Exp Brain Res (2007) 180:525–534
DOI 10.1007/s00221-007-0870-y

RESEARCH ARTICLE

Number magnitude potentiates action judgements

Arnaud Badets · Michael Andres · Samuel Di Luca · Mauro Pesenti

Received: 27 October 2006 / Accepted: 10 January 2007 / Published online: 6 February 2007

Abstract Motor actions can be simulated and generated through the perception of objects and their characteristics. Such functional characteristics of objects with given action capabilities are called *affordances*. Here we report an interaction between the perception of affordances and the processing of numerical magnitude, and we show that the numerical information calibrates the judgement of action even when no actual action is required. In Experiment 1, participants had to judge whether they would be able to grasp a rod lengthways between their thumb and index finger. The presentation of the rod was preceded by a number or a non-numerical symbol. When a small number preceded the rod, participants overestimated their grasp; conversely, when a large number preceded the rods, they underestimated their grasp. In Experiment 2, participants were requested to judge if two successive rods had the same length, a judgement that did not involve any grasping. The numerical primes had no effect on this judgement, showing that the magnitude/affordance interaction was not due to a simple perceptual effect. Finally, Experiment 3 showed that the interaction was not present with a non-numerical ordered sequence, thereby eliminating sequence order as a potentially confounding variable.

Keywords Number · Affordance · Magnitude · Action judgement

A. Badets · M. Andres · S. Di Luca · M. Pesenti (✉)
Unité de Neurosciences Cognitives,
Université Catholique de Louvain, Place Cardinal Mercier,
10, 1348 Louvain-la-Neuve, Belgium
e-mail: mauro.pesenti@psp.ucl.ac.be

Introduction

Specific actions can be generated, simulated or simply imagined on the basis of the physical properties and characteristics of objects. Moreover, perceiving an object automatically potentiates the motor components of possible actions that could be applied to it, irrespective of the subject's intention. The term *affordance* is used to refer to the motor patterns to which the perception of visual objects and their properties gives rise (Gibson 1979; Tucker and Ellis 1998). Perceptual performance may be consistent with predictions derived from affordances. For example, people asked to judge which stairs of varying height they could ascend normally make judgements in accordance with their actual stair-climbing capability (Warren 1984). Other studies show that participants are able to perceive affordances for actions in motor contexts such as gap crossing (Burton 1992), object reaching (Carello et al. 1989), and sitting height (Mark et al. 1990). Features of objects (e.g., size, shape, orientation, location) have also been shown to automatically activate specific components of reaching and grasping. For example, making a vertical orientation judgement about objects presented with an irrelevant horizontal orientation (e.g., deciding whether a frying pan with its handle pointing left is upright or inverted) produced a compatibility effect on left–right responses executed by the left and right hands, but only when there was a relation between the different responses and the different affordances produced by the irrelevant left–right orientation of the object: responses were faster with the right hand when the objects' horizontal orientation was compatible with a right hand grasp, and conversely for the left hand (Tucker and Ellis 1998). Finally, neurophysiological support for the concept of affordance has recently been found in brain-imaging studies. Indeed, the cerebral regions underlying motor representations (i.e., premotor, parietal and cerebellar cortices) are activated not only when real actions are prepared for or imagined (for a review, see Grèzes and Decety 2001) but also when objects are only perceived without there being any explicit intention to act on the objects (Grèzes and Decety 2002; Grèzes et al. 2003). Overall, affordances thus refer to motor representations that do not necessarily involve execution.

When actual motor processes are considered, interactions with reading words, or, more generally, semantic knowledge, have been observed (e.g. Glover and Dixon 2002; Jeannerod 1997; Rizzolatti and Arbib 1998). For example, the kinematics of reaching and grasping movements appears to be influenced by the meaning of words printed on the objects being reached for (e.g., largest movements when the word "long" was printed on the objects, and conversely with the word "short", irrespective of the real size of the objects; Gentilucci and Gangitano 1998). In other words, motor programmes associated with the objects are accessed by language, and naming a feature of an object with a direct relation to a sensory motor transformation can influence an action (Glover and Dixon 2002). Implicit semantic knowledge about objects can also affect hand movement: grip aperture was found to increase following the presentation of words referring to larger objects (e.g. "apple") rather than smaller objects (e.g. "grape"; Glover et al. 2004). Semantic interactions have also been found with abstract concepts such as number magnitude. Indeed, processing the magnitude of Arabic numbers has been shown to interfere with finger movements, leading to some compatibility effects: when the response involved a grip closure or aperture, grip closure was initiated faster in response to small digit presentation whereas grip opening was initiated faster in response to large digits (Andres et al. 2004). Moreover, there was a linear increase of response latencies with number size when the response was a grip closure and a decrease when the response was a grip opening. This was the first behavioural evidence supporting a functional interaction between the processing of number magnitude and the programming of a grip aperture. Where does this interaction stem from? It has been recently proposed that time, space and number may be processed within a common system of magnitude representation (Walsh 2003). This system would be located in the parietal cortex, known to be involved in numerical magnitude processing (Pesenti et al. 2000), and in various visuo-motor functions such as attention orientation in space and time (Coull and Nobre 1998), object manipulation (Binkofski et al. 1999), grasping (Culham et al. 2003) and visual pointing (Connolly et al. 2003). It is worth noting that all these functions involve the computation of magnitude estimates for representing space, time or object size. The determinants of the interaction may thus come from the shared influence of these factors on the programming of goal-directed actions.

However, it remains to be seen which components of action are involved in this interaction. So far, the effects of number semantics have only been assessed on actual actions, not on perceived affordances. This is the topic which we investigated. Rods of different lengths were presented in a series of three experiments. Experiment 1 aimed at testing the idea that number magnitude can change the perception of affordances, which, in turn, changes the judgement of a potential action. In this experiment, a small or a large Arabic number preceded the presentation of the rods, and participants had to judge whether or not they could grasp the rods between their index finger and thumb, while keeping both hands at rest. Experiment 2 tested whether this judgement could stem from a simple perceptual bias induced by the numerical primes, rather than stemming from a true number–action interaction. Finally, Experiment 3 tested whether this influence on the perception of affordances was due to the quantitative or ordinal properties of the numbers.

Experiment 1

The perception of an object results in the potentiation of possible actions involving it. An object such as a rod affords a whole range of behavioural possibilities including throwing, grasping, pushing and turning. The instructions in the present study oriented the participants towards a potential grasping of the rod between the thumb and index finger. The presentation of the rod being preceded by a small or a large Arabic number, three types of magnitude must be processed to make the grasping judgement possible: the rod length, the numerical magnitude, and a potential grip aperture. If number magnitude and grip aperture interactions affect the judgement of a potential action, the graspability judgement should change depending on the number magnitude. However, the direction of this change will differ depending on the actual interaction among the three magnitudes: the point of grasping uncertainty (i.e., the rod for which a participant will give an equal number of graspable/non-graspable answers) will move in opposite directions depending on what is actually affected by number magnitude.

If number magnitude primarily influences the grip magnitude programme, a small number should generate a small grip which in turn should produce a judgement of uncertainty on shorter rods than a neutral prime. The converse is true for a large number. On the other hand, if number magnitude primarily influences the rod in terms of the length necessary for an (potential) action, a small number should induce the perception of a given rod as shorter than a neutral prime, and so generate a judgement of graspability for longer rods. Again, the reverse would be true for a large number. Note, however, that number processing may affect the graspability judgement in a non-specific way, for example by only decreasing the attentional or processing resources that can be allocated to this judgement. Were this to be the case, uncertainty would express itself not through the sort of change of the uncertainty rod hypothesised above, but rather by an increase in either the response latency for the rod where the subjects were uncertain about graspability (without any change in the average size of this rod), or in an increase in the number of rods for which the participants were uncertain (with uncertainty spreading around the original uncertainty rod).

Method

Participants

Ten undergraduate students (mean age 19 ± 1 year; seven females) from the University of Louvain participated in this study for course credits. They all gave informed consent prior to their inclusion, had a normal or corrected-to-normal vision, declared themselves right-handed, and were unaware of the goals of the experiment. The experiment was noninvasive and was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Apparatus

The apparatus consisted of a Pentium III PC computer equipped with a 43.17 cm (diagonal) LCD computer screen, a microphone and a chin-rest. A customised *E*-prime programme (Schneider et al. 2002) controlled the experimental procedure and stored the data for further analysis; the experimenter assessed response accuracy.

Stimuli and procedure

Eighteen rectangular rods, ranging in length from 9 to 17.5 cm in increments of 0.5 cm were used. For each trial, the temporal sequence of events was as follows. A prime

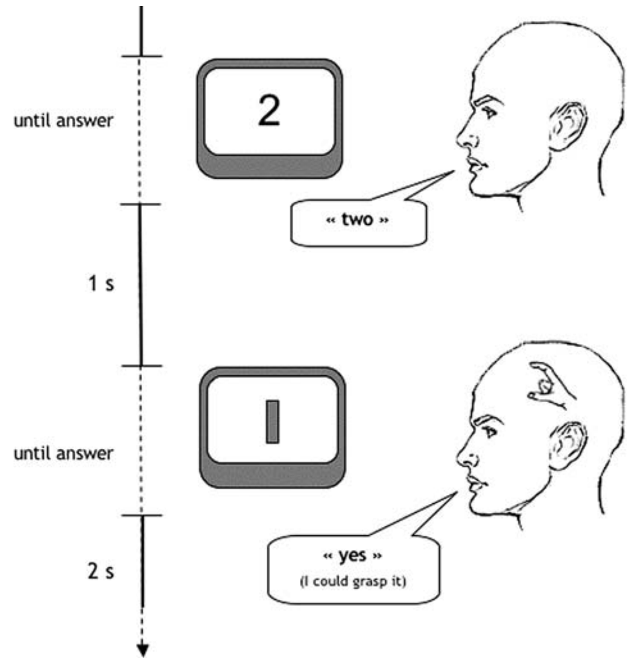

Fig. 1 Sequence of events in Experiment 1

composed of an Arabic digit (small magnitude: *2*; large magnitude: *8*[1]) or a neutral symbol (*$*) was presented at the centre of the screen. The participants were seated in a stationary chair with the head resting comfortably on the chin-rest at a viewing distance of 65 cm from the screen. They had to name the Arabic digit or say "GO" for the neutral symbol, which made the prime disappear and the image of a rod appear one second later in the same place (Fig. 1). The task was to decide whether the rod could be grasped lengthways between the thumb and index finger. The participants responded "YES" or "NO" aloud to indicate whether or not they thought they could grasp the rod, after which the image disappeared. Two seconds later, another trial began. The instructions emphasised the necessity to respond as quickly as possible while keeping errors to a minimum. After 12 practice trials, 3 blocks of 108 trials were administrated. In each block, the 18 rods were primed twice by each prime (2, 8 and $); the various combinations of primes and rods were presented in a random order.

Results

Uncertainty rod length

For each prime, the rod for which each participant gave 50% of graspable (i.e., "YES") and 50% of non-

[1] Digits *2* and *8* were used as exemplars of *small* and *large* digits to avoid any serial position effects that might have appeared with *1* and *9* due to their being the extremities of the single-digit series.

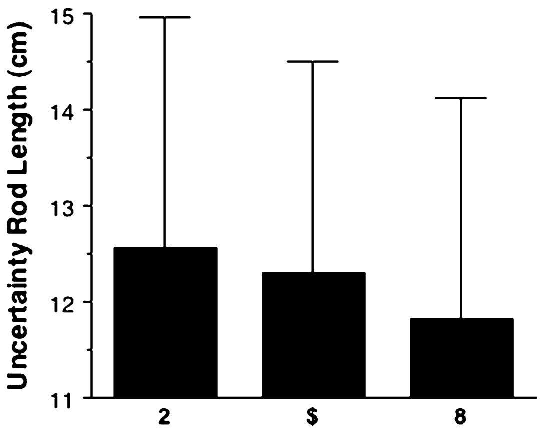

Fig. 2 Mean length of the uncertainty rod as a function of prime type in Experiment 1. *Errors bars* indicate the standard errors of the mean

graspable (i.e., "NO") answers represented the *uncertainty rod* whose length was used as the dependent variable in this analysis; when the uncertainty extended over several rods, the average length of these rods was used. To determine whether the magnitude of the Arabic primes influenced the length of the uncertainty rod, an analysis of variance (ANOVA) was performed with the type of prime (Small, Large, Neutral) as a within-subject factor. This analysis revealed an effect of the prime [mean uncertainty rod length ± SD for Small: 12.55 ± 2.37 cm, Large: 11.82 ± 2.28 cm, Neutral: 12.30 ± 2.17 cm; $F(2,18) = 24.51$, $P < 0.0001$; see Fig. 2]. Post-hoc paired *t*-tests showed that, compared to the neutral prime, the uncertainty rod was longer with the small prime and shorter with the large prime [Small vs. Neutral: $t(9) = 3.0$, $P < 0.015$; Large vs. Neutral: $t(9) = -3.943$, $P < 0.003$].

Response latencies

As the uncertainty rod for each prime varied among participants, a subset of 11 rods centred on the individual uncertainty rod was determined for each participant. Only 3 rods out of the 11 were used in this analysis: the individual uncertainty rod (50/50 graspable/non-graspable answers) and the two extreme rods (100% of graspable and 100% of non-graspable answers). Response latencies (RLs) were submitted to an ANOVA with the type of prime (Small, Large, Neutral) and rods (Uncertainty, Shortest, Longest) as within-subject factors. The analysis revealed a main effect of rods only: response latencies were longer for the uncertainty rod than for the shortest or longest rods [mean RL for the Uncertainty rod: 747 ± 78 ms, Shortest: 571 ± 172 ms, Longest: 608 ± 75 ms; $F(2,18) = 19.6$, $P < 0.0001$]. Post-hoc paired *t*-tests revealed significant main differences between the longest and the uncertainty rod [$t(9) = -4.260$, $P < 0.003$] and between the shortest and the uncertainty rod, [$t(9) = -3.217$, $P < 0.03$]; latencies for the shortest and longest rods did not differ [$t(9) < 1$].

Number of uncertainty rods

The number of rods over which there was some uncertainty (i.e. rods for which the percentage of YES/NO answers was not 100%) was entered in a one-way ANOVA with the type of prime (Small, Large, Neutral) as a within-subject factor. This analysis revealed no significant effect [mean number of uncertainty rods for Neutral: 4.7, Small: 5.4, Large: 4.8; $F(2,18) = 1.054$, $P = 0.36$].

Discussion of Experiment 1

Experiment 1 was designed to determine whether number magnitude could influence an action judgement (ability to grasp a rod between the thumb and index finger). Results clearly showed that numbers influenced this judgement: the uncertainty rod was longer with the small prime and shorter with the large prime than with the neutral prime. In other words, a small prime biased the grasping judgements towards longer rods, and a large prime biased it towards shorter rods. Moreover, further analyses showed that the uncertainty did not express itself as a global increase in RLs or in the number of rods over which uncertainty spread. This indicates that affordances were detected in the same way for numerical and non-numerical primes, and that numbers did not increase the informational load for the judgements, but only influenced the uncertainty point. This excludes non-specific numerical effects and supports the idea that number magnitude primarily influences the length of the rod in the context of a potential action. So far, however, our results may simply indicate that number magnitude influences the perception of the rod's length, without necessarily resorting to a motor interpretation. Experiment 2 was designed to clarify this possible perceptual effect.

Experiment 2

In Experiment 1, number magnitude influenced a potential action judgement. However, this could simply be a perceptual effect. A small prime could bias the perception of the rods and cause them to be perceived as shorter than they actually were, whereas a large prime could make them look longer. This perception effect might then lead to changes in the grasping judgement. Were this to be the case, the same pattern as in Experiment 1 should be observed when no potential action is required by the task. On the contrary, if the effect really stems from the motor component of the potential action, it should not be observed if no potential action is required. This possibility was tested here.

Method

Participants

Ten undergraduate students (mean age 19 ± 1 year; ten females) from the University of Louvain participated in this study for course credits. They all gave informed consent prior to their inclusion, had a normal or corrected-to-normal vision, declared themselves right-handed, did not participate in Experiment 1, and were unaware of the goals of the experiment. The experiment was noninvasive and was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Apparatus, stimuli and procedure

The same apparatus and stimuli as in Experiment 1 were used. Two rods were presented sequentially and an Arabic number or a neutral symbol primed the second rod. For each trial, the temporal sequence of events was as follows. The 13-cm rod was used as a reference point, and presented for 1 s. A prime composed of an Arabic digit (Small: 2, Large: 8) or a neutral symbol ($) was then presented in the centre of the screen. As in Experiment 1, the participants had to name the Arabic digit or say "GO" for the neutral symbol, which made the prime disappear and the second rod appear one second later in the same spot (Fig. 3). The participants had to compare the two rods and decide if the second one was longer than the 13 cm reference rod (which was never used as the second rod). Instructions emphasised the necessity to respond as quickly as possible while keeping errors to a minimum. After 12 practice trials, 3 blocks of 96 trials were administered. Sixteen[2] rods were primed twice by each prime (2, 8 and $). The various combinations of primes and rods were presented in a random order within each block.

[2] The 18 rods from Experiment 1 from which the 13 cm reference rod and the 17.5 cm rod were excluded.

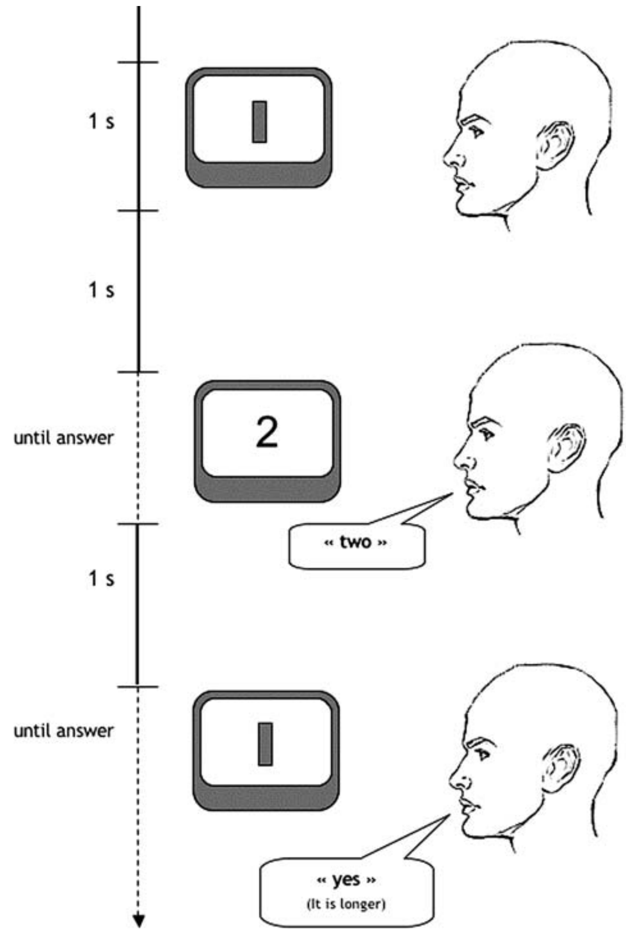

Fig. 3 Sequence of events in Experiment 2

Results

Uncertainty rod length

The uncertainty rods were determined as in Experiment 1, and their length was submitted to an ANOVA with the type of prime as the within-subject factor. This analysis revealed no main effect of prime type [mean uncertainty rod length ± SD for Small: 13.20 ± 0.63 cm, Large: 13.28 ± 0.95 cm, Neutral: 13.22 ± 0.79 cm; $F(2,18) < 1$; see Fig. 4].

Response latencies

As in Experiment 1, the uncertainty rod and the two extremes of a sample of 11 rods centred on the uncertainty rod were determined for each participant and the response latencies of these three data points were submitted to an ANOVA with the type of prime (Small, Large, Neutral) and rod (Uncertainty, Shortest, Longest) as within-subject factors. The analysis only revealed a main effect of rods [mean RL for the

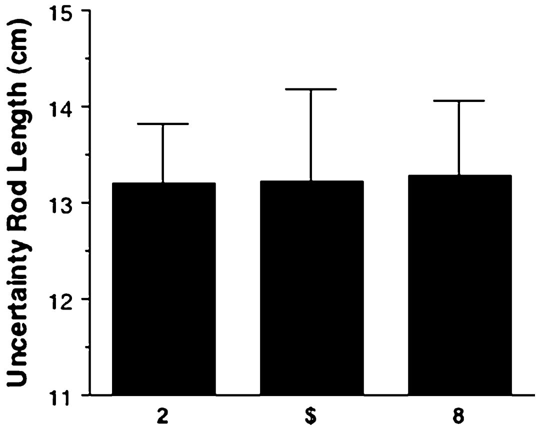

Fig. 4 Mean length of the uncertainty rod as a function of prime type in Experiment 2. *Errors bars* indicate the standard errors of the mean

Uncertainty rod: 708 ± 70 ms, Shortest rod: 598 ± 64 ms, Longest rod: 598 ± 68 ms; $F(2,52) = 37.8$, $P < 0.0001$]: response latencies were significantly longer for the uncertainty rod than for the shortest or longest rods. Post-hoc paired *t*-tests revealed significant main differences between the longest and the uncertainty rod [$t(9) = -5.33$, $P < 0.0001$] and between the shortest and the uncertainty rod [$t(9) = -9.22$, $P < 0.0001$].

Number of uncertainty rods

The number of rods over which uncertainty spread was entered in a one-way ANOVA with the type of prime (Small, Large, Neutral) as a within-subject factor and the experiment (1 vs. 2) as a between-subject factor to ensure that Experiments 1 and 2 were similar in terms of task difficulty (a perceptual judgement might be easier per se than a perceptual judgement for action). This analysis revealed no main effect of experiment [$F(1,18) < 1$] or prime type, and no interaction [mean number of uncertainty rods for Experiment 1—Neutral: 4.7, Small: 5.4, Large: 4.8; Experiment 2—Neutral: 4.4, Small: 4.3, Large: 4.4; both $F(2,36) < 1$].

Discussion of Experiment 2

Experiment 2 was designed to exclude a possible perceptual effect for the grasping judgement observed in Experiment 1 (where participants estimated that they would be able to grasp longer rods when a small number preceded the judgement, and conversely with a large number). Experiment 2 showed that the perceptual comparison of rod lengths was not influenced by the magnitude of the numerical primes. The results of Experiment 1 were thus not due to a general bias in object perception, but rather to an influence of numbers in the specific context of a grasping movement. In other words, the number magnitude really does influence the perception of the rods for a specific possible action, i.e. their affordances.

Experiment 3

Experiments 1 and 2 showed that Arabic numbers could change the affordances when a judgement about a potential grasping movement is involved. However, magnitude is not the only dimension that may produce such an interaction. It has been shown that various magnitude-related effects [such as distance, magnitude and SNARC effects[3]] observed with numbers are also observed with non-numerical ordered sequences (e.g. days of the week, months of the year, and letters of the alphabet; Friedman 1984; Gevers et al. 2003; Hamilton and Sanford 1978; Lovelace and Snodgrass 1971; Taylor et al. 1984). Order can thus produce the same effect as magnitude, with items occurring at the beginning or end of a given sequence behaving like small or large numbers respectively. In Experiment 3, we explored whether the observed magnitude/motor interaction could be attributed simply to order by asking participants to perform the same grasping judgement as in Experiment 1 using alphabetical primes. If the interaction is linked to order, then a letter from the beginning of the alphabet should bias the grasping judgement towards longer lengths, and a letter from the end of the alphabet towards shorter lengths. If the interaction is truly linked to numerical magnitude, it should not be observed with letters of the alphabet.

Method

Participants

Ten undergraduate students (mean age 19 ± 1 year; nine females) from the University of Louvain participated in this study for course credits. They all gave informed consent prior to their inclusion, had a normal or corrected-to-normal vision, declared themselves

[3] The *distance effect* refers to the fact that the time required to compare two digits is an inverse function of the numerical difference between them (Moyer and Landauer 1967). The *magnitude effect* indicates that, holding size difference roughly constant, the reaction time to compare two digits increases monotonically as the absolute size of the digits presented increases (Moyer and Landauer 1967). The *spatial–numerical association of response codes* (SNARC) *effect* refers to the fact that small numbers are preferentially responded to with the left-hand key, whereas the reverse is true for large numbers (Dehaene et al. 1993).

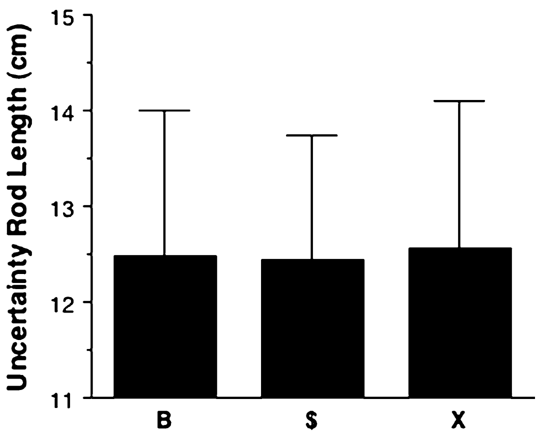

Fig. 5 Mean length of the uncertainty rod as a function of prime type in Experiment 3. *Errors bars* indicate the standard errors of the mean

right-handed, did not participate in Experiments 1 and 2, and were unaware of the goals of the experiment. The experiment was noninvasive and was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Apparatus, stimuli, procedure and dependent variables

The apparatus, task, and procedure were identical to those used in Experiment 1. However, the numerical primes *2* and *8* were replaced by the letters of the alphabet *B* and *X* (letters from the beginning and the end of the alphabet, so that the relative positions of the primes at the beginning and end of the numerical and alphabetical series match; note that letter *X* was used instead of letter *Y*, this latter having a double-word name which would have produced length differences affecting latencies recorded through a microphone; Kessler et al. 2002).

Results

Uncertainty rod length

The uncertainty rods were determined for each subject and prime as in Experiment 1, and their length was submitted to an ANOVA with the type of prime (Beginning, End, Neutral) as a within-subject factor. This analysis revealed no significant main effect of prime [mean uncertainty length ± SD for Beginning: 12.47 ± 1.52 cm, End: 12.55 ± 1.55 cm, Neutral: 12.45 ± 1.3 cm; $F(2,18) < 1$; see Fig. 5].

Response latencies

As in Experiments 1 and 2, the uncertainty rod and the two extreme rods from a sample of 11 centred on the uncertainty rod were determined for each participant, and the response latencies of these three data points were submitted to an ANOVA with the type of prime (Beginning, End, Neutral) and rod (Uncertainty, Shortest, Longest). The analysis only revealed a main effect of rods [mean RL for the Uncertainty rod: 748 ± 101 ms, Shortest rod: 625 ± 66 ms, Longest rod: 618 ± 97 ms; $F(2,34) = 24.9$, $P < 0.0001$]: response latencies were longer for the uncertainty rod than for the shortest or longest rods. Post-hoc paired *t*-tests revealed significant main differences between the longest and the uncertainty rod [$t(9) = -5.4$, $P < 0.0001$] and between the shortest and the uncertainty rod, [$t(9) = -4.6$, $P < 0.004$].

Discussion of Experiment 3

Experiment 3 shows that the letters of the alphabet did not influence the judgement of a potential grasping action. Consequently, order alone is not sufficient to produce the number/grip aperture interaction observed in Experiment 1.

General discussion

The purpose of this series of experiments was to investigate the effect of number magnitude on the ability to judge a possible action (i.e., grasping a rod between the index finger and thumb). The results of Experiment 1 indicated that when a small number primed the rods for which the grasping judgement had to be made, participants tended to overestimate their ability to grasp the rods; conversely, when a large number primed the rods, participants underestimated the extent of their grasp. In Experiment 2, participants were requested to judge whether two successive rods had the same length, a judgement that did not explicitly involve grasping. The numerical primes did not influence the outcomes, supporting the view that the results of Experiment 1 were not merely due to a perceptual effect. Finally, although intimately linked in healthy adults, quantity and order may be dissociated in brain-damaged patients (e.g., preserved magnitude meaning along with impaired ordinal meaning for numbers: Turconi and Seron 2002; impaired magnitude representation for numbers along with preserved ordinal representation for other ordered series: Zorzi et al. 2006) and can produce subtle behavioural (Turconi et al. 2006) and electrophysiological differences in healthy adults (Turconi et al. 2004). Experiment 3 showed that the magnitude/grip aperture interaction observed in Experiment 1 was not present when a non-numerical ordered sequence was used, which further supports this magnitude/order dissociation.

The present study replicates the interaction between number magnitude processing and grip-aperture programming found in previous studies (Andres et al. 2004; Glover et al. 2004). It further shows that number magnitude calibrates the judgement for action even when no actual action is required. This finding constitutes the first demonstration of an interaction between the processing of an abstract semantic concept (here, numerical magnitude) and the perception of affordances. More precisely, in Experiment 1, three types of magnitude had to be processed: the numerical magnitude of the prime (small or large number), spatial information related to the length of the rods, and motor information to calibrate the grip between the index finger and thumb. It turned out that number magnitude influenced the perception of the length of the rods only when a potential action was involved in the task. It is worth noting that our results show an effect of numerical magnitude on motor action similar but perhaps not identical to that observed by Andres et al. (2004). In that study, participants had to mimic a grasp closure or a grasp opening while an Arabic digit primed these motor actions. In compatible conditions (e.g. a small number with grip closure or a large number with grip opening), the numbers decreased the time needed to retrieve and prepare the response for motor execution. Since no object was presented, the results support at least a relationship between the numerical magnitude and the programming of the grip. Yet, whether this interaction originated in implicit relationships between grip programming and object size could not be assessed. In the present study, the effect clearly originated in the interaction between number magnitude and the estimation of rod length in the specific context of grasp: the numbers influenced the perception of the length of the rods on which action was considered, but not the representation of the action itself nor its programming. The main difference between these two studies was that the present paradigm used a covert action (Jeannerod 1999) to make the graspability judgement and an imagined goal-directed action. Despite this difference, both studies indicated that numbers influenced motor skill.

Interestingly, the present behavioural study may lead to critical anatomo-functional interpretations of the magnitude/affordances interaction. Let us first recall that the parietal cortex is engaged in various cognitive functions. In particular, it is, inter alia, engaged in the transformation of the properties of objects into action (Milner and Goodale 1995) and it underlies the processing of the meaning of numbers (Dehaene et al. 1998; Pesenti et al. 2000; Walsh 2003). It has been argued that goal-directed actions imply two different visual systems (for a review, see Goodale and Milner 2004; Milner and Goodale 1995). The ventral stream has been localised in a network of areas extending from the early visual areas in the occipital cortex to the infero-temporal cortex; these areas are in charge of object recognition (size, shape or orientation of objects), and the detailed perception of the representation of the environment. The dorsal stream has been localised in a network extending from the early visual areas into the posterior parietal cortex, areas which are responsible for object-directed action and play a major role in transforming visual signals into movement. It is worth noting that real movements are not needed to separate these two systems in healthy humans. For example, in a recent fMRI study, participants were asked to observe video clips of a goal-directed movement consisting of the hand grasping an object (Shmuelof and Zohary 2005). Results showed the dissociation between the dorsal and ventral streams: both were activated during the action observation, but the areas corresponding to the ventral stream were mainly activated during object perception, and those corresponding to the dorsal stream during the observation of hand grasping. Experiments 1 and 2 fit nicely into this theoretical framework. Processing rods for the action judgement (Experiment 1) would mainly engage the dorsal stream, whereas processing rods for the perceptual judgement (Experiment 2) would engage the ventral stream areas. The dorsal stream is responsible for the control of actions during the visual perception of objects, and may be seen as a detector for affordances (Goodale and Humphreys 1998) whereas the ventral stream is a computational system that encodes the visual properties of objects. Extension of the dorsal pathway into parieto-premotor circuits is compatible with a possible interference between affordance mechanisms and number processing. Increased activity has indeed been found in the network of parietal and premotor areas during magnitude comparison (Pinel et al. 2004), addition (Pesenti et al. 2000), multiplication (Zago et al. 2001) and subtraction (Simon et al. 2004). In healthy participants, the dissociation between the two visual pathways during behavioural experiments arises mainly from the illusion paradigm. For example, in the "Titchener" illusion (in which two target rings of equal diameter, surrounded by a circular display of either small or large rings, are presented to the participant) the target ring surrounded by smaller circles is judged perceptively larger than the one surrounded by large rings (Aglioti et al. 1995).[4] However, in this situation, grasping remains accurate, suggesting that unlike the ventral stream processes, the dorsal stream processes are not influenced by the Titchener illusion. Our experiments show the opposite dissociation: number magnitude influenced the judgement of action (i.e., the dorsal stream) but not the judgement of perception (i.e. the ventral stream). This, of course, now calls for more behavioural experiments as well as brain-imaging data assessing the potential involvement of the dorsal stream in the processing of number magnitude during a perceptual judgement of action.

Acknowledgments This study was supported by the Marie Curie Research Training Networks of the European Community (MRTN-CT-2003-504927, Numbra project), by grant 01/06-267 from the Communauté Française de Belgique—Actions de Recherche Concertées (Belgium), and grant P5/04 from the IUAP Program of the Belgian Federal Goverment. MA is postdoctoral researcher and MP is research associate at the National Fund for Scientific Research (Belgium).

References

Aglioti S, DeSouza JF, Goodale MA (1995) Size contrast illusions deceive the eye but not the hand. Curr Biol 5:679–685

Andres M, Davare M, Pesenti M, Olivier E, Seron X (2004) Number magnitude and grip aperture interaction. Neuroreport 15:2773–2777

Binkofski F, Buccino G, Posse S, Seitz RJ, Rizzolatti G, Freund H (1999) A fronto–parietal circuit for object manipulation in man: evidence from an fMRI study. Eu J Neurosci 11(9):3276–3286

Burton G (1992) Nonvisual judgement of the crossability of path gaps. J Exp Psychol Hum Percept Perform 18:698–713

Carello C, Grosofsky A, Reichel FD, Solomon HY, Turvey MT (1989) Visually perceiving what is reachable. Ecol Psychol 1:27–54

Connolly JD, Andersen RA, Goodale MA (2003) FMRI evidence for a "parietal reach region" in the human brain. Exp Brain Res 153(2):140–145

Coull JT, Nobre AC (1998) Where and when to pay attention: the neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. J Neurosci 18(18):7426–7435

Culham JC, Danckert SL, DeSouza JF, Gati JS, Menon RS, Goodale MA (2003) Visually guided grasping produces fMRI activation in dorsal but not ventral stream brain areas. Exp Brain Res 153(2):180–189

Dehaene S, Bossini S, Giraud P (1993) The mental representation of parity and number magnitude. J Exp Psychol Gen 122(3):371–396

Dehaene S, Dehaene-Lambertz G, Cohen L (1998) Abstract representation of numbers in the animal and human brain. Trends Neurosci 21:355–361

Friedman WJ (1984) Analog and semantic models of judgements about the months of the year. Mem Cognit 12(3):306–313

Gentilucci M, Gangitano M (1998) Influence of automatic word reading on motor control. Eur J Neurosci 10:752–756

Gevers W, Reynvoet B, Fias W (2003) The mental representation of ordinal sequences is spatially organized. Cognition 87:87–95

Gibson JJ (1979) The ecological approach to visual perception. Houghton-Mifflin, Boston

Glover S, Rosenbaum DA, Graham J, Dixon P (2004) Grasping the meaning of words. Exp Brain Res 154:103–108

Glover S, Dixon P (2002) Semantics affects the planning but not the control of grasping. Exp Brain Res 146:383–387

Goodale MA, Humphreys GK (1998) The objects of action and perception. Cognition 67:181–207

Goodale MA, Milner AD (2004) Sight unseen: an exploration of consciousness and unconscious vision. Oxford University Press, Oxford

Grèzes J, Decety J (2001) Functional anatomy of execution, mental simulation, observation and verb generation of actions: a meta-analysis. Hum Brain Mapp 12:1–19

Grèzes J, Decety J (2002) Does visual perception of object afford action? Evidence from a neuroimaging study. Neuropsychologia 40:212–222

Grèzes J, Tucker M, Armory J, Ellis R, Passingham PE (2003) Objects automatically potentiate action: an fMRI study of implicit processing. Eur J Neurosci 17:2735–2740

Hamilton JME, Sanford AJ (1978) The symbolic distance effect for alphabetic order judgements: a subjective report and reaction time analysis. Q J Exp Psychol 30:33–43

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

Jeannerod M (1999) To act or not to act: perspectives on the representation of actions. Q J Exp Psychol 52(A):1–29

Kessler B, Treiman R, Mullennix J. (2002) Phonetic biases in voice key response time measurements. J Mem Lang 47:145–171

Lovelace EA, Snodgrass RD (1971) Decision time for alphabetic order of letter pairs. J Exp Psychol 88(2):258–264

Mark LS, Balliet JA, Craver KD, Douglas SD, Fox T (1990) What an actor must do in order to perceive the affordance for sitting. Ecol Psychol 2:325–366

Milner AD, Dyde RT (2003) Orientation and disorientation: illusory perception and the real world. In: Johnson-Frey SH (eds) Taking action: cognitive neuroscience perspectives on intentional acts. MIT Press, Cambridge pp 3–28

Milner AD, Goodale MA (1995) The visual brain in action. Oxford University Press, Oxford

Moyer RS, Landauer TK (1967) Time required for judgements of numerical inequality. Nature 215:1519–1520

Pesenti M, Thioux M, Seron X, De Volder A (2000) Neuroanatomical substrate of Arabic number processing, numerical comparison and simple addition: a PET study. J Cognit Neurosci 121(3):461–479

Pinel P, Piazza M, Le Bihan D, Dehaene S (2004) Distributed and overlapping cerebral representations of number, size, and luminance during comparative judgements. Neuron 41(6):983–993

Rizzolatti G, Arbib MA (1998) Language within our grasp. Trends Neurosci 21:188–194

Schneider W, Eschmann A, Zuccolotto A (2002) E-Prime reference guide. Pittsburgh, PA: Psychology Software Tools

Shmuelof L, Zohary E (2005) Dissociation between ventral and dorsal fMRI activation during object and action recognition. Neuron 47:457–470

Simon O, Kherif F, Flandin G, Poline JB, Riviere D, Mangin JF, Le Bihan D, Dehaene S (2004) Automatized clustering and functional geometry of human parietofrontal networks for language, space, and number. Neuroimage 23(3):1192–1202

[4] For a review of the various behavioural paradigms and theoretical/methodological controversies see Milner and Dyde (2003).

Taylor DA, Kim JO, Sudevan P (1984) Representation of linear orders. J Exp Psychol Learn Mem Cognit 10(1):61–71

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

Turconi E, Seron X (2002) Dissociation between order and quantity meanings in a patient with Gerstmann syndrome. Cortex 38:911–914

Turconi E, Campbell JID, Seron X (2006) Numerical order and quantity processing in number comparison. Cognition 98:273–285

Turconi E, Jemel B, Rossion B, Seron X (2004) Electrophysiological evidence for differential processing of numerical quantity and order in humans. Cognit Brain Res 21:22–38

Walsh V (2003) A theory of magnitude: common cortical metrics of time, space and quantity. Trends Cognit Sci 7:483–488

Warren WH (1984) Perceiving affordances: visual guidance of stair climbing. J Exp Psychol Hum Percept Perform 11:683–703

Zago L, Pesenti M, Mellet E, Crivello F, Mazoyer B, Tzourio-Mazoyer N (2001) Neural correlates of simple and complex mental calculation. Neuroimage 13(2):14–27

Zorzi M, Priftis K, Meneghello F, Marenzi R, Umiltà C (2006) The spatial representation of numerical and non-numerical sequences: evidence from neglect. Neuropsychologia 44(7):1061–1067