Research report

Relative size of numerical magnitude induces a size-contrast effect on the grip scaling of reach-to-grasp movements

Rocco Y.-C. Chioub,d, Denise H. Wua,b, Ovid J.-L. Tzengb,c, Daisy L. Hunga,b and Erik C. Chang a,b,*

a Institute of Cognitive Neuroscience, National Central University, Taiwan
b Laboratories for Cognitive Neuroscience, National Yang-Ming University, Taiwan
c Institute of Linguistics, Academia Sinica, Taiwan
d Macquarie Centre of Cognitive Sciences, Macquarie University, Australia

ABSTRACT

Previous research found that quantitative information labelled on target objects of grasping movement modulates grip apertures. While the interaction between numerical cognition and sensorimotor control may reflect a general representation of magnitude underpinned by the parietal cortex, the nature of this embodied cognitive processing remains unclear. In the present study, we examined whether the numerical effects on grip aperture can be flexibly modulated by the relative magnitude between numbers under a context, which suggests a trial-by-trial comparison mechanism to underlie this effect. The participants performed visual open-loop grasping towards one of two adjacent objects that were of the same physical size but labelled with different Arabic digits. Analysis of participants’ grip apertures revealed a numerical size-contrast effect, in which the same numerical label (i.e., 5) led to larger grip apertures when it was accompanied by a smaller number (i.e., 2) than by a larger number (i.e., 8). The corrected grip aperture over the time course of movement showed that the numerical size-contrast effect remained significant throughout the grasping movement, despite a trend of gradual dissipation. Our findings demonstrated that interactions between number and action critically depend on the size-contrast of magnitude information in the context. Such a size-contrast effect might result from a general system, which is sensitive to relative magnitude, for different quantity domains. Alternatively, the magnitude representations of numbers and action might be processed separately and interact at a later stage of motor programming.

© 2011 Elsevier Srl. All rights reserved.

1. Introduction

The development of scientific research on actions used to be independent of that on symbolic cognition. As mental operations on symbols do not seem to directly involve action, it is not surprising that many researchers have treated these two topics separately. In recent years, however, a growing body of research has demonstrated a close link between

Please cite this article in press as: Chiu R.-C., et al., Relative size of numerical magnitude induces a size-contrast effect on the grip scaling of reach-to-grasp movements, Cortex (2011), doi:10.1016/j.cortex.2011.08.001
symbolic processing and action (Arbib, 2008; Barsalou, 2008; Fischer and Zwaan, 2008; Willems and Hagoort, 2007). The basic idea is that abstract symbolic knowledge such as numerical and linguistic representations is constructed on the basis of sensorimotor interaction with the external world, and can thus be conceptualized as being “embodied” in, or highly interactive with, cognitive processes responsible for actions (Andres et al., 2008a; Wilson, 2002). In line with this embodied view of cognition, Walsh (2003) proposed a hypothesis (known as ‘a theory of magnitude’ or ATOM) that the human parietal cortex serves as the cortical centre providing common metrics for time, space, and numbers owing to its functional role in encoding these variables for action. In an updated proposal, Bueti and Walsh (2009) went on to specify that, from an evolutionary perspective, the neural basis of numerical ability hitches onto the parietal lobe because it is already equipped with an analogue system that constantly computes quantities for action (‘Is my palm wide enough to grasp that? How much force should I use?’). Since its inception, the ATOM model has gained empirical supports from both neuroimaging (Kadosh et al., 2005; Pinel et al., 2004; Dormal and Pesenti, 2009) and behavioural studies (Andres et al., 2004; Badets et al., 2007; Chiou et al., 2009).

In terms of the neuroimaging literature that is consistent with ATOM, it has been shown that performing numerical tasks and grasping objects activate overlapping brain areas. For example, it is well established that subregions within bilateral intraparietal sulcus (IPS) show increased level of activity when participants process numbers and non-numerical quantities (Ansari, 2008, for a review). Parallel to the findings of the bilateral IPS being involved in numerical processing, this area has been implicated in the online control of reaching and grasping (Culham et al., 2006; Kroliczak et al., 2008; Cavina-Pratesi et al., 2007). Apart from the IPS, other brain areas of “grasping-related circuits”, such as the primary motor cortex and the premotor cortex (Cavina-Pratesi et al., 2007), were also found to be activated by numerical tasks (Kadosh et al., 2005; Pinel et al., 2004; Dormal and Pesenti, 2009). The involvement of the parietal cortex in grasping and quantity processing has been shown to reflect the functional need of transforming estimates of object size into an appropriate grip aperture (Cavina-Pratesi et al., 2007). In addition to brain-imaging evidence, two studies using transcranial magnetic stimulation (TMS) found increased excitability of right-hand muscles while participants were performing numerical parity judgements (Sato et al., 2007) or counting visual stimuli (Andres et al., 2007). Despite a study suggesting that the activation of action-related areas during numerical tasks can be explained by the need for response selection (Göbel et al., 2004), most researchers in the field of numerical cognition take the evidence reviewed above as consistent with the predictions of the ATOM model that action and numbers share neural substrates and can influence each other. These findings lead some researchers to suggest that numerical representations may ‘recycle’ the neural substrates of mental processes that appear early in evolution, like estimating size for grasping (Dehaene and Cohen, 2007).

In addition to neuroimaging studies, some behavioural studies are also compatible with the prediction of the ATOM model that numerical information would interact with non-numerical quantities (e.g., space, time, and action). For example, the Spatial Numerical Association Response Code (SNARC) effect indicated that numbers with small and large magnitude are represented in the left and right side of the mental number line, respectively (Dehaene et al., 1993; Fias et al., 1996), though the orientation of the number line in mental space can be affected by contexts and reading experience (e.g., Hung et al., 2008; Zebian, 2005). Task-irrelevant numerical information has been reported to affect the perception and reproduction of an interval (Chang et al., in press; Dormal et al., 2006; Xuan et al., 2009; Xuan et al., 2007). The interactions between numerical cognition and action control are also taken as supportive evidence for the ATOM model. Specifically, it has been reported that numerical magnitude modulated the response programming of grip closure or opening (Andres et al., 2004), the aperture size of precision or power grip (Lindemmann et al., 2007; Moretto and di Pellegrino, 2008), the graspability affordance of perceived visual stimuli (Badets et al., 2007; Chiou et al., 2009), and the response time of initiating a pre-designated level of force (Vierck and Kiesel, 2010).

A particularly interesting aspect of the interaction between symbolic and sensorimotor representations is the observation that the online scaling of grip aperture, a kinematic measure known to be sensitive to object size, is affected by the numeral or quantitative information labelled on the target object. As reach-to-grasp movement is more ecologically relevant than other types of responses, measuring the kinematics of grasping movement may better reveal how symbols and action interact in real-life contexts. For instance, Gentilucci et al. (2000) observed that, when performing a grasping movement, the maximum grip aperture was larger for target objects labelled with “LARGE” than those labelled with “SMALL”. Glover et al. further investigated how the impact of magnitude indicated by semantic symbols evolved during the course of grasping movement: When the words “LARGE” or “SMALL” (Glover and Dixon, 2002b) or the names of precision or power grip objects (Glover et al., 2004) were labelled on the target blocks, the influence of semantic meaning was more pronounced in the earlier phase ofprehensile movement and gradually declined as the hand approached the target. Recently, Andres et al. (2008b) demonstrated that grip aperture was larger in the presence of a large digit (8 or 9) than a small digit (1 or 2) in the early period of the prehension action. Similar to the semantic effect, the numerical effect gradually decreased as the prehension approached its completion. The gradually diminishing interference of number on grip aperture as the reach-to-grasp action unfolded may just reflect the practical need in scaling the grip to match the size of the target object. Andres et al. (2008b) referred to a “planning-and-control” model (Glover et al., 2004) to account for the emergence and dissipation of the numerical effect on grip aperture: In the earlier phase of grasping, the reach-to-grasp movement is governed by a planning system which incorporates the semantic information to plan a manual action. However, as the movement unfolds, the control of the action is taken over by a system whose computation relied solely on visual properties of the target, which led to the dissipation of the semantic effect.

While the findings of Andres et al. (2008b) demonstrated the online interaction between numerical and sensorimotor
processing, the nature of this interaction remains to be examined in further detail. Specifically, Andres et al. (2008b) presented a single target object with a numerical label in each trial, and the numerical label was always at the small or large end of the presented range (1, 2, 8, or 9). Thus, the numerical magnitude associated with an Arabic digit was fixed throughout the entire experimental session. With their design, it is not clear whether the mapping between grip aperture and number can be dynamically adjusted when the numerical label represents a different magnitude in other contexts.

Previous studies on numerical cognition, such as the demonstrations of the SNARC effect and the size congruity effect (Van Opstal et al., 2008), consistently reported range dependency of the magnitude associated with numbers. That is, the magnitude of a given number is derived from automatic comparison between the target digit and other digits used in the context. Once the relative size of a stimulus digit in a numerical range is settled with respect to the mean range of presented numbers, further mental processing on the digit would be influenced by its relative status of magnitude in the context (“automatic comparison hypothesis”; Gevers et al., 2006; Van Opstal et al., 2008; but see Choplin and Logan, 2005; Tzelgov et al., 1992 for a different view). To our knowledge, there is no study examining whether the numerical effect on grip aperture depends on the relative size of numerical magnitude, and it has never been shown that the magnitude status associated with a number can be altered by numerical comparison on a trial-by-trial basis. Hence, one of the goals of the present study is to verify whether the relative size of a number in the context affects its interaction with sensorimotor control, and whether automatic comparison of magnitude can be applied to the magnitude of the number that changes every trial.

Another issue with Andres et al. (2008b) is that they did not take into account the fact that the effect size of any kind of interference on grip aperture would naturally decrease as the reach-to-grasp action evolves (Franz et al., 2000; Glover et al., 2004). Their claim that their findings support the “plan-and-control” model thus needs further scrutiny. In order to properly assess the time-dependent nature of the numerical effect on grip aperture, proper correction needs to be carried out on the effect. One way to achieve this is by computing the slope of the linear regression line relating the physical object size and grip aperture at various time points spanning the time course of movement, and dividing the numerical effect on grip aperture with the slope at each time point for every individual participant (Franz, 2003b; Glover and Dixon, 2002b; Glover et al., 2004).

To address the two issues raised above, we recorded the kinematics of participants’ prehensile movements towards one of two objects with number labels, and the target object was determined by parity judgement. In each trial, the Arabic digit labelled on the target object may be either smaller or larger than the digit labelled on the adjacent distractor object. If the numerical effect on grip aperture changes flexibly depending on relative magnitude of quantity from trial to trial, grip scaling would be larger when a number labelled on the target object is the relatively large magnitude in the context, as compared to when the same digit is the relatively small magnitude, even if the magnitude of this number remains the same in the full range of numbers adopted in the experiment.

2. Materials and methods

2.1. Participants

After giving informed consent following the guideline of the declaration of Helsinki, 13 undergraduates from National Central University, Taiwan, were paid to participate in the present study. All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of neurological or mathematical disabilities. They were naive to the purpose of the experiment, and were all experienced in using Arabic digits.

2.2. Apparatus and stimulus

The participants sat in front of the long side of a rectangular table. A metal cone (with a radius of 5-mm at its base and 10-mm in height) was secured onto the tabletop with a distance of 20 cm from the participant’s body midline. This cone served as the starting position of every prehensile movement. The wooden target objects for the grasping task were white, with the dimensions 15 mm in thickness, 75 mm in height, and either 50, 60, or 70 mm in width. In each trial, two objects of identical physical dimensions were positioned in front of the participant at a distance of approximately 25 cm from the starting point along the mid-frontal direction. They were placed 7 cm away from each other and symmetrically across the body midline. Each object was placed on an inclined plane facing the participant and formed a 50° angle with the tabletop. An Arabic digit (2.2 cm × 3.2 cm) was labelled on each object on the surface facing the participants. The numeral pair displayed in every trial always contained an odd digit and an even digit. The odd digit was always 5, and the even digit could be either 2 or 8. During the experiment, 2 and 8 was the absolutely smallest and largest numerical magnitude, respectively. The status of 5 was contingent on the other digit: When 5 was paired with 2, it was the relatively large number in the context (5LARGE). In contrast, when 5 was paired with 8, it was the relatively small number (5SMALL).

The reach-to-grasp movements were recorded by a Phase-space Impulse motion tracking system (Phasespace Inc., San Leandro, California) with a sampling rate of 480 Hz. Two infrared emitting diodes (IREDS) were attached to the tips of the index finger and thumb of the participant’s right hand, respectively, and another IRED was attached to the radial styloid process of the right wrist. The infrared signals were captured by six different cameras installed on the ceiling of the experimental room. The cameras were spatially arranged in a way to optimize the signal capture within a 1 m³ cubic space above the tabletop where the participants performed grasping actions. Following the validation procedure of precision described in Haggard and Wing (1990; also see Andres et al., 2008a, 2008b), repeated measurements were taken on a 125-mm distance between two markers that were fixed on a calibration object. The calibration object was being moved within the working space for an extended period of time when the coordinates of the markers were recorded. The standard deviation of the fixed distance computed from all recorded frames was .44 mm.
2.3. Procedure and design

The participant wore a pair of computerized liquid crystal shutter glasses (Translucent Technologies Ltd, Canada) throughout the experiment. Before the beginning of each trial, participants were instructed to lightly pinch the starting cone, and the shutter glasses were set at the opaque state. Once the two objects were positioned, the shutter glasses changed from the opaque state to the transparent state for a 1000-msec preview period. At the same time as the objects became visible to the participant, a 50-msec tone was played to inform the participant which object to pick up in the current trial. The participant had to grasp the object labelled with the odd number (i.e., 5) if they heard a tone of the higher frequency, whereas they had to grasp the object labelled with an even number (i.e., 2 or 8) if they heard a tone of the lower frequency. These two types of trials were randomly interleaved, and there were equal numbers of trials for each object size. In order to select the correct target object for preparing a subsequent prehensile movement, participants must pay attention to the auditory cue and discriminate the identity of both digits in the numeral pair of each trial. After the 1000-msec preview period, the shutter glasses were reverted to the opaque state for a 700-msec delay period. The auditory tone indicating the target number in this trial was played again at the end of the delay period, and the participant had to perform an open-loop grasp on the object along its short axis as soon as they heard the tone.

There were twenty-four practise and seventy-two experimental trials. The seventy-two experimental trials consisted of the combination of three object sizes (50, 60, 70 mm), four numerical label/status (2, _5LARGE_, _5SMALL_, and 8), and two different locations of the target object (left or right). Each combination was repeated for three times during the experiment. Trials of different conditions were presented in a random sequence.

2.4. Data analysis

The raw movement kinematic data were first smoothed with a second-order, zero-phase lag, low-pass Butterworth filter (cut-off frequency 10 Hz). Because the thumb velocity was suggested to be more stable than the wrist velocity during prehensile movement (Haggard and Wing, 1997), the movement onset (i.e., RT) was set at the time point at which the thumb velocity exceeded 2.5 cm/sec for at least ten consecutive samples. Likewise, the movement offset was set at the moment at which the thumb velocity was smaller than 2.5 cm/sec for at least ten consecutive samples after the movement onset. The movement time (MT) was defined as the time interval between movement onset and offset. The grip aperture was defined as the distance between the markers attached to thumb and index finger.

In order to compare the evolution of grip aperture between trials with different MT, a normalization procedure was performed on the data of each trial (Andres et al., 2008b; Franz, 2003b; Glover and Dixon, 2002a, 2002b; Glover et al., 2004; Heath et al., 2004): MT was normalized by dividing into 20 intervals of equal duration, thus each interval represented 5% of the movement duration. Grip aperture was computed for each of the normalized time intervals, ranging from movement onset to offset. A trial was excluded from further analysis if: (1) its MT was shorter than 300 msec; (2) its parity judgment was incorrect, or (3) it was initiated before the auditory cue (anticipation error). These screening criteria led the exclusion of 4% of the trials from all trials the participants performed.

The dependent measures were subject to repeated-measure ANOVAs with factors appropriate for the experimental design. Post-hoc comparisons were corrected with the Holm–Bonferroni method (Holm, 1979) to ensure the family-wise alpha at .05.

3. Results

3.1. MT and RT

To ensure that effects in grip apertures were not confounded by other kinematic properties of the reach-to-grasp movement, the mean RT and MT values were subject to two separate two-way ANOVAs with object size (50, 60, and 70 mm) and numerical status (2, _5LARGE_, _5SMALL_, and 8) as the within-participant variables. The results showed that there were neither significant main effects nor interactions (all _p_ > .14). In particular, there was no effect of object size on the RT (F < 1, _p_ > .72) and on the MT (F[2,24] = 2.09, _p_ > .14), suggesting that the physical size of the target did not affect the initiation and duration of the reach-to-grasp movement.

3.2. Grip aperture

In order to examine how the relative numerical magnitude and actual object size influenced grip aperture and how this effect evolved with the time course of the reaching-to-grasp action, the average sizes of grip aperture at various time points throughout the MT were subjected to a three-way repeated-measures ANOVA, with object size (50, 60, and 70 mm), numerical status (2, _5LARGE_, _5SMALL_, and 8), and timing (20%, 40%, 60%, 80%, and 100% of the MT) as the independent variables (see Table 1 for the average of grip apertures in the combinations of all levels of each factor). The results revealed a significant main effect object size [F(2,24) = 87.05, _p_ < .001]. The average grip aperture was largest for the 70 mm objects (85.0 mm), followed by the 60 mm objects (78.8 mm), and smallest for the 50 mm objects (73.3 mm). Post-hoc comparisons showed significant differences among all pairs of sizes (all _p_ < .01).

The main effect of numerical status was also significant [F(3,36) = 4.05, _p_ < .02], indicating that the numerical labels on the target objects influenced the average grip apertures. Post-hoc comparisons showed that, average grip aperture for the object “_5LARGE_” (80.48 mm) was larger than “_5SMALL_” (77.4 mm; mean difference: 3.1 ± .7 mm, _p_ < .008). Average grip aperture was marginally larger for the object “8” (81.0 mm) than for the object “2” (77.4 mm; mean difference: 3.7 ± 1.0 mm, _p_ < .06) (see Fig. 1). None of the difference for other pairs approached significance (all _p_ > .13). The main effect of timing was significant [F(4,48) = 149.03, _p_ < .001]. This just reflected the fact that grip aperture evolved as the reach-to-grasp action proceeded (47.8, 76.1, 92.2, 93.6, and 85.6 mm for 20%, 40%, 60%, 80%, and 100% MT, respectively).
The interaction between object size and timing was significant [F(8,96) = 11.35, p < .001]. The differences among grip apertures for different object sizes (50, 60, and 70 mm) increased as the hand moved closer towards the target object. The differences were not significant at 20% of MT, but were significant at all of the later time points. This is reasonable because the grip aperture has to match the actual object size.

The interaction between numerical status and timing was also significant [F(2,144) = 2.14, p < .02], suggesting that the differences in the averaged grip apertures between numerical pairs, namely the numerical size effect, changed in distinct ways as the reaching-to-grasp action proceeded (Fig. 2). Some studies have raised the concern that the semantic effect is strong early in movement, while the effect of object size on grip scaling gradually emerges at later points (Glover et al., 2004; Franz et al., 2000; Glover, 2002; Glover and Dixon, 2001, 2002a, 2002b). To obtain an ‘unbiased’ measure of the numerical effect over time, we adopted the correction method reported in previous studies by dividing the numerical size effect with the slope of the linear function relating object size to grip aperture at each time point for every individual participant (Franz, 2003b; cf. Glover and Dixon, 2002b). The corrected effect was significantly different from zero for Relative differences (S_{LARGE} vs S_{SMALL}) at all time points, and for Absolute differences (2 vs 8) at 60%, 80%, and 100% of the MT (see Table 2). To evaluate the evolution of the effect over time, the corrected effects for both types of differences were subject to one-way repeated-measure ANOVAs, with timing (20%, 40%, 60%, 80%, and 100% of the prehensile movement) as the within-subject factor. The main effect of timing was significant for both Absolute difference [F(4,48) = 3.02, p < .05] and Relative difference [F(4,48) = 6.59, p < .05] between numerical status. Trend analyses also revealed linearly decreasing trends in both the Absolute condition [F(1,12) = 3.78, p = .07] and the Relative condition [F(1,12) = 7.93, p < .05]. Although such results suggested the corrected effect gradually decreased as the reach-to-grasp action proceeded, none of the pair-wise comparisons between different time points achieved significance (all ps > .16).

### 4. Discussion

The major finding of the present study is the numerical size-contrast effect on grip scaling. Namely, when the Arabic digit labelled on the to-be-grasped object represented a relatively large magnitude in a trial (S_{LARGE}), grip aperture was larger than when the same digit represented a relatively small magnitude (S_{SMALL}). Since the contextual magnitude of the Arabic digit “5” depended on the flanking digit (2 or 8), which varied from trial to trial, the present results demonstrated that the interaction between numbers and grip aperture was critically dependent on the relative size between two digits. The present results also supported the automatic comparison hypothesis (Gevers et al., 2006; Van Opstal et al., 2008), and further suggested that the cognitive mechanisms of automatic comparison can flexibly operate among individual trials, extending beyond the range dependency effect within a full block of trials reported in previous literature. However, the non-significant differences of other numerical pairs (i.e., 2 and S_{LARGE}; 8 and S_{SMALL}) indicated that the automatic comparison is not the only factor involved in this process and more research is needed.

<table>
<thead>
<tr>
<th>Object size (mm)</th>
<th>Absolutely small (2)</th>
<th>Relatively big (S_{LARGE})</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% 40% 60% 80% 100%</td>
<td>20% 40% 60% 80% 100%</td>
<td>20% 40% 60% 80% 100%</td>
</tr>
<tr>
<td>50</td>
<td>44.82 (3.00)</td>
<td>69.89 (3.90)</td>
</tr>
<tr>
<td>60</td>
<td>47.12 (3.18)</td>
<td>75.55 (4.29)</td>
</tr>
<tr>
<td>70</td>
<td>48.71 (2.25)</td>
<td>81.21 (2.76)</td>
</tr>
</tbody>
</table>

Note: Unit of the averages is millimetre (mm). Values in parentheses indicate standard deviation.

![Fig. 1 – Average grip apertures (mm) as a function of numerical status. The asterisk and bracket indicate significant differences between pairs. The error bars represent standard deviation.](image-url)
As mentioned in the introduction, most studies on numerical cognition present a number at a time (for example, Andres et al., 2008b; Dehaene et al., 1993; Fias et al., 1996; Lindemann et al., 2007). Experimental design as such is not sensitive to the relative size of numerical magnitude in every trial. Previous studies have shown that the SNARC effect was modulated by a number’s relative size within several blocks. It would be interesting to examine if the highly dynamic alternation in magnitude representation can be generalized to other types of numerical processing such as the SNARC and size congruity effects on a trial-by-trial basis.

To account for the present findings within the framework of ATOM model, the common metric underlying numerical and action processing has to be sensitive to the relative size of magnitude information in a context. Alternatively, the magnitude representations of numbers and action might be processed separately and interact (through the mediation of an ‘automatic comparison’ mechanism) at a later stage of motor programming. No matter which hypothesis is true, we reason that the view of ‘more quantity in one dimension maps to more quantity in another dimension’ might be too simplistic, as we show that contextual factors (e.g., relative size, comparison) also play a part in the interaction. Our findings also echo with an updated version of the ATOM model by Bueti and Walsh (2009) that not all aspects of space, time, and number lay within a single magnitude system (p. 1836). Instead, the observation of an interaction between different quantity dimensions (e.g., the numerical size-contrast effect reported here) may be the resulting products of multiple cognitive processes, such as the interplay among computation of multiple magnitude codes and the comparison mechanism.

The present study showed that the numerical size effect on grip aperture almost lasted throughout the entire movement duration (Table 2). Namely, when we scrutinise the results of pair-wise tests there was a numerically obvious but statistically non-significant trend of gradually decreasing effect across the movement duration. Although this trend is consistent with the findings in Andres et al. (2008b), we did not find strong evidence for a decreasing numerical effect. Considering that the numerical size effect was not corrected in Andres et al. (2008b) and the available method of correction (Glover and Dixon, 2002b; Glover et al., 2004) has been criticised to strongly inflate the effect at early stages of the

---

**Table 2** – Corrected numerical size effect for the Absolute and Relative differences as a function of time.

<table>
<thead>
<tr>
<th>Time</th>
<th>Absolute Difference (8 vs. 2)</th>
<th>Relative Difference (5_LARGE vs. 5_SMALL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Corrected effect</td>
<td>p-value</td>
</tr>
<tr>
<td>20%</td>
<td>28.91 (51.18)</td>
<td>.032</td>
</tr>
<tr>
<td>40%</td>
<td>10.71 (15.90)</td>
<td>.016</td>
</tr>
<tr>
<td>60%</td>
<td>8.91 (10.15)</td>
<td>.004*</td>
</tr>
<tr>
<td>80%</td>
<td>5.80 (5.13)</td>
<td>.001*</td>
</tr>
<tr>
<td>100%</td>
<td>1.84 (3.37)</td>
<td>.036*</td>
</tr>
</tbody>
</table>

Note: Values in parentheses indicate standard deviation. Asterisks indicate significant p-values (Holm-Bonferroni correction) of paired t-test for difference from zero at each time point.

---

Please cite this article in press as: Chiou RY-C, et al., Relative size of numerical magnitude induces a size-contrast effect on the grip scaling of reach-to-grasp movements, Cortex (2011), doi:10.1016/j.cortex.2011.08.001
reach-to-grasp movement (Franz et al., 2005; Franz, 2003a; Franz et al., 2009), whether the numerical/semantic effect on action decreases over MT or it is just a methodological artefact deserves further evaluation. A plausible explanation to reconcile the inconsistency between the current results and those of Andres et al. is that, in the present study, the participants had to perform grasping movement without any visual feedback, whereas the participants in the Andres et al. ‘s study saw their hand and the target object throughout the duration of prehension. It has been demonstrated that delayed grasping is more sensitive to the influence of illusion than visually guided grasping, even when the delay was very brief (Hu and Goodale, 2000; Westwood et al., 2001). Westwood et al. (2001) suggested that, without the online visual feedback during prehension, illusion-inducing factors are more likely to intrude into the computation of aperture scaling (also see Heath et al., 2005). Although the present experimental settings should not have elicited illusion of object size, the symbolic representations of numerical magnitude may have effects similar to illusory size-perception, and the effects were magnified when size information was retrieved from memory in the scenario of open-loop grasping. In other words, it is likely that performing delayed grasping without online vision prevents the number-elicited bias from being adjusted in the end of the movement.

It is of theoretical importance to evaluate how numerical effect on grip aperture also reflects intrinsic properties of numerical representations. Two points are addressed here: First, numerical stimuli convey information of not only magnitude but also sequential order (Nieder, 2005; Turconi et al., 2006). It is not clear whether both aspects influence the control of grip aperture as it is hard to disentangle numerical magnitude from ordinal meaning. Recently, by contrasting BOLD signals associated with comparison of numerical magnitude with those associated with comparisons of non-numerical stimuli carrying order information (letters and months), two neuroimaging studies reported that the anterior IPS responds equally to both numerical and non-numerical order information (Fias et al., 2007; Ischebeck et al., 2008). On the other hand, there is evidence from patient studies showing double dissociation between the processing of ordinal and cardinal (magnitude) information (Turconi and Seron, 2002). It seems that the cortical representations for serial order and magnitude are tightly linked but separable. However, the findings of Badets et al. have shown that, unlike numbers, ordinal stimuli caused no effects on graspability judgements. We postulate that the numerical effect reported here is more likely to reflect the magnitude representation of number, rather than the ordinal property. Future studies using sequential stimuli without cardinal meaning would be able to answer whether the numerical effect reflects the cardinal or ordinal aspect of numbers.

The second point concerns whether the numerical effect on grip scaling reflects a categorical mapping or proportional relationship. Although previous studies showed that a bigger number maps onto a larger grip, and a smaller number onto a smaller grip (Andres et al., 2004; Andres et al., 2008b; Lindemann et al., 2007), their experimental paradigms were inadequate for addressing the “categorical” versus “proportional” distinction because the lack of comparing the same numerical distance residing in different numerical range. The current results seem to be more consistent with a categorical mapping, as 5small elicits a comparable grip aperture to 2 (and the same pattern is observed on 5small and 8). It remains to be investigated whether grip aperture can proportionally reflect the numerical distance. For example, would the numerical effect on grip aperture be larger for “5 versus 9” than for “5 versus 7”, or would the effect be the same for these two pairs of numbers? In the former case (larger aperture for “5 vs 9” than “5 vs 7”), the relationship between numerical and sensorimotor representations could be an interval or ratio scale; in the latter case (the same aperture size for “5 vs 9” and “5 vs 7”), the relationship reflects the result of categorization. Similarly, this question can be examined by testing whether numerical effect differs for equal distance between smaller numbers (e.g., 5 vs 9) and large numbers (e.g., 10,005 vs 10,009). If the control of grip aperture mirrors genuine mental representation of magnitude, the results should follow Weber’s law and show that equal numerical distance leads to smaller size-contrast effect in grip aperture for larger numbers than for smaller numbers. Conversely, the results of a categorical mapping (i.e., comparable aperture size for “5 vs 9” and “1005 vs 1009”) would mean that, rather than stemming from a core representation level, numbers only affect grip scaling at a later stage of motor programming.

As a last note, the range of numbers adopted in the current experiment mostly situated across the boundary of the subitizing range. One may wonder whether we would get different effects if we used numbers in the subitizing range. Although the current experimental design was not a direct test of this issue, we noticed that the difference in grip aperture between “2 versus 5large” was approximately equivalent to that between “5large versus 8” (Fig. 1). Thus, our results suggest that the numerical size-contrast effects inside (“2 vs 5large”) and outside (“5large vs 8”) the subitizing range are not quantitatively different. Besides, there is no strong evidence in the literature that subitizing exists for the processing of symbolic numerosities. However, it would still be interesting to examine whether numerical effect exclusively within the subitizing range (e.g., “1–2” vs “2–3”) would differ from those exclusively outside (e.g., “7–8” vs “8–9”). Given the instant access of magnitude information within the subitizing range, the numerical effect within this range may not demonstrate the dynamic property observed in the current study.

### 5. Conclusion

According to the ATOM model (Walsh, 2003), the representations for numerical processing and the reach-to-grasp movements are closely linked by a generalized magnitude system, which transforms quantitative information into actions. The present study examined the specific nature of this transformation. While the results of numerical effects on grip aperture were consistent with previous findings, they also showed that the relationship between numerical and sensorimotor processing can be flexibly modulated by relative number size on a trial-by-trial basis. To construct a sound
theory of magnitude processing and embodied cognition, future research should examine more closely how well various properties of numerical cognition are transformed onto sensorimotor processing.

Acknowledgements

This study was supported by the National Science Council, Taiwan, with grants to ECC (NSC96-2413-H-008-003-MY2 and NSC 99-2410-H-008-008), to DLH and ECC (NSC99-2911-I-009-101), and to DHW (NSC98-2517-S004-001-MY3 and NSC 96-2628-S-008-009-MY2). The authors thank the three anonymous reviewers for their constructive comments.

References


Bueti D and Walsh V. The parietal cortex and the representation of time, space, number and other magnitudes. Philosophical Transactions of the Royal Society B: Biological Sciences, 365(1525): 1831–1840, 2009.


Chang AY-C, Tseng OJL, Hung DL, and Wu DH. Big time is not always long: Numerical magnitude automatically affects time reproduction. Psychological Science, in press.


Heath M, Rival C, and Binstein G. Can the motor system resolve a premovement bias in grip aperture? Online analysis of