0001$, n.s. not significant

the strength of the effect was low ($\eta^2=0.298$), the direction of the effect is consistent with literature, indicating that the deceleration phase of the movement is longer for smaller targets (Marteniuk et al. 1990).

Distractor main effects. No Distractor main effects were obtained, and this factor did not interact with Category or Size for the transport component (see Table 1). Thus, while there is some evidence for an influence of semantic category in the transport component, the weight of the evidence agrees with previous visuomotor control literature in indicating a more consistent effect of size.

Grasp component

Category main effects. No Category main effects were obtained (see Table 1).

Size main effects. Significant Size main effects were obtained for amplitude and temporal parameters (see Table 1). Averaged across Category and Distractor, peak grasp was significantly wider and opened faster (grasp opening velocity) for reaches to wide targets than to narrow targets ($\eta^2=0.966$ and 0.856 , respectively). Averaged across Category and Distractor, peak grasp was attained significantly earlier, as a percentage of movement duration, for narrow targets than for wide targets ($\eta^2=0.910$). This pattern is not surprising: participants need to open their grasp aperture for a wide target to a greater extent than a narrow target and need to do so faster to remain within a reasonably consistent movement duration interval.

Category \times Size interactions. We argue that the pattern of these interactions, obtained only for the grasp component, provide the most crucial information of this experiment about the coding specificity of the visuomotor system. Significant interactions between Category and Size were obtained for peak grasp and grasp opening velocity ($\eta^2=0.582$ and 0.279 , respectively; see Table 1 and Fig. 1A and B). Post-hoc 2-tailed t -tests were conducted for reaches to living versus non-living targets, in wide and narrow size conditions. Peak grasp was significantly wider for reaches to wide living than for those to non-living targets, but smaller for reaches to narrow living than for those to non-living targets ($t_{18}=4.993$, $P<0.0001$ and $t_{18}=-3.624$, $P<0.01$ respectively).

In a similar trend, grasp opening velocity to the living, wide target was 7 mm/s faster than to the non-living, wide target. Grasp opening velocity to the living, narrow target was 2.5 mm/s slower

than to the non-living narrow target. Post-hoc 2-tailed t -tests showed that these differences were significant ($t_{18}=2.334$, $P<0.05$ and $t_{18}=-2.079$, $P<0.05$, respectively).

Thus, grasp aperture opened faster and wider, but closed more slowly, to wide, living targets and to narrow, non-living targets. Crucially, however, the pattern of differences in the diameters of the objects maps precisely on the differences in peak grasp and grasp opening velocity. We argue, therefore, that this pattern is attributable primarily to the minor variations in diameter between the stimuli rather than semantic category.

Distractor main effects. No Distractor main effects were obtained in this analysis, and this factor did not interact with Category or Size (see Table 1).

In summary, in agreement with Bennett et al. (1998) and Jervis et al. (2001), category effects were obtained: movement duration was 10 ms faster. The pattern of means, however, indicates that this was not in a theoretically consistent direction. Moreover, the strength of the effect was low. Conversely, the size of the target influenced grasp parameters in a predictable direction, and the strength of the effects was high. Grasp aperture was wider and opened faster and earlier for the wide than for the narrow targets. This pattern is consistent with previous literature comparing reaches to large versus small objects.

However, the significant interactions obtained for peak grasp and grasp opening velocity were not in a consistent direction. Peak grasp and opening velocity were greater for the living, wide target (apple) than for the non-living, wide target (sphere). Conversely, the values for these parameters were lower for the living, narrow target (bean) than for the non-living, narrow target (cylinder).

Interestingly, Category entered into significant interactions with Size for a number of parameters. It is possible that the influence of semantic category was weak because it was irrelevant to the goal. Arguably, participants did not need to code the category of the target because, whether living or non-living, the only goal was to grasp it. We address this issue in experiment 2.

Experiment 2

The results of experiment 1 suggest that semantic category of the target is not of primary importance in the parameterisation of reach-to-grasp kinematics. The category of the targets, however, was not directly relevant to the action; thus, it is possible that se-

Table 2 Means and significance levels for the Category, Size and Distractor main effects and Category \times Size interactions of experiment 2. SDs in brackets

	Living wide	Living narrow	Non-living wide	Non-living narrow	Category main effect $F(1,19)$	Size main effect $F(1,19)$	Distractor main effect $F(4,19)$	Category \times Size interaction $F(1,76)$
Movement duration (ms)	850.15 (128.57)	834.21 (122.79)	834.94 (133.02)	835.12 (118.36)	0.372 n.s.	3.024 n.s.	1.865 n.s.	1.312 n.s.
Peak velocity (mm/s)	664.17 (57.00)	661.69 (56.12)	656.58 (56.94)	656.43 (53.39)	9.684** ($\eta^2=0.388$)	0.106 n.s.	0.651 n.s.	0.334 n.s.
% Time to peak velocity	46.49 (5.54)	47.09 (5.05)	46.29 (5.95)	46.62 (4.93)	2.034 n.s.	0.904 n.s.	1.603 n.s.	0.652 n.s.
Peak grasp (mm)	101.55 (8.67)	56.34 (9.69)	96.32 (8.45)	58.91 (8.52)	9.368** ($\eta^2=0.330$)	822.355**** ($\eta^2=0.997$)	0.894 n.s.	62.175**** ($\eta^2=0.766$)
% Time to peak grasp	69.09 (2.98)	59.33 (7.46)	69.96 (3.99)	60.55 (7.52)	7.112** ($\eta^2=0.272$)	33.659**** ($\eta^2=0.639$)	0.763 n.s.	0.171 n.s.
Grasp opening velocity (mm/s)	431.54 (117.71)	257.13 (92.52)	409.96 (100.69)	267.53 (92.91)	2.188 n.s.	235.125**** ($\eta^2=0.925$)	0.084 n.s.	22.545**** ($\eta^2=0.543$)

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, **** $P < 0.0001$, n.s. not significant

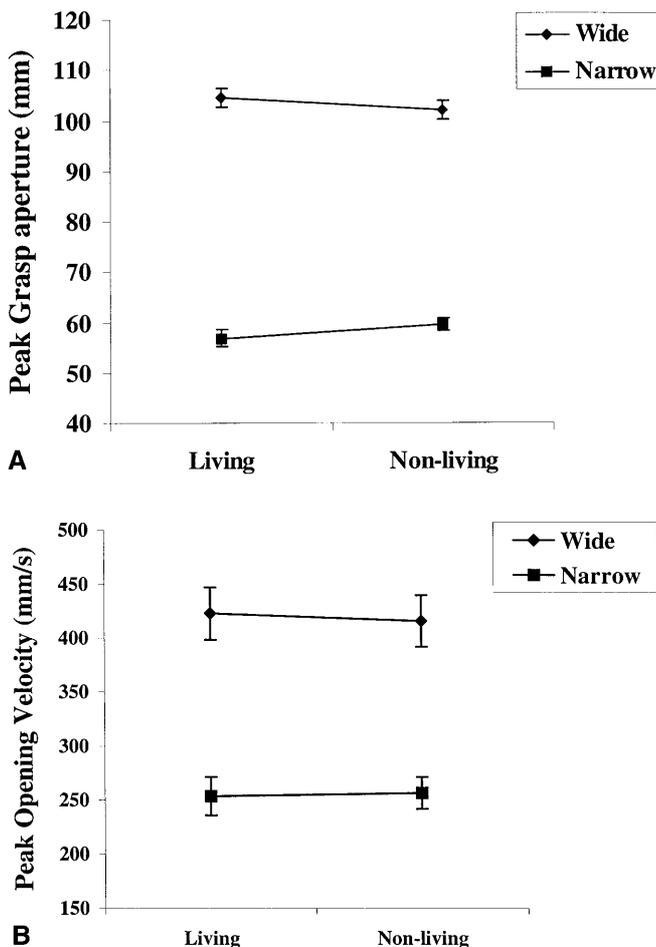


Fig. 1 **A** Mean (\pm SE) peak grasp aperture for wide and narrow targets in the living and non-living category in experiment 1. **B** Mean (\pm SE) grasp opening and closing velocity for wide and narrow targets in the living and non-living category in experiment 1

semantic category was not coded by the visuomotor system¹. In this experiment, we manipulate the relevance of the semantic category of the target to the goal of the movement. Participants need to code the semantic category in advance of movement planning and generation in order to perform the appropriate action. They are not required to generate a name; thus, we avoid potential confounds associated with simultaneous movement generation and naming. We hold two factors constant to facilitate comparison with experiment 1: we use the same objects, and we require the same *initial* action, reach-to-grasp. This is also comparable to “real” goal-related action: we first reach for an object, regardless of its identity, and thereafter we “do” something with it. Moreover, it is in this initial, reach-to-grasp part of the action that semantic-category influence of the target and distractor is reported (Bennett et al. 1998; Jervis et al. 2001).

If Category of the targets influences kinematic parameterisation, we expect to replicate the movement duration effect evident in experiment 1 and to obtain consistent Category main effects in the parameterisation of both the transport and grasp components, for example, faster movement and earlier temporal parameterisation, as reported by Bennett et al. (1998) and Jervis et al. (2001). If coding of volumetric properties is crucially important, however, the Size and Category \times Size interactions ought to be replicated.

Materials and methods

Twenty normal healthy participants (15 women, five men; mean age 26.8 years, $SD=3.5$) were recruited; they were either associates of the authors or first-year psychology students receiving course credit for their participation. All were right handed and had normal or corrected-to-normal vision.

Apparatus, materials, data recording procedure and design and data analysis were identical to experiment 1. However, ten of the participants were instructed to place the target to their right after picking it up if it represented a living object, and to the left if it represented a non-living object; the instructions were reversed for the other ten participants.

Results and discussion

Table 2 shows the means, F values and significance levels for the kinematic parameters analysed in experiment 2.

¹ We thank Professor Steve Tipper for this suggestion

Reach component

Category main effects. In the only significant main effect obtained for the transport component, peak velocity of the reaches was faster to living than non-living targets by 7 mm/s (663 mm/s, SD=57 and 657 mm/s, SD=54, respectively). The strength of this effect was low ($\eta^2=0.338$), indicating that very little of the variance was accounted for by Category. Thus, the Category main effect for movement duration in experiment 1 was not replicated in experiment 2.

Grasp component

Category main effects. Contrary to experiment 1, significant Category main effects were obtained for peak grasp and time to peak grasp. Grasp was wider for living (79 mm, SD=8.5) than for non-living (78 mm, SD=8.6 mm) targets. Peak grasp was attained earlier for reaches to living (64% of movement duration, SD=4%) than for those to non-living (65% of movement duration, SD=5%). Again, little of the variance was accounted for by Category ($\eta^2=0.330$ and 0.272 , respectively). Consistent with experiment 1, however, Category interacted significantly with Size (see below).

Size main effects. Replicating the findings of experiment 1, peak grasp, time to peak grasp and grasp opening velocity were significantly affected by Size of the target (see Table 2). These effects were again strong ($\eta^2=0.997$, 0.639 and 0.925 , respectively).

Category \times Size interactions. We replicated the interactions obtained in experiment 1: peak grasp was wider and opened faster to wide, living targets and to narrow, non-living targets (see Table 2). Moreover, the strength of these effects was comparatively greater than in experiment 1 ($\eta^2=0.766$ and 0.543 , respectively).

Post-hoc 2-tailed *t*-tests were conducted for reaches to living versus non-living targets, in wide- and narrow-size conditions. Peak grasp was significantly wider for reaches to wide living than for those to non-living targets, but smaller for reaches to narrow living than for those to non-living targets ($t_{19}=6.842$, $P<0.0001$ and $t_{19}=-4.832$, $P<0.0001$, respectively).

In a similar trend, grasp opening velocity to the living, wide target was 22 mm/s faster than that to the non-living, wide target. Grasp opening velocity to the living, narrow target was 10 mm/s slower than that to the non-living narrow target. Post-hoc 2-tailed *t*-tests showed that these differences were significant ($t_{19}=3.408$, $P<0.01$ and $t_{19}=-3.113$, $P<0.01$, respectively). Once again, the pattern of differences in the diameters of the objects maps precisely on the differences in peak grasp and grasp opening velocity, suggesting that this pattern is attributable to the minor variations in diameter between the stimuli rather than semantic category.

Distractor interactions. Although Distractor main effects were again not evident, in this experiment Distractor interacted significantly with Size for peak grasp and with Category for time to peak grasp (see Table 2). Again, however, caution is necessary in interpretation, because the significance of these effects was weak, and an almost negligible amount of variance was accounted for by Distractor interactions ($\eta^2=0.120$ and 0.117 , respectively).

Post-hoc 2-tailed *t*-tests were conducted for peak grasp for narrow and wide targets, in which each of the distractor conditions were compared with the no distractor condition. For peak grasp, the only significant comparison was for reaches to narrow targets accompanied by a distractor incongruent to both Category and Size: grasp was significantly wider than for reaches to narrow targets presented alone (58 mm, SD=9.8 and 57 mm, SD=9.5 respectively; $t_{19}=-3.842$, $P<0.001$).

Similarly, post-hoc 2-tailed *t*-tests were conducted for time to peak grasp for living and non-living targets, in which each of the distractor conditions was compared with the no distractor condition. Again, only one comparison reached significance: for reaches to living targets accompanied by a distractor congruent to

both Category and Size, time to peak Grasp was attained significantly later than for reaches to the living target presented alone (65% of movement duration, SD=4.1 and 64% of movement duration, SD=4.3 respectively; $t_{19}=-2.787$, $P=0.01$).

In summary, when participants were required to code the category of the target, peak velocity was higher and peak grasp was greater and reached earlier for reaches to living than for reaches to non-living targets. The strength of these effects was low, however, the significant Category main effect for movement duration was not replicated and earlier peak velocity again not evident. Thus, we argue that any influence of semantic category on kinematic parameterisation is inconsistent and not robust. By contrast, for the grasp component, the Category \times Size interactions were replicated, supporting our argument for the crucial role of volumetric properties in coding of grasp parameters. In addition, in this experiment, for the interaction of Distractor with Category (time to peak grasp) and with Size (peak grasp), there were some, albeit weak, indications of distractor effects.

General discussion

In this study, we investigated the influence of semantic category on the expression of kinematic parameters in reach-to-grasp movements. In experiment 1, we presented participants with two exemplars from the living category (apple and bean) and two from the non-living category (sphere and cylinder). To control for grasp size, we used objects requiring either a wide or narrow grasp. We also examined the role of distractors congruent or incongruent to the target in terms of category and grasp size. The pattern of results indicated that absolute differences in size, rather than category of the target, may be responsible for differences in kinematic parameterisation between targets. We replicated the paradigm in experiment 2, this time ensuring coding of semantic category of the target by making it relevant to the ultimate goal of the movement. Although there was some indication for an influence of category, the pattern was unreliable and not robust. By contrast, the findings suggesting a primary role for target size were replicated. There were also preliminary indications that distractor features may be coded and influence movement to the target. We first discuss briefly the possible influence of distractors and then concentrate on the possible role of semantic categorisation and volumetric properties in motor control.

Distractor interference in motor control

Indications of distractor interference effects were weak and evident only in experiment 2, where the semantic category of the target was relevant to the goal of the reach. Although detailed interpretation is not possible, two aspects of the data are immediately striking. First, Distractor interacted with Category and with Size, indicating that *both these features were salient*. Moreover, the significant Distractor comparisons involved an additive effect of distractor features. That is, Category and Size were both congruent in the case of time to peak grasp, or incongruent in the case of peak grasp. Thus, we speculate that the visuo-motor system may have assigned equal salience to “size”

and “category” as non-relevant features or properties of the distractor and treated them as units of information.

The second striking aspect of the data is that the *direction of interference was not systematic*, either according to size or category of the distractor. That is, wide distractors were not associated with wider grasp, and living distractors were not associated with earlier peak grasp. This is consistent with our earlier work (Kritikos et al. 2000) showing that there is no systematic relationship between the size of the distractor and the direction of kinematic parameter changes. Further, we suggested that the interference was attributable to a comparison process between target and distractor, rather than the absolute size of the distractor (Kritikos et al. 2000). More recent work confirms the importance of similarity between targets and distractors in the manifestation of interference in kinematics (Kritikos, submitted). Although detailed speculations are not warranted by the findings of this study, we note that the pattern of results in this and other work (Kritikos et al. 2000; Kritikos, submitted) is consistent with the postulations of Duncan and Humphreys (1989, 1992) and Theeuwes and Burger (1998). Based on reaction-time alterations in visual-search paradigms, they suggest that a comparison process takes place, based on the properties of the distractor *in relation to the target*. In other words, it is not simply the presence of a distractor that is important, but also the degree of its similarity to the target.

Semantic category and size of targets in motor control

Consistent with previous work (Bennett et al. 1998; Jervis et al. 2001), in experiment 1 movement duration was significantly, but not reliably, reduced for reaches to living compared with non-living targets. In experiment 2, we expected any influence of category on kinematics to be heightened because the category of the target was relevant to the action. Movement duration was unaffected, but this time peak velocity was faster and peak grasp faster and earlier to living than to non-living targets; though, again, these effects were not reliable.

Also consistent with previous literature (Arbib 1981; Marteniuk et al. 1990), peak grasp and peak velocity occurred significantly earlier for narrow than for wide targets. More illuminating, however, are the pattern of significant interactions between Category and Size obtained for peak grasp and grasp opening velocity: these reflected the pattern of absolute differences in the diameter of the stimuli. The amplitude of these parameters was both greater for the living, wide target (apple) and the non-living, narrow target (cylinder).

Crucially, we replicated the Category \times Size interactions, reflecting the pattern of absolute differences in the diameter of the stimuli. The strength of these main effects for Size and for the Category \times Size interactions, moreover, indicated that absolute dimensions of the targets accounted for the largest proportion of the variance. Thus, we were unable to obtain convincing evidence that semantic category reliably and systematically influences kinematic parameterisation.

Therefore, the consistency and strength of main effects and interactions across the two experiments suggests the parsimonious interpretation that Size, rather than Category, is of primary importance in the coding, programming and execution of movements. This pattern of results argues against a direct coupling between semantic information and visuomotor control. In other words, the physical features of an object (such as size and shape) determine how it is grasped, regardless of the meaning (category) of the object. In daily life terms, the critical issue is not how one executes an action towards an apple compared with a ball, but rather how one executes an action towards an object with a specific set of volumetric properties compared with a second object, with perhaps a slightly different set of volumetric properties.

The findings are consistent with recent models of a dual pathway in visuomotor control (Goodale and Milner 1992; Ungerleider and Mishkin 1982). The main thrust of these models is that there is a physiological as well as functional dichotomy in the use of visual information about an object. In the ventral visual stream, projecting from the primary visual cortex to the inferotemporal cortex (the “What” pathway), visual information forms the basis for object perception, identification, and other visuo-cognitive processing (for example, semantic categorisation). Thus, a green spherical object, with a slightly wider top half and with a recess on the top, is perceived as an apple. By contrast, the dorsal stream, projecting from the primary visual cortex to the posterior parietal cortex (the “Where” pathway), codes for size, shape, location and orientation of the target. Subsequent work showed that the dorsal stream codes for appropriate pre-shaping of the grasp according to egocentric co-ordinates: how to get to the apple and how best to pick it up (Georgopoulos 1990; Kalaska 1988; Kalaska et al. 1983; Rizzolatti et al. 1987, 1988; Shikata et al. 1996; Taira et al. 1990). Goodale and Milner (1992) suggested that this stream is more immediately involved in coding goal-directed actions and re-described it as the “How” pathway. In other words, both streams use the same information, but to different purposes (Goodale and Humphrey 1998).

It may be argued, therefore, that successful goal-directed actions require knowledge of location, size, and shape of an object. But do they require knowledge of object identity? Evidence from human neuropsychology suggests that this is not necessary. The dissociation in the functional properties of the two streams is illustrated by the visuomotor performance of patients with lesions in the posterior parietal compared with the inferotemporal cortex (see Goodale and Humphrey 1998 for a detailed review). A common concomitant of parietal cortical damage is optic ataxia, characterised by intact fixation on and identification of objects, but inability to execute successful actions towards them. Patients with lesions to the inferior temporal cortex, conversely, may show visual agnosia, characterised by impaired identification of objects through the visual modality. What is crucially relevant to the findings in this paper is that, although objects are not identified by these patients, they

are grasped successfully, not only with respect to locating the object in space, but also with respect to the placement of fingers and thumb on stable opposition (grasp) points. For successful actions, therefore, object identification is not as essential as location and shape computation. Thus, our pattern of results is entirely consistent with the findings of Goodale et al. (1991).

It is probable, nevertheless, that the ventral pathway does modify prehension. We posit that it is according to ventral-pathway information that we are able to choose one from an array of objects, but the action itself will be programmed within the dorsal stream. For example, we may choose the ripe apple on the left and avoid the stone on the right. But if we want to crack open a walnut, the stone is the more appropriate object. Under normal conditions, the programming and execution of the two reach-to-grasp movements may well be identical if the size and shape of the apple and stone are identical.

In summary, the pattern of findings suggests that volumetric properties (form and size) of a target are primarily important in movement programming and execution, rather than the semantic category to which the target belongs. As regards distractors, we replicate previous findings showing interference in the expression of kinematic parameters in the presence of a distractor. We speculate that interference is due to a comparison process, involving the features or units of information in common between target and distractor.

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