THE size or shape of an object, its perceptual features, determine the patterning of an arm and hand action involving that object. Little is known about the role played by the taxonomic semantic attributes of an object for perceptuomotor processing. In this study we investigated whether the semantic relationship between two target stimuli influences the kinematics of a bilateral reach-to-grasp action. The results showed that reach-to-grasp movements preceding the action of putting living-thing pairs together were faster, and showed earlier settings of reach and grasp temporal parameters, than movements involving pairs of non-living things. It is hypothesized that this reflects the recruitment of different categorical perceptuomotor pathways.

Upper limb movement differentiation according to taxonomic semantic category

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Introduction

Two post-sensory stages, perceptual processing and semantic (associative) processing, are often proposed in theories of object recognition.[1–3] However, in theories of motor control, very little emphasis is placed upon the semantic attributes of stimuli. Perceptual attributes, such as the shape and size of an object, have been regarded generally as exerting a major influence on movement organization (see Ref. 4 for review). Indeed, until the recent case study of LP[5] there was little theoretical support for investigating effects of semantic attributes on movement organization. Such research is not intuitive; in sliding two card pictures together, for example, it is expected that the kinematics of the action would differ if the cards changed in shape or size, but not if pictures on the cards changed. Yet, LP's unusual perceptuomotor deficit consisted of an inability to put together two cards depicting non-living things. If the pictures were of living objects from the same sub-category, LP performed the action in a coordinated manner. Hence, the ability of LP to perform a motor action varied according to the semantic attributes of the stimuli.

Results from object recognition research lend support to the concept that the neural mechanisms subserving recognition of living things differ from those subserving the recognition of non-living things. The literature now contains many examples of patients who show selective preservation or impairment of identification/naming functions according to category. For example, in a series of eight investigations of four patients recovering from herpes simplex encephalitis which affected the temporal cortices, Warrington and Shallice[6] consistently observed floor effects (all wrong) for the identification of living things, and ceiling effects (all correct) for the identification of non-living things within both the visual and verbal domains. Conversely, Sacchett and Humphreys[7] reported the case of a male patient with a lesion predominantly to the left fronto-parietal cortex who made significantly more errors when matching artefactual items than when matching pictures and words from the category of living things.

The existence of category-specific identification neural centres or channels is also supported by recent results from brain imaging studies of normal subjects. Spitzer et al.[8] used functional magnetic resonance imaging to assess the ability of five participants to name covertly pictures of animals, furniture, fruit and tools (matched for name frequency, luminance and contrast). These researchers concluded that there were localized cortical representations

of category-specific knowledge. Using positron emission tomography, Perani et al.[9] demonstrated that when participants are presented with animal picture pairs the activated brain areas differ from those activated in the case of tool picture pairs. Similar results were reported by Martin et al.,[10] and of specific interest to the current study was the selectively greater activation of the premotor cortex when tool as opposed to animal pictures were presented. Such results could imply that the visuomotor processing channels for living things differ from those for non-living things.

The case study of LP[5], together with the finding of differential activation of motor regions according to category,[10] pointed to the need for investigation of semantic influences on movement in normal humans. The aim of the current study was thus to determine if the taxonomic semantic relationship between two picture stimuli is related to the kinematic organization of bilateral upper limb movement involving the stimuli pair. For this purpose, the bimanual action of sliding two trolleys together was used because it was similar to the task which revealed dysfunction with LP.[5] A three-dimensional kinematic system was used to record the kinematics of the movement of each limb during the pre-contact movement of reaching to grasp the trolley handles. The semantic relationship between picture stimuli placed on the trolleys was changed from trial to trial so that both cards were pictures of living things, both were pictures of non-living things, or one card was of a living while the other, of a non-living thing. It was hypothesized that movement organization would differ according to the semantic relationship between the representations of the objects.

Materials and Methods

Eight university students, aged 19–32 years, volunteered to participate. All showed normal visual acuity (6/6), and were classified as strongly right-handed (scores 34–36) according to the Handedness Questionnaire of Coren.[11] Each participant attended three experimental sessions across a one week period. Each session consisted of 70 trials (lasting ~ 1 h) and was scheduled at the same time of day.

Each participant was seated comfortably at a table (1 × 1 m). Reflective passive markers (0.25 cm diameter) were attached to the radial aspect of the distal styloid process of the radius, to the radial side of the index finger nail, and to the ulnar side of the thumbnail. The starting position of each arm was with the ulnar border of the hand resting on a pressure-sensitive switch. In this position, the shoulder was in slight flexion, the elbow flexed (80–90°), the forearm semi-pronated, the
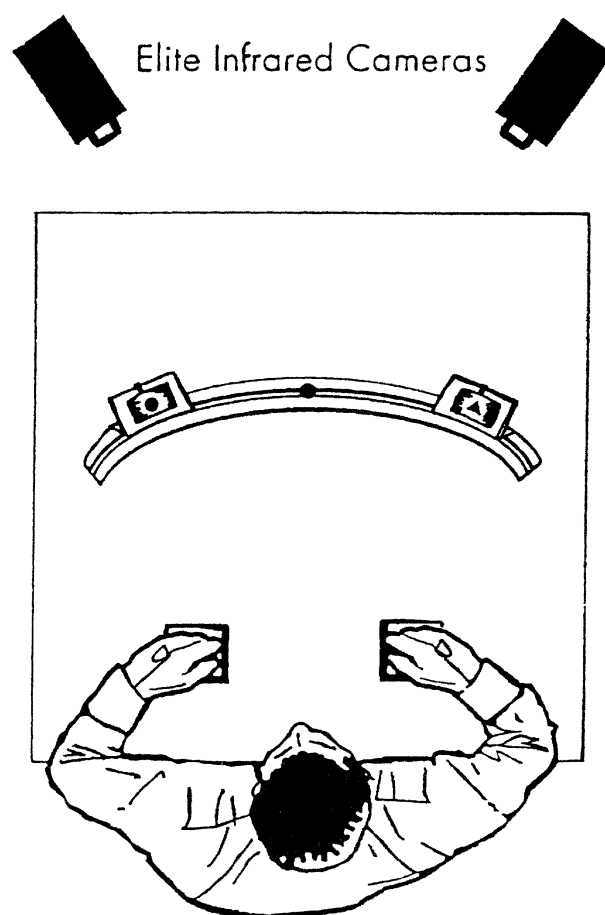

FIG. 1. Schematic diagram of the experimental set-up (not to scale). Picture cards were mounted onto one of two trolleys placed in the channel of an arc-shaped (radius 26 cm) aluminium trolley-track. Stops in the trolley track ensured consistency in the start and end positions of the trolleys. Participants were instructed to slide the trolleys together.

wrist in 10–15° of extension, and the index finger and thumb were held gently opposed.

The target stimuli were two opaque perspex trolleys (weight 60 g) upon which card pictures were positioned (Fig. 1). Each trolley was 33.5 cm from the starting switch for the corresponding hand and positioned 14 cm from the centre of the arc (radius 26 cm) against a stop in the oiled track. The starting switches were 32 cm apart, and each 17.5 cm from the front edge of the table. Each trolley had an ear-shaped tab on its top outer corner for the purposes of grasping.

The picture stimuli consisted of black outline drawings traced onto a white background (Fig. 2). They were a subset of 260 pictures standardized by Snodgrass and Vanderwart.[12] Prior to this study a separate group of 15 participants, with characteristics similar to those of the current study, were asked to rate 42 pictures according to familiarity, complexity and visual agreement using 5-point Likert type rating
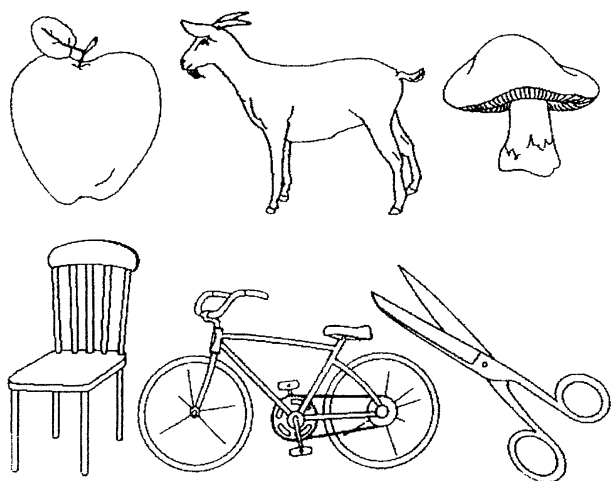
FIG. 2. Examples of picture stimuli[12] used in this study. The top row shows living things, with one example from each of the fruit, animal and vegetable categories. The bottom row shows non-living things with one example from each of the furniture, vehicle and tool categories.

scales. Following this standardization procedure, 30 cards were chosen, with five cards from each of the fruit, vegetable, animal, furniture, vehicle and tools sub-categories. The rating-scale scores for the 15 living pictures were not significantly different from those for the non-living pictures. Each picture was pasted to sit centrally upon a blank white card (5 × 5 cm).

Each participant performed a total of 210 bilateral trials, 70 in each session. Prior to each trial the trolleys were shielded from the participant's view and cards were positioned on each trolley. As one experimenter lifted this shield the other experimenter instigated a computer-generated acoustic tone (880 Hz; duration 250 ms) and sampling by the cameras. Upon hearing the tone, the participant was required to reach towards and grasp the handle of each trolley with the corresponding hand, and to slide the trolleys so that they met in the centre of the trolley track. No emphasis was placed on response or movement speed. At the end of the trial, the shield was replaced and the participant was required to name both picture cards.

The experimental manipulation was of the categorical relationship between the card pairs: (1) both cards from the same living things category ($n = 30$ pairs; e.g. both fruits); (2) both cards from the living things category but from different sub-categories ($n = 30$; e.g. one fruit, one animal); (3) both cards from the same non-living things category ($n = 30$); (4) both cards from the non-living category but from different sub-categories ($n = 30$); (5) one card from the living and one from the non-living category ($n = 90$). Presentation of the card pairs followed a computer-generated pseudo-randomized sequence.

The displacements of the markers on the upper limbs were detected by two infra-red cameras (ELITE, B|T|S, Italy), each inclined at an angle of ~30° to the vertical, positioned approximately 1.4 m above the table, 0.5 m in front of the back edge of the table, and 1.5 m apart. The sampling frequency was 100 Hz. Movements were performed within a parallelepiped working space (60 × 30 × 60 cm), calibrated such that the error for moving stimuli was less than 0.5 mm. Coordinates of the markers were reconstructed with an accuracy of 1/3000 over the field of view and sent to a host computer (Pentium75). The s.d. of the reconstruction was 1/3000 for the vertical (Y) axis and 1.4/3000 for the two horizontal (X and Z) axes.

Data were analysed using ELIGRASP software (ELITE B|T|S, Italy). This gives a three-dimensional reconstruction of each marker, filters the data (FIR linear filter, transition band 1 Hz, sharpening variable = $2^{13,14}$) and derives velocity and acceleration profiles, and the grip aperture/closure profile between the index finger and thumb markers. Dependent measures were taken from each limb during the action of reaching to grasp the trolley. (No measures were taken in the period from trolley grasp to its movement to the centre of the arc.) These measures were as follows: (a) movement initiation time (time from acoustic signal to release of the starting switch), (b) movement duration (time from release of the starting switch to grasp of the trolley), (c) transport component parameters (times from switch release to the peaks of reaching arm velocity, acceleration and deceleration, and the amplitudes of these peaks), and (d) manipulation component parameters (times from switch release to the peaks of hand opening and closing velocity, acceleration and deceleration, time to peak grip aperture between the index finger and thumb and the amplitude of this peak). Because the timing of many parameters often correlates with movement duration (e.g. a longer movement duration may mean a later peak deceleration), absolute temporal values were also expressed as a percentage of movement duration and are referred to as relative values in the results section.

Results

The mean for each dependent variable was entered into a repeated measures 2 × 2 × 2 analysis of variance (ANOVA) with category (living, non-living), compatibility (same, different), and hand (right, left) as the within-subjects factors. A second set of ANOVAs was conducted with a within-subjects factor, sub-category, of three levels. For living pairs, these levels were fruit, vegetables and animals. For non-living pairs, these levels were tools, furniture and

vehicles. A final set of ANOVAs was conducted, with card relationship (both living, both non-living, one living/one non-living) as the within-subjects factor. Post-hoc comparisons were with the Newman–Keuls procedure. The alpha level was adjusted to 0.0022.

The results clearly demonstrate that organization of the reach-to-grasp movement of both limbs varied according to the semantic relationship between the picture cards. A consistent result across all temporal dependent measures of the movement was a main effect for category (Fig. 3; Table 1). As shown by the

parameter movement duration, the reach-to-grasp movement was faster when both pictures were from the living-things category than when both were from the non-living things category. All temporal aspects of the reaching action (peak acceleration, peak velocity and peak deceleration) occurred earlier, and deceleration time was longer, for living than for non-living pairs. The lower part of Fig. 3 shows the results for each parameter when expressed as a percentage of movement duration. This illustrates that the earlier temporal setting of each reach parameter is not simply due to a decrease in the overall movement duration for living representations.

The action of opening and closing the hand during the reaching action also showed differences according to the semantic relationship between the cards. In absolute terms, all manipulation parameters showed significant categorical differences (all $p < 0.001$). For example, the time to peak hand opening acceleration occurred earlier for living than for non-living pairs. However, the categorical effect appeared to be slightly weaker than that observed for the reach component in that differences ($p < 0.0001$) in the relative temporal values were only during the hand opening phase of this action. As illustrated in the lower diagram of Fig. 3, relative parameters measured from the hand closing phase of the action showed non-significant differences according to category. The significance of the main effects for the relative parameters of the times to peak grip aperture ($tpga\%$) and to the grip opening velocity peak ($tpvo\%$) are indicated in Fig. 3 but should be interpreted with caution in view of the adjusted alpha level.

A main effect for hand was found with the analyses of several parameters. For example, the times to peak acceleration, peak velocity and peak deceleration of the reaching arm were all earlier for the left than for the right hand. Similarly, most relative manipulation parameters (except the time to the peak acceleration of hand opening) were later for left than for right hand movements. However, there were no significant interactions between hand and category, suggesting an equal bilateral effect of the semantic relationship between the cards upon movement.

Results from the analysis within each main category, across sub-categories, suggested an effect of 'potential mobility' of stimuli upon movement organization (see Fig. 4). However, very few parameters showed this effect. In the living main category, the peak of arm reaching velocity (tpv) and that of deceleration (tpd) were later for animal than for vegetable or fruit pairs. However, this was only in absolute rather than relative terms. In the non-living main category, deceleration time (dt), the time from peak reaching arm velocity to the end of the movement, was of lower duration for movements involving
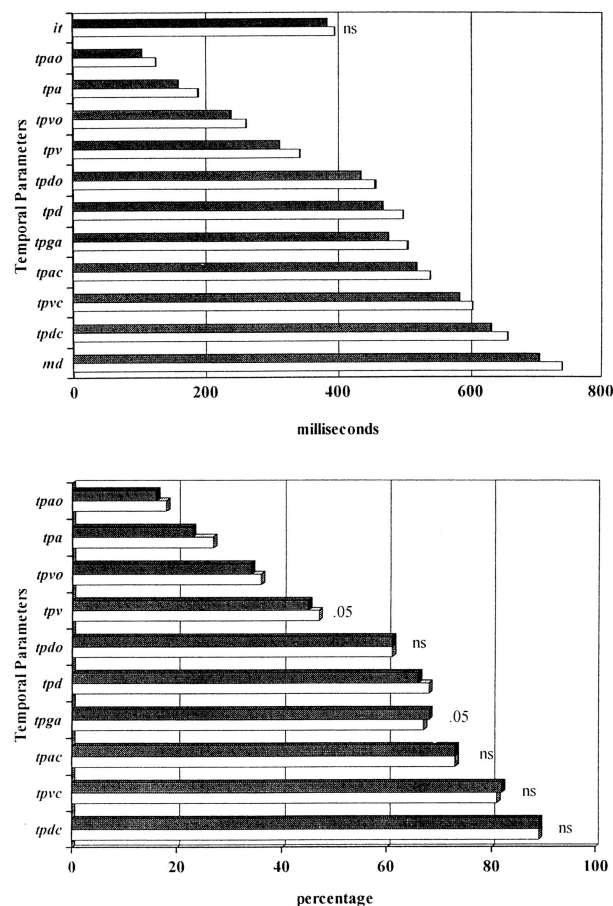

FIG. 3. Mean values of the temporal parameters measured from movements involving living-things (shaded bars) and non-living things (white bars) pairs. The upper diagram shows absolute values. The lower diagram shows relative values, that is, absolute temporal values expressed as a percentage of movement duration. Parameters are presented in a time-ordered sequence. *it*: movement initiation time. This time, from the auditory signal to the onset of movement (release of starting switch), shows no significant (*ns*) difference between living and non-living pairs. *md*: movement duration is lower for living than for non-living pairs. Transport parameters include: *tpa* (time to peak acceleration), *tpv* (time to peak velocity), and *tpd* (time to peak deceleration). In both absolute and relative terms these parameters are all significantly earlier for living than for non-living pairs. Manipulation parameters include: *tpao, tpvo, tpdo*, (the times to hand opening peak acceleration, velocity and deceleration, respectively), *tpga* time to peak grip aperture, *tpac, tpvc, tpdc*, (the times to hand closing peak acceleration, velocity and deceleration, respectively). In absolute terms, all manipulation parameters show significant categorical differences. In relative terms, only the earlier measures from the hand opening movement phase show significant differences.

Table 1. Mean values (s.d.) of selected parameters measured from movements involving living and non-living pairs. Absolute temporal values are shown above relative values where appropriate.

		Living pairs	Non-living pairs	F ratio
Movement initiation time	(ms)	384 (80)	396 (75)	$F(1,7) = 2.38$, $p = 0.167$
Movement duration	(ms)	705 (125)	740 (165)	$F(1,7) = 48.26$, $p < 0.0001$
Transport component				
Time to peak acceleration	(ms)	159 (30)	189 (37)	$F(1,7) = 98.50$, $p < 0.0001$
	(%)	23 (6)	26 (7)	$F(1,7) = 26.72$, $p < 0.001$
Time to peak velocity	(ms)	311 (69)	342 (72)	$F(1,7) = 197.18$, $p < 0.0001$
	(%)	45 (6)	47 (5)	$F(1,7) = 46.71$, $p < 0.0001$
Time to peak deceleration	(ms)	468 (116)	498 (125)	$F(1,7) = 48.81$, $p < 0.0001$
	(%)	66.5 (6)	68 (6)	$F(1,7) = 29.58$, $p < 0.001$
Manipulation component				
Hand opening				
Time to peak acceleration	(ms)	104 (46)	125 (52)	$F(1,7) = 38.62$, $p < 0.0001$
	(%)	16 (8)	18 (9)	$F(1,7) = 40.56$, $p < 0.0001$
Time to peak deceleration	(ms)	435 (137)	457 (144)	$F(1,7) = 43.02$, $p < 0.0001$
	(%)	61 (5)	61 (7)	$F(1,7) = 0.04$, $p = 0.84$
Time to peak grip aperture	(ms)	477 (150)	505 (151)	$F(1,7) = 46.65$, $p < 0.0001$
	(%)	68 (6)	67 (7)	$F(1,7) = 7.29$, $p < 0.05$*
Hand closing				
Time to peak acceleration	(ms)	518 (159)	539 (161)	$F(1,7) = 37.49$, $p < 0.0001$
	(%)	73 (6)	73 (6)	$F(1,7) = 1.01$, $p = 0.35$
Time to peak deceleration	(ms)	631 (176)	657 (175)	$F(1,7) = 21.09$, $p < 0.01$*
	(%)	89 (6)	89 (6)	$F(1,7) = 1.13$, $p = 0.32$

* greater than adjusted alpha level.

vehicles pairs. The relative value of this parameter showed no differences according to sub-category (54%, 54% and 52%, respectively for vehicle, tool and furniture pairs). The only other parameter to show differences with this sub-category comparison was amplitude of peak deceleration, which was greater for vehicle than for furniture or tool pairs. No manipulation component parameters showed differences across sub-categories.

Many trials consisted of a living picture on one trolley and a non-living picture on the other trolley. The kinematic organization of these trials showed no differences from those trials in which both cards were non-living. As shown in Fig. 5 the mean values of the temporal parameters measured from the reach and grasp components of movements involving living/non-living pairs showed no significant differences from those involving non-living pairs.

Discussion

The aim of this study was to determine whether the semantic relationship between two target stimuli influences the kinematic organization of reach-to-grasp movements involving the stimuli pair. Participants were required to reach-to-grasp two laterally positioned trolleys and slide them simultaneously along a trolley track until they met in the centre of a table. The experimental manipulation was achieved by changing the picture cards on these trolleys from trial to trial so that sometimes both pictures were from the living category and sometimes both were from the non-living category. It was

predicted that the movement would show differences according to this manipulation. This hypothesis was supported. Reach-to-grasp actions involving representations of pairs of living things were faster and showed earlier settings of most key temporal parameters than movements involving representations of non-living things.

The surprising findings of this study are even more remarkable when it is considered that the movement required for each of the 210 randomly sequenced card-pair trials, performed in blocks of 70 trials across three sessions, was the same. The starting position of each trolley and the action of reaching-to-grasp the trolley did not vary. There is no obvious expectation for differential effects in the reach or grasp components because there was no change in target position, or in the distance or direction moved by each limb. Trial after trial the physical characteristics of the trolleys (size, shape, etc.) remained constant, and the participant grasped exactly the same part of the trolley.

The semantic influence is apparent at a very early stage of the reach-to-grasp movement. Between 100 and 150 ms after movement onset, effects are evident in both the transport (peak reach acceleration) and manipulation (peak grip opening acceleration) components. (The absence of significant differences in the time taken to initiate the movement following the auditory starting signal suggests that processing times prior to the onset of the reach-to-grasp actions are not affected by the categorical relationship between the picture cards. However, because movement initiation time was not measured from the time
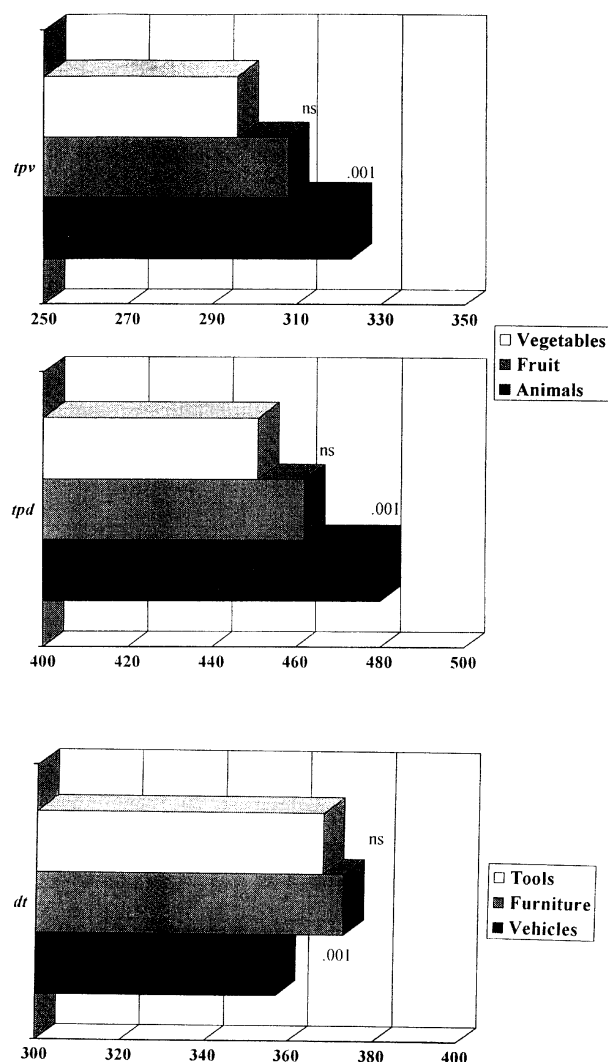
FIG. 4. Mean values of those temporal parameters that showed differences according to potential mobility of the stimuli pairs. Refer to the legend of Fig. 3 for abbreviations.

of initial stimulus presentation, no firm conclusion can be made about the effects on pre-movement processing time). Such early effects are surprising given the long time period between presentation and naming of the stimuli. Following each trial the trolleys were covered and the participant asked to name the pictures. This identification process occurred after the movement, and could conceivably have occurred during the trolley sliding phase or even after the trolleys had been placed together. The finding that the reach-to-grasp action was affected – an action performed well before object contact – indicates that processing of attributional relationships between the stimuli and the influence of this processing upon movement occur at a stage at or shortly after presentation of the stimuli.

These findings add support to the notion proposed by Mandler[15] that we have conceptual primitives of

objects in our environment which influence planning. Using well-known terminology it might seem logical to label the neural networks underlying this functional linkage between primitives and planning for action, as perceptuomotor pathways. However, to claim that the perceptuomotor pathways for living things differ from those for non-living things undermines the categorical differences. With real three-dimensional fruit and tools of varying sizes and shapes, differences in movement organization would be expected. What is intriguing is the difference even at a representational level. Because motor affordances of the trolleys (i.e. shape and size) were constant, the differences in movement organization appear to be mediated by two-dimensional stimulus characteristics of pictures on the trolleys.

Whether it is the semantic category or the perceptual attributes of the stimuli that determine differences is an issue of debate that has precedent in a developing body of research on patients with category-specific memory deficits (for reviews see Refs 16,17). Controlling for such factors as frequency, familiarity, of correspondence to a mental representation of a real object, and of complexity, researchers have identified certain groups of neurological patients who show a selective memory impairment according to category. Various theories have been proposed to account for living/non-living dissociations. Living things tend to be defined in terms of perceptual properties, while non-living things tend to be defined in terms of functional properties.[16,18] Living things are natural,[6] while non-living things are man-made.[16] However, recent research has highlighted the importance of perceptual features in determining results. For example, patients moderately affected with dementia of the Alzheimer's type showed a memory impairment for living things but only when the stimuli were black and white drawings rather than coloured pictures.[17]

The results reported here lend weak support to an additional differentiation according to potential mobility of the stimuli (Fig. 4). Gelman and colleagues[19,20] have suggested that animate (or mobile) objects may be processed in a manner which differs from that of inanimate objects. Although this expectation is supported partly by findings of differential parameterization, it is of note that the effect of potential mobility is observed in a very small range of parameters; unlike the effects on all measured temporal parameters found with the living/non-living pair comparisons.

Arguments as to the stimuli features which distinguish living from non-living things, or mobile from non-mobile things, are largely arbitrary given that the movements show differences according to these categories. Hence, regardless of the basis on
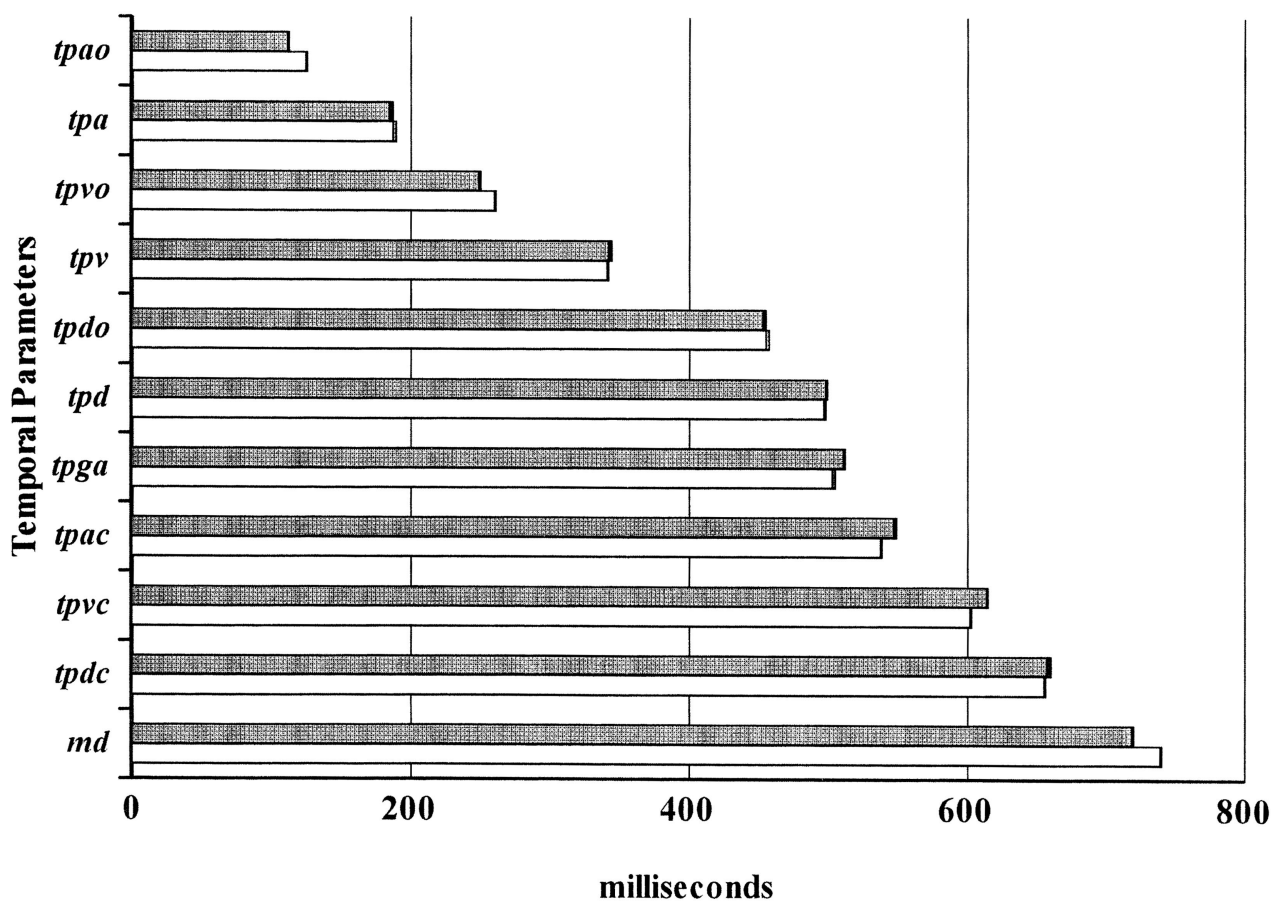
FIG. 5. Reach-and-grasp parameters that showed no significant differences when comparing non-living/living pairs (shaded bars) to non-living pairs (white bars). Refer to the caption of Fig. 3 for abbreviations.

which categorical distinctions may be made, we are faced with the novel result that taxonomic semantic features of stimuli influence our actions. This suggests that selection for action[21] includes stages which tap, apparently automatically, into semantic and, possibly, procedural, memory systems.[22] In these terms, the motor system can be thought of as a 'node' forming an interconnected relationship with other parts of the network of concepts within a semantic memory system.[23]

Conclusion

The neural processes underlying the differences between living and non-living things is an issue for speculation. One view is that the visuomotor pathways for living things differ from those for non-living things. This argument finds some support from the results of brain imaging studies undertaken during various naming or matching object recognition tasks.[8–10] Of particular relevance to the results of the current study is the category-specific regional cerebral blood flow differences in motor regions in the study by Martin *et al*.[10] When individuals

were required to name, silently, pictures of tools (as opposed to pictures of animals), one region of selectively greater activation was the left premotor cortex. These data, together with those reported here, suggest that the differences in movement organization with different categories represent the recruitment of different visuomotor pathways rather than processing within a common centre that differs according to the semantic relationship between the stimuli.

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