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SNARC-Like Congruency Based on Number Magnitude and Response Duration

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Recent findings demonstrated that number magnitude affects the perception of display time (B. Xuan, D. Zhang, S. He, & X. Chen, 2007). Participants made fewer errors when display time (e.g., short) and magnitude (e.g., small) matched, suggesting an influence of magnitude on time perception. With the present experiment, the authors aimed to extend these findings by investigating whether number magnitude and time are also connected at the response level. Participants judged the parity of single digits by pressing a response key for either a short or a long duration. Responses were faster when small numbers required short keypresses and large numbers required long keypresses. In addition, overall keypress durations were affected by number magnitude. The results suggest a connection between number magnitude and time at the levels of response initiation and execution, thus supporting theories outlining a common magnitude system comprising time, space, and magnitude.

Keywords: number magnitude, response duration, dit–dah responses, numerical–temporal congruency, SNARC

In recent years, a connection between space and number magnitude has been firmly established (e.g., Dehaene, Bossini, & Giraux, 1993; Dehaene, Dupoux, & Melcher, 1990; Keus & Schwarz, 2005). The assumption that number magnitude is related to space is based on two often-replicated behavioral findings. First, participants are faster to compare two numbers in terms of their magnitude when the numbers are numerically distant than when they are numerically close (Dehaene et al., 1990). Second, participants respond faster to small digits with their left hand and to large digits with their right hand than vice versa. This was first demonstrated by Dehaene et al. (1993), who presented one of the Arabic digits 0–9 in the center of the screen and asked participants to respond with their right or left hand depending on the parity of the digit. They found effects of magnitude and response side on reaction time (RT). Small digits were responded to faster with the left hand, whereas large digits led to an RT advantage with the right hand. This so-called *SNARC*, or spatial–numerical association of response codes, effect suggests that number magnitude is directly associated with response side.

Both the distance and the SNARC effects indicate that a spatial representation is accessed automatically when magnitude judgments are made. Accordingly, it has frequently been suggested that numbers are mentally represented in a way that is similar to a spatial number line (e.g., Dehaene et al., 1993; Kaan, 2005; Schwarz & Keus, 2004).

Recent studies addressed the question of the functional locus of the SNARC effect. Keus and Schwarz (2005) used centrally and laterally presented number stimuli in their experiments. Participants indicated the parity of the number either vocally (by saying "odd" or "even," thus without spatial association) or with the left or right hand. A SNARC effect arose only for manual responses regardless of stimulus position, which suggests that the SNARC effect mainly affects the response-selection stage. Similar conclusions have also been drawn from psychophysiological studies (Gevers, Ratinckx, de Baene, & Fias, 2006; Keus, Jenks, & Schwarz, 2005; see, however, Stoianov, Kramer, Umilta, & Zorzi, 2008).

In addition to affecting response selection, the SNARC effect has been shown to impact response execution (Fischer, 2003; Song & Nakayama, 2008). For example, Fischer (2003) used a parity judgment task in combination with a finger-pointing response. To indicate their judgment, participants had to lift their index fingers from a centrally arranged response box on the computer screen and place it on another box located to the left or right side of the center box. This arrangement allowed the measurement of RT and movement time, which is associated with response execution. Number magnitude had an effect on movement time; specifically, movement execution was faster for congruent trials than for incongruent trials, suggesting a SNARC effect on the response-execution level also.

Recently, a connection between time and magnitude has been demonstrated by Xuan, Zhang, He, and Chen (2007; see also Müller & Schwarz, 2008). These authors presented two stimulus displays in succession and asked participants to judge which stimulus display was presented for a longer duration. Displays were presented for a short duration (e.g., 600 ms) or a long duration (e.g., 750 ms). In one of their experiments, one of the two displays contained a small digit (1 or 2), whereas the other contained a large digit (8 or 9). Digit values were either congruent or incongruent with the display duration; for example, in the congruent condition, small digits were displayed for a shorter period of time and large digits were displayed for a longer period of time. Participants were told to ignore the digit identity and to focus on

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the display time only. Nevertheless, fewer errors were made in the congruent condition than in the incongruent condition. This experiment clearly established a connection between digit magnitude and time, but it is unclear where this effect takes place. From Xuan et al.'s results, it seems that the effect might stem from a perceptional processing stage, because the perception of time duration was judged.

Our goal in the present experiment was to investigate whether a connection between time and magnitude could also be observed when the time manipulation referred to the response stage of information processing. For this purpose, we used a parity judgment task within a classical SNARC paradigm. To tap into the time domain at the response stage, we replaced the spatial responses and introduced "dit–dah" responses, so called because of their labels in the standard Morse code (e.g., Klapp & Erwin, 1976; Klapp, McRae, & Long, 1978; Kunde & Stöcker, 2002). Participants were asked to judge odd numbers with a "dit" response and even numbers with a "dah" response or vice versa (counterbalanced over participants). In our experiment, *dit* refers to a short duration keypress (up to 150 ms), whereas *dah* refers to a long duration keypress (from 151 ms up to 300 ms). Please note that these response durations were too short to adopt a chronomatic counting strategy (Wearden, 1991). If the link between time and digit magnitude affects the response selection stage, then a congruency effect should be seen; that is, RTs should be faster for short "dit" responses when the digit to be judged is small and long "dah" responses when the digit to be judged is large. In addition, "dit–dah" responses provide information about response execution by allowing one to compare response durations for small and large magnitudes. If number magnitude has an effect on response execution, the actual keypress durations should depend on the number magnitude.

Method

Participants

16 volunteers (ages 19–30 years, 1 left-handed) took part in an individual session of approximately 30 min in fulfillment of course requirements. All reported having normal or corrected-to-normal vision.

Apparatus and Stimuli

Stimulus presentation and response recording were accomplished with an IBM PC compatible computer with a 17-in. VGA display controlled by E-Prime (Schneider, Eschman, & Zuccolotto, 2002). The digits 2–9 were used as targets, displayed in 44-point Arial type in white against a black background. Responses were executed with the index finger of the right hand and collected with an external response key positioned centrally in front of the screen. A short ("dit") response required participants to release the response key within 150 ms after response onset; a long ("dah") response required participants to release the key between 151 ms and 300 ms after response onset.

Design and Procedure

Each trial started with the presentation of a fixation cross for 200 ms in the center of the screen. After the offset of the fixation cross, the target digit was displayed for 200 ms. Participants were to respond within 3,000 ms after stimulus onset. Errors were indicated by the German word for error (*Fehler*), and participants were informed whether the response was too short or too long. The next trial started 1,200 ms after response onset.

Participants were instructed how to perform the "dit" and "dah" responses. They were then asked to indicate whether the target digit was odd or even by performing a "dit" or a "dah" response. Thereby the stimulus–response mapping (i.e., odd digits = "dit" response and even digits = "dah" response or vice versa) was counterbalanced over participants.

Each participant started with a practice block of 32 trials followed by 10 experimental blocks with 64 trials each. Within each experimental block, each of the eight target digits was presented eight 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 or 3, 4 or 5, 6 or 7, 8 or 9) and response duration (2: dit = short vs. dah = long) and subjected to a repeated-measurement analysis of variance (ANOVA). Please note that half of the participants performed short responses for odd and long responses for even digits, whereas for the other half of participants, this mapping was reversed. Consequently, the orthogonal variation of magnitude bin and response duration relied on different target digits depending on the counterbalancing of stimulus–response mapping.

To quantify the impact of response duration, we computed a regression analysis analogous to the ones computed to assess SNARC effects (e.g., Fias, 2001; Müller & Schwarz, 2007; for regression analysis in general, see Lorch & Meyers, 1990). We calculated long and short response differences by subtracting RTs and error rates for short responses from RTs and error rates for long responses for each magnitude bin. Then we regressed these long and short response differences separately for each participant on the magnitude bin whereby magnitude bin was dummy coded 1, 2, 3, and 4. As a result, we obtained an individual slope for each participant. Analogous to regression lines for right- minus left-hand responses in SNARC experiments (Dehaene et al., 1993), negative slopes were expected to be efficient indices for the impact of response duration: If response duration (short vs. long) 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 short compared with long response durations, resulting in a positive difference for long–short response differences, whereas for large numbers, RTs and error rates are increased for short compared with long responses, resulting in a negative difference.

RTs

The repeated-measurement ANOVA revealed no main effects ($ps > .22$) but a significant interaction, $F(3, 45) = 5.79$, $MSE =$

930.5, $p < .01$. Short responses were faster to smaller numbers compared with larger numbers and long responses were faster to larger numbers compared with smaller numbers (see Figure 1A).

The regression analysis revealed that RTs for long and short response differences decreased by 7.71 ms per magnitude bin, $t(15) = 3.35$, $SE = 2.30$, $p < .01$ (see Figure 1B). The best-fitting regression line is described by the equation dRT = 21.57 – 7.71 × (magnitude bin), whereby magnitude bin is dummy coded from 1 to 4.

Error Rates

The same ANOVA on error rates revealed a main effect of response duration, $F(1, 15) = 36.35$, $MSE = 4{,}124.2$, $p < .001$. Participants responded erroneously more often when long responses were required (24.9% vs. 13.5% for short responses). The interaction between the factors response duration and magnitude bin did not reach significance, $F(3, 45) = 2.47$, $MSE = 97.0$, $p = .074$. Descriptively, participants tended to make more errors when small numbers required long responses and large numbers required short responses (see Figure 2A).

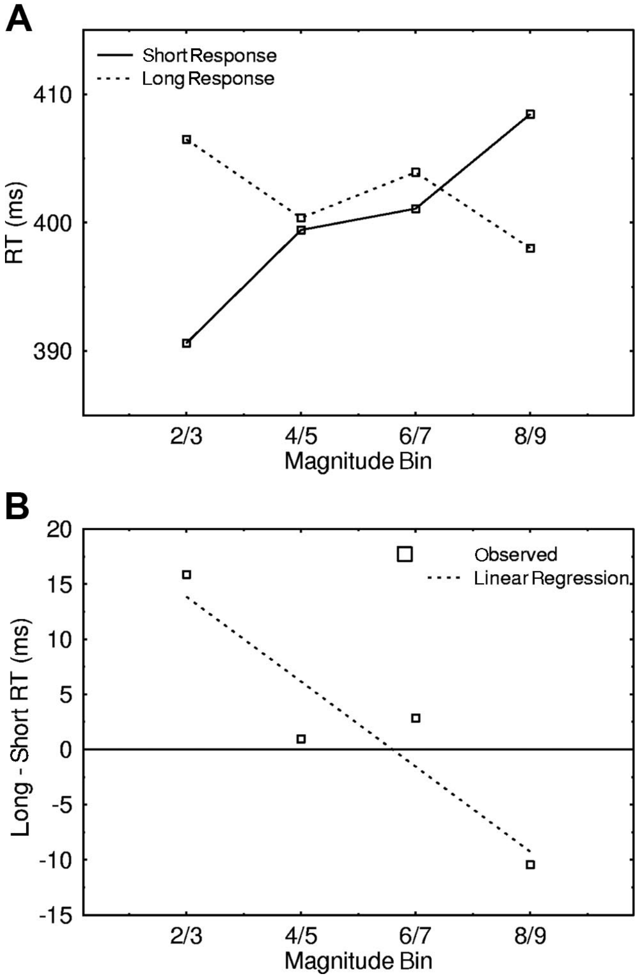

Figure 1. A: Mean response times (in milliseconds) for short (solid line) and long (dotted line) responses as a function of magnitude bin. B: Observed long and short response differences (squares) of RT (in milliseconds) and regression of RT differences on the magnitude bin (dotted line).

The regression analysis on error rate differences of long and short response differences revealed similar findings. Error rates decreased by 2.36% per magnitude bin, $t(15) = 2.22$, $SE = 1.06$, $p < .05$ (see Figure 2B). The best-fitting regression line is described by the equation dPE = 17.25 – 2.36 × (magnitude bin), whereby magnitude bin is dummy coded from 1 to 4.

Please note that the error rate difference for long and short response differences was positive for all magnitude bins because error rates were generally larger for long compared with short responses. Nevertheless, the negative slope indicates an association of response duration and number magnitude because the disadvantage of long responses diminished for larger numbers.

One reason why participants might have made more errors for long than for short responses is that long responses yielded two kinds of errors: Participants' responses were too short in 17.8% of all errors and too long (longer than 300 ms) in 7.2% of all trials when long responses were required. In contrast, when short responses were required, response durations longer than 300 ms occurred only in 0.3% of all trials, whereas participants erroneously performed the long response (150 ms to 300 ms) in 13.2% of all trials. Yet, when trials with response durations longer than 300 ms were excluded, the data pattern remained similar. Even after we excluded trials with response durations longer than 300 ms, our results still showed that participants made more errors when long compared with short responses were required, $F(1, 15) = 11.41$, $MSE = 1{,}073.6$, $p < .01$. As before, the interaction between the factors response duration and magnitude bin did not reach significance, $F(3, 45) = 2.69$, $MSE = 100.2$, $p = .0567$. The regression analysis computed for error rates of long and short response differences revealed that error rates decreased by 2.55% per magnitude bin, $t(15) = 2.50$, $SE = 1.02$, $p < .05$. The best-fitting regression line is described by the equation dPE excl = 12.17 – 2.55 × (magnitude bin), whereby magnitude bin is dummy coded from 1 to 4.

Response Duration

To verify our experimental manipulation and to evaluate response execution in connection to number magnitude, we also analyzed the actually performed response durations depending on required response duration and magnitude bin. When short responses were required, mean response duration was 108 ms ($SE = 3.96$), whereas for long response duration, it amounted to 218 ms ($SE = 5.30$), $F(1, 15) = 214.04$, $MSE = 386{,}627.6$, $p < .001$. It is interesting that the factor magnitude bin influenced response duration, $F(3, 45) = 3.92$, $MSE = 256.4$, $p < .05$. Participants' responses were shortest to the digits 2 and 3 ($M = 160$ ms, $SE = 3.31$); longer to the digits 4, 5, 6, and 7 ($M = 162$ ms for both magnitude bins, *SE*s = 2.34 for 4 and 5 and 3.41 for 6 and 7); and longest to the digits 8 and 9 ($M = 167$ ms, $SE = 3.04$). Thus, it seems that number magnitude is also associated with response execution in our experiment.

Discussion

In this experiment, we combined the classical parity judgment used within SNARC designs with temporally distinct responses,

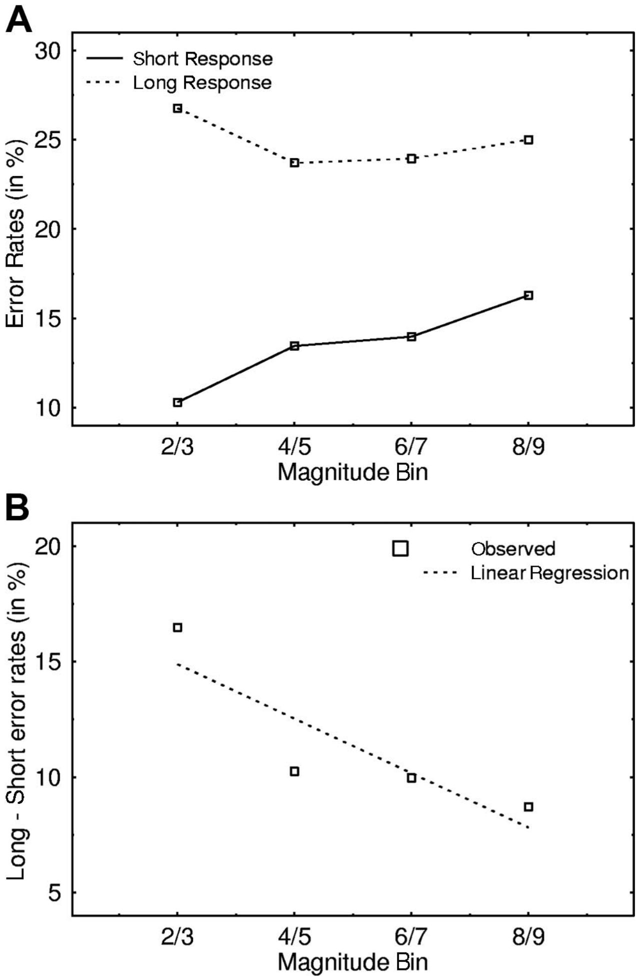

Figure 2. A: Mean error rates (percentage) for short (solid line) and long (dotted line) responses as a function of magnitude bin. B: Observed long and short response differences (squares) of error rates (percentage) and regression of error rate differences on the magnitude bin (dotted line).

that is, responses with short and long durations. Our results are very similar to the classical SNARC effect. Congruency between number magnitude and response duration—for example, between small numbers and short response durations and between large numbers and long response durations—led to faster responses than did incongruency between number magnitude and response duration. Our results suggest a common cognitive code for time and digit magnitude on the response stage and thus establish a new effect we termed *TiNARC*, or the time–numerical association of response codes.

Our results extend recent research on the association of time and number magnitude. But whereas Xuan et al. (2007) observed an impact of number magnitude on the perception of time, we focused on the response stage of information processing. The present experiment revealed an effect of number magnitude on response selection, because number magnitude affected the time required to initiate a response and thus confirms previous studies that offered a similar conclusion for spatial responses (e.g., Gevers et al., 2006; Keus et al., 2005; Keus & Schwarz, 2005; Müller & Schwarz, 2007) or grip closing and opening responses (e.g. Andres, Davare, Pesenti, Olivier, & Seron, 2004).

In addition, the duration for which the response key was pressed was associated with the magnitude of the number. This indicates that in our experiment, not only response selection but also response execution was affected by the magnitude of the number presented. Similar findings have been reported for a magnitude–space association by Fischer (2003), who reported an association of number magnitude to response execution in a pointing task, and by Lindemann, Abolafia, Girardi, and Bekkering (2007), who reported a connection between number magnitude and grip responses. Together with our results, these findings indicate that number magnitude is connected not only to response selection but also to response execution.

The present results fit well to recent neurophysiological findings, which describe both number magnitude and spatial processing as functions of the parietal lobes (e.g., Hubbard, Piazza, Pinel, & Dehaene, 2005; Liu, Wang, Corbly, Zhang, & Joseph, 2006; Luo & Luo, 2007; Rusconi, Turatto, & Umilta, 2007). In addition, there is also evidence for the involvement of the parietal lobes in size judgments (Pinel, Piazza, Le Bihan, & Dehaene, 2004) and temporal processing (Bueti, Walsh, Frith, & Rees, 2008; Onoe et al., 2001).

Neurophysiological findings like these together with reported links between number magnitude and space (e.g., Dehaene et al., 1993; Keus & Schwarz, 2005) led to the recent proposal by Walsh (2003a, 2003b) that space, time, and quantity are all part of a generalized magnitude system located in the inferior parietal lobe. This theory not only is further sustained by findings suggesting a link between magnitude and time perception (Xuan et al., 2007) but also received support from Weger and Pratt (2008) and Santiago, Lupiáñez, Pérez, and Funes (2007), who both demonstrated a connection between time and space by showing that the concepts of past and future have a spatial association to the left and right sides, respectively. For example, in Santiago et al.'s experiment, participants were asked to judge whether words presented at the left or right of fixation referred to the past or future. For congruent trials in which word meaning and response side matched, that is, when a word referring to the future required a right-hand response or a word referring to the past required a left-hand response, RTs were faster than they were for incongruent trials.

Our findings are also in agreement with the idea of a generalized magnitude system (Walsh, 2003b), because they indicate that magnitude judgments lead to an automatic activation of time estimation. Future research will have to show whether there is one generalized system dealing with space, time, and number magnitude or whether there are separate modules that interact depending on the current task requirements. In summary, our findings indicate an association between number magnitude and the time dimension on response selection and execution and thus support the idea that magnitude, space, and time are connected by a common code for action.

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