# Number magnitude and grip aperture interaction

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Behavioural, neuropsychological and functional imaging studies suggest possible interactions between number processing and finger representation. Since grasping requires the object size to be estimated in order to determine the appropriate hand shaping, coding number magnitude and grasping may share common processes. In the present study, participants performed either a grip closure or opening depending on the parity of a visually presented digit. Electromyographic recordings revealed that grip closure was initiated faster in response to small digit presentation whereas grip opening was initiated faster in response to large digits. This result was interpreted in reference to a recent theory which proposed that physical and numerical quantities are represented by a generalized magnitude system dedicated to action. *NeuroReport* 15:2773–2777 © 2004 Lippincott Williams & Wilkins.

**Key words**: Motor control; Numerosity; Parity; Precision grip

## INTRODUCTION

Several observations suggest a close relationship between number processing and finger movements. This interaction is apparent in finger-counting strategies and when pointing movements are performed to enumerate a collection of objects [1]. In children, scores on finger discrimination tasks are a better predictor of arithmetic abilities than standard developmental tests [2]. Moreover, acalculia and finger agnosia are often associated in the Gerstmann syndrome consequent to left parietal lesions [3,4]. Finally, single neuron recordings in monkeys performing repeated arm movements revealed a number-selective activity in the parietal areas coding the forthcoming action [5].

A further insight into the relationship between numbers and finger movements is given by functional imaging studies showing that arithmetic [6,7], number comparison [8,9], or the quantitative processing of non-numerical stimuli [10] activate parietal and premotor areas close to those involved in object manipulation or grasping [11–13]. Although the exact amount of overlap of these activations is still a matter of debate [14], it is sensible to hypothesize that the cortical network involved in the coding of numerical values also contributes to the transformation of object size into an appropriate hand posture. This assumption is the core of a recent theory of magnitude processing in the parietal cortex, which suggests that physical and numerical quantities are computed according to a common metric for action [15]. In particular, this theory predicts interference effects between different magnitudes. Because the adjustment of grip aperture to object size requires an implicit magnitude estimate [16], it should also be susceptible to interference from number magnitude.

In order to address this issue, we used a stimulus-response compatibility paradigm based on a forced choice between two responses (i.e. a grip closure or opening) that were either congruent or incongruent with the magnitude of the Arabic digits presented to participants. To ensure that number magnitude processing was kept implicit, participants had to perform a parity judgement. We hypothesized that processing large digits would interfere with finger movements when the response was a grip closure, whereas small digits would increase the processing cost when the response was a grip opening. Such an additional processing cost should be reflected in longer reaction times (RTs), as measured through electromyographic (EMG) recordings of intrinsic hand muscles.

## SUBJECTS AND METHODS

***Participants and procedure:*** Twenty-six French-speaking students gave their informed consent to participate in this experiment (16 females; age range 18–26 years). They were all right-handed according to the Edinburgh Handedness Inventory [17] and reported no history of neurological disease or mathematical disabilities. The protocol was approved by the local ethical committee for biomedical research.

Stimuli were Arabic digits ranging from 0 to 9 (Arial 48) presented at the centre of a computer screen, in black on a light grey background. Each trial began with the presentation of a fixation cross on the centre of the screen for 300 ms; the cross was then turned off and a digit was displayed at the same position for 1000 ms. Intertrial interval was 1200 ms. A personal computer Pentium III (Windows 98) was used to control the display of the stimuli. The presentation was designed with Superlab and EMG recording was triggered by the stimulus presentation by means of a CIO-DIO 24 card interface (Cedrus, USA).

Participants sat comfortably on an armchair, 60 cm in front of a computer screen, with the right hand resting on a padded support. The arm was lying perpendicularly to the mid-sagittal plane, on the right of the body, with the wrist relaxed (Fig. 1a). The hand mimicked a grasp posture, with the index finger and thumb aperture slightly open; this posture was adjusted to avoid any background activity in hand muscles. Participants were then required to make a forced choice between two responses, depending on the parity of the numeral. One response was a grip closure that required a flexion of both the thumb and index finger along the sagittal axis; the other response was a grip opening achieved by performing the opposite finger movement (Fig. 1b). Participants were asked to make a brisk movement; the first phasic EMG activity was used to determine the movement onset. After each response, they had to come back to the initial hand posture. Only the right hand was used to respond, the left hand being kept in a rest position throughout the experiment. In a first block, grip closure was associated with the response to even digits and grip opening with the response to odd digits for half of the participants; it was the opposite for the other half of participants. In a second block, the assignment of responses was reversed in all participants. Each block consisted of 12 presentations of each digit in a pseudorandom order. Twenty practice trials were performed before each block to familiarize the participants with the assignment of responses. Instructions encouraged both speed and accuracy. It is important to stress that the words 'small' and 'large' were never used in the instructions and that no reference was made to numerical magnitude. For each trial, the experimenter wrote down the response movement performed by the participant.

***Apparatus and EMG recordings:*** EMG recordings were made from surface electrodes (Neuroline, Medicotest, Denmark) placed on the first dorsal interosseus (FDI) and extensor indicis (EI). The FDI contributes to index abduction and flexion whereas the EI participates in index extension. Therefore, an increase in EMG activity in FDI and EI was related, respectively, with a grip closure and a grip opening. In an additional control experiment, the EMG activity was also recorded from the flexor pollicis brevis (FPB) and extensor pollicis brevis (EPB) in 6 participants to test whether the number magnitude interference observed in the index finger movements was also present in the thumb. The raw EMG signals were amplified and filtered (Neurolog, Digitimer, England; gain 1 K, high-pass 10 Hz), digitized at 6 kHz (CED 1401, Cambridge Electronic Design, England) and stored on a PC for further offline analyses (Signal, Cambridge Electronic Design, England). Figure 1c shows the EMG recordings in one participant while performing a closure (left panel) or an opening (right panel) of the hand grip.

***Data analysis:*** The dependent variable was the RT, defined as the time interval between the stimulus presentation and the EMG burst of the agonist muscles. Trials with a background EMG activity $>50\,\mu V$ (mean rate$\pm$s.d. $2.13\pm2.08\%$) as well as error trials ($4.05\pm2.89\%$) were discarded from the analysis. EMG recordings were then inspected visually and a cursor was moved manually at the onset of the phasic EMG activity. Median RTs were computed on correct trials for each participant and for each combination of number and movement.

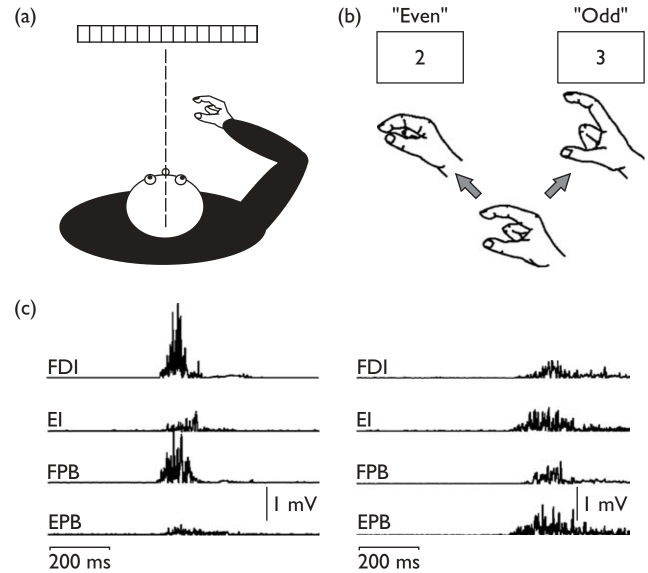


**Fig. 1.** (**a**) Schematic representation of subject's posture. (**b**) Illustration of both response movements using one possible assignment of responses: even digits are answered by a grip closure and odd digits by a grip opening. (**c**) Individual EMG recordings corresponding to the trials described in (b): on the left panel, grip closure activated the FDI and the FPB; on the right panel, grip opening recruited more specifically the EI and the EPB.

An ANOVA for repeated measures was performed on median RTs with order of blocks (grip closing in response to even digits either in the first or in the second block) as a between-subject variable and parity (odd or even), response (grip closure or opening) and digit magnitude ([0–1],[2–3],[4–5],[6–7],[8–9]) as within-subject variables. Trend analysis and paired *t*-tests (corrected for multiple comparisons) were used for *post-hoc* comparisons.

To investigate further the interaction between response movements and numerical variables, differences in reaction times (dRTs) were calculated for each participant and for each digit by subtracting the median RTs related to grip opening from the median RT associated with grip closure. A negative difference indicated shorter RTs for grip closure than for grip opening. For example, in subject 1, the median RT to digit 1 was 435 ms for grip closure and 585 ms for grip opening, the dRT was thus equal to $-150$ ms, indicating a shorter RT for grip closure. The dRTs were then entered in a regression analysis for repeated measures with digit magnitude (0–9) and parity (even $-0.5$; odd $+0.5$) as predictor variables (for a description of the statistical procedures see [18]). Only the regression analysis was applied to the RTs measured from the thumb muscles, given the small number of participants for whom this control measure was available.

## RESULTS

There was no speed–accuracy trade-off, as indicated by a positive correlation between RT associated with index finger movements and number of errors computed over 20 data pairs (10 numerals associated with index flexion or extension, $r(18)=0.79$, $p<0.001$).

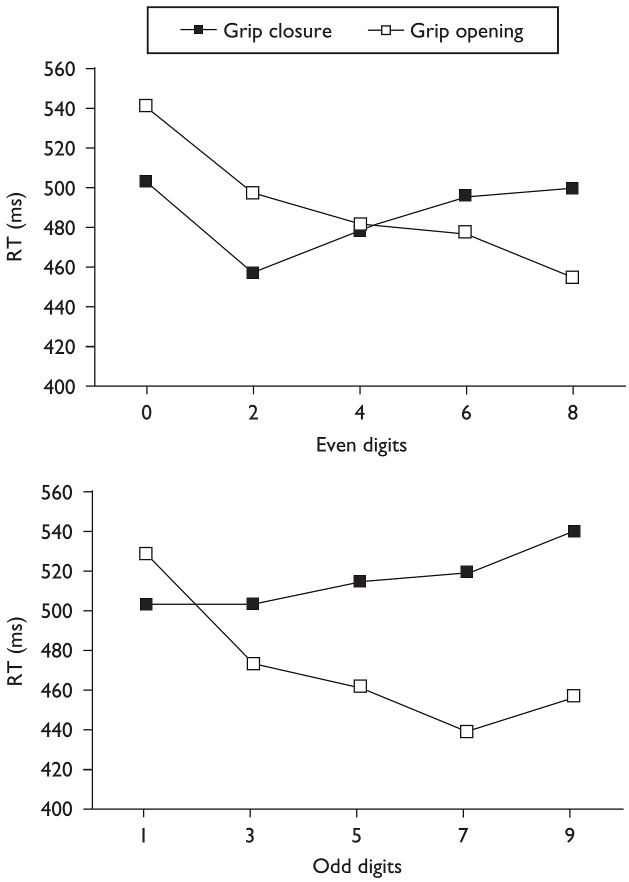


**Fig. 2.** Mean reaction times, measured from the index, for even and odd digits as a function of the response movement.

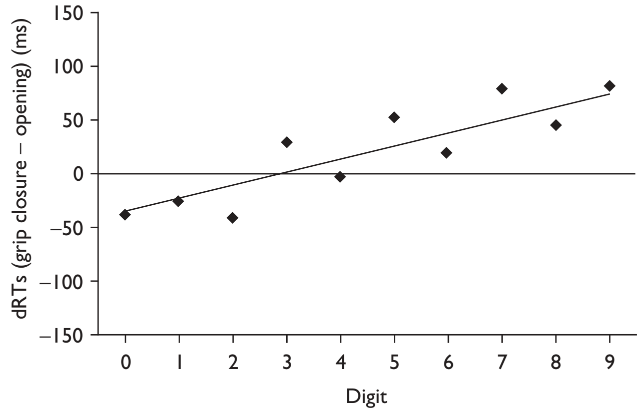


**Fig. 3.** Differences in reaction times (dRTs) between both index movements (grip closure − grip opening) as a function of the digit. Negative values indicate relatively faster reaction times for the grip closure and positive values indicate relatively faster reaction times for the grip opening. Diamonds indicate observed dRTs. They are represented along the line resulting from the regression of dRTs on magnitude.

The ANOVA performed on the RTs measured from the index movements revealed a main effect of magnitude ($F(4,96)=19.89$, $p<0.001$), indicating longer RTs for 0 and 1 than for the other digits. A main effect of response was also observed ($F(1,24)=20.83$, $p<0.001$), showing that grip closure was, on average, 19 ms slower than grip opening ($502\pm72$ *vs* $482\pm62$ ms). The main effects of parity and order were not significant ($p>0.1$).

There was a significant two-way interaction between response and magnitude ($F(4,96)=26.15$, $p<0.001$), integrated in a three-way interaction between response, magnitude and parity ($F(4,96)=2.89$, $p<0.05$). When separate ANOVAs were conducted on each level of parity, the interaction between response and magnitude remained significant for both odd ($F(4,100)=19.06$, $p<0.001$) and even digits ($F(4,100)=13.36$, $p<0.001$). As shown in Fig. 2, participants more rapidly classified small digits as odd or even when the response was a grip closure than when it was a grip opening. In contrast, RTs were shorter for grip opening than for grip closure when judging the parity of large digits. Trend analyses indicated that the effect of magnitude was linear for each combination of parity and response (all $p<0.001$), except when grip closure was performed in response to even digits. In this condition, the results were better explained by a quadratic trend ($F(1,25)=19.19$, $p<0.001$), indicating that the linear increase of RTs with magnitude was attenuated by longer reaction times for 0, an effect probably due to the particular semantic status of 0 [19]. The interaction between magnitude and parity ($F(4,96)=4.65$, $p<0.01$) showed that digit 0 elicited longer reaction times than 2, 4, 6 and 8 ($522\pm69$, $477\pm59$, $479\pm75$, $486\pm58$ and $477\pm54$ ms, respectively), whereas RTs were significantly longer for digit 1 than for 3, 5, 7 but not 9 ($517\pm75$, $490\pm80$, $490\pm78$, $481\pm82$ and $500\pm74$ ms, respectively).

Finally, a two-way interaction between response and parity ($F(1,24)=11.22$, $p<0.01$) indicated that grip closure was initiated more slowly in response to odd digits than to even digits ($517\pm88$ *vs* $486\pm64$ ms). No difference was observed between odd and even digits for grip opening ($474\pm68$ *vs* $490\pm61$ ms).

Regression analysis confirmed that numerical magnitude interacted with the selection of the index movements responsible for grip closure and opening. Indeed, as shown in Fig. 3, dRTs increased linearly from negative values (small magnitudes) to positive values (large magnitudes). The negative dRTs found for small digits indicated an increased processing cost when the response was a grip opening compared with a grip closure. This processing cost decreased progressively with magnitude and dRTs became positive for larger digits, showing that grip opening was actually initiated faster than grip closure as numerical magnitude increased. In addition, dRTs were larger for odd digits than for even digits, reflecting that odd digits elicited longer reaction times when answered by a grip closure. This resulted in the equation dRTs $=-35.11+12.24$ magnitude $+34.82$ parity. Both predictors had a significant contribution: magnitude, $t=8.85$, $p<0.001$, $R^2=0.21$; and parity, $t=2.51$, $p<0.05$, $R^2=0.05$. When removing the part of variance due to between-subject variability, the percentage of variance ($R^2$) accounted for by magnitude and parity reached respectively 0.64 and 0.16. A second regression equation was computed without the item 0 because of its different semantic status [19]. The regression analysis revealed equivalent coefficient estimates without 0: dRTs $=-40.38+12.72$ magnitude $+36.25$ parity.

In the six participants in whom EMG activity was recorded from both index finger and thumb muscles, a regression analysis conducted on the difference between RTs for the flexion and extension of the thumb confirmed that the interference of numerical magnitude on the selection of a grip posture was also present in thumb movements: dRTs$=-31.26+11.20$ magnitude$+24.28$ parity. Again, the equation accounted for the linear increase of dRTs with numerical magnitude (magnitude, t=3.05, $p<0.05$, $R^2=0.23$) and for the tendency for odd digits to lead to a slower grip closure (parity, t=1.30, $p<0.1$, $R^2=0.03$). In these participants, the dRTs measured from the thumb were highly correlated with the dRTs computed for the index ($r(58)=0.95$, $p<0.001$).

## DISCUSSION

Our results showed that RTs increased linearly, from small to large digits, when the response to parity judgment was a grip closure, whereas they decreased when the response was a grip opening. This interaction between the digit magnitude and grip aperture is consistent with Walsh's view that numerical values and object size exert a similar influence on motor programming because they share common representations in the dorsal visual pathway [15]. It is noteworthy that, in the present study, the task did not require an object to be grasped. However, this limitation does not exclude an interpretation in terms of grip aperture because it has been shown that positioning finger and thumb to mimic grasp postures activates the same parieto-premotor network as during actual grasping movements [14].

As number magnitude is known to interact strongly with space [20], it could also be argued that the interference we observed in the present study was actually due to spatial factors, such as the direction of index movements. Index movements towards the top (i.e. towards the computer screen) would be associated with larger digits whereas index movements towards the bottom (i.e. towards the participant's body) would be preferentially associated with small digits, as if movements were performed along the axis of a thermometer. However, this interpretation can be ruled out because we found that number magnitude had the same influence on the movement onset of both index and thumb, although they moved in opposite directions in our experiment.

The present interaction between numerical magnitude and grip aperture sheds light on the activation found in the premotor and parietal areas during number comparison or calculation [7,9]. As already mentioned, this shared activation could possibly reflect interactions between number processing and finger representation [9]. An alternative view is that the premotor cortex contributes to comparative judgements by accumulating information from parietal regions in order to take a decision [10]. Although the present results do not allow us to give a definite answer to this question, they favour the interpretation based on finger representation rather than on decision processes.

Although less relevant to the main point of this study, the present results also indicated that odd digits elicited longer RTs when they were associated with grip closure. A possible explanation for this observation is that, when presented with odd digits, participants implicitly activated the motor program for lip opening to pronounce the initial vowel of the word impair ([$\sim\epsilon p\epsilon R$]; French word for odd). This may interfere with the grip closure and yield longer RTs. A relationship between grasping and speech has already been proposed by Rizzolatti and Arbib [21] in their motor theory of language, and is supported by a research combining analysis of lip kinematics and voice spectrum [22].

## CONCLUSION

Our study provides the first behavioural evidence in favour of a functional interaction between number magnitude processing and grip aperture. In accordance with a theory of magnitude [15], we propose that this interaction reflects the computation of a magnitude estimate in the dorsal visual pathway where object size is processed to adjust grip aperture.

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