Vision Research 130 (2017) 85–96

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

The SNARC effect in two dimensions: Evidence for a frontoparallel mental number plane

Philipp Nikolaus Hesse *, Frank Bremmer

Neurophysics, Philipps-Universität Marburg, Marburg, Germany

ARTICLE INFO

Article history:
Received 4 August 2016
Received in revised form 10 October 2016
Accepted 11 October 2016
Available online 18 December 2016

Keywords:
SNARC
Saccade
Mental number line
Frontoparallel mental number plane
Modality dependent

ABSTRACT

The existence of an association between numbers and space is known for a long time. The most prominent demonstration of this relationship is the spatial numerical association of response codes (SNARC) effect, describing the fact that participants' reaction times are shorter with the left hand for small numbers and with the right hand for large numbers, when being asked to judge the parity of a number (Dehaene et al., J. Exp. Psychol., 122, 371–396, 1993). The SNARC effect is commonly seen as support for the concept of a *mental number line*, i.e. a mentally conceived line where small numbers are represented more on the left and large numbers are represented more on the right. The SNARC effect has been demonstrated for all three cardinal axes and recently a transverse SNARC plane has been reported (Chen et al., Exp. Brain Res., 233(5), 1519–1528, 2015). Here, by employing saccadic responses induced by auditory or visual stimuli, we measured the SNARC effect within the same subjects along the horizontal (HM) and vertical meridian (VM) and along the two interspersed diagonals. We found a SNARC effect along HM and VM, which allowed predicting the occurrence of a SNARC effect along the two diagonals by means of linear regression. Importantly, significant differences in SNARC strength were found between modalities. Our results suggest the existence of a *frontoparallel mental number plane*, where small numbers are represented left and down, while large numbers are represented right and up. Together with the recently described transverse mental number plane our findings provide further evidence for the existence of a three-dimensional *mental number space*.

1. Introduction

Number representations in the human brain "interact" with spatial representations in a characteristic way. As an example, digits induce a bias to the left for small numbers and to the right for large numbers, when subjects freely chose to press a left or a right button as a response to their visual presentation (Daar & Pratt, 2008). The strong link between numbers and space in the human brain can also be deduced from findings showing that number and magnitude perception is modulated during saccadic eye movements (e.g. Binda, Morrone, and Bremmer (2012), Binda, Morrone, Ross, and Burr (2011), Irwin and Thomas (2007)). Similar modulations have been described for the perception of space and time (Burr, Ross, Binda, & Morrone, 2010).

The most frequently used example for the link between numbers and space is the SNARC effect (spatial numerical association of response codes). Dehaene, Bossini, and Giraux (1993) showed that human subjects have shorter reaction times to the left for small numbers and to the right for large numbers, when judging number-parity with button-presses using the left and right hand. In general, the SNARC effect is seen as an indication of the concept of the *mental number line* (MNL) which states that humans organize numbers on a mental line with small numbers on the left and large numbers on the right.

Since its discovery, numerous follow-up studies on the SNARC effect have aimed to determine experimental parameters and cognitive settings causing or modulating it. The SNARC effect has been shown for different effectors such as manual responses (Dehaene et al., 1993), unimanual pointing responses (Bingley & Heath, 2011; Fischer, 2003), saccadic eye movements (Schwarz & Keus, 2004) and pedal responses (Schwarz & Müller, 2006). These findings implied that the SNARC effect might be effector-independent. A recent study, investigating the SNARC effect in different effectors (eye, arm, and finger) in the same subjects, however, provided evidence that this most likely is not the case (Hesse, Fiehler, & Bremmer, 2016).

The SNARC effect has been reported for stimulus sets being different from Arabic digits, such as written number words, dice

* Corresponding author at: AG Neurophysik, Karl-von-Frisch-Straβe 8a, 35032 Marburg, Germany.
E-mail address: Philipp.Hesse@physik.uni-marburg.de (P.N. Hesse).

http://dx.doi.org/10.1016/j.visres.2016.10.007
0042-6989/

patterns, or spoken number words (Nuerk, Wood, & Willmes, 2005). Based on these and related findings, the SNARC effect was suggested to be amodal, i.e. independent of the stimulus modality. If this was indeed the case, it would imply that the strength of the SNARC effect should be similar (if not identical) regardless of whether stimuli were visual or auditory. On the other hand, recent research has shown, that visual numerical information is processed in the so called number form area (NFA) while auditory information is not (e.g. Grotheer, Ambrus, and Kovács (2016); see Merkley, Wilkey, and Matejko (2016) for a review on NFA). Hence, such differences in number processing might lead to modality-dependent differences in SNARC effect strength. Accordingly, results from the literature were inconclusive concerning the outcome to be expected from our experiment.

In addition to the above mentioned effects, the SNARC effect has been shown for both cardinal axes in a frontoparallel plane with bi- and unimanual button presses (Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006; Hartmann, Gashaj, Stahnke, & Mast, 2014; Holmes & Lourenco, 2011, 2012; Ito & Hatta, 2004; Shaki & Fischer, 2012) and saccadic eye movements (Schwarz & Keus, 2004) with a preference for large numbers at the top and small numbers at the bottom.

One important aspect concerning a SNARC effect along the vertical axis concerns the response mode: in some of these studies (Gevers et al., 2006; Holmes & Lourenco, 2011; Ito & Hatta, 2004 (Exp. 1); Shaki & Fischer, 2012) responses for the "vertical" axis were measured with button presses on a computer keyboard which was ordinarily placed on a table. Hence, the responses were given in the transverse plane (on the mid-sagittal axis) and could alternatively be described as "near" and "far" rather than as "down" and "up" (see Hartmann et al. (2014), Holmes and Lourenco (2011, 2012), Winter, Matlock, Shaki, and Fischer (2015), for the same issue). In addition to the studies listed above the SNARC effect in depth has also been shown by Chen, Zhou, and Yeh (2015). In this study, the response latencies along the sagittal axis for "near" positions were shorter for small as compared to large numbers. In line with a SNARC effect, the opposite was true for large numbers. Other studies which investigated a vertical SNARC effect by means of responses along the vertical axis found differences in strength of the SNARC effect. For saccadic eye movements a strong vertical SNARC effect was found (Schwarz & Keus, 2004). For button presses along the vertical axis a significant SNARC effect was reported by Hartmann et al. (2014, Exp. 1). In contrast to these findings, Holmes and Lourenco (2011, 2012) reported a significant vertical SNARC effect with manual responses only when subjects were "primed" with vertical numerical magnitude (e.g. levels in a building). In this study, participants were told to think of numbers as floors in a building, levels of depth in a swimming pool or items on a shopping list. In the latter condition (shopping list) and for "unprimed" subjects Holmes and Lourenco found no significant vertical SNARC effect for.

Gevers et al. (2006) and Holmes and Lourenco (2011), Holmes and Lourenco (2012) investigated the SNARC effect also along diagonal axes. Both studies found a strong SNARC effect along one diagonal axis (named "right-diagonal" or "congruent diagonal") that required responses to up-right and down-left. Along the other diagonal axis ("left-diagonal" or "incongruent diagonal") that required responses to up-left and down-right, no SNARC effect was found. The observation that no SNARC effect was found along the "left-diagonal" has been explained by Gevers and colleagues by the fact, that along this diagonal two incongruent "categories" were activated: For example, reaction times on number "1" should be shorter for responses to the left and to the bottom. When investigating the "left-diagonal" participants' reaction times to "left up" could be shorter due to congruence with "1" and "left", but participants' reaction times could also be shorter to "right down" due to congruence with "1" and "down", hence resulting in no advantage for any response-direction. In contrast, Holmes and Lourenco interpreted their results as evidence that there would be no (or only rare) *spontaneous vertical organization of numbers*. They assumed that any vertical SNARC effects would therefore be a result of a kind of "overrulement" of the horizontal SNARC effect.

The above mentioned studies do have in common that subjects were only tested for a SNARC along the cardinal or the diagonal axes. Accordingly, it was impossible to infer subjects' performance along the diagonal axes from their performance along the cardinal axes. Consequently, in our study, we measured the SNARC effect along four axes (horizontal, vertical and both diagonals) within the same participants, which allowed us to predict the subjects' behaviour for responses along the diagonals from their own behaviour as obtained from responses along the cardinal axes and to compare it with our observations. Our data clearly show that the SNARC effect along the diagonal axes can be described as a linear combination of the participants' SNARC behaviour along the cardinal axes. Our results provide further evidence for the idea of a frontoparallel SNARC plane and, ultimately, the idea of a frontoparallel mental number plane (MNP). Furthermore, we found significant differences in the SNARC effect between auditory and visual stimulus presentation modality, indicating that the SNARC effect might not be strictly amodal.

2. Methods

2.1. Participants

A total of 28 participants (11 male) aged between 20 and 31 (mean 25) were recruited from the university population. All participants had normal or corrected to normal vision and were native German speakers. Participants' handedness was no control variable in our study. This was since (i) it is known that handedness has no influence on the SNARC effect (Dehaene et al., 1993) and (ii) participants had to respond with an eye rather than a hand movement. While an influence of handedness has been demonstrated for horizontal, leftward vs. rightward saccades (Hutton & Palet, 1986), this modulatory influence would have been independent from the magnitude of the stimulus (number) and, hence, independent from the SNARC effect. They performed two SNARC-like tasks, adapted for two modalities (*auditory* and *visual*). All subjects except one (author PNH) were naïve to the purpose of the study and were compensated with 6 € or 8 € per hour (compensation was increased over data collection time for external reasons) for participation. After completing the full experiment each interested participant was given full disclosure concerning the goal of the experiment. Participants provided written informed consent before commencing the experiment and all procedures were approved by the local ethics committee and were in agreement with the Declaration of Helsinki.

2.2. Setup

Experiments were performed in a dark and sound attenuated room. Participants sat on a chair resting their head on a chin rest, placed centrally in front of a projection screen. The distance between the screen and the participant's eyes was 70 cm. The screen was a 120 cm (81°) wide and 90 cm (65.5°) high. All visual stimuli were back-projected on this screen by a video-projector (Christies DS+6K-M, Christie Digital Systems Canada Inc., Kitchener, Canada). The resolution of the screen was set to 1152 × 864 pixels and the refresh rate to 60 Hz. Participants' binocular eye positions were recorded with an EyeLink II (SR Research Ltd., Ottawa, Canada) at a sampling rate of 500 Hz. Both eyes were calibrated separately.