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SHORT REPORT

Self-motion perception influences number processing: evidence from a parity task

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Abstract We investigated the role of horizontal body motion on the processing of numbers. We hypothesized that leftward self-motion leads to shifts in spatial attention and therefore facilitates the processing of small numbers, and vice versa, we expected that rightward self-motion facilitates the processing of large numbers. Participants were displaced by means of a motion platform during a parity judgment task. We found a systematic influence of self-motion direction on number processing, suggesting that the processing of numbers is intertwined with the processing of self-motion perception. The results differed from known spatial numerical compatibility effects in that self-motion exerted a differential influence on inner and outer numbers of the given interval. The results highlight the involvement of sensory body motion information in higher-order spatial cognition.

Keywords Mental number line · Body motion · Number processing · Numerical cognition · Vestibular interaction · Spatial attention

Introduction

In Western cultures, small numbers are cognitively represented in the left and large numbers in the right side of space (Hubbard et al. 2005; Fias and Fischer 2005). The small-left and large-right association has been shown to affect performance in spatial and numerical tasks and gave rise to the concept of the mental number line. For example, small numbers are faster responded to with left-sided responses, and large numbers with right-sided responses, as described by the SNARC (spatial numerical association of response codes) effect (Dehaene et al. 1993). Moreover, leftward or rightward shifts of spatial attention influence the processing of small or large numbers (Loftus et al. 2008; Rossetti et al. 2004; Gobel et al. 2006; Zorzi et al. 2002). Interestingly, shifts of spatial attention can be evoked by body motion (Figliozzi et al. 2005), and, consequently, the direction of body motion has been found to influence numerical cognition. Loetscher et al. (2008) asked participants to generate random numbers while they turned their head alternately to the left and to the right side. The authors found that small numbers were generated more often during leftward than during rightward head turns. In the same vein, Hartmann et al. (2011) found that verbally presented small numbers were responded to faster during leftward than during rightward passive whole-body motion in a magnitude judgment task (Experiment 2). These results suggest that the direction of body motion shifts attention along the mental number line and can therefore interact with higher-order processing of numerical information. The findings by Hartmann et al. (2011) raise an important question: Is there an automatic association between self-motion perception and number processing? In their study, participants were asked to categorize numbers as smaller or larger than five. Thus, magnitude information was relevant in order to correctly categorize the numbers. Moreover, one could assume that in this task, numbers smaller than five are mapped to the left, and numbers larger than five to the right side of space (Gevers et al. 2006) and that this spatial mapping contributes to the interaction between number

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magnitude and self-motion direction. The aim of the present study was to investigate whether horizontal self-motion information influences number processing when magnitude information is irrelevant to the task and without inducing any small/large spatial mapping of numbers by the task itself. We designed a parity task in which participants were asked to categorize numbers as quickly as possible as odd or even. If self-motion and numerical information are linked in a more automatic manner, we would expect effects similar to those found for the magnitude judgment task (Hartmann et al. 2011).

Another aim of this study was to more thoroughly assess the influence of self-motion direction on number processing. In the magnitude judgment task, responses to numbers with a close numerical distance to the reference number are usually slower because these numbers are more difficult to discriminate when compared to numbers with a larger numerical distance (Moyer and Landauer 1967). Self-motion direction influenced the processing of numbers that are closely represented to the reference number five but had no influence on the outer numbers (Hartmann et al. 2011). It remained an open question whether the processing of numbers is influenced by self-motion direction only then when the numerical judgment involves a certain level of difficulty. In the parity judgment task that we used in the present study, the difficulty of a numerical judgment was not confounded with numerical distance. Therefore, we can test the hypothesis whether task difficulty is a critical factor for the interaction with self-motion direction, or whether the previous results reflected a rather task-independent influence of self-motion direction on number processing.

Methods

Twenty-four undergraduate students participated in this study (12 female). The mean age was 26.8, ranging from 20 to 33. Translational (linear) motion stimuli were generated by means of a motion platform (6DOF2000E, MOOG Inc., East Aurora, NY, USA). We used single-cycle sinusoidal acceleration motion profiles (Grabherr et al. 2008). Each motion stimulus displaced the participant leftward or rightward by 0.3 m with a peak velocity of 0.3 m/s. The duration of each motion was 2000 ms. Peak velocity was reached 1000 ms after motion onset.

Participants were securely seated in a chair that was mounted on the motion platform (see Fig. 1 of Hartmann et al. 2011, for an image of the apparatus). Participants' head was restrained with fixation straps. Blindfold participants were asked to decide as fast as possible whether a number was even or odd. Responses were collected by means of two response buttons that participants held in their left and right hands. Numbers ("1", "2", "3", "4", "6", "7", "8", and "9") were verbally presented via headphones during either a leftward or a rightward motion. Number stimuli (500 ms) were presented 200 ms before peak velocity was reached. The next trial was triggered by the experimenter as soon as the response was given, and the previous motion had stopped. A variable inter-trial interval (2000–3000 ms) preceded the onset of the next motion stimulus. Leftward and rightward motion stimuli alternated.

Each participant performed two blocks. In one block, "even" had to be indicated with a left-hand response and "odd" with a right-hand response. In the other block, the response mapping was reversed. The order of the two blocks was counterbalanced across participants. In each block, each number was presented eight times during leftward and eight times during rightward whole-body motion, resulting in a total of 256 trials per participant. Numbers were presented in random order with the only limitation that the same number was not presented more than twice consecutively.

Results and discussion

Inaccurate trials (2.44 %) and RTs that deviated more than 2.5 SDs from the individual mean (0.73 %) were excluded from the analysis. SNARC effects are usually indicated by a negative linear relationship between dRT (right-handed response–left-handed response) and number magnitude (e.g., Dehaene et al. 1993; Gevers et al. 2003; Pinhas et al. 2011). In line with previous studies, there was a significant negative linear trend of dRT as a function of number magnitude as revealed by repeated measures analysis of variance (ANOVA),[1] $F(1, 23) = 32.61$, $p < 0.001$, $\eta_p^2 = 0.586$, see Fig. 1a. The mean standardized linear regression slope was -0.35.

In order to analyze the influence of self-motion direction on number processing, we computed the same ANOVA for dRT defined as RT during rightward motion−RT during leftward motion (independent of response hand). There was no linear trend, $F(1, 23) = 0.18$, $p = 0.676$, $\eta_p^2 = 0.01$. However, there was a significant cubic trend, $F(1, 23) = 6.49$, $p = 0.018$, $\eta_p^2 = 0.22$, indicating that self-motion direction interacted systematically with number magnitude, see Fig. 1b. Particularly, the hypothesized negative linear relationship is present within the inner numbers ("2", "3", "4", "6", "7", "8") but is disrupted

[1] Spatial numerical association of response codes effects are usually indicated by a negative regression slope of dRT as a function of numbers whereby individual regression slopes are tested against zero by means of a simple *t* test. In the present report, we analyzed linear (and cubic) effects within the framework of repeated measures ANOVA as suggested by (Pinhas et al. 2011).

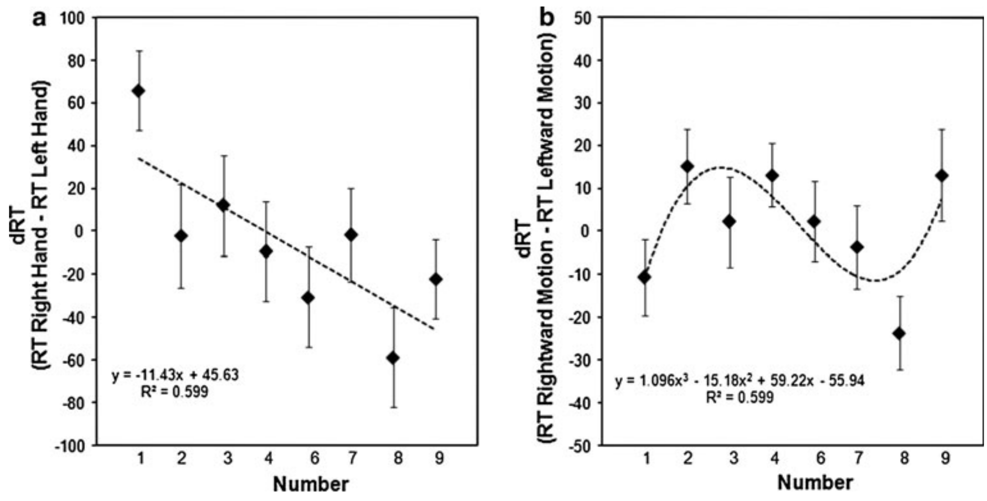

Fig. 1 **a** Classical SNARC effect with difference in response time (dRT) defined as RT right hand–RT left hand. The *dotted line* represents the typical negative relationship between dRT and number magnitude. *Right panel* **b** effect of self-motion direction on number processing with dRT defined as RT during rightward motion–RT during leftward motion. The *dotted line* represents the cubic relationship between dRT and number magnitude. *Error bars* depict ± 1 SEM

by the two outer numbers "1" and "9". Accordingly, the typical negative linear relationship between dRT and number magnitude becomes significant when the outer numbers ("1", "9") are excluded from the analysis, $F(1, 23) = 7.22$, $p = 0.013$, $\eta_p^2 = 0.23$, mean standardized linear regression slope = − 0.17.

These analyses point out two important findings. First, motion direction influenced the processing of numbers in a parity judgment task. We found a SNARC-like effect for the inner numbers whereby the processing of relative small numbers was facilitated during leftward self-motion, and the processing of relative larger numbers was facilitated during rightward self-motion. These results are in line with previous findings (Loetscher et al. 2008; Hartmann et al. 2011) and support the idea that self-motion leads to shifts in spatial attention (Figliozzi et al. 2005), thus influencing the processing of numbers. Particularly, we were able to demonstrate an interaction between self-motion direction and number magnitude in a task where magnitude information was not relevant and where a spatial mapping of small and large numbers was not encouraged by the task. Our results therefore suggest a rather automatic link between self-motion and numerical information, which is not instilled by the task demands. These findings provide further support for shared mechanisms involved in numerical cognition and self-motion perception (see Hartmann et al. 2011, for a discussion).

Second, our analyses show that the effect of self-motion direction is different from the classical SNARC effect. While the SNARC effect shows the largest difference between left-handed and right-handed responses for the outer numbers of a given interval, this was not true for the effect of self-motion direction. Leftward self-motion did not facilitate the processing of the smallest number, and rightward motion did not facilitate the processing of the largest number. The resulting function of dRT showed the same shape as for the magnitude judgment task (Hartmann et al. 2011).[2] However, unlike in the magnitude judgment task, these outer numbers are not characterized by a less difficult numerical discrimination and faster RTs (mean RTs for the outer and inner numbers: $M_1 = 664$, $M_9 = 655$, $M_{2\text{-}8} = 638$). Therefore, the interaction between self-motion and number processing is not determined by task difficulty. These results favor a task-independent influence of self-motion direction on number processing. The egocentric reference frame that underlies the mental number line (Conson et al. 2009) could provide a conceivable explanation for the differential effect of self-motion on inner and outer numbers. The mental number line is bound to body-centered coordinates. Therefore, the endpoints of the mental number line are remote and only numbers that are represented closely to the mid-number are susceptible to shifts in spatial attention elicited by self-motion.

Conclusion

In this study, we investigated the role of self-motion perception on the processing of numbers. We provide new evidence that self-motion direction influences the processing of numbers even when number magnitude is irrelevant for task performance. These results suggest a close link between the processing of self-motion and numerical information. The results highlight the important role of sensory self-motion cues in the allocation of spatial attention and especially in higher-order cognition.

[2] Note that the outer numbers in this study ("1" and "9") where not the same as those used in the previous study ("2" and "8"). This suggests that the observed pattern of dRT represents an influence of self-motion direction on the outer numbers of a given interval.

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