Getting a Grip on Numbers:

Numerical Magnitude Priming in Object Grasping

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Abstract

To investigate the functional connection between numerical cognition and action planning, we required participants to perform different grasping responses depending on the parity status of Arabic digits. The results showed that precision grip actions were initiated faster in response to small numbers, whereas power grips were faster to large numbers. Moreover, analyses of the grasping kinematics revealed an enlarged maximum grip aperture in the presence of large numbers. RT effects remained present when controlling for the number of fingers used while grasping but disappeared when participants pointed to the object. Our data indicate a priming of size-related motor features by numerals and support the idea that representations of numbers and actions share common cognitive codes within a generalized magnitude system.

Keywords: numerical cognition, action planning, generalized magnitude system, common representation, object grasping, SNARC

In the last few decades many authors have emphasized that cognitive representations of perceptual and semantic information can never be fully understood without considering their impact on actions (cf. Gallese & Lakoff, 2005). In this context interactions between perception and action have been extensively studied (for a review see e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001). More recently, researchers also started to focus on the interactions between language and action (e.g., Gentilucci, Benuzzi, Bertolani, Daprati, & Gangitano, 2000; Glenberg & Kaschak, 2002; Zwaan & Taylor, 2006; Lindemann, Stenneken, van Schie, & Bekkering, 2006). However, a cognitive domain that has been hardly investigated in respect to its impact on motor control is the processing of numbers. This is surprising since information about magnitude plays an important role in both cognition and action. Accurate knowledge about size or quantity is not only required for high-level cognitive processes such as number comprehension and arithmetic (cf. Dehaene, 1997; Butterworth, 1999) but also for the planning of grasping movements (cf. Jeannerod, Arbib, Rizzolatti, & Sakata, 1995; Castiello, 2005). Since magnitude processing in mathematical cognition and in motor control has been studied typically independent from each other, little is known about possible interactions between these two cognitive domains.

Interestingly, some authors have recently argued that the coding of magnitude information may reflect a direct link between number processing and action planning (Walsh, 2003; Göbel & Rushworth, 2004; Rossetti, Jacquin-Courtois, Rode, Ota, Michel, & Boisson, 2004). This idea is so far primarily based on neuroimaging studies that found an overlap in activated brain areas during processes related to numerical judgments and those related to manual motor tasks. In particular, the intraparietal sulcus has been suggested to be the locus of an abstract representation of magnitude information (for a review see

Dehaene, Molko, Cohen, & Wilson, 2004). At the same time, it is widely agreed that this particular brain region, as part of the dorsal visual pathway, is also concerned with visuomotor transformations and the encoding of spatial information required for motor actions (cf. Culham & Valyear, 2006). Based on these findings, Walsh (2003) proposed a neuropsychological model of magnitude representation which states that space and quantity information are represented by a single generalized magnitude system located in the parietal cortex. Such a system may provide a common metric for all sorts of magnitude information whether this information relates to numerical quantities while counting or to physical sizes of objects while performing grasping actions. In other words, the model claims that number cognition and action planning are linked by a shared abstract representation of magnitude, which is strongly connected with the human motor system.

First indirect behavioral evidence that symbolic magnitude information interferes with motor processes has been provided by language-based studies. For example, Gentilucci et al. (2000) reported that grasping actions are affected by words representing size-related semantic information (see also Glover & Dixon, 2002; Glover, Rosenbaum, Graham, & Dixon, 2004). The authors required participants to grasp objects on which they attached different word labels and observed that the word *large* leads to a larger maximum grip aperture when reaching out for the object than the word *small*. This finding indicates that the processing of size-related semantic information interferes with action planning. However, as demonstrated by behavioral, neuropsychological, and animal research, semantic knowledge about magnitudes constitutes a very domain-specific cognitive ability that does not require any verbal processing but that is based on a language-independent abstract representation of quantity and size (e.g., Dehaene, Dehaene-Lambertz, & Cohen, 1998; Gallistel & Gelman, 2000; Brannon, 2006). Consequently, the findings of

interference effect between semantics and action can hardly be generalized to the domain of numerical cognition and it remains an open question whether number processing interferes with action planning as would be predicted by the notion of a generalized magnitude system.

A characteristic property of nonverbal number representations is the direct coupling of magnitude information with spatial features (Hubbard, Piazza, Pinel, & Dehaene, 2005; Fias & Fischer, 2005). Such an association between numbers and space is nicely demonstrated by the so called SNARC effect (i.e., effects of spatial-numerical associations of response codes), which has been first reported by Dehaene, Bossini, and Giraux (1993). The authors required their participants to indicate the parity status of Arabic digits (i.e., odd or even) by left and right keypress responses and observed that responses with the left hand were executed faster in the presence of relatively small numbers as compared to large numbers. Responses with the right hand, however, were faster in the presence of large numbers. The SNARC effect has been interpreted as evidence that numerical magnitude is spatially represented; an idea that has been often described with the metaphor of a "mental number line" on which numbers are represented in ascending order from the left side to the right. Although the origin of spatial numerical associations is still under debate (see Fischer, 2006; Keus & Schwarz, 2005), there is growing evidence suggesting that SNARC effects do not emerge at the stage of motor preparation or motor execution. For example, it is known that spatial-numerical associations are independent from the motor effectors, because they could be observed for different types of lateralized responses such as pointing movements (Fischer, 2003), eye-movements (Fischer, Warlop, Hill, & Fias, 2004; Schwarz & Keus, 2004) or foot responses (Schwarz & Müller, 2006). Additionally, it has been shown that numbers do not only affect the initiation times of lateralized motor response but

can also induce attentional (Fischer, Castel, Dodd, & Pratt, 2003) and perceptual biases (Fischer, 2001; Calabria & Rossetti, 2005). These findings suggest that space-number interferences occur during perceptual processing or response selection but not in later, motor-related stages of processing. Recently, this interpretation received direct support from electrophysiological experiments on the functional locus of the SNARC effect (Keus, Jenks, & Schwarz, 2005). Regarding the idea of a generalized magnitude system, SNARC and SNARC-like effects can be considered as evidence that numbers and space are coded on a common metric but it appears to be unlikely that they reflect an interaction between number processing and motor control.

However, if numerical cognition and motor control share a cognitive representation of magnitude, numerical information should affect the preparation or execution of motor response. In other words, effects of numerical magnitude should not only be present in movement latencies but also in kinematic parameters of the action. Moreover, the notion of a generalized magnitude system implies that numerical stimulus-response compatibility effects are not restricted to associations with spatial locations as indicated by the SNARC effect and predicts rather a direct interaction between numerical and action-related magnitude coding. Consequently, the processing of numerical magnitudes should affect the programming of size-related motor aspects—an effect that could be described as within-magnitude priming effect of numbers on actions (cf. Walsh, 2003). First supporting evidence for this hypothesis is coming from the observation of an interaction between number processing and finger movements recently reported by Andres, Davare, Pesenti, Olivier, and Seron (2004). In this study, participants were required to hold the hand in such a way that the aperture between index finger and thumb was slightly open. Then participants judged the parity status of a visually presented Arabic digit and indicated their

decision by means of a flexion or extension of the two fingers (i.e., a closing or opening of the hand). Electromyographic recordings of the hand muscles indicated that closing responses were initiated faster in the presence of small numbers as compared to large numbers, whereas opening responses were faster in the presence of large numbers. This interaction between number size and finger movements demonstrates an interesting example of a numerical priming of size-related action features. Andres et al. (2004) argued that the performed movements may represent mimicked grasping actions and supposed that the observed interaction may point to a possible interference between number processing and the computation of an appropriate grip aperture as needed for object grasping. However, to date, there is little empirical evidence that numerals affect reach-to-grasp movements. To test this hypothesis directly, we decided to investigate natural grasping movements that involve, in contrast to finger movements, a physical object, and that comprise a reaching phase, which is characterized by both an opening and closing of the hand (cf. Castiello, 2005).

Thus, the present study investigates the effects of number processing on the planning and execution of prehension movements in order to test the hypothesis that numerical cognition and motor control share a common representation of magnitude. As mentioned above, previous research has demonstrated that reach-to-grasp movements are sensitive to abstract semantic information (Gentilucci et al., 2000; Glover & Dixon, 2002; Glover et al., 2004). Considering this and the fact that the planning to grasp an object depends to a large extent on magnitude processing since it requires a translation of physical magnitude information (i.e., object size) into an appropriate grip aperture, grasping responses appeared to us to be promising candidates to study the presumed functional connection between numbers and actions. To be precise, we expected that the processing of

Arabic numbers could prime the processing of size-related action features (i.e., within-magnitude priming effect; cf. Walsh, 2003) and consequently affect the initiation times and movements kinematics of reach-to-grasp movements.

Experiment 1

Experiment 1 investigated whether processing of numerical magnitude information affects the response latencies and movement kinematics of grasping movements. Participants had to judge the parity status of visually presented Arabic digits. The decisions had to be indicated by means of two different reach-to-grasp movements toward a single target object placed in front of the participants. Specifically, participants were required to grasp the object with either a precision grip, i.e., grasping the small segment of the object with thumb and index finger, or a power grip, i.e., grasping the large object segment with the whole hand. If magnitude representations for numerical cognition and action planning have a common basis, we expected to find a stimulus-response compatibility effect between number magnitude and the prehension act. Thus, power grip actions should be initiated faster in response to relatively large numbers and precision grip actions should be faster in response to relatively small numbers.

Since we know from research on eye-hand coordination that subjects tend to fixate a to-be grasped object before initiating the reach-to-grasp movement (cf. Land, 2006), we obscured the right hand and the object from the view of the participants and trained them to grasp the object correctly without visual feedback. There were two major reasons for the use of memory-guided grasping actions in this paradigm: First, if actions have to be executed without visual feedback, participants' visual attention remains constantly directed

towards the parity judgment task until the movement is executed and does not alternate between the to-be grasped object and the monitor. The task requirements as well as the reaction time measurements are therefore comparable to those in classical number processing experiments using button press responses. Second, online adjustments of memory-guided actions are more difficult to perform as compared to adjustments of visually-guided actions (e.g., Schettino, Adamovich, & Poizner, 2003). As a result, participants are less prone to execute the reaching movements before they complete their judgment and have selected the required grip. This control is crucial for our paradigm, because the hypothesized response latencies effects can be only detected if number processing and grip selection are fully completed before the initiation of the reach-to-grasp movement. With respect to the measurement of the maximum grip apertures it is noteworthy to mention that several studies have shown that hand kinematics during memory-guided grasping actions do not differ from those found during visually-guided actions (Santello, Flanders, & Soechting; 2002; Winges, Weber, & Santello; 2003; Land, 2006). It seems therefore to be unlikely that the absence of visual feedback influences the appearance of potential number magnitude effects in the grip aperture data.

Method

Participants

Fourteen students of the Radboud University Nijmegen participated in the experiment in return of 4.50 Euro or course credits. All were naive to the purpose of the study, had normal or corrected-to-normal vision, and were free of any motor problems that would have influenced their performance on the task.

Setup and Stimuli

Participants sat in front of a computer screen (viewing distance 70 cm) and were required to grasp a wooden object consisting of two segments: a larger cylinder (diameter 6 cm; height 7 cm) at the bottom and a much smaller cylinder (diameter 0.7 cm; height 1.5 cm) attached on top of it (see Figure 1). The object was placed at the right side of the table behind an opaque screen (height: 44 cm, width: 45 cm) allowing the participants to reach it comfortably with their right hand but without having the possibility of visual control (see Figure 1a). At a distance of 30 cm from the object center we fixated a small pin (height: 0.5 cm; diameter: 0.5 cm), which served as a marker for the starting position of the reach-to-grasp movements.

Please insert Figure 1 about here

As stimuli for the parity judgments task we chose the Arabic digits *1*, *2*, *5*, *8*, and *9* printed in black fonts without serifs on a light grey background. They were displayed at the center of the computer screen and subtended a vertical visual angle of approximately 1.8°.

Procedure

At the beginning of the experiment, participants were required to practice to grasp the object with either the whole hand at its large segment (i.e., power grip) or with thumb and index finger at its small segment (i.e., precision grip). Figure 1b illustrates the two required responses in the experiment. Only if participants were able perform the grasping movements correctly and fluently without vision, the experimental trial block was started.

The participant's task was to indicate as soon as possible the parity status of the presented Arabic digit (i.e., even vs. odd) by means of the practiced motor responses. That

is, depending on the parity status the participant was required to reach out and grasp the object with either a power or a precision grip. However, in the case of the digit *5*, participants were required to withhold from responding. This 'no-go' condition was introduced to ensure that reaching movements were not initiated before the number was processed and the parity judgment was made.

Each trial began with the presentation of a grey fixation cross at the center of the screen. If participants placed their hand correctly at the starting position the cross turned black and disappeared 1000 ms later. After a delay of random length between 250 ms and 2000 ms the digit was presented. Participants judged its parity status and executed the corresponding grasping movements. The digit disappeared with the onset of the reach-to-grasp movement or after a maximal presentation time of 1000 ms. After an inter-trial interval of 2000 ms the next trial started. If participants moved their hands before the digit was shown or if they responded on a no-go trial, a red stop sign combined with a 4400-Hz beep sound lasting 200 ms was presented as error signal.

Design

The mapping between digit parity and required grasping response was counterbalanced between the participants. That is, half of the participants performed a power grip action in response to even digits and a precision grip action in response to odd digits. For the other half, the stimulus-response mapping was reversed.

The digits *1*, *2*, *8*, and *9* were presented 50 times. The experiment comprised thus 100 power grip responses and 100 precision grip responses, whereas each grip type had to be performed towards both small and large digits. Additionally, there were 25 no-go trials

(i.e., digit *5*). All trials were presented in a randomized sequence. The experiment lasted about 45 minutes.

Data acquisition and analysis

An electromagnetic position tracking system (miniBIRD 800^{TM}, Ascension Technology Corporation) was used to record hand movements. Two sensors were attached on the thumb and index finger of the participant's right hand. The sampling rate was 100 Hz (static spatial resolution: 0.5 mm). The movement kinematics were analyzed off-line. We applied a fourth-order Butterworth lowpass filter with a cut-off frequency of 10 Hz on the raw position data. The onset of a movement was defined to be the first moment in time when the tangential velocity of the index finger sensor exceeded the threshold of 10 cm/s. We used the reversed criteria to determine the movement offset. For each subject and each experimental condition, we computed the mean reaction time (RT; i.e., the time elapsed between onset of the digit and the onset of the reaching movement) and the mean maximum grip aperture (i.e., average of the maximum Euclidean distances between thumb and index finger during the time between reach onset and offset).

Anticipation responses (i.e., responses before onset of the go signal and RTs < 100 ms), missing responses (i.e., no reactions and RTs > 1500 ms), incorrect motor responses (i.e., all trials in which participants failed to hit the object or stopped their reaching and initiated a new reach-to-grasp movement) and wrong parity judgments were considered as errors and excluded from further statistical analyses. In all statistical tests, a Type I error rate of $\alpha = .05$ was used. To report standardized effect size measurements, we calculated the parameter omega squared (ω^2) as suggested by Kirk (1996).

Results

Anticipations and missing responses occurred in 0.3 % of the trials. 2.7 % of the grasping responses were performed incorrectly. The error rate for the parity judgments was 2.2 %.

Please insert Figure 2 about here

The mean RT data were submitted to a two-way repeated measures analyses of variance (ANOVA) with the factors Number Magnitude (small magnitude: 1 & 2, large magnitude: 8 & 9) and Type of Grip (power grip, precision grip). Figure 2 depicts the mean RTs. Power grip responses (605 ms) were initiated faster than precision grip responses (621 ms), $F(1,13) = 5.17$, $p < .05$, $\hat{\omega}^2 = .13$. Most importantly, however, the analysis yielded a significant interaction between the factors Number Magnitude and Type of Grip, $F(1,13) = 7.13$, $p < .05$, $\hat{\omega}^2 = .10$. That is, precision grips were initiated faster to small numbers (612 ms) as compared to larger numbers (631 ms), $t(13) = -2.30$, $p < .05$. This difference appeared to be reversed for the power grip responses, since actions were initiated faster to large (600 ms) than to small numbers (609 ms). This contrast, however, failed to become significant, $t(13) = 1.10$, $p = .32$.

Please insert Table 1 about here

The mean maximum grip apertures were analyzed with the same two-way ANOVA as used for the RT data (see Table 1 for means). The main effect of Grip Type was significant, $F(1,13) = 376.5$, $p < .001$, which reflects the trivial fact that maximum grip aperture was larger for the power grip responses (120.0 mm) than for the precision grip

responses (75.0 mm). Interestingly, we also found a main effect of Number Magnitude, $F(1,13) = 5.31$, $p < .05$, $\hat{\omega}^2 = .13$. This finding indicates that grip apertures were somewhat larger in the context of large numbers (97.8 mm) than in the context of small numbers (97.2 mm). The interaction between the two factors did not reach significance, $F(1,13) = 3.8$, $p = .08$.

Discussion

Experiment 1 demonstrates a magnitude priming effect of numerals on grasping latencies. That is, the grasping responses to small digits were faster initiated if the object had to be grasped with a precision grip and responses to large numbers were relatively faster if a power grip was required. In addition, we found that number magnitude affected the grasping kinematics, i.e., the maximum grip apertures were enlarged when the object was grasped in presence of a large number. Although the interaction between Grip Type and Number Size was not significant, the mean maximum grip apertures seem to suggest that the main effect of the number size is restricted to the precision grip actions only. A possible reason for this dissociation is the fact that many participants had to open their hand to a maximum degree in order to perform the power grip response and clasp the bottom cylinder with its large diameter. Under these circumstances, the processing of large numbers can hardly result in a further enlargement of the grip aperture. The number magnitude effect on the grasping kinematics is therefore less pronounced as it could be observed for precision grip actions.

The magnitude priming effect on the grasping latencies and the number effect on the grip aperture indicate that the processing of numbers has an impact on the prehension actions. Both findings are in line with the hypothesis that numerical cognition and action

planning share common cognitive codes within a generalized system for magnitude representation (Walsh, 2003). A possible objection to the interpretation that the numerical magnitudes primed the size-related motor features of the grasping actions is that the two responses did not only vary with respect to the required grip size (i.e., precision or power grip), but they were also directed toward different parts of the object. That is, each precision grip was directed toward the small top segment, whereas each power grip was directed toward the large bottom segment. It can therefore not be excluded that the observed response latency differences reflect a compatibility effect between numerical magnitudes and spatial response features along the vertical direction. That is, it might be possible that responses to the top were facilitated for small numbers and responses to the bottom were faster for large numbers. Such SNARC-like effects for the vertical direction have been previously shown by different researchers (e.g., Ita & Hatta, 2004; Schwarz & Keus, 2004). However, these studies consistently suggest a spatial-numerical association of upward movements with large numbers and an association of downward movements with small numbers. Although we observed in Experiment 1 the opposite pattern of effects, we can not exclude at this point that the differences in the latencies of the grasping response might be driven by a reversed vertical SNARC effect. A second possibility to account for the data of Experiment 1 is the assumption of correspondence effects between the numerical size and the size of the object segment to which the action was directed. That is, reach-to-grasp responses toward the small or large segment could be facilitated in response to small or large numbers, respectively. This possible association between abstract magnitude information and physical object properties would also argue against our interpretation of numerical priming effects on grasping actions. To evaluate these alternative explanations we conducted a second experiment.

Experiment 2

The aim of Experiment 2 was to control for a possible confound of the required grip size and the relative vertical goal location of the reaching movements in Experiment 1 and to exclude thus that the observed response latency effects were driven by a spatial association between numerical magnitudes and the vertical dimension (e.g., vertical SNARC effect). To do so, we required the participants in Experiment 2 to merely reach out for the object without grasping it (i.e., pointing movement). That is, the parity status of Arabic digit had to be indicated by means of pointing movements toward the small top or large bottom segment of the object. If our previous findings would reflect a reversed vertical SNARC effect or compatibility effect between number size and the size of the object segments that served as goal location for the response, the same response latency effects should be present in pointing movements. However, if the effects reflected a priming effect of aperture size, the intention to grasp should be crucial to find stimulus-response compatibility effects between numerical information and object-directed actions. In that case, we expected the pointing response to be unaffected by the presented digits.

Method

Participants

Twenty-two students of the Radboud University Nijmegen participated in Experiment 2 in return for 4.50 Euro or course credits. None of them took part in the

previous experiment. All were naive to the purpose of the study and had normal or corrected-to-normal vision.

Setup and Stimuli

The experimental setup and stimuli were identical to Experiment 1.

Procedure

The procedure and the design were the same as in Experiment 1. The only modification was that, instead of the previous grasping movements, participants performed pointing movements. That is, depending on the parity status of the presented digit the participants were required to point either to the small top or to large bottom segment of the object. Since the pointing movements needed to be performed accurately without sight, the responses were again practiced at the beginning of the experiment.

Design

Half of the participants had to point to the small top segment in response to even digits and to the large bottom segment in response to odd digits. The other half were given the reverse stimulus response mapping. The experiment comprised again 225 trials (50 repetitions of the digits *1, 2, 8,* and *9* plus 25 no-go trials with the digit *5*) presented in a random order and lasted about 30 minutes.

Data acquisition and analysis

An electromagnetic motion tracking sensor was attached to the participant's right index finger and used to record the pointing trajectories. Movement onsets were determined and analyzed as described in Experiment 1. In addition, we calculated for each pointing trajectory the path curvature index (PCI), which was defined as the ratio of the largest

deviation of the pointing trajectory from the line connecting the movement start and end location to the length of this line (see Desmurget, Prablanc, Jordan, & Jeannerod, 1999).

Trials with incorrect parity judgments were excluded from the reaction time analysis. In order to increase the chance to find an effect of the number magnitude on the pointing, we also considered movements with strongly curved trajectories (i.e., movements with a PCI larger than .5) as incorrect responses, because in these cases participants may have initiated the pointing movement before having completed their parity judgment or may have corrected their judgment during the movement.

Results

Anticipation and missing responses occurred in 0.4 % of the trials. 2.6 % of the pointing movements were performed incorrectly (i.e., PCI > .5).[1] The average error rate for the parity judgments was 1.1 %.

Please insert Figure 3 and Table 2 about here

We applied a two-way repeated measures ANOVA with the factors Number Magnitude (small, larger) and Pointing Goal Location (small top segment, large bottom segment) on the RT data (see Figure 3) and the PCI data (see Table 2 for means). Pointing movements toward the small top segment were initiated faster than movements to the large bottom segment (530 ms vs. 543 ms), $F(1,21) = 4.80$, $p < .05$, $\hat{\omega}^2 = .08$. Responses toward small numbers were faster than to large numbers (541 ms vs. 531 ms), $F(1,21) = 7.38$, $p < .01$, $\hat{\omega}^2 = .12$. Most important, however, the analysis did not show a significant interaction between the factors Number Magnitude and Pointing Goal Location, $F(1,21) < 1$, even though the statistical power[2] of the performed ANOVA was sufficient to

detect an interaction effect that was only half the size of the effect found in Experiment 1, i.e., (1-β) = .83 for an expected ω^2 = .05 and an assumed population correlation between all factor levels of ρ = .75 (conservatively estimated from the observed empirical correlations).

The analysis of the PCI data revealed that pointing movements toward the top segment (PCI = .29) were more curved than the movements toward the bottom segment (PCI = .20), $F(1,21) = 26.98$, $p < .001$. Importantly, there were no significant effects for the factor Number Magnitude and the interaction between the factors Number Magnitude and Pointing Goal Location, both Fs(1,21) < 1.5, which shows that number processing had no impact on the pointing kinematics.

Discussion

If participants made pointing instead of grasping movements, the interaction between numerical magnitudes and motor responses disappeared. Likewise, the analysis of movement curvature data failed to reveal any influence of the numerals. This absence of numerical magnitude effects on the pointing movements excludes that the priming effects observed in Experiment 1 were driven by spatial associations between numbers and relative vertical locations or by associations between number magnitude and physical object size. Since other authors reported numerical associations with locations along the vertical axis, it might be possible that the absence of effects for pointing movements was caused by two opposite effects resulting from contrary associations of numerical magnitude with vertical space (i.e., vertical SNARC effect) and with physical object size (i.e., association between number and size of object segment). Independent from this speculation, however, the outcome in Experiment 2 shows clearly that numerals did not affect the motor actions if the responses did not involve a grasping component and consisted only of a pointing

movement. Together with the results of Experiment 1, we can therefore conclude that the intention to grasp is a prerequisite for the present of numerical magnitude priming of actions, which in turn indicates that the observed interference effects must have emerged while the selection and preparation of the grip.

Nevertheless, our interpretation of a within-magnitude priming effect between numerical cognition and action planning could still be questioned. The reason is that the motor responses in Experiment 1 did not only differ with respect to the size of the required grip but also with respect to the number of fingers that had to be used for grasping. That is, precision grips always implied grasping movements with two fingers (e.g., only thumb and index finger), whereas power grips always involved the use of all five fingers of the hand. We can therefore not exclude that our findings were driven by the different amount of fingers involved in the grasping responses. Such an explanation is not farfetched and it appears to be even plausible to assume that there is a strong association between the fingers of the hand and the semantic knowledge about numerical magnitudes (see e.g. Di Luca, Grana, Semenza, Seron, & Pesenti, 2006). This connection is for instance nicely illustrated by children's use of finger-counting strategies when learning to deal with abstract quantities. And, in fact, there is empirical evidence for this relation coming from developmental studies indicating that the performance of a child in a finger agnosia test is a good predictor for later numerical skills (Noel, 2005). Moreover, neuropsychological research has shown that symptoms of finger agnosia are often associated with symptoms of dyscalculia (so called Gerstmann's syndrome: Mayer, Martory, Pegna, Landis, Delavelle, & Amnoni, 1999). Consequently, we conducted a third experiment to control for the number of fingers involved in the grasping responses.

Experiment 3

Experiment 3 sought to provide further evidence that number processing interferes with the processing of action-coded magnitude information for motor preparation and aimed to exclude that this compatibility effect was caused by overlearned associations between numbers and the fingers of the hand. To do so, we tested whether magnitude priming effects of numerals could also be found in grasping movements that required a fixed number of fingers for both required types of grip. As in the first experiment, participants grasped the object in different ways to indicate the parity status of Arabic digits. Now, however, power and precision grips had to be performed both with thumb and index finger only. Consequently, the two grasping responses differed only in aperture size.[3] In order to ensure that ring, middle and little fingers were not used to grasp the target object, we required our participants to hold with these three fingers a little stick. If the response latency differences in Experiment 1 were driven by a number-finger association, we should not observe any magnitude priming effects. If they reflected, however, a magnitude priming of size-related response features of the grasping action, we should be able to replicate our previous findings.

Method

Participants

Eighteen students of the Radboud University Nijmegen, who had not participated in one of the previous experiments, took part in Experiment 3. The participants were paid 4.50 Euro or received course credits. All were naive to the purpose of the study and had normal or corrected-to-normal vision.

Setup and Stimuli

The experimental setup and stimuli were identical to Experiment 1.

Procedure and Design

The procedure and the experimental design were identical to Experiment 1. Again, participants were required to indicate the parity status of the presented digits by performing different types of grasping responses with their right hand. However, in contrast to Experiment 1, the object had to be grasped with thumb and index finger only. That is, depending on the presented digits participants grasped the object with two fingers either at the large segment (i.e., power grip) or at the small segment (i.e., precision grip). In order to ensure that no other finger of the right hand were used for grasping, participants had to hold during the experiment a little stick (5 cm length, 1.5 cm diameter) between their right middle, ring and little finger.

Data acquisition and analysis

Data acquisition and analysis were identical to those employed in Experiment 1. An additional motion-tracking sensor was mounted inside the stick and used to control that participants held the stick in their right hand during all trials.

Results

Anticipations and missing response occurred in 0.7 % of the trials. Only 0.9 % of the grasping movements were performed incorrectly. The error rate for the parity judgments was 1.6 %.

Please insert Figure 4 about here

The RT and grip aperture data (see Figure 4 & Table 1) were analyzed as in Experiment 1. The 2 (Number Magnitude: small vs. large) x 2 (Type of Grip: precision grip vs. power grip) ANOVA of the RTs revealed no main effects, both *F*s < 1. Importantly, a significant interaction effect between these two factors was found, $F(1,17) = 5.46$, $p < .05$, $\hat{\omega}^2 = .06$. Post-hoc *t*-tests indicated that the precision grip RTs were shorter to small numbers (556 ms) than to large numbers (571 ms), $t(17) = -2.13$, $p < .05$, whereas for the power grips there was a non-significant trend towards the reversed effect, that is, shorter RTs to larger (560 ms) than to smaller numbers (571 ms), $t(17) = 1.95$, $p = .058$. The two-way ANOVA of the mean maximum grip apertures revealed a main effect for Type of Grip, $F(1,17) = 292.76$, $p < .001$, which showed that the grip apertures were larger for power grip actions (116.7 mm) than for precision grip actions (73.9 mm). Although the mean grip apertures difference between responses toward small and large numbers was identical to the main effect observed in Experiment 1, the factor Number Magnitude did not reach statistical significance, $F(1,17) = 2.11$, $p = 0.16$.

Discussion

Experiment 3 replicates the reaction times effect of Experiment 1 and shows an interaction between numbers and grasping actions that involve a fixed number of fingers. The finding excludes that the observed response latency effects were driven by an association between numbers and the fingers of the hand and provides additional support for the idea of numerical priming of size-related motor features.

In contrast to Experiment 1, the size of the maximum grip apertures did not differ for small and large numbers. A possible reason for this might be that the grasping responses in Experiment 3 had to be performed in a rather unnatural manner. Since participants were

required to hold a stick with the three remaining fingers while grasping the object with thumb and index finger, the responses were certainly more difficult to perform and might thus have been more disturbed than in Experiment 1. Evidence for this is provided by the observation that the within-subject confidence interval for the grip aperture data was larger for Experiment 3 as compared to Experiment 1.[4] It is therefore likely that the increased movement complexity was responsible for the absence of grip aperture effects when objects had to be grasped with two fingers only.

General Discussion

The present finding of an interaction between representations of numerical information and representations of action-coded magnitude information for grasping provides evidence for a close link between numerical cognition and motor control. We asked participants to indicate the parity status of visually presented Arabic digits by means of different reach-to-grasp movements (Experiments 1 & 3) and observed that precision grip actions were initiated faster in response to relatively small numbers, whereas power grip actions were initiated faster in response to large numbers. This finding indicates a magnitude priming of grasping actions by Arabic numerals. Beside that, we observed that the numerical magnitude had also an impact on the grip aperture kinematics. With both effects, we provide behavioral support for the idea that number processing and action planning share common cognitive codes within a generalized system for magnitude representation (Walsh, 2003).

Interestingly, the present study indicates that the intention to grasp the object was crucial for the interference between number processing and action planning. Numerical

magnitudes did not affect the actions if they involved no grasping component and consisted merely of a reaching movement (i.e., pointing response) toward the smaller or larger (respective upper or lower) part of the object (Experiment 2). This findings clearly discards the possibility of a compatibility effect between numbers and the reaching component of the actions—an effect that could have been caused by an association of number size with the size of to-be grasped object part or with the end position of the reaching movement along the vertical dimension (vertical SNARC effect; cf. Ito & Hatta, 2004; Schwarz & Keus, 2004). In addition, we excluded the possibility that interactions between grasping actions and number magnitude were driven by the different amount of fingers involved in the two different grasping responses, since the priming effects of the Arabic numerals were also present when the grasping actions were performed with two fingers only (Experiment 3).

Arabic numerals did not only affect the time to plan and initiate the grasping action but also influenced the way in which the action was performed. That is, when participants grasped the object without any restrictions concerning the fingers to be used, maximum grip apertures were enlarged in the presence of large numbers. Taken together, we conclude that the processing of numerical magnitude information somehow biased the processing of size-related motor features when preparing the grasping responses. Possibly, this effect originates from processes in the dorsal pathway where magnitude information needed to select an appropriated grip aperture is computed and represented (cf. Castiello, 2005).

The present magnitude priming effect in object grasping substantially extends previous findings of numerical stimulus-response compatibility effects that were caused by an association between numbers and spatial locations. The most prominent example of this relationship is the SNARC effect reflecting the tendency to respond fast with a left-side

response toward small and a right-side response toward large numbers (Dehaene et al., 1993; for review see, Hubbard et al., 2005). So far, SNARC effects have been shown for several types of lateralized motor responses (Fischer, 2003, Schwarz & Keus, 2004; Schwarz & Müller, 2006). It is, however, important to notice that in the present study the grasping actions did not differ with respect to a lateralized left/right response feature. Instead, participants moved always with the same hand toward the same object at the same location. Consequently, the observed differences in the latencies of the reaching responses can not be explained by an association between numbers and spatial response features. Rather, our data revealed an interaction between numerical magnitude information and size-related features of the motor response (i.e., the grip aperture). Thus, the demonstrated magnitude priming of grasping actions shows also that numerical stimulus-response compatibility effects are not restricted to an association between numerical values and spatial locations along the mental number line (e.g., Dehaene et al., 1993).

The experiments reported here represent a direct behavioral test of the idea of a generalized magnitude system for number processing and action planning. Importantly, the present findings go beyond the number finger-movement interaction previously shown by Andres et al. (2004). Although also the authors speculated that the compatibility effects observed between numbers and the extension/flexion of the index finger might be the result of a common representation involved in number processing and hand aperture control, the reported evidence for this was quite indirect since the task did not require any grasping action. For example, it can not be excluded that the effects in the study of Andres et al. (2004) were the result of an association between numbers and space along the sagittal axis, because each response comprised an index finger movement either towards or away from the body. The findings could be therefore also explained in terms of the more classical idea

of the mental number line. Moreover, the assumed connection with grasping behavior appears to be problematic, not only because the actions did not involve objects but also because an opening or closing of two fingers differs in several crucial motor features from natural grasping movements. As we know from several studies on motor control, reach-to-grasp movements consist always of both an opening and a closing of the hand rather than a single change of the grip aperture (for review see Castiello, 2005). Since the hand preshaping is strongly linked to the transport phase of the hand, we argue that magnitude effects in grasping actions can not be investigated appropriately without considering the whole reaching movement. It is thus important to notice that, in contrast to previous work, the present findings were not driven by finger movements per se and reflect an effect on the reach onset times and grasping kinematics while reaching out for the target object. Since the observed numerical magnitude priming is an effect of the intended end postures of the grasping actions, our results indicate that the size of the required grip aperture at the end of the reaching is the crucial motor feature responsible for the observed cognitive interference. This interpretation is in line with recent theories in the field of motor control assuming that the motor planning is mainly guided by the desired end postures of a goal-directed movement (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001). Taken together, the major advancement made by studying number effects on natural grasping actions is that our findings provide clear-cut evidence for the presence of within-magnitude priming between numbers and size-related motor features and demonstrate furthermore that these effects emerge during action planning well before the object is actually grasped.

Since Arabic digits represent broadly speaking an instance of symbolic semantic information, our findings may also contribute to research investigating the relationships between semantic processing and motor actions. Similar to the current number effect on the

grasping kinematics, an impact of word meanings on the grip aperture has been demonstrated by several studies (Gentilucci et al., 2000; Glover & Dixon, 2002; Glover et al., 2004). For example, semantic action effects have been found of words representing categorical magnitude relations (i.e., *small* or *large*) as well as for words denoting objects that are associated with a specific physical size (i.e., *grape* or *apple*) and therefore also with a specific type of grip (cf. Tucker & Ellis, 2001). The present study extends these findings and provides first empirical evidence for a comparable grip aperture effect of Arabic numerals. This shows that semantic effects on motor actions are not restricted on words representing physical or relative magnitudes but that they can be also elicited by stimuli representing knowledge about abstract and absolute magnitudes. Glover and Dixon (2002) performed a very detailed analysis of the grip aperture kinematics and found that semantic effects of word reading are only present very early on in the reach. As the hand approaches the target object this effect gradually declines. The authors concluded therefore that semantic information interferes with motor planning but not with processes of movement control, which become effective only after the action has been initiated. Following this reasoning, it is likely that the kinematic effects of numbers also occurred while motor preparation. We assume therefore that the grip aperture effects of numerals originated from the same cognitive interference during the stage of action planning as the magnitude priming effect found in the reaching latencies.

Several authors have suggested recently that semantic processing and action planning should be understood as two mutually dependent processes (e.g., Glenberg & Kaschak, 2002; Gallese & Lakoff, 2005). This idea implies not only that semantic processing affects action planning but also that action planning may affect semantic processing. Evidence has been provided recently for this by the observation that the

planning and execution of an action is capable to facilitate semantic judgments on the meaning of action-related words or sentences (Zwaan & Taylor, 2006; Lindemann et al., 2006). Whether such a reversed effect of action planning on higher cognitive processes exists as well for the processing of numbers is an intriguing open question for future investigations.

In sum, not much is known about the role of magnitude information in the coupling between motor control and other cognitive processes. The present study indicates the existence of a functional connection between numerical cognition and action planning. As the magnitude priming of grasping actions by Arabic digits shows, the coding of numbers interferes with the coding of size-related response features. This finding suggests that number processing and motor preparation share common cognitive codes (cf. Hommel et al., 2001) and supports in particular the idea of a generalized magnitude system (cf. Walsh, 2003) in which representations of numbers and actions are linked by a common metric for size and quantity information.

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Footnotes

1. A two-way repeated measures ANOVA with the factors Number Magnitude (small, larger) and Pointing Goal Location (small top segment, large bottom segment) on the error data (i.e., amount of incorrect performed motor response) yielded no significant effects, all *p*s>.*20*.

2. The statistical power analysis was conducted using the program *G*Power 3* (Faul, Erdfelder, Lang, & Buchner, in press).

3. For reasons of simplicity we keep here the label “power grip” for the grasping of the large segment with thumb and index finger, although the term is usually reserved for grasping actions with all fingers of the hands.

4. The within-subject confidence interval (*CI*; cf. Loftus & Masson, 1994) for the mean maximum grip apertures in presence of small and large numbers was *CI* = ±0.56 in Experiment 1 and *CI* = ±.91 in Experiment 3.

Tables

Table 1

Mean Maximum Grip Aperture (in mm) during the Reach-to-grasp Movements in Experiment 1 and 3 as a function of the Factors Number Magnitude and Type of Grip

Grip	Small number	Large number
	Experiment 1	
Precision	74.6	75.9
Power	119.6	119.7
Mean	*97.2*	*97.8*
	Experiment 3	
Precision	73.7	74.2
Power	116.3	117.0
mean	*95.0*	*95.6*

Table 2

Mean Path Curvature Indices (PCI) for the Pointing Movements in Experiment 2 as a Function of the Factors Number Magnitude and Pointing Goal Location

Segment	Small number	Large number
Small top	.29	.29
Large bottom	.20	.21
mean	*.24*	*.25*

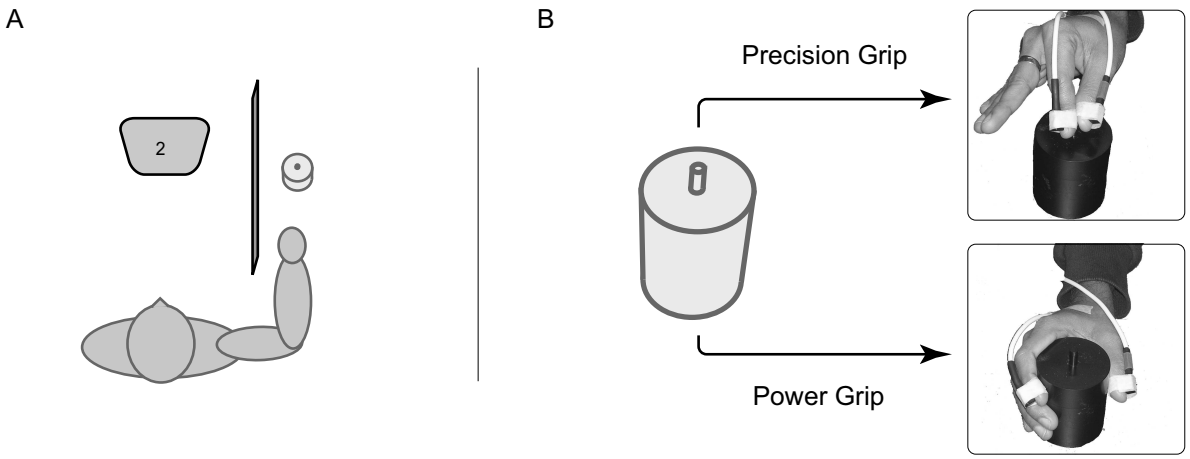
Figure Captions

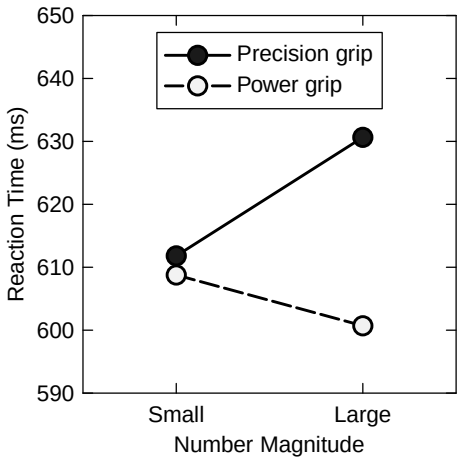
Figure 1. Basic experimental setup. (A) Participants sat at a table with a computer screen and a manipulandum. An opaque screen obscured the to-be grasped object and the right hand from view. (B) The object consists of two segments: a large cylinder at the bottom affording a power grip and a small cylinder at the top affording a precision grip.

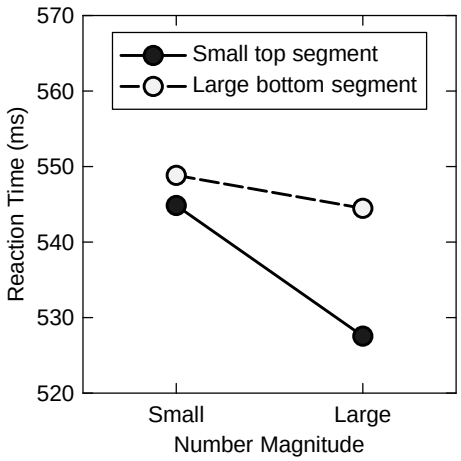
Figure 2. Mean response latencies in Experiment 1 as a function of the factors Number Magnitude and Type of Grip.

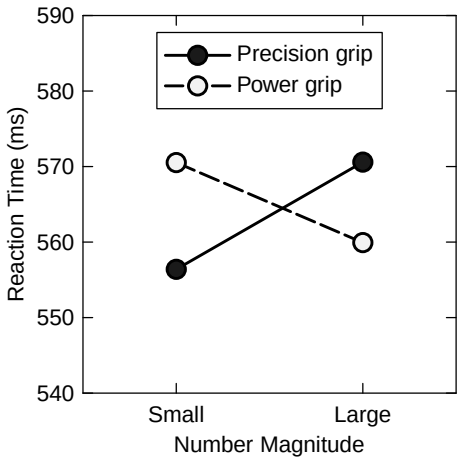
Figure 3. Mean response latencies in Experiment 2 as a function of the factors Number Magnitude and Pointing Goal Location.

Figure 4. Mean response latencies in Experiment 3 as a function of the factors Number Magnitude and Type of Grip.


A
2
B
Precision Grip
Power Grip


650
640
630
620
610
600
590
Reaction Time (ms)
Precision grip
Power grip
Small
Large
Number Magnitude


570
560
550
540
530
520
Reaction Time (ms)
Small top segment
Large bottom segment
Small
Large
Number Magnitude


590
580
570
560
550
540
Reaction Time (ms)
Precision grip
Power grip
Small
Large
Number Magnitude