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RESEARCH REPORTS

Congruency Effects Between Number Magnitude and Response Force

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Numbers are thought to be represented in space along a mental left–right oriented number line. Number magnitude has also been associated with the size of grip aperture, which might suggest a connection between number magnitude and intensity. The present experiment aimed to confirm this possibility more directly by using force as a response parameter. Participants judged parity of a single digit by executing a weak or forceful key press. Response selection was faster when small digits required a weak response and large digits required a forceful response than when this mapping was reversed. These findings indicate an effect of number magnitude on the initiation of response intensity. There was no evidence for such an effect on response execution because the actually applied response force was not associated with number magnitude. These findings confirm a previously postulated link between different magnitude domains such as number magnitude and intensity as a basis for action.

Keywords: response force, number magnitude, SNARC, intensity

A recent theory by Walsh (2003) postulated the existence of a generalized magnitude system in the inferior parietal lobe. This system represents magnitudes of different areas, such as space, numbers, intensity, and time as a basis for action. The theory is supported by findings that tie the different components to each other. For example, Pinel, Piazza, Le Bihan, and Dehaene (2004) asked participants to perform comparative judgments for identical stimuli that varied on three dimensions—number, size, and luminance—while fMRI scans were conducted. The analysis showed that all three dimensions were processed within the intraparietal sulci.

Likewise behavioral research on number processing revealed links of number magnitude to space, time, and intensity. First, the link between number magnitude and space frequently has been examined. Two main findings indicate a close connection: the distance effect (Dehaene, Dupoux, & Melcher, 1990) and the spatial-numerical association of response codes (SNARC) effect (Dehaene, Bossini, & Giraux, 1993). The distance effect describes the finding that numbers that are numerically close to a standard number are more difficult to compare than numbers that are numerically distant (e.g., Dehaene et al, 1990; Pinel et al., 2004). The SNARC effect describes results showing reaction time (RT) advantages for small numbers when responded to with the left hand and for large numbers when responded to with the right hand. These findings led to the view that numbers are represented spatially in the form of a mental number line (e.g., Daar & Pratt, 2008; Dehaene et al., 1993; Fias, 2001).

Second, recent experiments demonstrated a connection between number magnitude and time (e.g., Kiesel & Vierck, 2009; Xuan, Zhang, He, & Chen, 2007). For example, Xuan et al. asked participants to judge which of two successively presented stimuli displays were shown for a longer duration. In one of their experiments, the displays contained irrelevant digits that were either small or large. If digit values were congruent with the display duration, for example, a small (large) digit was paired with a short (longer) display time, fewer errors were made. This experiment clearly established a connection between digit magnitude and time on perceptual processing. Kiesel and Vierck expanded these findings to motor processes. They asked participants to judge parity for Arabic digits presented in the center of a computer screen and to indicate their decision with either short or long key presses. Results showed that participants responded faster when small numbers required short key presses and large numbers required long key presses as compared with the reversed mapping of number magnitude and response force. Together, these findings established a clear link between time and number magnitude.

Third, the link between number magnitude and intensity has not been demonstrated directly up until now. To our knowledge, there is only one study by Lindemann, Abolafia, Girardi, and Bekkering (2007) that points to a connection between number magnitude and intensity. Lindemann et al. used a parity judgment task, but instead of left–right key presses, responses were indicated by two different types of grips: a precision grip and a power grip. The precision grip was executed with thumb and index finger, whereas the power grip was carried out with the whole hand. Smaller digits led to an earlier initiation of the precision grip, whereas larger digits had the same effect on the power grip. In addition, the magnitude of the digit affected the grip aperture, that is, the distance between thumb and index finger during reaching movements. Grip aperture was

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larger for large numbers. The two types of grips may be considered as varying with regard to intensity. A precision grip prepares for fine motor movements and thus requires only low intensity. In contrast, a power grip prepares for gross motor movements and requires much more intensity. In this regard, the above findings provide indirect evidence for a connection between number magnitude and intensity.

However, in order to claim that number magnitude is linked to space, time, and intensity, we need more direct evidence for a connection of number magnitude and intensity. Recently, R. Fischer and Miller (2008) used a classical parity judgment task with left–right response keys that measured both response time and response force. Response force has been used extensively to explore the generation of motor responses (e.g., Jáskowski & Verleger, 1993; Miller, Franz, & Ulrich, 1999; Ulrich & Mattes, 1996). Two variables are commonly measured: (a) reaction time (RT) of the response, that is, RT until response force crosses a threshold when the response key is pressed and (b) maximum of the applied response force, that is, the peak amplitude of the force course, which reflects the intensity with which the motor response was executed (Jáskowski, van der Lubbe, Wauschkuhn, Wascher, & Verleger, 2000). The focus of the R. Fischer and Miller task was on speeded left and right responses, and as expected, these authors observed the classical SNARC effect. In their study, response force was not task relevant and was only a byproduct of the response. The authors did not find any impact of number magnitude on response force. Consequently, this study may be interpreted as evidence against a link between number magnitude and intensity.

However, it is unclear whether similar results would be obtained when response force is the focus of the task. To evaluate this possibility, we used force as the main response parameter. We employed a parity judgment task and asked participants to press a force-sensitive key weakly or forcefully for odd or even numbers instead of using left–right responses with incorporated response force measures (R. Fischer & Miller, 2008). If the link between number magnitude and action extends to response force, that is, intensity, then we should see a congruency effect: The time until the force key was pressed should be shorter when weak presses were required for small numbers and forceful presses were required for large numbers as compared with a mapping where weak presses were required for large numbers and forceful presses were required for small numbers. In addition, response force allowed us to evaluate the actual force applied for small and large magnitudes. If the execution of weak and forceful responses is affected by number magnitude, then the actually applied response force should depend on digit magnitude.

Method

Participants

Twelve volunteers (ages 19–27 years, one of whom was left-handed) took part in an individual session of approximately 60 min in fulfillment of course requirements or in exchange for pay. All reported having normal or corrected-to-normal vision.

Apparatus and Stimuli

Stimulus presentation was accomplished by an IBM-PC compatible computer with a 17-in. (43.2-cm) video graphics array (VGA) display controlled by E-Prime (Schneider, Eschman, & Zuccolotto, 2002). The digits 2 through 9 were used as targets, drawn in Arial 44 point in white against a black background. Response recording was accomplished by another computer equipped with an external force-sensitive response key positioned centrally in front of the screen. The force key was equipped with a strain gauge (manufactured by Hottinger Baldwin Messtechnik, Darmstadt, Germany) and registers force electronically with a rate of 250 Hz. Force measurements are linear from 0 to approximately 2,500 cN (centi-Newtons). The force key moved less than 1 mm when participants press the key such that isometric force was measured. Both computers were connected via parallel port, enabling us to give feedback to participants. Responses were executed with the index finger of the preferred hand. A weak response required participants to press the response key with a force between 157 cN and 668 cN, and a forceful response required participants to press the key with a force between 846 cN and 1,739 cN. Prior to the experiment, participants were given some practice to perform weak and forceful responses. The minimum amount of force that would be registered as response was 157 cN; this force was defined as the criterion level for response onset for the purposes of measuring RT. The same criterion was also used to define response offset.

Design and Procedure

Each trial started with the presentation of a fixation cross for 1,000 ms in the center of the screen. After the offset of the fixation cross, a 50-ms blank followed. Then the target digit was displayed for 110 ms. Participants were to respond within 3,000 ms after stimulus onset. Participants received feedback directly after response offset or after the response window had elapsed. In case of correct responses, the German word “Richtig” was displayed. In case of incorrect responses, the German word “Falsch” and the information of whether the response was too weak, too forceful, or not registered was fed back. The next trial started 250 ms after offset of the feedback, which lasted for 1,250 ms.

Participants were asked to indicate whether the target digit was odd or even by performing a weak or a forceful response. Thereby the stimulus–response mapping (i.e., odd digits–weak response; even digits–forceful response or vice versa) was counterbalanced over participants.

Each participant started with a practice block consisting of 32 trials, followed by 20 experimental blocks consisting of 32 trials each. Within each experimental block, each of the eight target digits was presented four times.

Results

Trials with RTs deviating more than 2.5 standard deviations from the mean RT of each experimental condition per participant (1.6%) were considered outliers and were excluded from the analysis. For the remaining trials, mean RTs for correct trials and mean percentages of error (PEs) were computed for each participant and separately for each combination of the factors magnitude bin (4: 2/3, 4/5, 6/7, 8/9) and response force (2: weak vs. forceful) and subjected to a repeated measurement analysis of variance (ANOVA). Half of the participants performed weak responses for odd digits and forceful responses for even digits, whereas for the other half of participants, this mapping was reversed. Consequently, the orthogonal variation of magnitude bin and response force relied on different target digits depending on the counterbalancing of stimulus–response mapping.

To quantify the impact of response force, we computed regression analysis analogous to the analyses computed to assess SNARC effects (e.g., Fias, 2001; Müller & Schwarz, 2007; for regression analysis in general, see Lorch & Myers, 1990). We calculated forceful–weak response differences by subtracting RTs and error rates for weak responses from forceful responses for each magnitude bin. We then regressed these forceful–weak response differences separately for each participant on the magnitude bin whereby magnitude bin was dummy-coded as 1, 2, 3, and 4. As a result, we obtained an individual slope for each participant. Analogous to regression lines for right-hand minus left-hand responses in SNARC experiments (Dehaene et al., 1993), we expected negative slopes to be efficient indices for the impact of response force: If response force (weak vs. forceful) is associated with number magnitude, then RT and error rate differences for response differences should be negatively related to number magnitude, that is, for small numbers, RTs and error rates are presumably smaller for weak compared with forceful responses resulting in a positive difference for forceful–weak response differences, whereas for large numbers, RTs and error rates are increased for weak compared with forceful responses, resulting in a negative difference.

Response Times

The repeated measurement ANOVA on the factors magnitude bin (4: 2/3, 4/5, 6/7, 8/9) and response force (2: weak vs. forceful) revealed a significant interaction, $F(3, 33) = 16.43$, $MSE = 6{,}721.8$, $p < .001$. Weak responses were faster to smaller numbers, and forceful responses were faster to larger numbers (see Figure 1, upper panel). Descriptively, participants responded slower with weak (522-ms) compared with forceful (507-ms) key presses, but the main effect of response force, $F(1, 11) = 3.26$, $MSE = 5{,}317.5$, $p = .099$, did not reach significance. Response times increased slightly with number value (511, 512, 515, and 519 ms for the magnitude bins 2/3, 4/5, 6/7, 8/9), but the main effect of magnitude bin, $F(3, 33) = 1.67$, $MSE = 297.6$, $p = .19$, did not reach significance either.

The regression analysis revealed that RT for forceful–weak response differences decreased by 25.74 ms per magnitude bin, $t(11) = 5.52$, $SE = 4.66$, $p < .001$ (see Figure 1, lower panel). The best fitting regression line is described by the equation dRT = 49.46 – 25.74 × (magnitude bin), whereby magnitude bin is dummy coded ranging from 1 to 4.

Error Rates

The same analysis of variance (ANOVA) on error rates revealed a significant interaction between the factors response force and magnitude bin, $F(3, 33) = 9.45$, $MSE = 711.5$, $p < .001$. Participants made more errors when small numbers required forceful responses and large numbers required weak responses (see

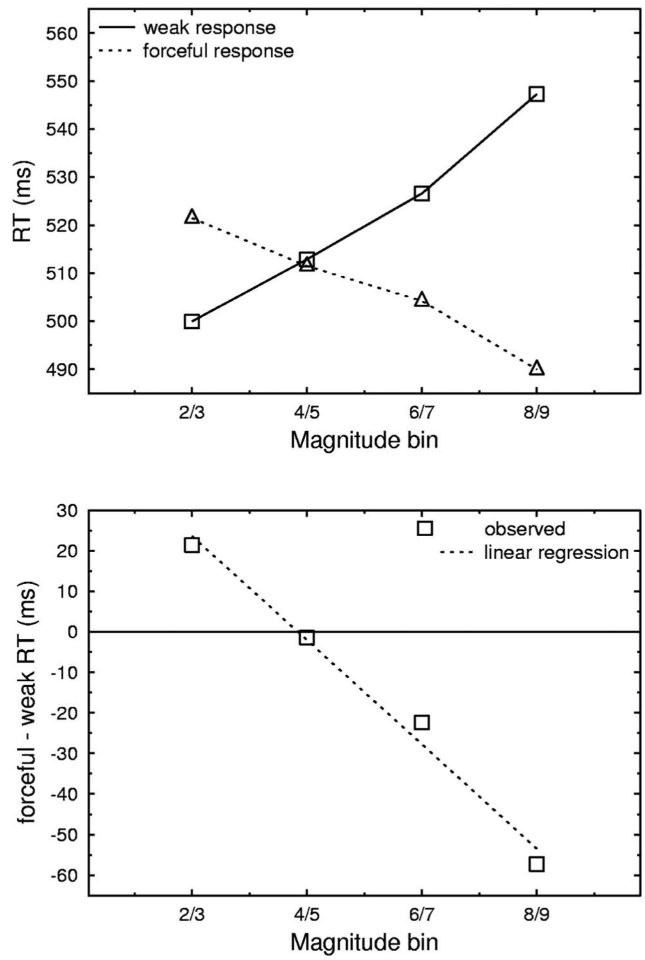

Figure 1. Upper panel: Mean response times for weak (solid line) and forceful (dotted line) responses as a function of magnitude bin. Lower panel: Observed forceful–weak response differences (squares) of reaction time (RT) (in ms) and regression of RT differences on the magnitude bin (dotted line).

Figure 2, upper panel). In addition, there was a main effect of response force, $F(1, 11) = 9.87$, $MSE = 1{,}600.1$, $p < .001$. Participants responded more often erroneously when forceful responses were required (21.98% versus 13.80% for weak responses). The main effect of magnitude bin, $F(3, 33) = 1.49$, $MSE = 41.4$, $p = .23$, did not reach significance.

The regression analysis on error rate differences of long–short response differences revealed similar findings. Error rates decreased by 8.28% per magnitude bin, $t(11) = 3.37$, $SE = 2.45$, $p < .01$ (see Figure 2, lower panel). The best fitting regression line is described by the equation dPE = 28.86 – 8.28 × (magnitude bin), whereby magnitude bin is dummy coded ranging from 1 to 4.

Response Force

To verify our experimental manipulation and to evaluate response execution in connection to number magnitude, we also analyzed the actually performed response force depending on required response force and magnitude bin. When weak responses

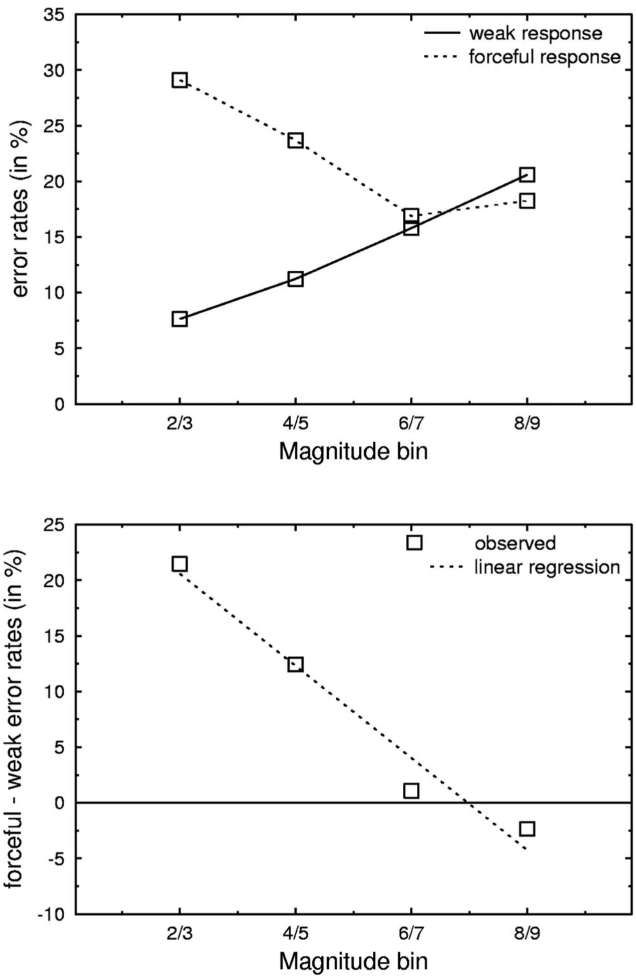

Figure 2. Upper panel: Mean error rates for weak (solid line) and forceful (dotted line) responses as a function of magnitude bin. Lower panel: Observed forceful–weak response differences (squares) of error rates and regression of error rate differences on the magnitude bin (dotted line).

were required, mean response force was 380.8 cN (SE = 15.8), whereas for forceful responses it amounted to 1,207.5 cN (SE = 16.2), $F(1, 11) = 896.15$, $MSE = 16{,}402{,}707.4$, $p < .001$. The factor magnitude bin had no impact on response force, $F(3, 33) = .47$, $MSE = 209.1$, $p = .71$, and the interaction between response force and magnitude bin was also not significant, $F(3, 33) = 1.02$, $MSE = 326.3$, $p = .40$. The actually applied forces amounted to 373.2, 381.0, 383.3 and 385.6 cN for the magnitude bins 2/3, 4/5, 6/7, 8/9 when weak responses were required, and it amounted to 1207.7, 1207.8, 1212.1, and 1202.4 cN for the magnitude bins 2/3, 4/5, 6/7, 8/9 when forceful responses were required. Thus, it seems that number magnitude is not associated with response execution in our experiment.

Discussion

In this experiment, we instructed participants to categorize digits as even or odd by responding weakly or forcefully to investigate the connection between number magnitude and intensity. We found that when the mode of response (weak/forceful) and the number magnitude (small/large) were congruent, that is, when weak responses were related to small numbers and forceful responses were associated with large numbers, response selection was faster and error rates smaller. These results clearly demonstrate a connection between number magnitude and intensity on the response selection stage.

Our findings suggest that the representations of number magnitude and intensity are associated. This is similar to the frequently reported connection between number magnitude and space (e.g., Daar & Pratt, 2008; Dehaene et al., 1993). Interestingly, compatibility effects between number magnitude and space have also been reported when number magnitude was rendered irrelevant in the current task context. Fias, Lauwereyns, and Lammertyn (2001) superimposed upward or downward pointing triangles on digits and asked participants to press left and right response keys according to the orientation of the triangles. Although the digits were completely task irrelevant, a reliable SNARC effect was observed. In our experiment, the number magnitudes were task relevant because digits had to be categorized as odd or even to fulfill task requirements. Regarding the connection reported here between number magnitude and intensity, future research will have to show whether the observed compatibility between number magnitude and intensity also occurs when number magnitude is irrelevant for the task.

The maximal applied response force was not associated with number magnitude, which suggests that response execution was not affected by our manipulation. Our results thus confirm the locus of number magnitude on the response selection level but not on the response execution level, as reported in other studies (e.g., Gevers, Ratinckx, de Baene, & Fias, 2006; Keus, Jenks, & Schwarz, 2005). However, they are in contrast to the results of M. H. Fischer (2003), who used a parity judgment task with finger pointing as a response parameter and found an effect of number magnitude on finger movement time. The failure to find such a connection might indicate that an effect of numbers only exists on response selection. Alternatively, our findings might be due to the specific properties of response force. The strength of the response is thought to depend on arousal (Jáskowski & Włodarczyk, 2005). For example, brightness and loudness have been shown to affect peak force (Jáskowski & Włodarczyk, 2005, 2006). It is likely that in our design, small numbers were similarly arousing to large numbers and that this feature is reflected in our findings.

Our results regarding the actually applied response force are comparable to the only other study that looked at the influence of number magnitude on the motor parameter response force. R. Fischer and Miller (2008) used a parity judgment task with left–right response keys that also measured response force as a by-product. In two experiments—one where responses were given with both hands and one where responses were given with two fingers of one hand—a SNARC effect emerged only for reaction time measures for left–right responses, but magnitude had no effect on the actually applied response force. These results suggest an effect of number magnitude on response selection but not response execution when response force was not emphasized. In our experiment, response force was the main focus. Participants had to categorize the force they applied into weak and forceful. Because our findings are similar to R. Fischer and Miller's findings, it seems that even with a direct focus on response force, number magnitude has no effect on response execution.

Walsh (2003) proposed a system in the inferior parietal lobe, in which magnitudes of different domains are represented together and used as the basis for action. Within this framework, the impact of number magnitude has frequently been investigated. Number magnitude has been shown to be connected to several domains, for example, space (e.g., Dehaene et al., 1993) and time (e.g., Xuan et al., 2007). Our findings extend the existing knowledge because they provide evidence for an additional connection between number magnitude and intensity. Our results thus support the idea of a generalized magnitude system.

The parity judgment task employed in our experiment has not only been investigated with regard to number magnitude effects but also with regard to the concept of linguistic markedness. Nuerk, Iversen, and Willmes (2004) reported response facilitation for the combinations even number–right hand and odd number–left hand relative to the combinations even–left and odd–right in a parity task, an effect they referred to as markedness of response code (MARC). According to the markedness concept, these two words (even and right) are linguistically unmarked, which allows them to be retrieved more quickly (Hines, 1990; Zimmer, 1964). If two unmarked words are combined, compatibility effects occur. In a post hoc analysis, we evaluated such a possibility for our data. In our case, the forceful response would be the unmarked condition. The German words *schwach* (weak) and *stark* (strong) are the words associated with the response type in our experiment. *Stark* is much more frequently used than *schwach* in the German language. *Stark* is also the word that is commonly used in questions such as "How strong is John?" Such a sentence does not add presuppositions, as the word *weak* in this question would, which, according to Schriefers (1990), is another sign of an unmarked word.

Post hoc analysis revealed a strong main effect of markedness on RT, $F(1, 10) = 4.90$, $MSE = 177{,}769.8$, $p = .051$, but in an unexpected direction. Responses for the mapping even–weak and odd–strong were 86 ms faster than for the mapping even–strong and odd–weak. Likewise, those participants who performed the mapping even–weak and odd–strong tended to respond 14 cN more forcefully than the participants who performed the mapping even–strong and odd–weak, but this effect missed the level of significance, $F(1, 10) = 3.1$, $p = .12$. Because this analysis is based on a very small number of participants, this effect might be spurious, but it suffices to exclude the possibility of response facilitation due to markedness in our experiment. It might be that the connection between the semantic representation of numbers and the linguistic markedness of the response need to be mediated by space, which did not vary in our experiment.

SNARC effects are generally small and range from 2 to 14 ms (e.g., Dehaene et al, 1993; Keus et al. 2005; Müller & Schwarz, 2007). In contrast, the congruency effect observed in our experiment was rather large at 25 ms. Interestingly, this effect size is similar to the compatibility effect (approximately 21 ms) described in R. Fischer and Miller's (2008) Experiment 1. Both our study and R. Fischer and Miller's study used response force as the dependent variable. It might be that preparing speeded force responses instead of simple speeded responses requires more motor preparation and therefore enhances compatibility effects. This possibility is corroborated by findings reported by Kunde (2001). He demonstrated compatibility effects of 50 ms for an association between auditory stimuli and response force. In his study, soft tones corresponded with weak response force and loud tones corresponded with forceful responses. The observed effect was much larger than the compatibility effect of about 20 ms generally observed for situations in which response and imperative stimuli occur on the same side (e.g., Kunde, 2001; Melara, Wang, Vu, & Proctor, 2008).

Overall, our results confirm a link between number magnitude and intensity for the response selection stage but not for the response execution stage. Thus, our findings extend research on number processing from established links between number magnitude and space and number magnitude and time to number magnitude and intensity.

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