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THE REPRESENTATION OF NUMB3RS IN SPACE:

A JOURNEY ALONG THE MENTAL NUMBER LINE

Dissertationsschrift

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Für meine Familie.
Mams, Pams und Rike.

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CHAPTER 1

INTRODUCTION:
THE MENTAL REPRESENTATION OF NUMB3RS

> Numbers constitute the only
> universal language.
>
> Nathanael West

The mental representation of numbers: A short overview

Animals as well as humans are required to represent numerosities which help them to understand and communicate environmental facts. For example, it is essential for a bird to know its number of chicks to pick up enough food. Or consider a fight-or-flight situation in which animals have to compare the number of their flock with the number of enemies. We also deal with numerical magnitude in everyday life, for example, when buying some food. In this case we have to compare the money we currently have available to the cost of a delicious sandwich. But how are numbers mentally represented? Do animals and humans share common mechanisms of representing numbers?

In their seminal paper, Moyer and Landauer (1967) asked participants to compare digit pairs. The authors found that the larger the distance between the two digits the faster participants reacted; and they also made fewer errors. This effect has been labelled the *distance effect*. Another effect typically seen in number comparison tasks is the *magnitude effect*: for a given distance the time to compare two digits increases with the magnitude of the digit pair (i.e., the digit pair 1–2 is compared faster than the digit pair 8–9). The distance effect and the magnitude effect led to the conclusion that numbers are represented on a *mental number line* along which they are ordered in a continuous and analogical manner (Dehaene, 1997; Restle, 1970; see also Schwarz & Ischebeck, 2003). The representation of numbers along a mental number line, though, seems not unique to humans. The distance effect and the magnitude effect are also found for a wide range of animals such as salamanders, pigeons, dolphins, and monkeys (Brannon & Terrace, 1998; Dehaene, Molko, Cohen, & Wilson, 2004; Gallistel & Gelman, 2000; Piazza & Dehaene, 2004). Thus, animals are able to discriminate numerosities like humans (even spontaneously; Hauser, Dehaene, Dehaene-Lambertz, & Patalano, 2002). Chimpanzees even seem to be able to represent ordinal meanings of numerals (Biro & Matsuzawa, 1999, 2001). Furthermore, infant studies showed that infants as young as five months can discriminate different numerosities (Wynn, Bloom, & Chiang, 2002; see also Brannon, 2002; Xu & Spelke, 2000). These findings led to the conclusion that the mental representation of numbers is an inherited evolutionary primitive (Brannon, 2002; Gallistel & Gelman, 1992). Additionally, they also support the notion that the mental conceptualisation of numbers exists well before the acquisition of spoken or written language. In line with this Pica, Lemer, Izard, and Dehaene (2004) reported that members of the Mundurukú who only have a limited counting system (from one to five) are able to mentally represent larger numerical magnitudes up to 80. Hence, it was concluded that “sophisticated numerical competence can be present in the absence of a well-developed lexicon of number words” (Pica et al., 2004, p. 503; see also Gelman & Gallistel, 2004; Gordon, 2004). Similarly, Gelman and Butterworth (2005, p. 9) state: “It would be surprising if there were no effects of language on numerical cognition, but it is one thing to hold that language facilitates the use of numerical concept and another that it provides their causal underpinning”. In sum, animals and humans share a “number sense” (Dehaene, 1997) which provides a basic understanding of numerosity.

But how are numbers actually represented along this mental number line? Two possible forms of the mental number line have been proposed: a mental number line which is logarithmically compressed and a mental number line based on scalar variability (see e.g., Feigenson, Dehaene, & Spelke, 2004). Along a number line with scalar variability numbers are linearly represented but the variability of the mental activation a number evokes increases as its magnitude increases (fuzzy magnitudes; Gallistel & Gelman, 2000; Brannon, Wusthoff, Gallistel, & Gibbon, 2001; see Figure 1a). Along a logarithmically compressed mental number line the distance of two numbers logarithmically decreases as their magnitude linearly increases (Dehaene, 2001, 2003; see Figure 1b).

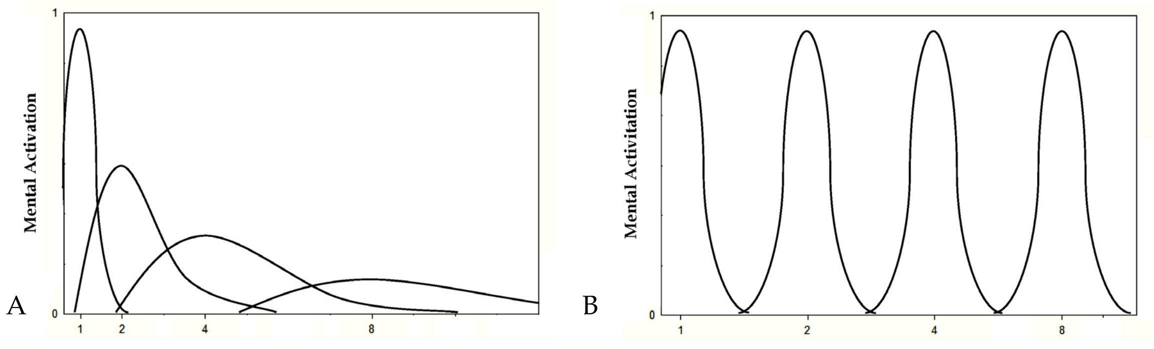

Figure 1
Models of the mental number line. Both models make the same behavioural predictions such as the distance effect and the magnitude effect. The graphs show the mental activation as functions of the digits 1, 2, 4 and 8.

a. Linear mental number line with scalar variability: the distances between digits are equal but the variability increases as the size of the digits increases.
b. Logarithmic compressed mental number line: the distances between the digits logarithmically decrease as the size of the digits increases; the variability is fixed. According to this view the performance in comparison tasks depends on the ratio between the two digits following the Weber-Fechner Law (Dehaene, 2003).

At present, it this still a matter of debate which of the two possible forms of the mental number line might best explain empirical findings. Brannon and her colleagues (2001) trained pigeons to compare a standard number with the difference of two other numbers. Their results clearly favored a linear mental number line. For rats the trial–to–trial variability of button presses increases as the number of required presses to get food increases; this finding also supports the assumption of a linear representation of numbers (see Gallistel & Gelman, 2000, for an overview). On the other hand, Nieder and Miller (2003) measured the firing rate of single cells in the prefrontal cortex of monkeys and found that the activity can be best described by a logarithmically compressed mental number line. One possible explanation for these controversial findings might be that numbers are represented along a logarithmically compressed as well as a linear mental number line. The access to one of these mental number lines might, then, be determined by the specific task requirements (Brannon et al., 2001). For example, Siegler and Opfer (2003) observed in a number–to–position task and position–to–number task that up to the fourth grade children represent digits on a logarithmically compressed mental number line whereas results of older children point to the utilization of a linear mental number line. The authors concluded, similar to Brannon et al. (2001), that we might "utilize multiple numerical representations" (Siegler & Opfer, 2003, p. 242).

Neuroanatomical correlates of the mental number line

The most promising candidate area within the human brain to host a representation of numerical quantity and the mental number line lies within the parietal cortex; specifically, the horizontal segment of the intraparietal sulcus (HIPS; see Dehaene, Piazza, Pinel, & Cohen, 2003, 2005; Dehaene et al., 2004; Göbel & Rushworth, 2004 for summaries). When participants compare two digits or perform simple arithmetic tasks the activity of the HIPS is larger compared to when participants just name the specific digits (Chochon, Cohen, van de Moortele, & Dehaene, 1999). Moreover, the activity of the parietal area was found to increase as the numerical distance of two digits decreases, independent of the notation of the digits (Pinel, Dehaene, Rivière, & Le Bihan, 2001; see also Kaufmann et al., 2005; Pinel, Piazza, Le Bihan, & Dehaene, 2004; Sandrini, Rossini, & Miniussi, 2004). A distance effect was also observed in electrophysiological recordings in the vicinity of this area in 5–year–olds and adults (Temple & Posner, 1998).

The activation of the HIPS was also found to be category specific: it is more activated when participants perform number–related tasks rather than tasks on other non–numerical categories of objects, such as animals (Thioux, Pesenti, De Volder, & Seron, 2002). Additionally, neuropsychological case studies revealed that even small parietal lesions can cause severe problems in numerical tasks (see Dehaene & Cohen, 1995). Taken together, the "HIPS codes the abstract meaning of numbers rather the numerical symbols themselves" (Dehaene et al., 2003, p. 492).

Similar to humans, in monkeys' parietal activation was also observed to be sensitive to numerosity (Sawamura, Shima, & Tanji, 2002). Nieder and Miller (2004) recorded single-cell activity in different brain areas while monkeys performed a number comparison task. The authors found high rates of numerosity-selective neurons in the intraparietal sulcus; the neurons "discharged maximally to a preferred numerosity" (Nieder & Miller, 2004, p. 7458). Patterns of chronometrically later activity were recorded in the prefrontal cortex, indicating that a wider parieto-frontal network is responsible for the manipulation of numerosity (see also Nieder, 2004; Nieder, Freedman, & Miller, 2002). Hence, Nieder and Miller (2004) suggest that the intraparietal sulcus is responsible for the early extraction of visual quantity. Piazza, Izard, Pinel, Le Bihan, and Dehaene (2004) observed quite analogous tuning curves in the human HIPS while participants performed a number comparison task. The similarity of activation patterns in monkeys and humans indicate that both share common mechanisms for the representation and manipulation of numerical information (Nieder, 2004, 2005). Thus, humans seem to have an "evolutionary basis for [..] elementary arithmetic" (Piazza et al., 2004, p. 547).

The spatial orientation of the mental number line: The SNARC effect

The spatial representation of numbers has been first described by Francis Galton in 1880. He reported that some adults represent numbers in a visuo-spatial fashion, such as seen in Figure 2a (Galton, 1880a,b; see also Sagiv, Simner, Collins, Butterworth, & Ward, 2006; Seron, Pesenti, Noël, Deloche, & Cornet, 1992).

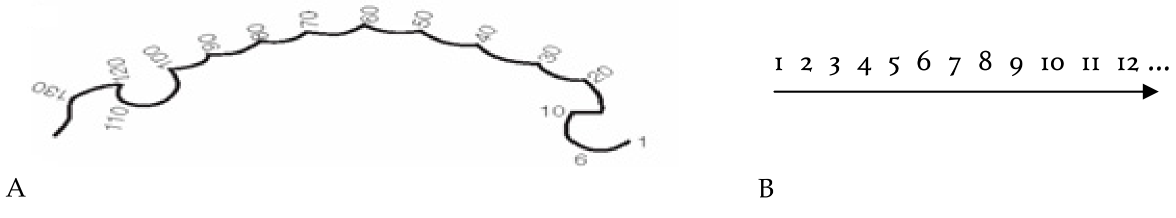

Figure 2

a. Visualized numerals found by Galton (1880a). Some normal adults reported and demonstrated that they perceive numbers as visual forms.
b. Sagiv et al. (2006) reported that 60 % of grapheme-color synaesthetes and about 10 % of non-synaesthetes report number forms. Most of those reported number forms run from left to right, mostly as a straight line.

About a century later the association of numbers and space was experimentally examined: Dehaene, Bossini, and Giraux (1993) described the *Spatial Numerical Association of Response Codes (SNARC) effect.* In the standard experiment the authors asked participants to indicate the parity status of visually presented digits ranging from zero to nine by pressing a left or right button. Participants exhibited faster left–hand responses to smaller numbers and faster right–hand responses to larger numbers compared to the reversed mapping (see Figure 3). The numerical magnitude, although task irrelevant, was automatically activated and provided a spatial code: small numbers are represented on the left side and large numbers are represented on the right side of the mental number line. Put differently, the SNARC effect suggests that the mental number line is spatially oriented from left–to–right.[1]

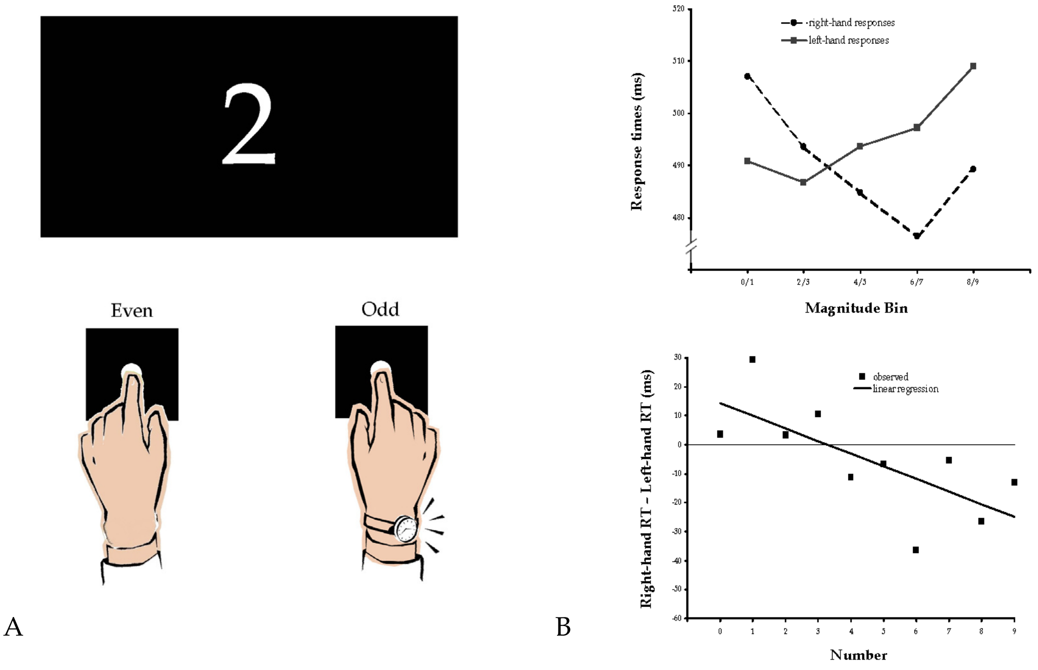

Figure 3

a. Schematic presentation of a typical parity–judgment task to induce the SNARC effect. Participants are asked to indicate the parity status of a digit (ranging from 0 to 9) by pressing a left or right button. In this case, the digit 2 is presented and the participant should correctly press the left button. In a second session, the mapping of parity–to–button would change; thus, the participants should correctly press then the right button. Together, for each digit we could obtain a left and a right hand key press.

b. Typical finding in a SNARC experiment. For smaller digits responses with the left hand are faster than responses with the right hand. For larger digit responses with the right hand are faster than responses with the left hand. A usual way to illustrate this association of numbers and space is to regress, for each participant, the difference of right hand responses and left hand responses on the numerical magnitude. The mean slope is, then, an effective and sensitive index of the SNARC effect.

Further evidence for the automatic activation of the numerical magnitude and, thus, spatial codes comes from even less mandatory tasks such as phoneme monitoring.

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[1] The standard mental number line seems to run from left to right and is observed in most of the participants. Naturally, there might be individual expectations such as described by Galton (1880a) and seen in Figure 1a.

Fias, Brysbaert, Geypens, and d'Ydewalle (1996) asked participants to indicate whether the number word of presented Arabic digits contains an /e/. Again, a SNARC effect obtained although participants performed a strictly non-numerical task. Similarly, Fias, Lauwereyns, and Lammertyn (2001) found a SNARC effect when participants determined the orientation of triangles or lines which were superimposed on digits. Fischer, Castel, Dodd, and Pratt (2003) observed a spatial-numerical association in a target-detection task. Targets which appeared on the associated spatial side of a preceding number were detected faster than targets presented on the other side. For example, the presentation of the digit one (nine) causes a shift in spatial attention to the left (right) side. The authors concluded that the "mere observation of numbers obligatorily activates the spatial representations associated with number meaning" (Fischer et al., 2003, p. 556). The automatic activation of numerical magnitude information is independent of the format in which numbers are presented. For example, in a parity-judgment task Nuerk, Wood, and Willmes (2005) observed a SNARC effect when numbers were presented auditory, as Arabic digits, as number words and as dice patterns.

Neuroimaging and neuropsychological studies indicate that the parietal cortex is crucially involved in spatial processing (see Andersen, Snyder, Bradley, & Xing, 1997; Colby & Goldberg, 1999; Hubbard, Piazza, Pinel, & Dehaene, 2005 for overviews). Given the involvement of the parietal cortex in the internal quantity representation of numbers, it has been concluded that "these numerical-spatial interactions arise from common parietal circuits for attention to external space and internal representation of numbers" (Hubbard et al., 2005, p. 435). This conclusion is further supported by evidence from neglect patients.[2] Zorzi, Priftis, and Umiltà (2002) asked neglect patients with a spatial deficit for the left side to indicate the midpoint of number intervals (e.g., 11-19). They observed that the patients shifted the midpoint to the right (for 11-19, midpoint = 17) the more the interval-size increased. The authors interpreted this finding to indicate a left-to-right ordering of numbers (see also Zorzi, Priftis, Meneghello, Marenzi, & Umiltà, 2006). The results of Zorzi et al. (2002) further suggest that the mental number line extends to numbers greater than nine. In line with this, Dehaene et al. (1993) reported a tendency for faster left-hand responses to small decade digits (e.g. 10s and 20s) and faster right-hand responses to larger digits (e.g., in the 80s and 90s; see also Dehaene, Dupoux, & Mehler, 1990; Brysbaert, 1995; Reynvoet & Brysbaert, 1999).

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[2] Patients suffering from neglect ignore one side of the space due to a lesion in the parietal lobe (Walsh & Darby, 1999).

A closely related research question is whether the spatial orientation of the mental number line also extends to negative digits. Fischer (2003a) observed faster comparison times to spatially correctly oriented negative digit pairs [−9 −4] compared to incorrectly oriented pairs [−4 −9]. This finding points to an extension of the mental number line to negative numbers. In contrast, Fischer and Rottmann (2005) observed that, in a parity-judgment task, the absolute value of negative digits induces a SNARC effect. For example, the digit −8 was responded to faster with the right hand and the digit −2 was responded to faster with the left hand (i.e., reversed SNARC effect for negative digits). Shaki and Petrusic (2005) investigated the SNARC effect in a digit comparison task with pairs of negative and pairs of positive digits and found that the SNARC effect varied as a function of the experimental setting. In a blocked (i.e., separated) presentation of negative and positive digit pairs a reversed SNARC effect was found for negative digits, indicating an inverse negative number line. Small negative digit pairs (e.g., −9 and −8) were responded to faster with the right hand and large negative digit pairs (e.g., −1 and −2) were responded to faster with the left hand. In contrast, for the intermixed condition (i.e., negative and positive digit pairs were presented within one given block) a SNARC effect, compatible with the notion of an extended number line, was found. Specifically, small negative digit pairs were responded to faster with the left hand and large positive digit pairs were responded to faster with the right hand. The conflicting results of studies, using negative digits, suggest that the processing of negative numbers is less automatic than that of positive numbers (Fischer & Rottmann, 2005) or that the extension of the mental number line to negative digits is influenced by the context (Shaki & Petrusic, 2005). Hence, the SNARC effect seems to reflect a flexible rather than rigid association of numbers to space. In line with this interpretation, Dehaene et al. (1993) observed another context-dependency of the SNARC effect. Responses to 4 and 5 were faster with the right hand when all digits displayed ranged from 0 to 5. However, in a range from 4 to 9, responses to the digits 4 and 5 were faster with the left hand. Bächtold, Baumüller, and Brugger (1998) asked participants to imagine the face of an analog clock. Here, left-hand responses were faster for large digits (e.g., digit 9) and right-hand responses were faster for small digits (e.g., digit 3). These two findings again point to the flexibility of the SNARC effect.

Many other studies examined and evaluated the nature of the SNARC effect. Most of these studies are closely related to our own studies and are, therefore, elaborated in more detail within the following chapters. For further comprehensive summaries concerning the SNARC effect see Fias and Fischer (2005), Gevers and Lammertyn (2005) as well as Hubbard and colleagues (2005).

An overview of the studies presented in this thesis

The present studies all deal with the exploration of the nature of the spatially oriented mental number line. More specifically, they aimed to examine the SNARC effect under specific conditions and task sets. The idea and motivation of the four studies will be shortly described in the following section.

Chapter 2: A comparison of manual and pedal responses

The first study deals with the question whether the spatial mental number line is ontogenetically or phylogenetically derived. According to an ontogenetic view the spatial orientation of the mental number line derives from the writing system the participants are adapted to. First evidence in support of this view comes from a study reporting a reversed SNARC effect for Iranian participant who are used to a right-to-left writing system (Dehaene et al., 1993). On the other hand, the SNARC effect might have a phylogenetic origin as animals as well as infants represent numbers along a mental number line. To evaluate these two interpretations we asked participants to perform a parity-judgment task with their hands as well as their feet. Under the condition that the SNARC effect is based upon the direction of writing, it should be limited to the effectors which are important to write (such as hands and eyes; see Schwarz & Keus, 2004 who observed the SNARC effect for eye movements) and should therefore not obtain with feet.

Chapter 3: The association of numbers to hands

Another issue concerning the SNARC effect is the question whether it is caused by an association of numbers to hand (i.e., spatio-anatomical mapping) or by an association of numbers to extracorporal space. To contrast these possible explanations Dehaene et al. (1993) initially asked participants to indicate the parity status of digits with crossed hands. Under this condition, smaller numbers were responded to faster with the left key which was pressed by the right hand. Larger numbers were responded to faster with the right key deflected by the left hand. The authors, therefore, concluded that the SNARC effect reflects an association numbers to extracorporal space (see also Tlauka, 2002). In the second study we evaluated this assumption again, and tested whether there are specific conditions under which numbers can be related to hands rather than to extracorporal space. To this end, participants indicated the parity status of digits by pressing vertically arranged buttons. Additionally, two different instructions were given. In the first experiment the location of the buttons was emphasized whereas in the second experiment the placement of the participants' hands was emphasized. In the third experiment we also asked participants to press horizontally arranged buttons with crossed and uncrossed hands (see Dehaene et al., 1993). Similar to the second experiment, the instruction emphasized participants' hands.

Chapter 4: Exploring the functional locus of the SNARC effect

The third study aimed to examine the functional locus of the SNARC effect. According to Sternberg (1969) stimulus processing can be subdivided into three serial processing stages, namely the perceptual encoding, central response-selection and motor execution. At the present date, studies obtained controversial results with regard to the locus of the SNARC effect. Fias et al. (2001) observed a SNARC effect when participants determined the orientation of triangles or lines superimposed on digits. In contrast, no SNARC effect obtained when participants indicated the color of digits. The authors concluded that the SNARC effect is linked to perceptual encoding. On the other hand, Fischer (2003b) obtained the SNARC effect for the movement time but not for the reaction time pointing to a late movement-related locus of the effect. Electrophysiological studies, again, suggest that the SNARC effect arises while the response is selected (Gevers, Ratinckx, De Baene, & Fias, 2006; Keus, Jenks, & Schwarz, 2005; Keus & Schwarz, 2005). We used the psychological refractory period paradigm (Pashler, 1998) to examine the functional locus of the SNARC effect. Participants are required to perform two tasks in rapid succession. In the first experiment participants first indicated the pitch of a tone and then the parity status of a digit (locus-of-slack paradigm). In a second experiment the order of tasks changed (effect-propagation paradigm). Given the central bottleneck model these paradigms allow clear conclusions with regard to possible loci of a specific effect (Miller & Reynolds, 2003).

Chapter 5: "1-2-3": The ordering of numbers on a temporal number line

The studies described before dealt with the exploration of the spatially oriented mental number line. As stated above, it is conceivable that the association of numbers and space could be facilitated because both dimensions are processed and represented in the parietal cortex. In his theory of magnitude (ATOM) Walsh (2003) pointed out that time is also partly processed in the parietal cortex. Therefore, he concluded that numbers and time might interact with each other as well. To test for such an association we asked participants to compare two serially presented digits. Participants had to indicate either the smaller or the larger of the two digits. It was hypothesized that an effect of temporal numerical order, that is temporally ascending digit pairs such as 2–3 might be responded to faster than temporally descending digit pairs such as 3–2, would point to a temporal mental number line. Moreover, the study aimed to test whether analogous effects, usually found with spatially arranged digit pairs, such as the SNARC effect and the numerical semantic congruity effect, can also be observed in the temporal domain.

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CHAPTER 2

SPATIAL ASSOCIATIONS IN NUMBER RELATED TASKS: A COMPARISON OF MANUAL AND PEDAL RESPONSES

Abstract

Bimanual parity judgments of numerically small (large) digits are faster with the left (right) hand (the SNARC effect; Dehaene, Bossini, & Giraux, 1993). According to one explanation, this effect is culturally derived and reflects ontogenetic influences such as the direction of written language; it might therefore be limited to, or at least be larger with, pairs of lateralized effectors which are instrumental to the production and comprehension of written language. We report two experiments which test for SNARC effects with pedal responses, and compare these effects to manual results. Pedal responses yielded highly systematic SNARC effects; furthermore, these effects did not differ from manual SNARC effects. These results argue against accounts in which the SNARC effect is specific for effectors that are habitually associated with the production or comprehension of written language.

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Introduction

In daily life we are surrounded by numbers which inform us about our environment and which help us to communicate relevant facts. Given the ubiquity of numbers in everyday life, much research has been conducted in the last two decades to examine the nature of human numerical cognition (for summaries, see Butterworth, 1999; Dehaene, 1997; Dehaene, Molko, Cohen, & Wilson, 2004; Piazza & Dehaene, 2004). One important finding related to how we represent numerosities is the so-called SNARC (Spatial Numerical Association of Response Codes) effect originally demonstrated by Dehaene, Bossini, and Giraux (1993). These authors asked participants to indicate the parity status (odd vs. even) of digits ranging from 0 to 9 by pressing a button with their left or right index finger; the parity-to-response mapping was varied across blocks of trials. Irrespective of this mapping, numerically large numbers were responded to faster with the right hand, whereas smaller numbers were responded to faster with the left hand; thus, numbers seem to be associated with spatial information. Note especially that the SNARC effect obtains even though numerical magnitude per se was not predictive of the correct response. Other experiments (Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; Fias, Lauwereyns, & Lammertyn, 2001; Gevers, Reynvoet, & Fias, 2003; Keus & Schwarz, 2005; Mapelli, Rusconi, & Umiltà, 2003; Schwarz & Keus, 2004) confirmed and extended this effect; for example, Fias et al. (1996) demonstrated a SNARC effect with mandatory tasks even less numerical such as phoneme monitoring.

A common opinion holds that the SNARC effect reflects a left-to-right ordering of numbers (Dehaene et al., 1993; Fischer 2003; Restle, 1970). This hypothesized left-to-right representation of numbers is often conceptualized as a mental number line (Dehaene, 1997; Restle, 1970) along which digits are represented in a continuous and analogical space-related manner, much like other extensive physical attributes such as length. Evidence for this concept of a mental number line comes, for example, from the numerical distance effect (Moyer & Landauer; 1967; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002): participants require less time (and show decreasing parietal activation; Pinel, Dehaene, Rivière, & Le Bihan, 2001) to determine the larger of two digits when the numerical distance of those digits increases.

Two major types of hypotheses have been advanced to explain the concept of a mental number line and, therefore, the SNARC effect. First, the acquisition of the mental number line might be influenced by the specific cultural context in which the participant was raised. Following Fischer (2003), we refer to this view as an *ontogenetic* interpretation. More specifically, the orientation of the mental number line and the SNARC effect might critically depend upon the direction of the writing system to which the participant is adapted. For example, Dehaene et al. (1993, p. 387) concluded that "the organization of the Western writing system has pervasive consequences on the everyday use of numbers" (for further elaboration, see Dehaene, 1997, p. 82). According to this view, the SNARC effect reflects the close relation between the left-to-right direction in which most Western languages are written and read and the way in which users of those languages tend to mentally represent linear orders. Evidence in support of the ontogenetic view comes from SNARC studies with Iranian participants (accustomed to a right-to-left writing system) who had recently immigrated into France (Dehaene et al., 1993; Experiment 7). These participants "presented a weaker or reversed association" (Dehaene et al., 1993, p. 387), with faster left (right) hand responses to larger (smaller) numbers. In contrast, Iranians who had lived in France for several years already "tended to associate large numbers with the right-hand side" (Dehaene et al., 1993, p. 387). Thus, Dehaene et al. reasoned that within a left-to-right writing system, numbers usually come to be represented in an increasing linear order from left-to-right. In support of this view, note that most computer keyboards, technical scales, and slide rulers are constructed in a corresponding fashion. Similarly, Bächtold, Baumüller, and Brugger (1998) demonstrated a reversed SNARC effect with manual responses when participants were asked to internally represent digits along the face of an analog clock. These authors reasoned that this reversal effect exploits our life-long experience with analog clocks: in contrast to, for example, the design of rulers, faces of circular clocks place small numbers (e.g., hour 3) on the right side whereas larger numbers (e.g., hour 9) are represented on the left. Finally, Dehaene et al. (1993; Experiment 3) showed that whether responses to intermediate digits such as 4 or 5 are faster with the left or the right hand depends on the numerical context in which these digits are presented. More specifically, right-hand responses to the digit 5 are faster in a context of 0 to 5 as compared to a context of 4 to 9 (for similar results, see Tlauka, 2002). Taken together, these results certainly suggest that the SNARC effect is dependent on context and culture to some degree. More specifically, the effect might be a specific characteristic of highly overlearned sensorimotor associations such as e.g. the ubiquitous mapping of relatively small (large) numbers to the left (right) hand. Therefore, the occurrence and size of the SNARC effect might depend on the specific response requirements. Such an effector-dependency would not at all be unprecedented: for example, the size of the classical Stroop effect – which is quite similar to the SNARC effect in a number of ways (cf. Mapelli et al., 2003) – is well-known to be much larger for verbal than for manual responses (MacLeod, 1991, pp. 182–183; White, 1969). It could be argued that the occurrence of a SNARC effect even with crossed hands (Dehaene et al., 1993, Exp. 6) argues against the existence of highly specific sensorimotor associations. This finding, as the one of Bächtold et al. (1998) reviewed above, certainly suggests that specific digits are not mapped onto a given hand in a fixed and immutable way, but it does of course not rule out an account in which the SNARC effect is intrinsically related to effector systems in general that are fundamental to the production of written language (see Schwarz & Keus, 2004, p. 653f., and Wascher, Schatz, Kuder, & Verleger, 2001, for a review of some open questions in the context of crossed-hand experiments).[1]

Alternatively, the mental number line might reflect a preverbal cognitive left-to-right representation of numbers, quite independent of the characteristics of written language, a hypothesis which Fischer (2003) referred to as the *phylogenetic* view. This view holds that the analogical representation of numbers exists before any writing competence or even verbal skills are acquired. In fact, evidence in support of a preverbal mental number line and elementary numerical knowledge derived from it has been found for infants and even animals. For example, pigeons, salamanders, rats, dolphins, and monkeys are able to discriminate among small numerosities of arbitrary objects (for summaries see Dehaene, 1997; Dehaene et al., 2004; Gallistel & Gelman, 2000) and do show a numerical distance effect (Brannon & Terrace, 1998; Gallistel & Gelman, 1992). Also, five-month old infants are able to discriminate numerosities (Wynn, Bloom, & Chiang, 2002) and already exhibit ordinal numerical knowledge (Brannon, 2002). Finally, children show a distance effect at least from the age of six (Rubinsten et al., 2002). Taken together, these results suggest that a mental number line exists well before the acquisition of any spoken, read or written language; therefore, the mental number line could be viewed as an inherited evolutionary primitive (Brannon, 2002; Gallistel & Gelman, 1992). In this view, the SNARC effect does not emerge from exposure to specific writing systems, but rather depends on a genuinely preverbal and space-related representation of numbers. According to this interpretation, the SNARC effect should then not be limited to effectors habitually associated with written language but should also be found with

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[1] A weaker interpretation of the ontogenetic view holds that whereas the directional characteristics of written language are, in a general sense, an important determinant of the SNARC effect, this does not necessarily imply that this effect is limited to the specific effector systems typically involved in writing or reading. We will consider this weaker interpretation of the ontogenetic view in more detail in our General Discussion.

other pairs of lateralized effectors (e.g., feet) as well that are completely unrelated to written language (for recent related evidence see Ito & Hatta, 2004).

One way to contrast these rivalling accounts of the SNARC effect is to vary the effector with which participants of a SNARC experiment are asked to respond. More specifically, if a SNARC effect shows up, for example, with manual, but not pedal, responses; then the "preverbal number-line" phylogenetic view would clearly be contradicted and falsified. In a related experiment, Schwarz and Keus (2004; see also Fischer, Warlop, Hill, & Fias, 2004) asked participants to indicate the parity status of a digit by executing eye movements to the left or right. A standard SNARC effect was observed, a result which in principle seems more in line with the phylogenetic hypothesis. However, this finding does not definitely rule out the ontogenetic hypothesis either as eye and hand movements tend to be highly correlated (cf. Milner & Goodale, 1995): we often visually monitor and guide our hands while, for example, writing or grasping; furthermore, we routinely move our eyes from left to right when reading written language. Therefore, the ontogenetic view might accommodate the Schwarz and Keus (2004) findings: after all, our eyes play a central role in comprehending written language and might have come to preferentially associate increasing linear orders with a left-to-right orientation. Hence, according to the ontogenetic view one could still assume that both the production (hands) and comprehension (eyes) of written language play a crucial role in the formation of the SNARC effect. Therefore, it remains as yet a largely open question whether the SNARC effect critically depends on our intimate familiarity with left-to-right notational systems, or whether it is a consequence of our preverbal space-related number representation.

The present article aims to distinguish between these different explanations of the SNARC effect. As in previous experiments, participants indicated the parity of visually presented digits ranging from 0 to 9 (cf. Dehaene et al., 1993). As explained above, one way to contrast the two hypotheses is to ask participants to indicate their parity decisions with lateralized effectors which are unrelated to the production or comprehension of written language. Specifically, we asked participants to indicate the parity of digits by deflecting pedals with their feet. According to the strong ontogenetic view which assumes an acquired effector-dependency of the SNARC effect, no such effect should be obtained with pedal responses because foot movements (in contrast to eye movements) are completely unrelated to manual movements, writing, and reading. In contrast, according to the phylogenetic hypothesis, the SNARC reflects effect an inherently space-related number representation which is preverbal and effector-independent; therefore, it should propagate onto any pair of lateralized effectors alike and, in particular, show up when parity decisions are indicated by pedal responses.

Experiment 1

Experiment 1 had two aims: first, to explore whether participants show a regular SNARC effect when they indicate their parity decisions with their feet; second to contrast the hypotheses reviewed in the Introduction.

Method

Participants Twenty-seven (6 male, 21 female; 3 left-handed and 24 right-handed participants) students of the University Potsdam aged between 19 and 29 participated in the two sessions of the experiment; they received 12 Euro or else a course credit in return. Participants gave their informed consent before the beginning of the actual experiment.

Stimuli and apparatus The stimuli consisted of the digits 0 to 9 which were presented in the Times Roman font in white against a dark background. From a viewing distance of 120 cm, the digits had a height of approximately 1.4 deg; they were presented on a 480 x 640 VGA monitor. Participants responded (with shoes taken off) by pressing foot pedals (8 cm in length, 6 cm in width) downwards which were mounted on a ramp-like board with an inclination of 30 deg towards the participant. The onsets of the responses were registered to the nearest millisecond (ms) via the parallel port of the PC. Participants were instructed to rest their hands on the table which stood in front of them.

Procedure The task of the participant was to indicate the parity status of digits ranging from 0 to 9. Participants performed two sessions on two different days. Each session implemented one of the two mappings: left-foot vs. right-foot responses to even numbers and right-foot vs. left-foot responses to odd numbers. The order of mapping was counterbalanced across participants, who were asked to respond as fast and accurate as possible. Given that feet responses are less common, participants first practiced the task for 10 trials in presence of the experimenter to adapt to the response requirements.

Each trial started with a fixation cross in the middle of the screen which lasted for 1000 ms and was then replaced with a single digit that was response-terminated. Response time (RT) was defined as the time from the onset of the digit until one of the two pedals was deflected. The next trial started 2000 to 2500 ms after the response. If a response was incorrect, the word "Error" appeared for 500 ms on the monitor.

Each block consisted of 100 trials. Within a single block each of the ten digits was presented ten times in a randomized order. A block was followed by a self-paced break of at least 30 seconds. The experiment consisted of 6 blocks and lasted about 45 minutes.

Data analyses All RTs shorter than 150 ms and longer than 1200 ms were excluded from further analyses (0.2 %). Mean RTs for each participant were calculated across all correct trials and subjected to a 5 x 2 x 2 repeated measures ANOVA with three within-subject factors: magnitude bin (5: 0/1, 2/3, 4/5, 6/7, 8/9; cf. Dehaene et al. 1993; Schwarz & Keus, 2004), parity (2: odd vs. even), and response side (2: left vs. right). Error rates were first transformed to arcsin ($\sqrt{p}$) values to stabilize the variances (Bishop, Fienberg, & Holland, 1975, pp. 367), and then subjected to the same 5 x 2 x 2 repeated measures ANOVA as RTs. However, the data graphs shown below depict untransformed error rates so as to be more intelligible. All effects were tested at a level of α=0.01.

Results

Response Times

Overall mean RT was 609 ms. All three main effects were significant. Responses to magnitude bins 0/1 (617 ms) and 8/9 (618 ms) were slower than responses to 2/3 (603 ms), 4/5 (606 ms) and 6/7 [604 ms; $F(4,104) = 6.89$, $MS_e = 856.29$]. Also, right-foot responses (597 ms) were faster than left-foot responses (622 ms), and responses to even digits (606 ms) were faster than responses to odd digits [614 ms; $F(1,26) = 14.83$, $MS_e = 5537.50$, and $F(1,26) = 10.65$, $MS_e = 889.67$, respectively]. Further, magnitude bin interacted with parity [$F(4,104) = 11.93$, $MS_e = 725.89$]: within the magnitude bin 6/7 responses to 6 (even) were slower than responses to 7 (odd), whereas within all other bins responses to even digits were faster.

Most relevant for the present study, we found a magnitude bin x response side interaction [i.e., SNARC effect; $F(4,104) = 13.08$, $MS_e = 875.89$]: differences between right-foot and left-foot RTs increases as numerical magnitude increases (Figure 1a). To further quantify the SNARC effect, we regressed, for each participant, the difference of right-foot minus left-foot RT on the numerical value of the digit (0-9) presented (Figure 1c). Mean regression slope across all participants equaled –5.80 [$t(26) = -4.04$, $SEM = 1.44$].

None of the other effects were found to be significant. Specifically, we did not find a MARC (Markedness of Response Codes; cf. Nuerk, Iversen, & Willmes, 2004) effect which refers to faster left–side responses to odd digits and faster right–side responses to even digit [$F(1,26) = .53$, $MS_e = 8462.14$, $p > .47$].

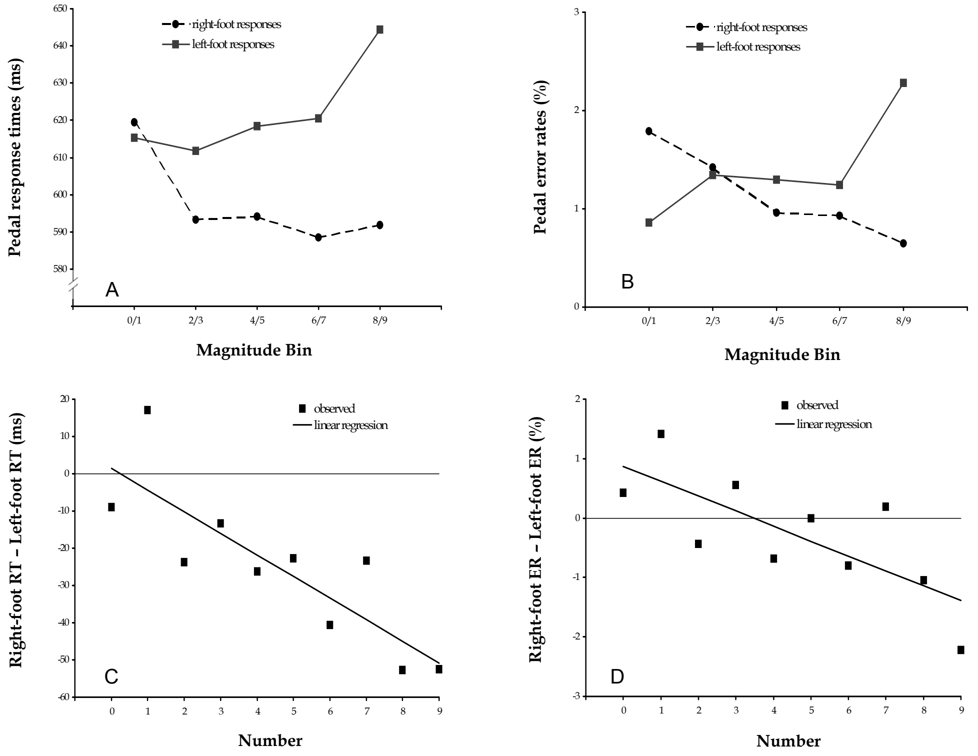

Figure 1

a. Mean response times (in ms) for right–foot (dots) and left–foot (squares) responses as a function of magnitude bin.
b. Error Rates (ER, in %) for right–foot (dots) and left–foot (squares) responses as a function of magnitude bin.
c. Observed differences (squares) of right–foot and left–foot response times (in ms) and regression of RT differences (dRT) on the number presented (solid line; $dRT = -5.80 * digit + 1.35$).
d. Observed differences (squares) of right–foot and left–foot error rates (ER, in %) and regression of ER differences (dER) on the number presented (solid line; $dER = -0.25 * digit + 0.87$).

Error Rates

The overall error rate was 1.3 %. No main effects were found. An interaction between magnitude bin and responses side (i.e., SNARC effect) was observed [$F(4,104) = 9.07$, $MS_e = 0.0056$]: for small numbers, more errors were made when the digit presented required a right–foot response as compared to left–foot responses; for large numbers, this effect was reversed (Figure 1b). This SNARC effect was more pronounced for odd digits, yielding a three–way interaction between magnitude bin x response side x parity [$F(4,104) = 3.92$, $MS_e = 0.0048$]. As with RTs, we regressed, for each participant, differences of right–foot minus left–foot arcsin ($\sqrt{p}$) transformed error rates on the numerical value of the digit (0–9) presented (Figure 1d). Mean regression slope across all participants equaled –0.012 [$t(26) = -4.16$ *SEM* = 0.0029]; the difference between right minus left error rates increased by 0.25 % per digit.

Again, none of the other effects reached statistical significance.

Discussion

In Experiment 1 we aimed to find whether participants show a SNARC effect when they indicate the parity status of a digit with pedal responses. A robust SNARC effect was observed for RT as well as for error rates. Specifically, RT difference between right–side and left–side responses increases as magnitude increases. Moreover, for smaller numbers more errors were made when a right–foot response was required than when a left–foot response was required, whereas for larger numbers the opposite effect was observed.

Foot movements are functionally unrelated to manual or eye movements; more specifically, they are unrelated to the production and comprehension of written language. Given that we observed a robust SNARC effect with pedal responses, our results indicate that the requirement of manual or eye movements is not a necessary condition of the SNARC effect to show up. As reviewed in the Introduction, this finding is clearly in line with the prediction of the phylogenetic view.

A possible objection to this preliminary conclusion, though, is that the SNARC effect observed for pedal responses might differ in its size or in other characteristics (e.g., error rates) from the standard manual SNARC effect. Clearly, our conclusions would be further strengthened if we could demonstrate that the standard signatures of the SNARC effect obtain in very much the same way with manual vs. pedal responses in a direct within–participants comparison. To address this potential objection, we directly compared the manual and pedal SNARC effect in a second experiment.

Experiment 2

Experiment 2 was conducted to further explore and quantify the SNARC effect for pedal responses, especially in relation to manual responses. Thus, in different experimental conditions, 23 new participants indicated the parity status of a digit with either manual or pedal responses.

Method

Participants Twenty-three students (6 male, 17 female; 2 left-handed and 21 right-handed) aged between 19 and 27 took part in the second experiment; none of them had participated in Experiment 1; all gave their informant consent prior the experiment.

Stimuli and apparatus Buttons for the registration of manual responses (given with the index finger of the right and left hand) were additionally connected to the PC via the parallel port. They were placed on the table symmetrically in front of the participants and were horizontally separated by 9 cm.

Procedure The task of the participants was again to indicate the parity status of digits presented (range 0–9). Each participant performed two sessions on two different days; as in Experiment 1 each session implemented one of the two left-right/odd-even mappings. Within each session manual and pedal responses were to be given. Half of the participants started their sessions with manual responses, and half of them indicated the parity status of the digit presented with pedal responses first. For a given participant, the order of the to-be-used effectors remained the same across sessions. Participants first performed three blocks with one effector, and then an instruction on the screen asked them to change to the other effector. The four combinations of the order of the left-right/odd-even mapping and of the effectors to be used were counterbalanced across participants.

Again each session started with ten practice trials. The experiment was made up of six blocks (three for each effector), each of which consisted of 120 trials (each digit was presented twelve times) and lasted about 55 minutes. Trial and block structure were identical to Experiment 1.

Data analyses All RTs shorter than 150 ms and longer than 1200 ms were excluded from further analyses (0.2 % and 1.3 % for manual and pedal responses, respectively). Data analyses were identical to Experiment 1 except of one new within-subject factor: effector (2: foot vs. hand). Thus, mean RTs and transformed error rates (Bishop et al., 1975) were both subjected to a 5 x 2 x 2 x 2 repeated measures ANOVA with four within-subject factors.

Results

Response Times

Mean RT across all participants was 534 ms. We found three main effects. First, manual responses (493 ms) were faster than pedal responses [574 ms; $F(1,22) = 176.96$, $MS_e = 8562.02$]. Second, right-side responses (526 ms) were faster than left-side responses [541 ms; $F(1,22) = 16.36$, $MS_e = 2989.10$]; this difference between left and right-side responses was more pronounced for pedal responses than for manual responses, yielding a two-way interaction between response side and effector [$F(1,22) = 14.34$, $MS_e = 1531.02$]. Third, responses to magnitude bins 0/1 (541 ms) and 8/9 (540 ms) were again systematically slower than responses to 2/3 (530 ms), 4/5 (529 ms) and 6/7 [528 ms; $F(4,88) = 6.83$, $MS_e = 1124.32$].

Similar to the results of Experiment 1, magnitude bin interacted with parity [$F(4,88) = 5.59$, $MS_e = 1758.35$]: within the magnitude bin 6/7, responses to 6 (even) were slower than responses to 7 (odd), whereas responses to even digits were faster within all other magnitude bins. More central to our aims, we observed an interaction between magnitude bin and response side [i.e., SNARC effect; $F(4,88) = 14.51$, $MS_e = 759.44$]: the difference between right and left-side responses increases as numerical magnitude increases (see Figures 2a,c). However, no magnitude bin x response side x effector interaction was obtained [$F(4,88) = 1.21$, $MS_e = 436.45$, $p > .31$], indicating that the SNARC effect holds in much the same way for manual and pedal responses. The visual comparison of Figures 2a and 2b might superficially suggest that the SNARC effects differ for manual and pedal responses. It should, however, be noted that this apparent difference simply reflects the main effect of response side, and the fact that this effect is much larger for feet than hands. To obtain a purer signature of the SNARC effect, we regressed, for each participant, right-side minus left-side RT on the numerical value of the digit (0–9; see Figures 2b,d).

Although we did not find an interaction between the SNARC effect and the effector, we carried out these regression analyses separately for manual and pedal responses to better demonstrate how parallel the outcomes were for both effectors. Mean regression slope across all participants for manual responses equaled –4.36 [$t(22) = -4.23$, $SEM = 1.03$]; for pedal responses it equaled –4.44 [$t(22) = -4.19$, $SEM = 1.06$]. Obviously, the regression slopes for hand and foot responses did not differ from each other ($t < 1$).

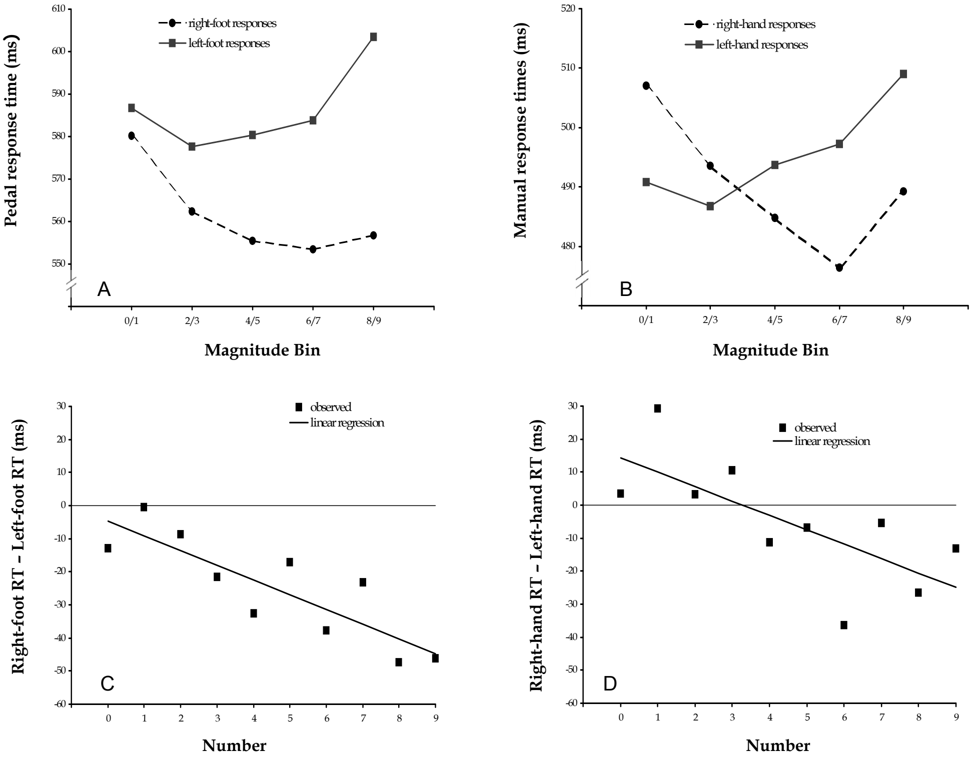

Figure 2

a. Pedal condition of Experiment 2: Mean response times (in ms) for right-foot (dots) and left-foot (squares) responses as a function of magnitude bin.
b. Manual condition of Experiment 2: Mean response times (in ms) for right-hand (dots) and left-hand (squares) responses as a function of magnitude bin.
c. Pedal condition of Experiment 2: Observed differences (squares) of right-foot and left-foot response times (in ms) and regression of RT differences on the number presented (solid line; dRT = -4.44 * digit - 4.79).
d. Manual condition of Experiment 2: Observed differences (squares) of right-hand and left-hand response times (in ms) and regression of RT differences on the number presented (solid line; dRT = -4.36 * digit + 14.34).

To further illustrate the degree of consistency between manual and pedal SNARC effects, the slopes of the two separate (hand and foot) regressions of left minus right RT on numerical magnitude per participant are shown as a scatterplot in Figure 3. The line shown is the principal axis minimizing the squared perpendicular distances (Sokal & Rohlf, 1991, ch. 15.7). Neither is its slope of 1.05 significantly different from 1 [the 95% C.I. equals (0.47, 2.43)], nor is its intercept of 0.142 significantly different from 0. Obviously, then, the hand and foot SNARC slopes are well described by the identity function, y=x. The correlation of the two slope estimates across participants is equal to 0.56 [$t(21) = 3.10$].

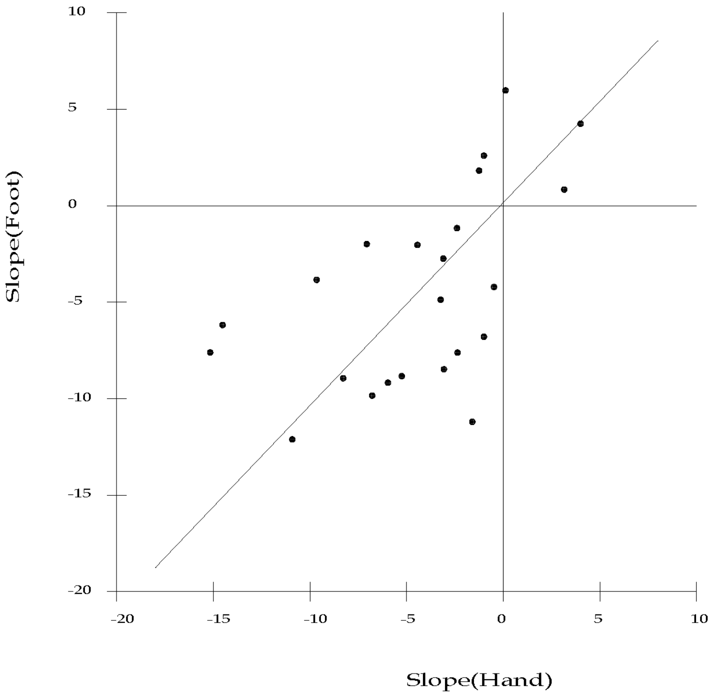

Figure 3
Scatterplot of the slopes of the two separate regressions of left minus right RT on numerical magnitude. Manual (abscissa) and pedal (ordinate) slopes for each participant are shown as the coordinates of the circles. The line indicates the principal axis ($y = 1.05\ x + 0.142$) which minimizes the sum of the squared perpendicular distances. The correlation of the two slope estimates across participants is equal to 0.56 [$t(21) = 3.10$].

As in the first experiment we did not find a significant interaction of side of response and parity [i.e., MARC effect, Nuerk et al., 2004; $F(1,22) = .60$, $MS_e = 12282.65$, $p > .44$]; no other interaction was significant.

Error Rates

Overall error rate equaled 2.6 %. More errors were made with pedal (3.0 %) than with manual responses [2.1 %; $F(1,22) = 28.89$, $MS_e = 0.0068$]. As with RTs, we found a significant magnitude bin x response side interaction [i.e., SNARC effect; $F(4,88) = 14.49$, $MS_e = 0.0116$]: for small numbers, more errors were made when right-side responses were required as compared to left-side responses; for large numbers, this effect was reversed (see Figures 4a,c). No interaction of magnitude bin x response side x effector was observed [$F(4,88) = 1.52$, $MS_e = 0.0089$, $p > .20$].

For each participant and effector separately, we regressed differences of right-side minus left-side arcsin ($\sqrt{p}$) transformed error rates on the numerical value of the digit (0–9) presented (see Figures 4b,d). The mean regression slopes for manual responses and pedal response across all participants equaled –.0216 [$t(22) = -4.31$, $SEM = 0.0050$] and

–.0135 [t(22) = –3.95, *SEM* = 0.0034], respectively; they did not differ [t(22) = –.084]. Per digit the difference between right and left error rates increased by 0.73 % for manual responses and by 0.45 % for pedal responses.

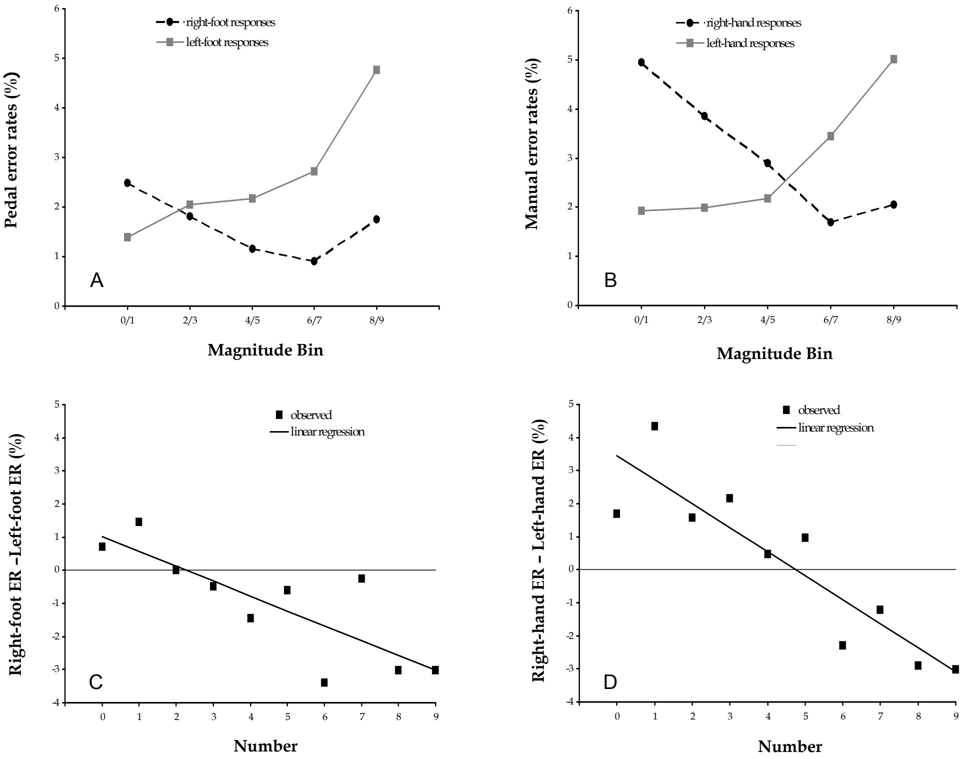

Figure 4

a. Pedal condition of Experiment 2: Error rates (ER, in %) for right–foot (dots) and left–foot (squares) responses as a function of magnitude bin.
b. Manual condition of Experiment 2: Error rates (ER, in %) for right–hand (dots) and left–hand (squares) responses as a function of magnitude bin.
c. Pedal condition of Experiment 2: Observed differences (squares) of right–foot and left–foot error rates (ER, in %) and regression of ER differences on the number presented (solid line; dER = –0.45 * digit + 1.02).
d. Manual condition of Experiment 2: Observed differences (squares) of right–hand and left–hand error rates (ER, in %) and regression of ER differences on the number presented (solid line; dER = –0.73 * digit + 3.45).

Comparison of regression slopes in Experiment 1 and 2

To check the consistency of our results, we compared the regression slopes for pedal responses between–subjects across the two experiments. No difference of RT regressions slopes (means of –5.80 and –4.44 for Experiment 1 and 2, respectively) was found (t < 1). Similarly, the error regression slopes (means of –0.012 and –0.0135 for Experiment 1 and 2, respectively) were identical in both Experiments (t < 1).

Discussion

Experiment 2 aimed to directly compare the SNARC effect for pedal and manual responses. We observed robust SNARC effects on latencies and error rates for both manual and pedal responses. A detailed within-subjects comparison of the SNARC effect for manual and pedal responses revealed no difference in either size or other characteristics of the two conditions: in fact, neglecting trivial effector main effects, manual and pedal responses yielded virtually identical results. Furthermore, a comparison between the pedal SNARC effects of Experiment 1 and 2 did not reveal any difference; thus the present experiment replicated our findings of Experiment 1.

As in Experiment 1 (for similar results, see Keus & Schwarz, 2005, and Schwarz & Keus, 2004) we found that within the magnitude bin 6/7, "even" responses to 6 were slower than "odd" responses to 7 whereas responses to even digits are faster within any other magnitude bin. A possible explanation is that participants represent the number seven as a prototype of odd digits, leading to particularly fast responses. In contrast, the number six might be represented as the sum of three plus three. Given that the number three in turn is odd, a response conflict may prolong RTs for the digit 6.

General Discussion

Dehaene et al. (1993) first demonstrated in a bimanual parity-judgment task that relatively small numbers are preferentially associated with the left extracorporal space and are responded to faster with buttons placed on the left-hand side whereas relatively large numbers are responded to faster with buttons placed on the right-hand side (the SNARC effect). Two major hypotheses (ontogenetic vs. phylogenetic; see Fischer, 2003) have been advanced to explain this effect. According to the first view, the SNARC effect critically depends on the dominant direction of the writing system to which the participant is adapted. A strong interpretation of this view holds that the SNARC effect reflects highly overlearned sensorimotor associations formed in the production and comprehension of written language. Therefore, the occurrence and size of the SNARC effect might critically depend on the specific response requirements; more specifically, it might be limited to lateralized effectors (such as hands and eyes), which are strongly associated with the production or comprehension of written language. Just note, though, that the strong ontogenetic view can not account for the fact that the SNARC effect involves RT facilitations and slowing of both hands although, for example, right handers only use their right but not left hand to write. In contrast, the phylogenetic hypothesis holds that the SNARC effect reflects an inherently space-related number representation which is preverbal and which should propagate onto any pair of lateralized effectors in a similar way.

The first question we raised in the present study was whether a SNARC effect can also be demonstrated for an effector that is not at all related to the production or comprehension of written language. To answer this question, we first conducted an otherwise standard SNARC experiment (i.e., judging the parity status of a visually presented digit; cf. Dehaene et al., 1993) but asked participants to respond with their feet. Second, if participants do show any SNARC effect with pedal responses, the question arises whether or not this effect differs for manual and pedal responses. Therefore, in our second Experiment participants indicated the parity status of a digit with manual as well as with pedal responses.

In Experiment 1 we found a robust pedal SNARC effect for RT as well as for error rates. That is, the difference between right-foot and left-foot RTs and error rates increases as numerical magnitude increases. These results fit with the view that the SNARC effect does not depend on overlearned sensorimotor associations related to written language. However, this finding in itself does not logically rule out that there might still be systematic differences in the size or other characteristics of the SNARC effect for manual vs. pedal responses. Therefore, in Experiment 2 we directly contrasted manual and pedal responses in a within-subjects design. For both effectors, a standard SNARC effect for RTs as well as for error rates showed up. Most importantly, we did not find any hint of a qualitative or in fact even quantitative difference of the SNARC effect (neither for RTs nor for error rates) between manual and pedal responses.

Our findings thus provide support for the phylogenetic hypothesis, and seem harder to reconcile at least with a strong written-language interpretation of the ontogenetic hypothesis, given that no systematic sensorimotor associations at all exist between reading and writing on the one hand and pedal responses on the other. According to a phylogenetic conceptualization, then, the regular SNARC effect seems to arise from a generic left-to-right number representation but not from specific highly overlearned motor associations between digits and manual responses.

However, as already mentioned in the Introduction, a considerably weaker interpretation of the ontogenetic hypothesis is possible as well. According to this weaker interpretation, the preferred direction of writing and reading does originally influence the acquisition, development and organisation of a habitual mental representation of magnitude information, but the important qualification is that this representation subsequently is not limited to those specific effector systems (i.e., hands/writing, and eyes/reading) which were initially instrumental to first establish it. More specifically, a left-to-right mental number organization might well be originally induced by the prevalent writing system, but subsequently generalize to just about any effector, independent of whether this effector is related to written language or not. Obviously, this "weak" interpretation of the ontogenetic hypothesis is in line with the present results, too, as it does not stipulate any particular effector-dependencies of the SNARC effect. Indeed, in many ways -- and especially with regard to testable experimental predictions -- the weak ontogenetic and the phylogenetic hypothesis seem quite compatible: both assume a space-related numerical representation or a mental number line, and both predict a SNARC effect for essentially any lateralized effector pair. Thus, in contrast to the strong, effector-dependent view based on overlearned sensorimotor associations, the weak interpretation of the ontogenetic hypothesis and the phylogenetic hypothesis seem not at all mutually exclusive. More specifically, the preverbal mental number line as an evolutionary primitive might actually provide the developmental mechanism that is exploited and adapted in establishing a preferred space-like number representation, e.g. through the orientation of the writing system that prevails in the specific cultural context. Still, some principal differences of these interpretations remain even so, which we discuss in the sequel with respect to the presently available evidence, and to additional evidence that might be obtained in future studies.

First, Berch, Foley, Hill, and Ryan (1999) found that children from grade 3 on show a regular SNARC effect, but second graders did not. In principle, this result seems in line with the weak ontogenetic hypothesis. However, Berch et al. (1999, p. 305) argue that the reason that "the SNARC effect [...] did not emerge for the second graders may be attributable in part to their comparatively slow RTs, if not the high level of both between-trial and between-subjects variability in their latency data". For example, judging from the RTs obtained, second graders seem to take a very long time until they retrieve parity information, so that any transient response activation originally induced by the magnitude information might already have faded by the time the parity decision is eventually made and the response is selected (cf. Schwarz & Ischebeck, 2003). To further test these two explanations of Berch et al.'s findings further developmental studies are needed in which children are asked to indicate features of visually presented digits which are easier (i.e., faster) to identify than their parity status (e.g., orientation task, see Fias et al., 2001). More generally, it would be of critical importance to know whether a SNARC effect is observed in children who have not yet acquired reading and writing skills, or even in higher, but preverbal mammals, who are well-known to show numerical distance effects (e.g., Brannon & Terrace, 1998; see also Tversky, Kugelmass, & Winter, 1991). Such a finding would be hard to explain on an ontogenetic view based on written language; it would mean that the acquisition of written language may perhaps strengthen and modify the SNARC effect, but would not be a strictly necessary condition for it to obtain.

A second relevant finding to distinguish the phylogenetic and the weak ontogenetic hypothesis is the SNARC effect which Dehaene et al. (1993) found for Iranian participants who had recently immigrated into France; they "presented a weaker or reversed association" (Dehaene et al., 1993, p. 387), with faster right (left) hand responses to smaller (larger) numbers. Careful inspection of their data reveals that this "reversed" SNARC effect of these Iranian participants was conspicuously small and inconsistent when compared to the normal SNARC effect as found for French participants. One obvious reason for this less regular SNARC effect is that whereas Iranians write words from right to left (as is standard in Arabian languages), they actually use a number notation system which proceeds from left to right (see Ifrah, 1998, for detailed information about number and language notation systems in different cultures). On the ontogenetic view, given the left-to-right number notation system used in the Iranian culture, it is actually somewhat surprising that Iranians showed a tendency towards a reversed SNARC effect. A related recent study reported a vertical SNARC effect with manual responses from Japanese participants: larger numbers were associated with the top button whereas smaller numbers were responded to faster with the bottom button (Ito & Hatta, 2004). Given that Japanese is written from top to bottom, this finding reveals a dissociation of the SNARC effect and the direction of writing, casting further doubt on a tight relation between reading/writing habits and the SNARC effect (see also Pansky & Algom, 2002, who reported no SNARC effect with participants raised in Israel). Clearly, more systematic studies from cultures with different notation systems are needed to clarify exactly which notational properties shape the direction and strength of the SNARC effect.

In summary, the present results clearly rule out any account of the SNARC effect that is based on highly overlearned sensorimotor associations, as they might be formed, in particular, through the acquisition of written language. Rather, our results support any view based on the assumption that the SNARC effect reflects a genuine internal space–related representation which propagates onto any pair of lateralized effectors in essentially the same way – in particular, even if these effectors are completely unrelated to the standard production or comprehension of written language, as are feet. This genuine space–related representation might be conceptualized either as a preverbal mental number line which we inherit as an evolutionary primitive, or it might be seen as a learned cognitive code that is mainly shaped by culture and context, and, in particular, by the direction of the dominant writing system. These views are certainly not mutually exclusive; further evaluations of their relative merits require additional experimental work as outlined above.

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CHAPTER 3

IS THERE AN INTERNAL ASSOCIATION OF NUMBERS TO HANDS? THE TASK SET INFLUENCES THE NATURE OF THE SNARC EFFECT

Abstract

The SNARC effect refers to an association of smaller numbers to the left side of extracorporal space and of larger numbers to the right side of extracorporal space (Dehaene, Bossini, & Giraux, 1993). We test the assumption that, in addition, numbers are also related to the participants' hands. We report two experiments with vertically arranged buttons in which the nature of the SNARC effect depended on the button-related vs. hand-related task set which was created: in the first case, a vertical location-related SNARC effect obtains whereas in the second case a hand-related SNARC effect is found. Our third experiment confirms that space-related number representations dominate the SNARC effect when the buttons are horizontally arranged. We conclude that both effector- and space-related number representations can influence and modify the SNARC effect.

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Introduction

In daily life the processing of numerical information plays a crucial role in the comprehension of our environment and the communication of relevant facts. Much research has been conducted over the past twenty years to explore and examine the nature of human numerical cognition (for detailed summaries see Butterworth, 1999; Dehaene, 1997; Hubbard, Piazza, Pinel, & Dehaene, 2005; Piazza & Dehaene, 2004).

In a seminal paper, Dehaene, Bossini, and Giraux (1993) first demonstrated the so-called SNARC (Spatial Numerical Association of Response Codes) effect: numerically smaller numbers are responded to faster with the left-side key, whereas numerically larger numbers are responded to faster with the right-side key. Participants were asked to indicate the parity status of a digit ranging from 0 to 9 with a left or right key press. Here, the actual numerical magnitude was in fact task-irrelevant but apparently it was automatically activated and provided a stable spatial numerical association. Various other experiments confirmed and extended the SNARC effect since then (e.g. Bächtold, Baumüller, & Brugger, 1998; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; Fias, Lauwereyns, & Lammertyn, 2001; Gevers, Reynvoet, & Fias, 2003; Fischer, 2001; Schwarz & Keus, 2004; see Gevers & Lammertyn, 2005 for a review of SNARC effect findings). The SNARC effect seems to reflect a space-related left-to-right representation of numbers which is often conceptualized as a "mental number line" (Dehaene et al., 1993; Restle, 1970). Further evidence supporting the mental number line concept comes, for example, from the distance effect: the larger the numerical distance of two digits the less time it requires to discriminate them (Moyer & Landauer, 1967, see also e.g., Schwarz & Ischebeck, 2003). The distance effect has been found for children as well as for a wide range of animals suggesting that the mental number line is a preverbal, inherited evolutionary primitive (Brannon, 2002; Brannon & Terrace, 1998; Brannon, Wusthoff, Gallistel, & Gibbon, 2001; Gallistel & Gelman, 1992, 2000; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002; Temple & Posner, 1998).

Corporal space of the responding hand or extracorporal space of the response button?

Two major hypotheses for the association of numbers and space have been advanced: first, the SNARC effect might reflect a specific association of spatially represented body sides and numerical magnitude. Thus, the left hand and smaller numbers may be represented as spatially left and be preferentially linked to each other, and vice versa for larger numbers. Therefore, responses with spatially left and right lateralized effectors would be a necessary condition for the SNARC effect. In view of the lateralized hemispheric representation of our effectors, the effect could describe a hemispheric dominance effect (Dehaene et al., 1993, p.383). For example, if small (large) numbers are predominantly represented in the right (left) brain hemisphere, then left-hand (right-hand) responses would gain a speed advantage because they are activated from the same brain hemisphere. Clearly, this account is reminiscent of the classic Poffenberger effect (see Berlucci, Crea, Di Stefano, & Tassinari, 1977), the important difference being that with the Poffenberger effect the stimuli appear along an external meridian whereas with the SNARC effect they are represented along a (potentially lateralized) internal number line. It should be noted, though, that more central representational schemes, not based on the concept of a strict hemispheric lateralization, could equally well account for an association of small/large numbers with left/right effectors. In either case, we refer to this class of accounts as the effector hypothesis of the SNARC effect: in this view, the effect describes essentially a spatio-anatomical mapping. Alternatively, the SNARC effect might reflect an association of extracorporal space with numbers. According to this view, the response sides are coded as spatially left and right. Hence, "the SNARC effect operates at a more abstract level of representation of the left and right side of response" (Dehaene et al., 1993, p. 383), so that lateralized response locations might be a necessary condition for the SNARC effect to show up: the location hypothesis of the SNARC effect. To test if the SNARC effect is an effect of hemispheric lateralization, participants were asked to indicate the parity status of digits by pressing horizontally arranged response buttons with crossed hands (Dehaene et al., 1993; Experiment 6). Note that, under an uncrossed condition the responding hand and the button-location are completely redundant and confounded: the responding hand and the extracorporal space provide exactly the same spatial code. Dehaene et al. found that numerically smaller numbers were responded to faster with the left-side key pressed by the right index finger, and that larger numbers were responded to faster with the right-side key pressed by the left index finger. This result clearly favors the location hypothesis; accordingly, Dehaene et al. concluded that numbers are associated to extracorporal space irrespective "of the particular hand that is making the response in that part of the space" (p. 384).

Is the location hypothesis the best explanation of the SNARC effect?

Many of the SNARC related results can be best explained by the location hypothesis, which is therefore a widely accepted explanation. For example, Fischer (2003) asked participants to indicate the parity status of a digit by moving the left or right index finger to the left or right side of a touch screen. He found that left-side movements were faster to smaller numbers and right-side movements were faster to larger numbers, irrespective of the specific finger performing the movement. Quite similar results were obtained for eye-movements in a parity-judgment task (Fischer, Warlop, Hill, & Fias, 2004; Schwarz & Keus, 2004). Finally, Vuilleumier, Ortigue, and Brugger (2004) found a SNARC effect when participants had to deflect a left or right button with the same finger.

These results are clearly in line with the location hypothesis because they show that lateralized effectors are not a necessary condition for the SNARC effect to show up. However, it is conceivable that these experimental conditions minimized the potential for a contribution of the spatio-anatomical mapping. Moreover, in the crossed hands experiment the responding hand and button-location provide different and independent spatial information. In this case, a conflict between the two different spatial codes might arise; possibly this conflict is settled by the dominant spatial representation of the buttons and leads to a net location-related SNARC effect. Such a conflict can be indicated, for example, by longer overall response times for crossed hands compared to uncrossed hands (Nicoletti, Umiltà, & Ladavas, 1984; Umiltà & Nicoletti, 1990).

Are there other ways to contrast the effector and the location hypothesis?

To re-evaluate the effector hypothesis we choose an experimental setting which maximizes the potential contribution of the spatio-anatomical representation to the SNARC effect. We asked participants to indicate the parity status of a digit by pressing vertically arranged buttons. In this setting, the extracorporal button-location and the space occupied by the responding effector are dissociated: the button-location provides vertical spatial information whereas the hands provide horizontal spatial information (but see Bauer & Miller, 1982).

Similarly, Ehrenstein, Schroeder-Heister, and Heister (1989) reported a hand-related spatial stimulus-response compatibility (SRC) effect[1] for vertically arranged buttons and horizontally arranged stimuli: right lights were responded to faster with the

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[1] The SRC effect refers to the finding that in a detection task left lights are responded to faster with the left button and right lights with the right button (Fitts & Seeger, 1953; see also Proctor & Reeve, 1990).

middle finger (anatomically right) and left lights were responded to faster with the index finger (anatomically left) of the right hand. In this setting fingers and stimuli provide consistent spatial codes and are related to each other: the spatio-anatomical component comes to dominate the extracorporal component. Moreover, the authors argue that if the button-locations match the spatial dimension of the stimuli, then the spatial codes of the buttons will dominate the spatial codes provided by the hands (see also Heister, Schroeder-Heister, & Ehrenstein, 1990). This association of extracorporal space and stimulus-location was also supported by results of crossed hands and crossed sticks experiments (Riggio, Gawryszewksi, & Umiltà, 1986). The authors refer to this set of assumptions as the hierarchical model (Ehrenstein et al., 1989; Heister et al., 1990).

Does a hierarchical model also account for the SNARC effect?

A similar hierarchical model is conceivable also in the context of Dehaene et al.'s (1993) finding that numbers are preferentially coded from left-to-right, possibly as a consequence of our left-to-right writing system. Therefore, with horizontally arranged buttons numbers are associated with the extracorporal space occupied by the response buttons because, irrespective of the responding hand, button-location matches our left-to-right mental number line. However, with vertically arranged buttons the spatial representation of our hands could map the internal left-to-right ordering of numbers, which might yield a hand-related SNARC effect. Such an outcome would support the assumption that the relative contribution of the effector and extracorporal space depends on the spatial arrangement of the response button.

Recently, Ito and Hatta (2004) reported a vertical SNARC effect: smaller numbers were responded to faster with the bottom button and vice versa for larger numbers, irrespective of the responding hand (see also Schwarz & Keus, 2004). These results seem to suggest that the SNARC effect refers exclusively to an association of numbers and extracorporal space (see also Dehaene et al., 1993), independent of which hand operates which button. It should be noted, though, that in the experiments of Ito and Hatta (2004) the hand-to-button mapping varied only as a between subjects factor. That is, half of the participants deflected the top button with the right index finger and the bottom button with the left index finger and vice versa for the other participants. For each participant the parity-to-button mapping changed within the session; i.e., in the first part participants responded to odd digits with the top button and to even digits with the bottom button. In the second part, participants responded to odd digits with the bottom button and to even digits with the top button. Thus, for each participant the parity–to–button mapping, and therefore the parity–to–hand mapping, changed within the session which implies that top/bottom button and left/right hand are confounded in any single experiment. Moreover, in such a task set, it is unclear whether participants represented the task requirements in hand–related or in button–related terms. Therefore, we asked if the SNARC effect can be modulated by the instructional design (i.e., task set) applied.

In conclusion, experiments with vertically arranged buttons represent an informative basis to test the hierarchical model of the SNARC effect, extending the strict location hypothesis originally proposed by Dehaene et al. (1993). Thus, the aim of the experiments reported below was not to refute the location hypothesis of the SNARC effect altogether but rather to delimit its scope and to search for its boundary conditions.

General Method

Participants All participants were students of the University of Potsdam aged between 18 and 44 years. They either received 6 Euro for one session (Experiment 1) or 12 Euro for two sessions (Experiments 2 and 3), or else course credit. All participants had normal or corrected–to–normal eye vision and gave their informed consent. Handedness of participants was additionally recorded and analyzed. Handedness did not influence the nature of the SNARC effect in any experiment and was therefore, not considered as a separate factor. This pattern was also found by Dehaene et al. (1993; Experiment 5).

Stimuli and Apparatus Digits ranging from 0 to 9 were presented in Times New Roman font in white against a dark background on a 480 x 640 VGA monitor. The viewing distance was 120 cm at which the digits had a height of approximately 1.4 deg. Participants indicated the parity status of a digit by deflecting vertically arranged (Experiments 1 and 2) or horizontally arranged (Experiment 3) response buttons with their left or right index finger. The onsets of responses were registered to the nearest millisecond (ms) via the parallel port of the PC.

Procedure We asked participants to indicate the parity status of visually presented digits ranging from 0 to 9. Participants either performed one (Experiment 1) or two sessions (Experiments 2 and 3). Each session consisted of 6 blocks each of which comprised 120 trials. A block was followed by a self-paced break of at least 30 seconds. Within one block each digit was presented twelve times in a randomized order.

Each trial started with a centrally presented fixation cross which was replaced with the single digit after 1000 ms. The digit was response-terminated; response time (RT) was defined as the time from the onset of the digit until a response. If a response was incorrect the word "Error" appeared for 500 ms on the screen; the next trial started 2000 to 2500 ms after the response was given. One session lasted about 50 minutes.

Data analyses RTs shorter than 150 ms or longer than 1200 ms were excluded from further analyses.[2] Across all correct trials mean RTs were calculated for each participant and then subjected to the corresponding ANOVA of the experiments (see below). Mean error rates were first transformed to arcsin ($\sqrt{p}$) values to stabilize the variances (Bishop, Fienberg, & Holland, 1975, p. 367) and then subjected to an ANOVA of the same design as RT. To facilitate understanding of the error rates, descriptive data and figures illustrate untransformed error rates.

To further quantify the SNARC effect we regressed for each participant right minus left RT or top minus bottom RTs and error rates on the numerical magnitude or magnitude bin presented (cf. Fias et al., 1996; Fias, 2001; Lorch & Meyers, 1990). The means of the slopes are a sensitive and efficient index of the SNARC effect (cf. Dehaene et al., 1993) and were analyzed by t-tests. All effects were tested at a significance level of $\alpha = 0.05$.

Experiment 1

The aim of Experiment 1 was to test the specific predictions of the hierarchical model of the SNARC effect for vertically arranged buttons. We asked participants to indicate the parity status of visually presented digits by pressing vertically arranged buttons with their left and right index finger. In direct contrast to Ito and Hatta (2004), for any given participant the parity-to-button mapping was fixed throughout the session. Moreover, the hand-to-button mapping alternated from block-to-block so as to avoid any confounding of responding hand and response button.

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[2] The reason for choosing these outlier criteria is to maximize the similarity of our own procedure to that of other SNARC studies (Dehaene et al., 1993; Fischer, 2003; Fias, 2001; Fias et al., 1996).

Method

Participants Thirty-six participants took part in this experiment.

Stimuli and Apparatus Buttons were vertically separated by a distance of 3 cm and arranged perpendicular to the body midline. Vu, Proctor, and Pick (2000) found compatibility effects between buttons arranged vertically but perpendicular to the body and stimuli presented on top or bottom locations of a screen. Thus, although these button locations also resemble a close-far dimension, these findings strongly suggests that top and bottom buttons perpendicular to the body are spatially represented in exactly the same way as buttons arranged along the gravitational axis.

Procedure Participants performed one session in which even digits were mapped to the top button and odd digits to the bottom button for 18 participants or vice versa for the other participants. Moreover, the hand-to-button mapping alternated from block to block. Half of the participants started with their right index finger pressing the top button whereas the other participants first deflected the top button with their left index finger (see Appendix for the verbatim instruction).

Data Analyses Overall 2.87 % of all trials were excluded from further analysis. Mean RTs and arcsin ($\sqrt{p}$) error rates were subjected to a 5 x 2 x 2 x 2 repeated measures ANOVA with three within-subject factors: magnitude bin (5: 0/1, 2/3, 4/5, 6/7, 8/9; cf. Dehaene et al., 1993; Schwarz & Keus, 2004), button-location (2: top vs. bottom), responding hand (2: left vs. right), and parity-to-button mapping which varied as between-subjects factor [2: top (bottom)-button responses to even (odd) digits vs. top (bottom)-button responses to odd (even) digits].

Results

Response Times

Overall mean RT equaled 565 ms. We found two significant main effects: first, responses to magnitude bin 0/1 (583 ms) were slower than responses to the other magnitude bins [2/3: 558 ms, 4/5: 560 ms, 6/7: 556 ms, 8/9: 564 ms; $F(4,136) = 11.50$, $MS_e = 1495.77$]. Second, we found a small but reliable advantage of top-button responses (561 ms) compared to bottom-button responses [568 ms; $F(1,34) = 7.98$, $MS_e = 1277.48$]. Responding hand did not exert a main effect ($F < 1$). Parity-to-button mapping interacted with button-location [$F(1,34) = 17.76$, $MS_e = 1277.48$]. For those participants who responded to even digits with the top button and to odd digits with the bottom button, top responses were faster than bottom responses. In contrast, for participants who responded to even digits with the bottom button and odd digits with the top button, bottom responses were faster than top responses. Therefore, the interaction of parity-to-button mapping and button-location simply refers to a parity main effect: responses to even digits were generally faster than responses to odd digit. This simple interaction was modulated by the triple interaction of parity-to-button mapping and button-location with magnitude bin [$F(4,136) = 5.98$, $MS_e = 1271.76$]. As described above, overall "even" responses were faster than "odd" responses. This pattern holds except for the magnitude bin 6/7 where responses to the odd digit 7 were faster than responses to the even digit 6.

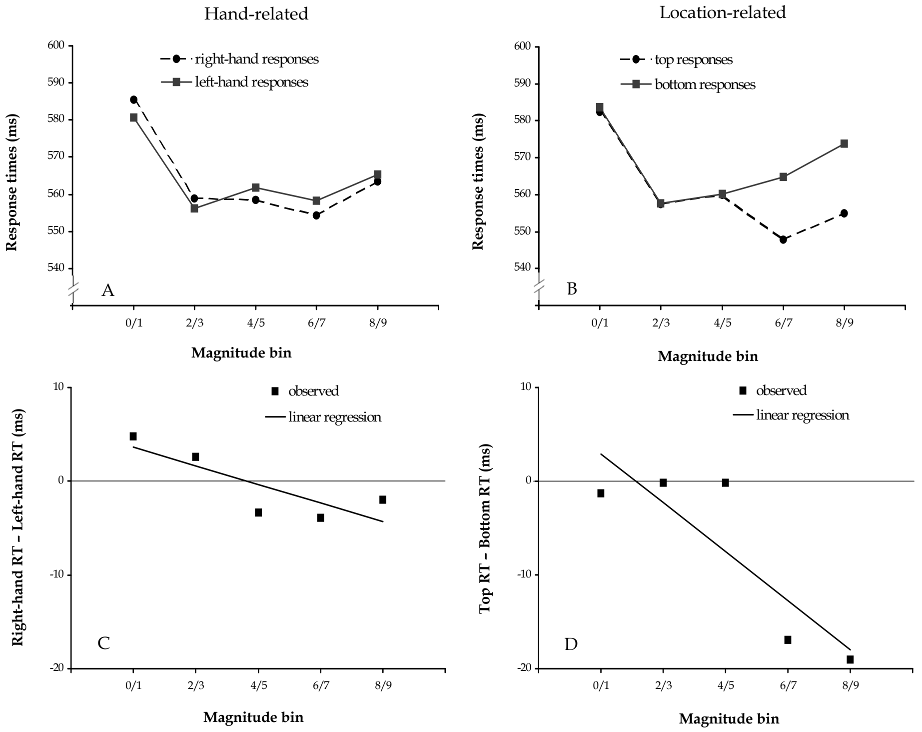

Figure 1

a. Mean response times (in ms) for right-hand (dots) and left-hand responses (squares) as a function of magnitude bin.
b. Mean response times (in ms) for top-button (dots) and bottom-button (squares) responses (dots) as a function of magnitude bin.
c. Observed differences (squares) of right-hand and left-hand response times (in ms) and regression of RT differences (dRT) on the magnitude bin presented (solid line; dRT = −2.00 * magnitude bin + 5.65).
d. Observed differences (squares) of top-button and bottom-button response times (in ms) and regression of RT differences (dRT) on the magnitude bin presented (solid line; dRT = −5.23 * magnitude bin + 8.16).

Most relevant for our hypotheses, we found a significant interaction of magnitude bin and button-location: the difference of top and bottom buttons RT gets more negative as magnitude bin increases; this interaction thus represents a vertical location-related

SNARC effect [$F(4,136) = 2.59$, $MS_e = 1271.82$, see Figure 1b]. In line with this finding, top–button RT minus bottom–button RT decreased by 5.23 ms per magnitude bin which was marginally significant [$t(35) = -1.97$, $SEM = 2.66$, $p = .057$, see Figure 1d]. In contrast, neither the simple interaction of magnitude bin and responding hand nor the triple interaction of magnitude bin and button–location and responding hand was found significant [$F < 1$, see Figure 1a; and $F(4,136) = 1.22$, $MS_e = 792.44$, $p > .30$, respectively]. The mean regression slope of right–hand RT minus left–hand RT on magnitude bin did not significantly deviate from zero [b = –2.00, $t(35) = -1.32$, $SEM = 1.51$, $p > .19$, see Figure 1c].

Error Rates

Overall error rate equaled 2.12 %. As with RTs, more errors were made within the magnitude bin 0/1 (3.32 %) compared to the other bins [2/3: 1.83 %, 4/5: 1.45 %, 6/7: 1.73 %, 8/9: 2.28 %; $F(4,136) = 5.80$, $MS_e = 0.0013$]. Furthermore, we found an interaction of parity–to–button mapping, magnitude bin and button–location [$F(4,136) = 4.26$, $MS_e = 0.0012$]. Again, this interaction refers to a parity effect as described for the RT data and to a reversal of this pattern for the magnitude bin 6/7.

In contrast to the RT data we did not find a significant interaction of magnitude bin and button–location ($F < 1$). The interaction of magnitude bin and responding hand failed to reach significance as well ($F < 1$). These results were also confirmed by regression analyses (hand–related: $p > .23$, location–related: $p > .54$).

Discussion

In the first experiment participants performed a parity–judgment task with vertically arranged buttons. Parity was mapped to a specific button. Thus, we emphasized the spatial organization of the response buttons. In fact, we replicated Ito and Hatta's (2004) finding: the difference of top vs. bottom RT decreased as numerical magnitude increased (vertical location–related SNARC effect). In contrast, the responding hand does not modulate the SNARC effect. In this experiment, parity was mapped to fixed, specific buttons. The instruction, therefore, strongly emphasized the vertical dimension of the response buttons. It is conceivable that this strongly modified the nature of the SNARC effect. To evaluate this potential influence of the instruction we conducted a second experiment which was similar to Experiment 1 in its arrangements of the response buttons but differed in its instruction.

Experiment 2

In Experiment 2 we consistently mapped a specific parity status to a specific hand within a session to emphasize that participants focus on the spatial dimension of their hands rather than on the location of the buttons. Therefore, two sessions were performed and a fixed hand-to-parity mapping persisted throughout a session. Moreover, the hand-to-button mapping did not alternate from block to block; instead it changed after three blocks within a given session.

Method

Participants Twenty-four new participants took part in this experiment.

Stimuli and Apparatus All features were the same as in Experiment 1.

Procedure Participants performed two sessions on two different days. In each session one hand-to-parity mapping was used consistently: right (left) index finger to odd (even) responses, or vice versa. Half of the participants first performed three blocks under condition A (top button = right index finger, and bottom button = left index finger) whereas the other participants first performed under condition B (top button = left index finger, and bottom button = right index finger). After three blocks participants were asked to change the hand-to-button mapping whereas the hand-to-parity mapping persisted throughout a session (see Appendix for the verbatim instruction).

Data Analyses Overall 2.94 % of all trials were excluded from further analyses. Mean RTs and arcsin ($\sqrt{p}$) error rates were subjected to a 5 x 2 x 2 x 2 repeated measures ANOVA with four within-subject factors: magnitude bin (5: 0/1, 2/3, 4/5, 6/7, 8/9), parity (2: odd vs. even), button-location (2: top vs. bottom), and responding hand (2: left vs. right).

Results

Response Times

Mean RT equaled 520 ms. Three of the four main effects were significant. First, responses to magnitude bin 0/1 (529 ms) and 8/9 (525 ms) were slower than responses to the other magnitude bins [2/3: 514 ms, 4/5: 514 ms, 6/7: 516 ms; $F(4,92) = 11.44$,

MS_e = 841.86]. Second, responses to even digits (514 ms) were faster than responses to odd digits [525 ms; $F(1,23)$ = 18.33, MS_e = 1449.11]. Third, top responses (514 ms) were faster than bottom responses [525 ms; $F(1,23)$ = 24.92, MS_e = 1117.11]. As in Experiment 1, hand did not exert a main effect per se [$F(1,23)$ = 2.55, MS_e = 2783.85, p > .12]. Furthermore, we found two significant interactions. Magnitude bin interacted with parity: within the bin 6/7 responses to the even digit (6) were slower than responses to the odd digit (7) whereas within all other bins the opposite pattern was found [$F(4,92)$ = 9.70, MS_e = 1329.62].

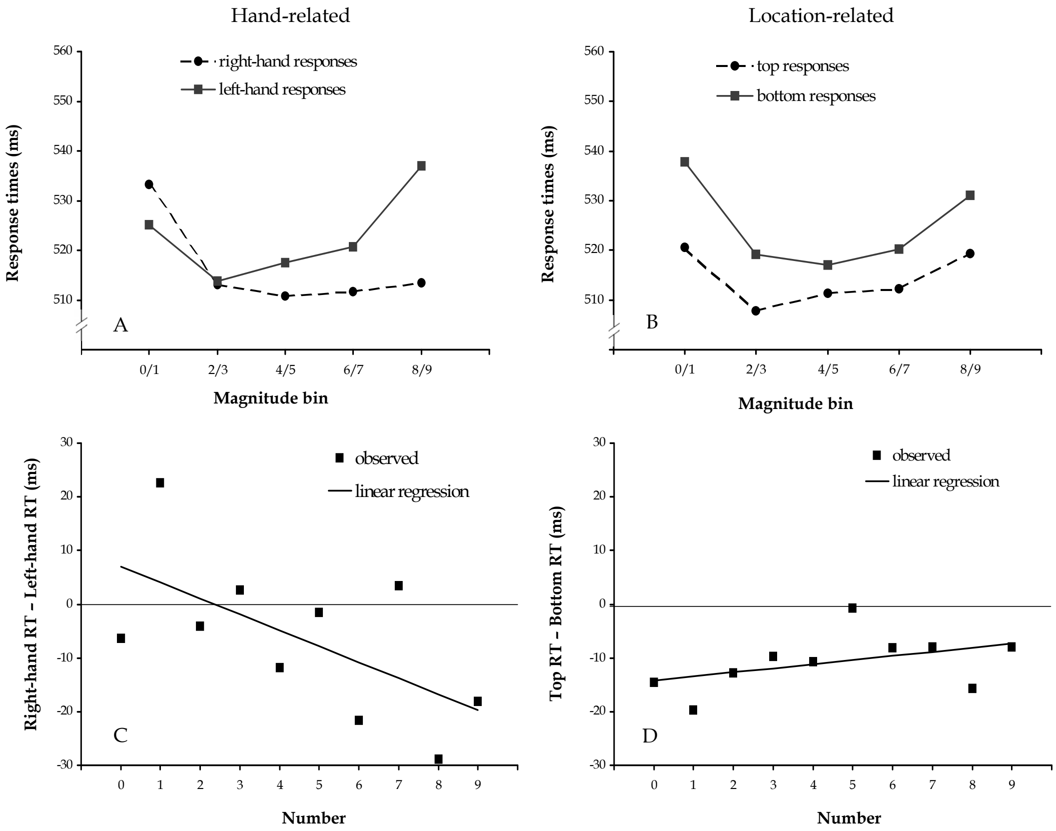

Figure 2
a. Mean response times (in ms) for right-hand (dots) and left-hand (squares) responses as a function of magnitude bin.
b. Mean response times (in ms) for top-button (dots) and bottom-button (squares) responses as a function of magnitude bin.
c. Observed differences (squares) of right-hand and left-hand response times (in ms) and regression of RT differences (dRT) on the number presented (solid line; dRT = –2.96 * digit + 7.03).
d. Observed differences (squares) of top-button and bottom-button response times (in ms) and regression of RT differences (dRT) on the number presented (solid line; dRT = 0.77 * digit – 14.22).

Second, and most important for the present study, we found a significant interaction of magnitude bin and responding hand, i.e., a hand-related SNARC effect obtained: smaller numbers were responded to faster with the left hand whereas larger numbers were responded to faster with the right hand [$F(4,92)$ = 4.26, MS_e = 1523.19, see Figure 2a]. We did not obtain a location-related SNARC effect, i.e. a significant interaction of magnitude bin and button-location [$F(4,92)$ = 1.48, MS_e = 609.13, p > .21, see

Figure 2b]. The triple interaction of magnitude bin, button-location and responding hand also clearly failed to reach significance ($F < 1$).

To further quantify the hand-related SNARC effect, right-hand RTs minus left-hand RTs and top-button RTs minus bottom-button RTs were regressed on the numerical value of the digits. Across all participants, the difference of right-hand RT minus left-hand RT decreased by 2.98 ms per digit [$t(23) = -2.20$, $SEM = 1.35$, see Figure 2c]. In contrast, we did not find a significant decrease of top-button minus bottom-button RTs [$b = .76$, $t(23) = 1.09$, $SEM = .70$, $p > .28$, see Figure 2d].

Error Rates

Mean error rate was 2.43 %. Only magnitude bin showed a significant main effect: most errors were made within the magnitude bins 0/1 (2.89 %) and 8/9 (2.80 %), relative to the other bins [2/3: 2.34 %, 4/5: 1.82 %, 6/7: 2.30 %; $F(4,92) = 2.99$, $MS_e = 0.0037$]. Moreover, two significant interactions were found. First, magnitude bin interacted with parity [$F(4,92) = 3.39$, $MS_e = 0.0066$] describing a pattern analogous to RT. Second, we found an interaction of magnitude bin and responding hand: more errors were made when a smaller number required a right-hand response whereas for larger numbers more errors were made when they required left-hand responses [$F(4,92) = 3.55$, $MS_e = 0.0060$]. Per digit the difference of right minus left-hand error rates decreased by 0.23 %, the slope was marginally significant [$t(23) = -2.06$, $SEM = 0.0026$, $p = .051$[3]].

Again, we did not find an interaction of magnitude bin and button-location ($F < 1$). A regression analysis confirmed this pattern: the difference of top-button minus bottom-button error rates did not change significantly per digit [$b = 0.09$ %, $t(23) = 1.20$, $SEM = 0.0014$, $p > .24$]. The interaction of magnitude bin, button-location and responding hand was not found significant ($F < 1$).

Discussion

In Experiment 2 parity was consistently mapped to participants' hands within a given session; thus the instruction focused on the spatial dimension of the participants' hands. We obtained a hand-related SNARC effect: smaller numbers were responded to faster with the left hand and more errors were made when they required right-hand responses. Conversely, larger numbers were responded to faster with the right hand and more errors were made when they required left-hand responses. In contrast to

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[3] Here and in the following sections t-values and SEM refer to regression analyses with transformed error rates.

Experiment 1, button-location did not modulate this SNARC effect. This is an important finding as it reveals that numbers are not exclusively represented in extracorporal space but can be linked to hands as well; i.e., the SNARC effect also comprises a spatio-anatomical component.

Taken together, the results of Experiment 1 and 2 show that instructions exert a powerful influence on the SNARC effect at least for vertically arranged buttons. Moreover they reveal that with vertically arranged buttons, numbers can be associated with hands as predicted by the hierarchical model. We will address the implications of Experiment 1 and 2 in more detail in the General Discussion. At this point, however, the question arises whether the standard SNARC effect with horizontally arranged buttons can similarly be modulated by the instruction. Dehaene et al. (1993) already showed in a crossed hands experiment that the horizontal SNARC effect is button- rather than hand-related. We next asked if a hand-related SNARC effect with horizontally arranged buttons occurs if the instruction emphasizes the spatial dimension of participants' hands.

Experiment 3

In the third experiment participants had to indicate the parity status of a digit by pressing the left or right button with uncrossed as well as crossed hands. Similar to Experiment 2, we emphasized the spatial dimension of the participants' hands, rather than those of the response buttons. Therefore, for each participant the parity-to-hand mapping was fixed throughout a session whereas the hand-to-button mapping changed after three of six blocks.

Method

Participants Twenty-four participants took part in this experiment.

Stimuli and Apparatus Left and right response buttons were arranged horizontally, at a distance of approximately 40 cm.

Procedure Participants performed two sessions on two different days. For a given participant in each session one mapping was realized: right (left) hand responses to odd (even) digits or vice versa. The parity-to-hand mapping did not change within one session. Half of the participants first performed three blocks in normal hand position whereas the other participants first performed three blocks with crossed hands. After three blocks participants were asked to change the hand-to-button mapping (see Appendix for the verbatim instruction).

Data Analyses Overall 1.31 % of all trials were excluded from further analysis. Mean RTs and arcsin ($\sqrt{p}$) error rates were subjected to a 5 x 2 x 2 x 2 repeated measures ANOVA with four within-subject factors: magnitude bin (5: 0/1, 2/3, 4/5, 6/7, 8/9), parity (2: odd vs. even), button-location (2: left vs. right), and responding hand (2: left vs. right).

Results

Response Times

Mean RT equaled 527 ms. All four main effects were significant. Responses to magnitude bins 0/1 (534 ms) and 8/9 (535 ms) were slower than responses to the three other bins [2/3: 520 ms, 4/5: 523 ms, 6/7: 520 ms; $F(4,92) = 10.25$, $MS_e = 1027.872$]. Again, responses to even digits (521 ms) were faster than responses to odd digits [532 ms; $F(1,23) = 20.44$, $MS_e = 1228.63$]. Moreover, right-side responses (517 ms) were faster than left-side responses [536 ms; $F(1,23) = 36.06$, $MS_e = 2389.28$] and right-hand responses (520 ms) were faster than left-hand responses [533 ms; $F(1,23) = 7.62$, $MS_e = 5637.42$]. These main effects were modulated by an interaction of button-location and responding hand: left-hand responses were faster when this hand deflected the left button, and right-hand responses were faster with the right button [$F(1,23) = 54.19$, $MS_e = 4891.70$]. Thus, uncrossed responses (510 ms) were faster than crossed responses (543 ms). This pattern was more pronounced for odd digits, resulting in a three-way interaction of parity, button-location and responding hand [$F(1,23) = 10.74$, $MS_e = 640.84$]. Additionally, magnitude bin interacted with parity: overall, responses to even digits were faster than to odd digits, except for magnitude bin 6/7, here responses to the odd digit 7 were faster than to the even digit 6 [$F(4,92) = 8.51$, $MS_e = 1174.82$].

Most relevant for the present study, magnitude bin interacted with button-location; i.e., a location-related SNARC effect obtained [$F(4,92) = 8.79$, $MS_e = 776.33$; see Figures 3a,b]. However, we did not find a simple interaction of magnitude bin and responding hand nor did we find a triple interaction of magnitude bin, button-location, and responding hand [$F(4,92) = 1.26$, $MS_e = 922.16$, $p > .29$, and $F < 1$, respectively]. To further quantify the location-related SNARC effect we regressed right-side minus left-side RTs on the numerical magnitude of the digit presented.

Overall, we found a decrease of RT differences of 3.84 ms per digit [$t(23) = -5.03$, $SEM = .76$]. Specifically, for uncrossed responses the difference between right- and left-side RT decreased by 3.07 ms per digit [$t(23) = -2.14$, $SEM = 1.43$, see Figure 3c]. In the crossed condition we found a decrease of RT difference of 4.61 ms per digit [$t(23) = -4.57$, $SEM = 1.01$, see Figure 3d]. These two regression slopes did not differ [$t(23) = -1.54$, $SEM = 1.95$, $p > .43$].

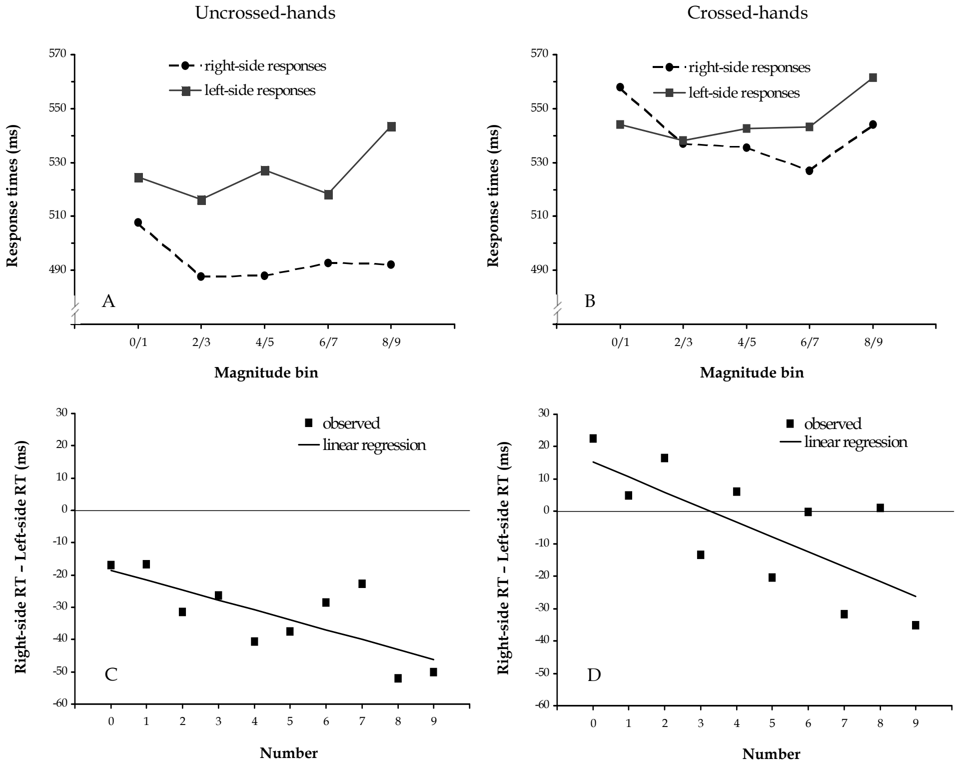

Figure 3
a. Uncrossed hands: Mean response times (in ms) for right-side (dots) and left-side responses (squares) as a function of magnitude bin.
b. Crossed hands: Mean response times (in ms) for right-side (dots) and left-side responses (squares) as a function of magnitude bin.
c. Uncrossed hands: Observed differences (squares) of right-side and left-side response times (in ms) and regression of RT differences (dRT) on the number presented (solid line; dRT = −3.07 * digit − 18.52).
d. Crossed hands: Observed differences (squares) of right-side and left-side response times (in ms) and regression of RT differences (dRT) on the number presented (solid line; dRT = −4.61 * digit + 15.20).

Error Rates

Overall 1.83 % of all trials were answered incorrectly. Most errors were made within the magnitude bins 0/1 (2.14 %) and 8/9 (2.17 %) in comparison to the other three magnitude bins [2/3: 1.72 %, 4/5: 1.63 %, 6/7: 1.48 %; $F(4,92) = 3.12$, $MS_e = 0.0088$]. Moreover, left-side responses were more error prone than right-side responses [2.18 % vs. 1.48 %; $F(1,23) = 11.95$, $MS_e = 0.0011$]. In line with RT results we found an interaction of magnitude bin and parity, which refers to the same pattern as described for RT results [$F(4,92) = 6.71$, $MS_e = 0.0011$]. We did not find an interaction of magnitude bin and button-location [$F(4,92) = 1.29$, $MS_e = 0.0012$, $p > .27$]. Similarly, the interaction of magnitude bin and responding hand did not reach significance [$F(4,92) = 1.09$, $MS_e = 0.0096$, $p > .36$]. Also, the triple interaction of magnitude bin, button-location, and responding hand did not obtain ($F < 1$). In line with these results none of the regression slopes was found significant (overall: $p > .14$; uncrossed hands: $p > .14$; crossed hands: $p > .44$).

Discussion

In Experiment 3 participants performed a parity-judgment task with horizontally arranged buttons and crossed or uncrossed hands. Parity was consistently mapped to a specific hand within one session to ensure that participants focus on their hands rather than on the location of the button. We aimed to evaluate if the instructional emphasis on the left and right hand also modulates the horizontal SNARC effect.

Despite this emphasis we found clear evidence for a location-related SNARC effect: smaller numbers were responded to faster with the left-side button and vice versa for larger numbers. This pattern was evident for uncrossed hands as well as crossed hands, thus the responding hand did not modulate the SNARC effect in this setting. Our results, therefore, clearly confirm and extend previous findings of Dehaene et al. (1993). Specifically, we show that the standard SNARC effect with horizontally arranged buttons is not modulated by the instructions: the extracorporal space determines the SNARC effect. However, we found considerably slower overall response times for the crossed hands condition compared to responses with uncrossed hands. Following Umiltà and Nicoletti's (1990; see also Nicoletti et al., 1984) reasoning, this specific aspect indicates that the SNARC effect comprises an extracorporal space component but also a separate spatio-anatomical component. With crossed hands a conflict might arise between these two components which is ultimately settled by the space-related representation but only at the cost of longer response times.

General Discussion

Before we discuss findings which are specific to the SNARC effect, it is well worth to look at general effects consistently seen in all three experiments. First, we obtained main effects of magnitude bin, mainly due to slower responses to the magnitude bins 0/1 and 8/9. Relatively slow RTs for the magnitude bin 0/1 are in part caused by participants' unfamiliarity with the parity status of digit zero (cf. Dehaene et al., 1993; Fischer et al., 2004). Furthermore, within the other magnitude bins the odd digits three, five and seven are all prime numbers whereas digit nine is not, probably yielding longer RTs for the magnitude bin 8/9 (cf. Dehaene et al., 1993; Keus & Schwarz, 2005). Next, responses to even digits were faster overall than responses to odd digits. There is considerable evidence, that this so-called odd-effect (Hines, 1990) is based on a quicker retrieval of the linguistically non-marked word "even" compared to the marked word "odd". Linguistic markedness means that in some languages, such as German, for complementary adjectives (e.g. odd – even) the marked word is determined by a prefix, negating the original unmarked word [e.g., German: even = "gerade" (nonmarked) and odd = "un-gerade", i.e. un-even (marked); see Nuerk, Iversen, & Willmes, 2004]. A consistent exception to this odd-effect occurs with the magnitude bin 6/7 for which shorter RTs are found with the digit 7 (for similar results, see Berch, Foley, Hill, & McDonough Ryan, 1999; Dehaene et al., 1993; Schwarz & Müller, 2006). One explanation is that the digit 7 is represented as a prototypic odd number, yielding shorter response times. On the other hand, in contrast to all other even digits, the digit six is not part of the salient mental category "power of two" (Dehaene et al., 1993; Shepard, Kilpatric, & Cunningham, 1975).

The SNARC effect as originally reported by Dehaene et al. (1993) refers to the fact that smaller numbers are responded to faster with buttons placed on the left side, and larger numbers are responded to faster with buttons placed on the right side. These authors originally suggested that this effect exclusively relies on the extracorporal spatial layout of the response buttons. We conducted three experiments to test and to evaluate this suggestion. In Experiments 1 and 2 participants indicated the parity status of visually presented digits with vertically arranged buttons. In Experiment 1 we strongly emphasized the spatial layout of the response buttons. With this task set, we obtained a vertical location-related SNARC effect, confirming similar results by Ito and Hatta (2004). In Experiment 2 we changed the instructions and strongly emphasized the spatial dimensions of the participants' hands. With this task set, we found a hand-related, but no location-related SNARC effect. This is an important finding: it shows that numbers are not only represented in terms of extracorporal space but are also related to the specific spatial representation of our hands. Although other authors have theoretically considered such an association (Dehaene et al., 1993; Hubbard et al., 2005; Ito & Hatta, 2004), the results of the present study provide the first direct empirical evidence for a specific association of numbers to hands. In contrast, the standard horizontal SNARC effect (Experiment 3) remains location-specific, not hand-specific, even with an instruction stressing the parity-to-hand mapping.

Our results support the hierarchical model according to which the SNARC effect comprises a spatio-anatomical and an extracorporal component. As hypothesized in the Introduction, the dominance of one component depends partly on the arrangement of the response buttons and partly on the instructional design. With vertically arranged buttons, it seems that numbers are not automatically related to the vertical extracorporal space, or to hands per se. Rather, in this condition the SNARC effect is determined by the task set created in the experiment. With horizontally arranged buttons, numbers seems rigidly associated with the extracorporal space occupied by the response buttons, and the mental representation which codes numbers in coordinates of extracorporal space then dominates the spatio-anatomical component. A likely reason for this dominance is that in this condition the response buttons provide consistent spatial information of what is left and what is right. Note that in crossed hands experiments the spatial information provided by the hands is variable and inconsistent. That is, although the right hand is absolutely represented on the anatomical right side, it is in relative terms on the left side because it is the left button that it deflects.

More generally, our results, especially those of Experiment 1 and 2, reveal that the mental representation of, and responses to, numbers are strongly influenced and modified by the specific conditions and contexts in which numerical information is presented. This conclusion is supported, for example, by a recent study by Fischer, Dewulf, and Hill (2005) who observed shorter decision times for vertically oriented bar graphs compared to horizontally oriented bar graphs. Similarly, Bächtold et al. (1998) showed that when participants imagined an analog clock, then smaller numbers (such as three) are associated with the right side of space and larger numbers (such as nine) are associated with the left side of space, exactly contrary to the standard pattern of SNARC findings. Studies like these can help in finding and creating experimental conditions and practical contexts which facilitate processing of, and responding to, numerical information.

Our findings also support the idea that numbers are not exclusively represented along a left-to-right mental number line. At the same time, our results suggest that a left-to-right ordering of numbers is more natural than a bottom-to-top ordering which, in a vertical task setting, permits numbers to be related to the space occupied by the participants' hands. One likely explanation for this finding is that the spatial orientation of the mental number line is determined by the reading (scanning) habits (Dehaene et al., 1993; Gevers & Lammertyn, 2005; Maass & Russo, 2003; Tversky, Kugelmass, & Winter, 1991). The fact that many western cultures read and write from left to right could imply that numbers are preferentially encoded in a horizontal left-to-right manner rather than in a vertical fashion. Recently, for example, Turconi, Campell, and Seron (2006) reported that ascending pairs of numbers (e.g., 2 5) which conform to a left-to-right mental number line are processed faster than descending pairs (e.g., 5 2). Zebian (2005) directly compared participants adapted to different writing systems. Her results suggest that Arabic Monoliterates, who write from right-to-left, also represent numbers in that direction (reverse SNARC effect; see also Dehaene et al., 1993). For example, Arabic Monoliterates are faster in comparing number pairs which are presented in a descending order (such as 9 1) rather than in an ascending order (such as 1 9). More cross-cultural studies are required which attempt to evaluate the automatic access to the mental number line, for example by using paradigms in which the numerical magnitude is task-irrelevant (such as parity judgments). Such studies might lend further support to the hypothesis that the association of numbers and space is an example of how language can shape abstract thought (see also Boroditsky, 2001).

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Appendix

Instruction Experiment 1

In this experiment your task is to decide if a visually presented digit is even (digits 0, 2, 4, 6, and 8) or odd (digits 1, 3, 5, 7, and 9). If a digit is even then you always have to press the top button. If the digit is odd then you always have to press the bottom button, regardless of the specific index finger deflecting this button. Thus, the mapping of odd/even to the buttons remains the same throughout the entire session. However, the mapping of the hands to the buttons changes after each block. Specifically, in the first block, your left index finger deflects the top button, and your right index finger deflects the bottom button. In the second block, the left index finger deflects the bottom button, and the right index finger the top button, and so forth. But remember, throughout the entire session the top button is the correct response to the even digits, and the bottom button is the correct response to the odd digits.

Instruction Experiment 2

In this experiment your task is to decide if a visually presented digit is even (digits 0, 2, 4, 6, and 8) or odd (digits 1, 3, 5, 7, and 9). If a digit is even then you always have to respond with your left index finger. If the digit is odd then you always have to response with your right index finger, regardless of the specific button this finger deflects. Thus, the mapping of odd/even to the index finger remains the same throughout the entire session. The mapping of the hands to the buttons changes after three block. Specifically, in the first three blocks, your left index finger deflects the top button, and your right index finger deflects the bottom button. In the last three blocks, the left index finger deflects the bottom button, and the right index finger the top button. But remember, throughout the entire session the left index finger responses correctly to the even digits, and the right index finger to responses correctly to the odd digits.

Instruction Experiment 3

In this experiment your task is to decide if a visually presented digit is even (digits 0, 2, 4, 6, and 8) or odd (digits 1, 3, 5, 7, and 9). If a digit is even then you always have to respond with your left index finger. If the digit is odd then you always have to response with your right index finger, regardless of the specific button this finger deflects. Thus, the mapping of odd/even to the index finger remains the same throughout the entire session. The mapping of the hands to the buttons changes after three block. Specifically, in the first three blocks, your left index finger deflects the left button, and your right index finger deflects the right button (uncrossed hands condition). In the last three blocks, the left index finger deflects the right button, and the right index finger the left button (crossed hands condition). But remember, throughout the entire session the left index finger responses correctly to the even digits, and the right index finger responses correctly to the odd digits.

CHAPTER 4

EXPLORING THE MENTAL NUMBER LINE: EVIDENCE FROM A DUAL–TASK PARADIGM

Abstract

In a parity–judgment task smaller numbers are responded to faster with the left–hand key and vice versa for larger numbers (SNARC effect; Dehaene, Bossini, & Giraux, 1993). We used the psychological refractory period paradigm involving a parity–judgment task and tone–discrimination task to address the question at which stage this effect arises. When the parity–judgment task is performed second, then we found equal SNARC effects for the short and the long SOA. According to the central bottleneck model, this indicates that the effect arises during the response–selection or execution stage. In Experiment 2 the parity–judgment task was performed first. The pattern of results indicates that the SNARC effect originates during the perceptual encoding or response–selection. Together, our results suggest that the SNARC effect originates while the response is selected.

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Introduction

An at least rudimentary preverbal sense of number and numerosity has been ascribed not only to humans but also to a wide range of animals such as pigeons, rats, dolphins, and monkeys (for summaries see Brannon, 2005; Campbell, 2005; Dehaene, 1997; Dehaene, Molko, Cohen, & Wilson, 2004; Gallistel & Gelman, 2000). Part of this evidence, such as the numerical distance effect (Moyer & Landauer, 1967), suggests that humans and animals represent numerical magnitudes in an analog fashion, along a mental number line. On this mental number line numbers seem internally ordered in a continuous manner (Dehaene, 1997; Restle, 1970). The so-called Spatial Numerical Association of Response Codes (SNARC) effect further suggests that the mental number line is spatially oriented from left-to-right; i.e., smaller numbers are represented on the left side and larger numbers on the right side (Dehaene, Bossini, & Giraux, 1993; see also e.g., Zorzi, Priftis, & Umiltà, 2002). Dehaene et al. (1993) asked their participants to indicate the parity status of visually presented digits (0-9) by left-side or right-side responses. Although numerical magnitude was in principle irrelevant in this task, yet it influenced performance: smaller numbers were responded to faster with the left-hand key whereas larger numbers were responded to faster with the right-hand key. Subsequent research explored basic characteristics and boundary conditions of the SNARC effect. For example, the SNARC effect is effector-independent (Fischer, Warlop, Hill, & Fias, 2004; Schwarz & Keus, 2004; Schwarz & Müller, 2006), and is found with various tasks other than parity judgments, such as phoneme monitoring and orientation identification (Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; Fias, Lauwereyns, & Lammertyn, 2001; see e.g. Gevers, Reynvoet, & Fias, 2003; Mapelli, Rusconi, & Umiltà, 2003 for further extensions of the effect, and Hubbard, Piazza, Pinel, & Dehaene, 2005 and Fias & Fischer, 2005 for recent summaries).

An issue that is more controversial is at which stage(s) of information processing the effect arises. For example, evidence for an early (perceptual) locus of the SNARC effect comes from a study of Fias et al. (2001). When participants were asked to manually indicate the color of a visually presented digit then the standard SNARC effect did not obtain. In contrast, the effect did show up when participants determined the orientation of triangles or line segments which were superimposed onto a digit. The authors argue that the overlap of the neural pathways for the relevant feature (such as color or orientation) and the irrelevant feature (numerical magnitude) determines the manifestation of the

SNARC effect. Fias et al. (2001) conclude that "the SNARC effect must have emerged at a stage of information processing before motor control, that is, while encoding perceptual/cognitive representations" (p. 421; see Fischer, Castel, Dott, & Pratt, 2003; Mapelli et al., 2003; Tlauka, 2002 for further related evidence).

In contrast, other authors have claimed a relatively late (response-related) functional locus of the effect (Fischer, 2003; Otten, Sudevan, Logan, & Coles, 1996; Fias, 2001, Keus & Schwarz, 2005). For example, Fischer (2003) asked participants to move their index finger to the left or right side of a touch screen to indicate the parity status of a digit. A significant interaction of numerical magnitude and response side was found for the motor movement time which points to a late locus of the SNARC effect (see also Caessens, Hommel, Reynvoet, & van der Goten, 2004, for similar conclusions). Keus and Schwarz (2005) recently showed that simply presenting small vs. large digits in the left vs. right visual field does not induce a SNARC-like effect for vocal responses and therefore also rejected a purely perceptual locus of the SNARC effect. Moreover, a study examining the lateralized readiness potential provided additional psychophysiological support for the view that the effect arises at a response selection stage of information processing (Keus, Jenks, & Schwarz, 2005; see also Gevers, Ratinckx, De Baene, & Fias, 2006).

To help resolving these conflicting views we conducted two experiments with the aim to determine, or at least to confine, the locus (or loci) of the SNARC effect. To this end, we used a well-established diagnostic tool – the so-called psychological refractory period (PRP) paradigm for dual-task situations which we adapted to the SNARC effect.

Psychological Refractory Period (PRP) Paradigm

In the PRP paradigm participants are asked to perform two tasks in rapid succession (Pashler, 1994; Pashler, 1998). For this purpose, two stimuli, S_1 and S_2, are presented to the participant, separated by some stimulus onset asynchrony (SOA). Often, one stimulus is auditory and one is visual, and both require speeded choice responses (R_1 and R_2). A major finding with the PRP paradigm is that the response time to the second stimulus (RT_2) decreases with increasing SOA: responses to the second task require more time if S_2 immediately follows S_1 (short SOA), compared to a longer SOA (the PRP effect; Telford, 1931; McCann & Johnston, 1992; Pashler, 1984; Pashler, 1993a,b).

A major account of the PRP effect is the central bottleneck model (see Pashler & Johnston, 1998 for a review of this model and the evidence supporting it; for alternative conceptualizations, see Tombu & Jolicœur, 2003, 2005). In short, the central bottleneck model is based on the assumption that information processing can be subdivided into three serially organized subprocesses (Sternberg, 1969). First, the stimulus is identified and encoded (perceptual stage, P). Next, the response that is appropriate for that stimulus is selected (central stage, C). Finally, the selected response is initiated and executed (response execution stage, M). According to the central bottleneck model the perceptual and the motor stage of the two tasks can be carried out in parallel. However, the central stages of the two tasks can not be performed simultaneously, leading to a (central) bottleneck. According to this assumption, the response for the second task can not be selected before the response–selection stage for the first task has been finished. Therefore, a waiting period (slack) for Task–2 may arise which increases with decreasing SOA (Pashler, 1993b for a summary, or Schwarz & Ischebeck, 2001, for a detailed stochastic analysis of this model; see also Figures 1 and 2). These assumptions enable the prediction of effects on RT_1 or RT_2 of experimental manipulations which selectively affect one of the processing stages in either task. We next describe two of these predictions which are of crucial importance for the present study.

First, at short SOA experimental manipulations of Task–2 which influence the perceptual (i.e., pre–bottleneck) stage do not fully propagate onto RT_2 (see Figure 1a). The reason is that the completion of the second task has to wait until the response to S_1 is selected; thus, a prolonged duration of the perceptual stage in Task–2 is partly (or even fully) absorbed in this “slack”, leading to an underadditive joint effect of SOA and the factor prolonging stage P_2 (Pashler & Johnston, 1998; Schweickert, 1978; see also, de Jong, 1993; Schwarz & Ischebeck, 2001). In contrast, experimental manipulations affecting the Task–2 stages at (stage C_2) or after (stage M_2) the central bottleneck do fully propagate onto RT_2 (see Figure 1b).

Second, the central bottleneck model implies that RT_2 also depends on factors which selectively influence the duration of the processing stages of Task–1. If, at short SOA, the Task–1 perceptual or central stage (i.e., before/at the central bottleneck) is prolonged, then the waiting period for Task–2 (and thus RT_2) increases (cf. Smith, 1969). However, manipulations which affect the Task–1 motor stage (M_1) would not increase RT_2 because the motor stage only starts after the central bottleneck is left.

The central bottleneck model thus allows for some specific predictions, which depend critically on the assumed locus of a given experimental effect. We therefore combined in the two experiments presented below the PRP paradigm with the SNARC effect in two ways which correspond to the two effects outlined above. First, in the so-called locus-of-slack paradigm (cf. Miller & Reynolds, 2003, p. 1129) the to-be-localized effect is related to the second task. With respect to the present study this refers to the standard parity-judgment task which induces the SNARC effect. In this design, in any given trial the digit is preceded by a high or low tone which requires a vocal choice response. Second, in the so-called effect-propagation paradigm (cf. Miller & Reynolds, 2003, p. 1130) the parity-judgment task is performed first and the tone-discrimination task second. In both experiments RT in Task-2 is of crucial importance, and the specific SNARC-related predictions are described in the following sections.

The SNARC Effect and the Locus-of-Slack Paradigm

In the locus-of-slack paradigm the task which contains to the to-be-localized effect is performed second. In the experiments described below, we used an auditory discrimination as the first task. Following a short or a long SOA a digit was then visually presented. Participants were asked to respond vocally to the pitch of the tone, and then to indicate manually the parity status of the digit. In this experiment we are mainly interested in the time required to respond to the parity of a digit as a function of the SOA. With respect to the general predictions described above, this setting allows for discriminating between an early perceptual locus (P) of the SNARC effect, and a later locus that is related to either selecting (C) or executing (M) the response. In a parity-judgment task, the digit and its parity status is identified in the perceptual stage. In the central stage, the response associated with this parity status is selected; for example, an odd digit is mapped to the right button. Finally, during the motor stage, the chosen response is manually executed. Figures 1a and 1c depict the predictions if the SNARC effect is localized at the perceptual stage of information processing. SNARC effect "compatible" digits refer to trials in which smaller numbers require a left-key press, or larger numbers require a right-key press. In contrast, SNARC effect "incompatible" digits refer to trials in which smaller numbers require a right-key press, or larger numbers require a left-key press. If the SNARC effect arises at the pre-bottleneck perceptual stage, then the time to identify incompatible digits should be prolonged, relative to compatible digits. However, as described above at short SOA these differences should not fully propagate onto Task-2 response times. Specifically, differences in the identification of compatible vs. incompatible digits would partly or even fully be absorbed in the cognitive slack so that SOA and compatibility show underadditive effects (see Figure 1a). In contrast, at long SOA a waiting period for Task–2 is less likely to arise because the response in Task–1 should often already be selected by the time the digit is identified. Under this scenario, perceptual differences between compatible and incompatible digits should fully propagate onto RT_2 (see Figure 1c). Thus, if the SNARC effect arises at the perceptual stage, we would predict a smaller (or even no) SNARC effect for the short SOA, compared to the long SOA, so that the SNARC effect should interact with SOA.

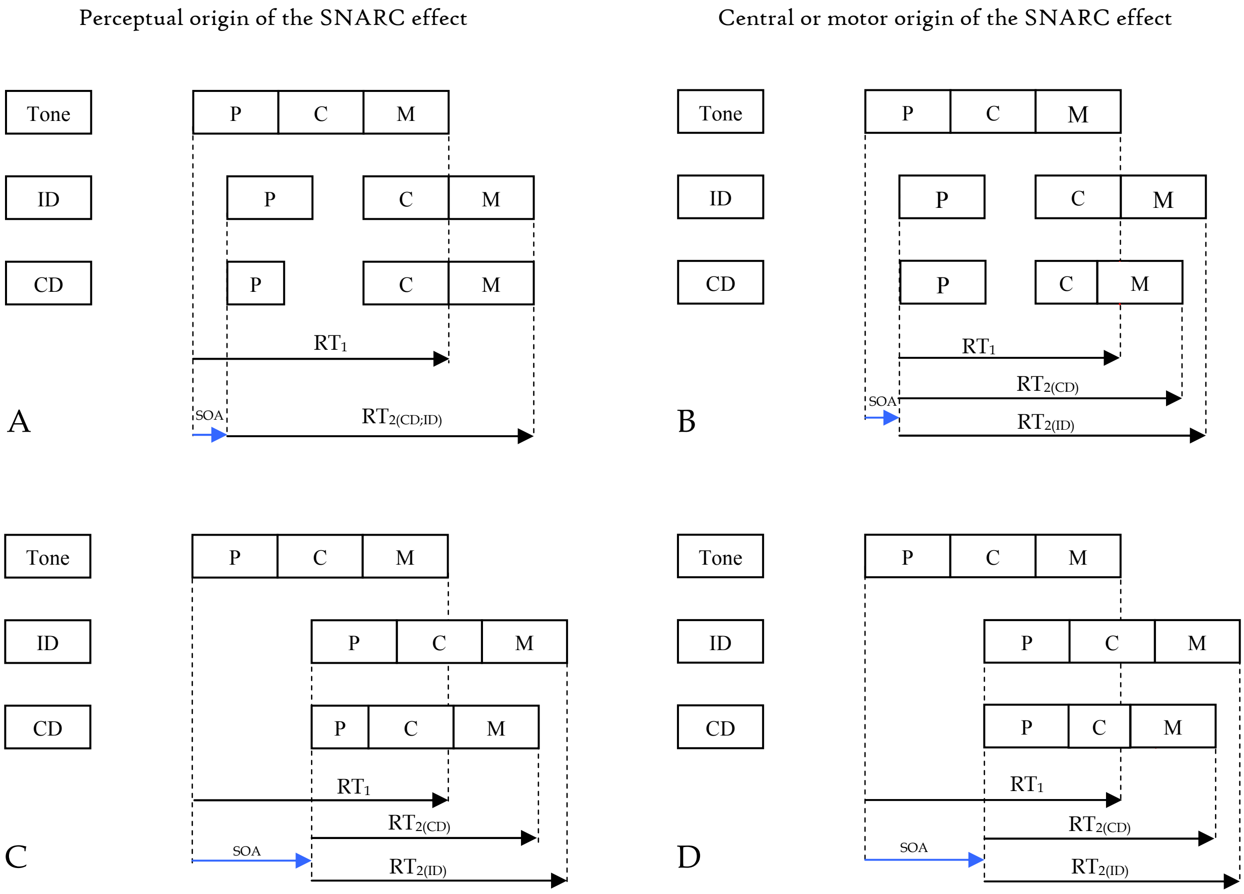

Figure 1
Predictions of the Locus–of–slack paradigm in which the parity–judgment task to induce the SNARC effect is performed second. (Note: CD = compatible digits in which, for example, a smaller number requires a left–side response; ID = incompatible digits in which, for example, a smaller number requires a right–side response).

a. Short SOA: Outcome if the SNARC effect has a perceptual locus. In this case we should not observe a SNARC effect because it is absorbed in the cognitive slack.
b. Short SOA: Outcome if the SNARC effect has a central or motor related locus. In this case we should observe a SNARC effect because C and M are placed at/after the central bottleneck.
c. Long SOA: Outcome if the SNARC effect has a perceptual locus. In this case we should observe a SNARC effect because at long SOA the response in Task–1 should often already be selected by the time the digit is identified.
d. Long SOA: Outcome if the SNARC effect has a central or motor related locus. In this case we should observe a SNARC effect.

Alternatively, the SNARC effect could arise at the stage of response selection (C), or response execution (M; Figures 1b and 1d). In this case, the overall time to select and/or to execute the response should be prolonged for incompatible digits, relative to compatible digits. Because both stages are at/after the bottleneck, any effect of the digit's compatibility should fully propagate onto the response times of Task-2, independent of the SOA. Consequently, for both SOAs a SNARC effect of the same size should obtain so that the SNARC effect should not interact with SOA (see Figures 1b,d).

In summary, the locus-of-slack paradigm enables us to discriminate between an early perceptual locus, and a central or motor-related locus of the SNARC effect. If the SNARC effect is related to the identification of the digit and its parity, then we should observe an interaction of the SNARC effect with SOA. In contrast, if the SNARC effect arises during later processing stages, then the SNARC effect and effects of the SOA should be additive.

The SNARC effect and the Effect-Propagation Paradigm

In the effect-propagation paradigm the parity-judgment is performed first and the tone-discrimination second. Specifically, first a digit is visually presented, followed after a short vs. long SOA by a high vs. low tone. Participants first indicate manually the parity status of the presented digit and then they name the pitch of the tone. The main focus of the analyses is the examination of the vocal RT as a function of the SNARC effect. This paradigm – when compared to the locus-of-slack paradigm described before – enables us to discriminate between a perceptual/central locus of the SNARC effect, and a late motor-related locus of the effect.

Figure 2a illustrates the predictions if the SNARC effect originates at the perceptual or central stage. In this case, the time to identify the digit's parity and to select the associated response is shorter for compatible than for incompatible digits. These stages are located before/at the central bottleneck and, therefore, they should often prolong the response time of the tone-discrimination task if the SOA is short. Put differently, the response for the tone-discrimination task can be selected earlier when preceded by compatible digits, relative to incompatible digits. Thus, tones preceded by compatible digits should be responded to faster than tones preceded by incompatible digits (Figure 2a). We will refer to this effect as a “SNARC-like effect”: this terminology is intended to indicate that unlike in the standard SNARC effect the critical dependent variable here is the vocal RT in the tone-discrimination task. On the other hand, at the long SOA vocal response time should be unaffected by manipulations of the parity-judgment task if the proper response in Task-1 is already selected by the time that the tone in Task-2 is perceptually identified, as is likely with long SOAs. Thus, we would not predict a SNARC–like effect for long SOAs. Taken together, if the SNARC effect arises while a digit is identified or the response is selected, then we should observe an interaction of the SNARC–like effect with SOA.

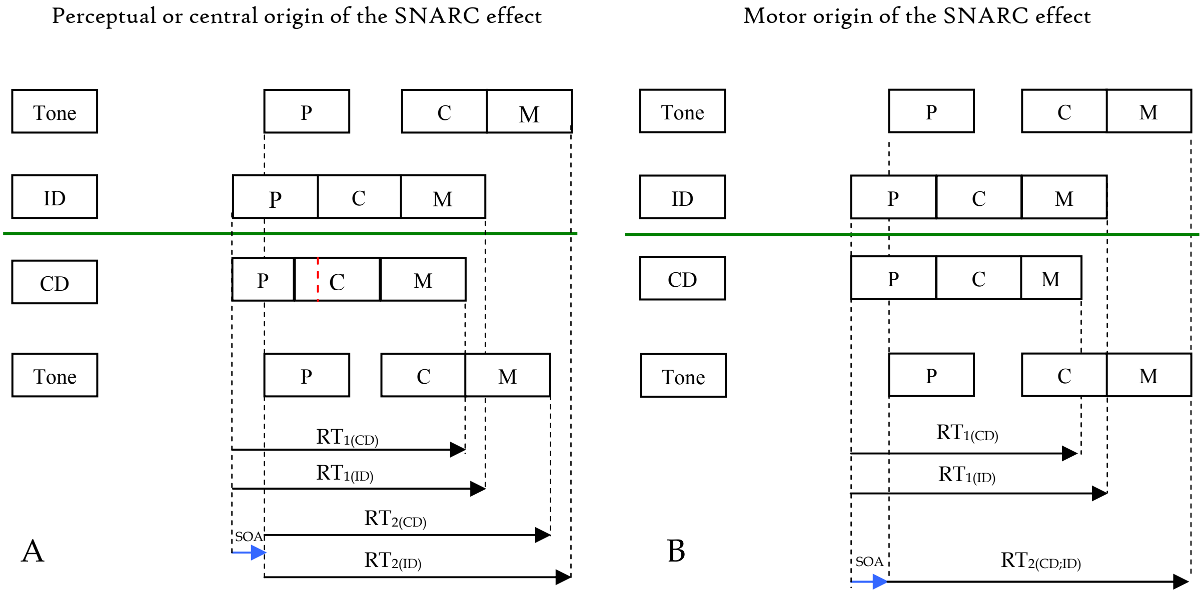

Figure 2
Predictions for the Effect–propagation paradigm in which the parity–judgment task to induce the SNARC effect is performed first. Figures shown here only represent the outcome for short SOA. For long SOA we would not predict a SNARC–like effect either for a perceptual/central or motor stage origin of the SNARC effect (see text). (Note: CD = compatible digits in which, for example, a smaller number requires a left–side response; ID = incompatible digits in which, for example, a smaller number requires a right–side response).

a. Outcome if the SNARC effect arises at the perceptual or central stage. In this case we should observe a SNARC–like effect because the waiting time for the tone is prolonged after incompatible digits compared to compatible digits in the parity–judgment task–1.
b. Outcome if the SNARC effect arises at the motor stage. In this case we should not observe a SNARC–like effect because the motor stage of Task–1 is placed after the central bottleneck and should, therefore, not affect Task–2.

Alternatively, the SNARC effect might originate later, with the execution of the manual Task–1 response. In this case, the time to execute the response to compatible digits is shorter than with incompatible digits. According to the central bottleneck model, this difference, however, should not affect Task–2 vocal RT with either SOA; thus, we should then not observe a SNARC–like effect (Figure 2b).

Finally, it is conceivable that separable components of the SNARC effect arise both at the perceptual/central stage, and during response execution. If the SNARC effect is localized at the perceptual or central stage, we should observe a SNARC–like effect, as described above. If the SNARC effect exclusively arises at one of these two stages, then the standard SNARC effect (as evidenced in the manual RT in Task–1) and the

SNARC-like effect (as evidenced in the vocal RT in Task-2) should be of similar size. On the other hand, if part of the SNARC effect additionally arises at the response execution stage, then the SNARC-like effect as seen in Task-2 should be correspondingly smaller than the standard SNARC effect in Task-1.

To recapitulate, the joint application of the locus-of-slack paradigm and the effect-propagation paradigm enables us to identify the locus of the SNARC effect. Following the locus-of-slack logic, we can discriminate between a perceptual and a central/motor related origin of the effect. Furthermore, the effect-propagation paradigm enables us to distinguish between a perceptual/central and motor stage locus of the SNARC effect.

Miller and Reynolds (2003) demonstrated the utility of the joint application of both paradigms to localize the effect of specific experimental manipulations (see also McCann, Remington, & Van Selst, 2000). These authors adapted the PRP paradigm to the redundant-target effect (RTE) which describes a “speedup of responses with multiple targets” (Miller & Reynolds, 2003, p. 1126) and the nontarget effect (NE) which refers to “the slowing of target-absent responses” (Miller & Reynolds, 2003, p. 1126). They followed the same logic as described above, and their consistent results suggest that the RTE and NE arise while a response is selected.

Closely related to the present study, Sigman and Dehaene (2005) were recently able to localize the number notation effect, the numerical distance effect, and the effect of response complexity in a number discrimination task using the PRP paradigm. Their results suggest that the number notation effect (Arabic digits vs. spelled number words) originates when the stimuli are perceptually encoded. Specifically, it takes longer to encode the numerical magnitude of a spelled number word compared to an Arabic digit. The numerical distance effect, though, originates while the response is selected; that is, the closer two digits are represented along the mental number line the longer it takes the participant to select the smaller/larger response (see also Oriet, Tombu, & Jolicœur, 2005). The manipulation of the response complexity (one vs. two taps), however, seems to affect exclusively the motor stage.

The present study seeks to utilize the PRP paradigm to improve our understanding of the nature of the SNARC effect. Specifically, we use the locus-of-slack paradigm and the effect-propagation paradigm as two variants of the general PRP setting to identify or at least to confine the functional locus of the SNARC effect.

Experiment 1

In Experiment 1 we used the locus-of-slack paradigm to discriminate between a perceptual and central/motor related origin of the SNARC effect: in a given trial participants first respond vocally to the pitch of a tone, and then indicate manually the parity of a digit. As explained above, if the SNARC effect arises while a digit is perceptually encoded, we predict a smaller SNARC effect at the short SOA, relative to the long SOA. In contrast, if the SNARC effect arises while the response to a given digit is selected or executed, we predict that the SNARC effect should not vary as function of the SOA.

Method

Participants Thirty-six students of the University of Potsdam participated in this study; they were aged between 19 and 44 years. All gave their informed consent to the experiment, had normal or corrected-to-normal eye vision and either received 6 Euro or course credit.

Stimuli and Apparatus

Tone discrimination task: A low tone with a pitch of 550 Hz or a high tone of 1050 Hz was presented stereophonically for 50 ms via headphones. Participants were asked to say the German word “Braut” (“Bride”) to the high tone and the German word “Brand” (“Fire”) to the low tone.[1] The onsets of the responses were registered to the nearest millisecond (ms) via a voice key.

Parity-judgment task: Digits 1,2,3,4 and 6,7,8,9 were presented in Times New Roman font in white against a dark background on a 480 x 640 VGA monitor. At a viewing distance of 120 cm the digits subtended a visual angle of approximately 1.4 deg in height. Participants deflected a left or right button with the corresponding index finger to indicate the parity status of the presented digit. Buttons were horizontally separated by approximately 40 cm. The onsets of manual responses were also registered to the nearest ms via the parallel port of the PC.

Procedure Each participant performed one session: half of the participants deflected the right button to even digits and the left button to odd digits; the other half used the

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[1] These words were used to ensure similar voice onset latencies for both responses.

complementary mapping. One session consisted of six blocks; the first block of 32 trials was considered practice. The remaining five blocks each of which comprised 96 trials were used for further data analyses.

Each trial started with a centrally presented fixation cross. After 1000 ms a tone was presented for 50 ms while the fixation cross was still visible. Either 50 ms (short SOA) or 400 ms (long SOA) after tone–onset the fixation cross was replaced with a single digit which disappeared following the execution of the manual response. RTs for vocal as well as for manual responses were defined as the time from the onset of the respective stimulus until the associated response was given. If the response to a digit was incorrect the word "Error" appeared for 500 ms on the screen; the next trial started about 1500 to 2000 ms after both responses were given. Participants were asked to indicate the pitch of the tone first and only then to respond to the digit. They were specifically reminded to avoid any strategic grouping of the responses. To minimize response interference, the tone required a vocal, and the digit a manual response.

Each block was followed by a self–paced break of at least 30 seconds. Within one experimental block each combination of tone pitch (2) by SOA (2) by digit (8) was presented three times in a randomized order. One session lasted about 60 minutes.

Data Analyses Participants were asked to first indicate the pitch of the tone and then to indicate the parity of the presented digit. This response order is crucial for the predictions of the central bottleneck model to hold. Therefore, trials in which participants reversed the order of responses (i.e., they first indicated the parity status of the digit and then the pitch of the tone) were discarded (4.11 %; cf. Miller & Reynolds, 2003). In a second step we excluded trials which did not meet at least one of the following criteria: vocal RT between 150 ms and 1600 ms, manual RT between 150 ms and 1800 ms (3.74 % of the remaining trials). The reason for choosing our outlier criteria was to maximize the similarity of our own procedure to that of influential other SNARC papers (Dehaene et al., 1993; Fischer, 2003; Fias, 2001; Fias et al., 1996) as well as to influential dual–task papers (Pashler, 1994; McCann & Johnston, 1992). Altogether 7.69 % of the trials were eliminated from further analyses.

Analyses of Vocal Responses (Task-1) Our equipment did not permit a separation of correct and incorrect responses; therefore, we only analyzed RT data.[2] Mean RTs for each participant were calculated and then subjected to a 2 x 2 repeated measures ANOVA with two within-subject factors: tone (2: low vs. high) and SOA (2: short vs. long).

Analyses of Manual Responses (Task-2) For manual responses we conducted a more detailed analysis in order to evaluate the SNARC effect as a function of SOA. Across all correct trials and for each participant, mean RTs were calculated and then subjected to a 4 x 2 x 2 x 2 x 2 repeated measures ANOVA with four within-subject factors: magnitude bin (4: 1/2, 3/4, 6/7, 8/9), response-side (2: left vs. right), tone (2: low vs. high), and SOA (2: short vs. long), and one between-subjects factor: group (2: right responses to odd digits: group one vs. right responses to even digits: group two).

For inferential statistics mean error rates were first transformed to arcsin ($\sqrt{p}$) values to stabilize the variances (Bishop, Fienberg, & Holland, 1975, p. 367), and then subjected to an ANOVA of the same design as RT. However, for sake of clarity descriptive statistical summaries and graphs refer to untransformed error rates.

Each participant performed one session in which the parity-to-hand mapping was fixed. Therefore, in one group all participants responded to the odd digits with their right hand and to the even digits with their left hand; this digit-to-hand mapping was reversed for the second group. To quantify the SNARC effect, we calculated the right-hand minus left-hand RT and error rate for each magnitude bin. For example, for one group we computed for the magnitude bin 1/2 the right-hand RT for digit 1 minus the left-hand RT for digit 2. For the other group we computed the right-hand RT for digit 2 minus the left-hand RT for digit 1. We then regressed, for each participant separately, the right minus left RTs and error rates on the magnitude bin presented (cf. Fias et al., 1996; Fias, 2001; Lorch & Meyers, 1990). Thus, for each participant we obtained an individual slope; the negative slope of this regression line is an efficient and sensitive index of the size of the SNARC effect (cf. Dehaene et al., 1993). The group factor showed no main or interaction effect; therefore, the mean regression slope was calculated over both groups and tested if it differed from zero. All effects were tested at a significance level of $\alpha = 0.05$.

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[2] We also conducted the experiment with six participants and manually recorded their vocal responses. The pattern of results (for both the tone-discrimination task and the parity-judgment task) obtained were the same as those reported below in which the vocal errors were included. Moreover, the vocal error rate was very low (1.35 %). We conclude that the vocal error rates do not influence the main pattern of our findings.

Results

Vocal Responses (Task–1)

Mean RT equaled 646 ms. Responses to the high tone (640 ms) were slightly faster than responses to the low tone [651 ms; $F(1,34) = 5.52$, $MS_e = 892.17$]. Also, there was a small but reliable increase of vocal RT with SOA [638 vs. 653 ms; $F(1,34) = 11.54$, $MS_e = 694.08$].

Manual Responses (Task–2): Response Times

Overall RT was 856 ms. We found a magnitude bin main effect with fastest responses to the magnitude bin 1/2 (844 ms) and slowest responses to the magnitude bin 8/9 [867 ms, 3/4: 860 ms, 6/7: 855 ms; $F(3,102) = 4.52$, $MS_e = 5452.16$]. Moreover, responses were faster in trials with a long SOA (724 ms) compared to the short SOA [989 ms; $F(1,34) = 840.39$, $MS_e = 23985.54$]. This difference of 265 ms corresponds to a mean RT decrease in Task–2 of 0.76 with increasing SOA (a slope of –1 would indicate that with a reduction of the SOA RT_2 increases correspondingly; cf. Pashler, 1998).

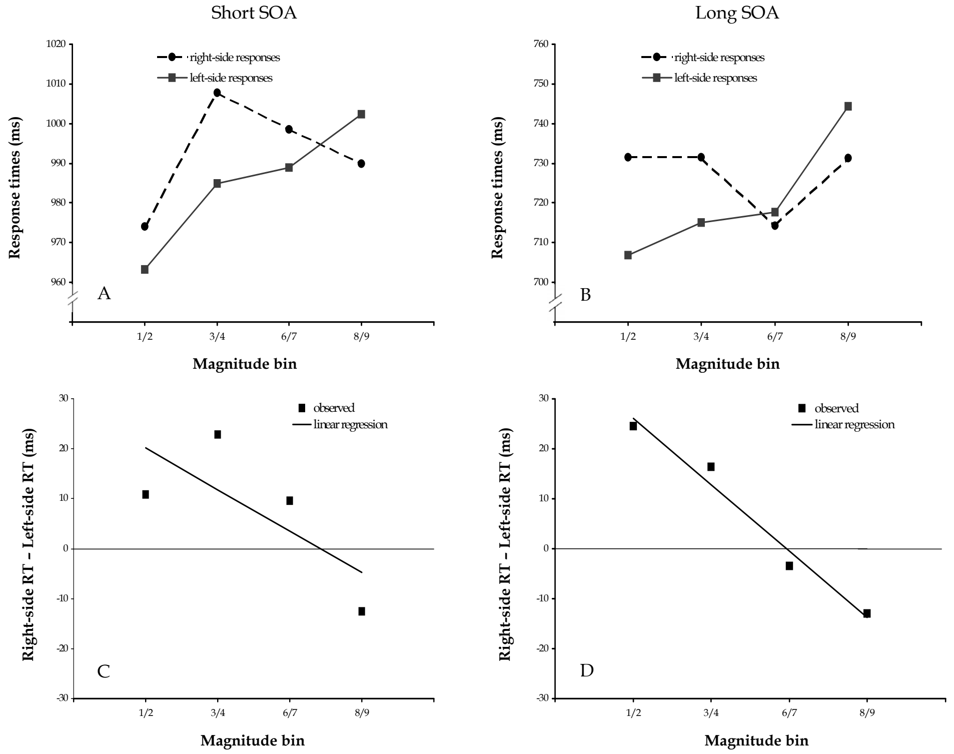

Figure 3

a. Short SOA: Mean response times (in ms) for right–side (dots) and left–side (squares) responses as a function of magnitude bin.
b. Long SOA: Mean response times (in ms) for right–side (dots) and left–side (squares) responses as a function of magnitude bin (Note that the origins of the scales of Figures 3a and 3b differ).
c. Short SOA: Observed differences (squares) of right–side and left–side RTs (in ms) and regression of RT differences (dRT) on the magnitude bin presented (solid line).
d. Long SOA: Observed differences (squares) of right–side and left–side RTs (in ms) and regression of RT differences (dRT) on the magnitude bin presented (solid line).

Most important for the purpose of this study we obtained a clear SNARC effect in Task–2: left–hand responses were faster to smaller numbers whereas right–hand responses were faster to larger numbers [$F(3,102) = 3.29$, $MS_e = 4959.77$; see Figures 3a,b]. We did not find a triple interaction of magnitude bin x button–location x SOA [$F(3,102) = 0.68$, $MS_e = 3489.25$, $p = 0.57$], indicating that the SNARC effect does not vary as a function of SOA.

To quantify the SNARC effect in more detail, we regressed, for each participant separately, right–hand RT minus left–hand RT on the magnitude bin presented (see Figures 3c,d). For the short SOA, these RT differences decreased by 8.33 ms per magnitude bin [$t(35) = -2.04$, $SEM = 4.09$; see Figure 3c]. For the long SOA, the RT differences decreased by 13.27 ms per magnitude bin [$t(35) = -2.30$, $SEM = 5.77$; see Figure 3d]. The difference between these regression slopes was far from significant [$t(35) = .78$, $SEM = 6.31$, $p = .44$].

Manual Responses (Task–2): Error Rates

Overall, 2.02 % of all trials were answered incorrectly. Most errors were made for the magnitude bin 1/2 (2.57 %), and fewest for the magnitude bin 6/7 [1.52 %, 3/4: 1.76 %, 8/9: 2.23 %; $F(3,102) = 3.67$, $MS_e = 0.0143$]. More errors were made (2.29 %) when a right–hand response was required than in trials requiring a left–hand response [1.63 %; $F(1,34) = 7.54$, $MS_e = 0.0190$].

We did not find an interaction of magnitude bin and button–location nor did we find an interaction of magnitude bin, button–location, and SOA [$F(3,102) = 1.47$, $MS_e = 0.0198$, $p = .22$, and $F(3,102) = 1.39$, $MS_e = 0.0165$, $p = .25$; see Figures 4a,b].

Regression analyses confirmed these patterns: for both SOAs regression slopes failed to reach significance (short SOA: $p = .11$; long SOA: $p = .42$; see Figures 4c,d).

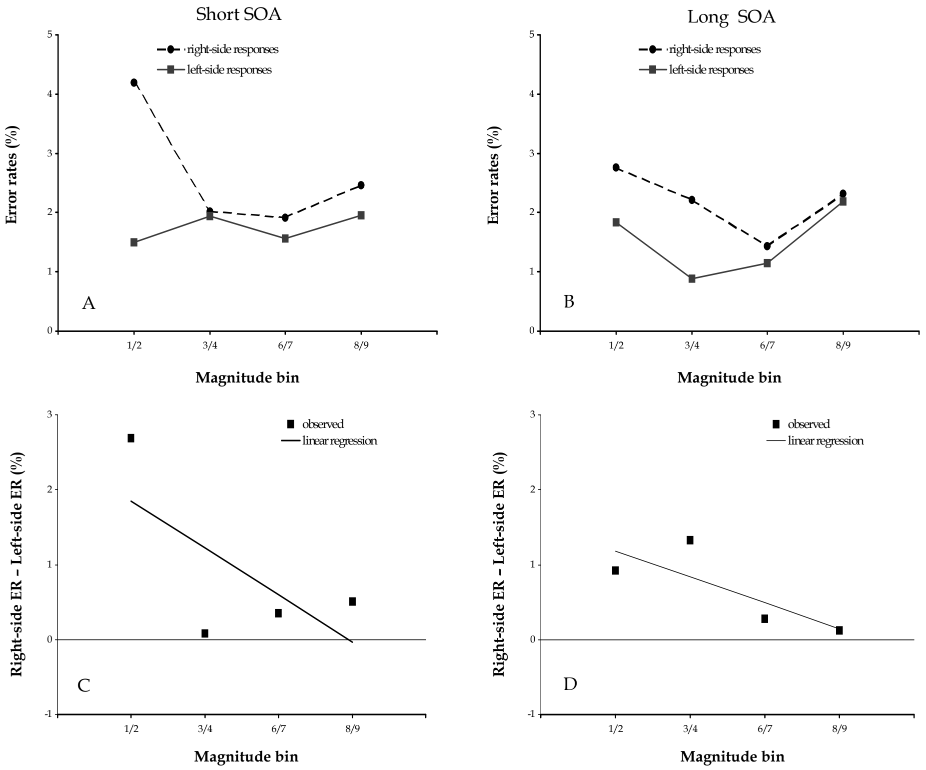

Figure 4

a. Short SOA: Mean error rate (in %) for right-side (dots) and left-side (squares) responses as a function of magnitude bin.
b. Long SOA: Mean error rate (in %) for right-side (dots) and left-side (squares) responses as a function of magnitude bin.
c. Short SOA: Observed differences (squares) of right-side and left-side error rates (in %) and regression of error rate differences (dER) on the magnitude bin presented (solid line).
d. Long SOA: Observed differences (squares) of right-side and left-side error rates (in %) and regression of error rate differences (dER) on the magnitude bin presented (solid line).

Discussion

Experiment 1 was conducted to differentiate between a perceptual and a central/motor-related origin of the SNARC effect. Therefore, we adapted the PRP paradigm so that the parity-judgment task which induces the SNARC effect was performed second (locus-of-slack paradigm).

First, we note that the SOA manipulation influenced the RT in the parity-judgment task (Task-2): RT_2 was about 265 ms longer for the short SOA compared to the long SOA, which in turn was 350 ms longer than the short SOA. This result clearly confirms the PRP standard finding that RT_2 decreases markedly as a function of SOA.

We also found a robust SNARC effect: the difference of right minus left RT decreased as numerical magnitude increased. This pattern holds in similar way for both SOAs. We predicted that if the SNARC effect originates while the digit's parity is identified, then this effect should increase with SOA. Alternatively, if the SNARC effect arises while the response to the digit's parity is selected or executed, then it should not vary as a function of SOA. Thus, the similar SNARC effects, which we found for both SOAs, suggest that the effect originates when the response is selected or executed. At the same time, our results are harder to reconcile with an early perceptual locus of the SNARC effect, such as the identification of the digit's parity. Together, then, our findings are well in line with previous results which support a relatively late locus of the SNARC effect (e.g. Fischer, 2003; Keus & Schwarz, 2005). Nevertheless, Experiment 1 does not conclusively localize the SNARC effect to either the stage of response-selection or response-execution. To this end, we performed a second experiment in which the order of the two tasks was reversed compared to Experiment 1.

Experiment 2

In our second Experiment, we aimed to test if the SNARC effect arises during a late processing stage in which the selected response is executed, or else if the effect already arises at an earlier stage, preceding response execution. Therefore, we reversed the order of the tasks, relative to Experiment 1, and used the logic of the effect-propagation paradigm. As explained in the Introduction, at least with short SOA a SNARC-like effect for the vocal responses in Task-2 should obtain if the regular SNARC effect in Task-1 arises prior to the response execution stage. If, on the other hand, the Task-1 SNARC effect originates only with the execution of the manual response, then no SNARC-like effect is predicted for Task-2.

Method

Participants Thirty-six students of the University Potsdam participated in this study. They were aged between 18 and 36 years. All gave their informed consent to the experiment, had normal or corrected-to-normal eye vision, and received 6 Euro or course credit.

Stimuli and Apparatus All features were the same as in Experiment 1.

Procedure Similar to Experiment 1, participants were asked to perform the two tasks in rapid succession. They were instructed to first deflect a left-hand or right-hand button depending on the parity of a visually presented digit and then to vocally indicate the pitch of the tone. Each participant performed one session: half of the participants pressed the right–hand button to even digits and the left–hand button to odd digits; the other half received the complementary mapping. One session consisted of seven blocks; the first block comprised 32 trials and was considered practice. The remaining six blocks, each of which comprised 96 trials, were used for further data analyses.

Each trial started with a centrally presented fixation cross for 1000 ms which was then replaced with a digit. Either 150 ms[3] (short SOA) or 400 ms (long SOA) after digit onset a tone of 50 ms duration was presented via headphones. RT for both responses was defined as the time from the onset of the relevant stimulus until the appropriate response was given. If the response to a digit was incorrect, the word “Error” appeared for 500 ms on the screen; the next trial started about 1500 to 2000 ms after both responses were given. Participants were asked to first respond to the digit and then to the tone, and to avoid any grouping of the responses.

Each block was followed by a self–paced break of at least 30 seconds. Within one experimental block, each combination of tone pitch (2) by SOA (2) by digit (8) was presented three times in a randomized order. A session lasted about 60 minutes.

Data Analyses Similar to Experiment 1 we first excluded trials in which the order of responses was reversed; i.e., participants indicated the pitch of the tone first and then they indicated the parity status of the presented digit (3.13 %). In a second step, trials which did not meet at least one of the following criteria were excluded: manual RT between 150 ms and 1600 ms, vocal RT between 150 ms and 1800 ms (5.78 % of the remaining trials). Altogether 8.73 % of all trials were eliminated from further analyses.

Analyses of Manual Responses (Task–1) Across all correct trials and for each participant mean RTs were calculated and then subjected to a 4 x 2 x 2 x 2 x 2 repeated measures ANOVA with four within–subject factors: magnitude bin (4: 1/2, 3/4, 6/7, 8/9), response–side (2: left vs. right), tone (2: low vs. high) and SOA (2: short vs. long) and one between–subjects factor: group (2: right responses to odd digits: group one vs. right responses to even digits: group two). Again, arcsin ($\sqrt{p}$) values were subjected to an ANOVA of the same design as RT; descriptive data illustrate untransformed error rates. To further quantify the SNARC effect, mean RTs and error rates were regressed on the magnitude bin presented (for detailed description of the procedure see Experiment 1).

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[3] We used a short SOA of 150 ms (in contrast to 50 ms in Experiment 1) as pre–experiments had indicated that a SOA of 50 ms made it very difficult for participants to discriminate which stimulus was presented first.

Analyses of Vocal Responses (Task–2) The main focus in this experiment was on the vocal RTs in Task–2 as a function of the SNARC effect in Task–1: thus, vocal RTs were analyzed as a joint function of the magnitude bin and location of the deflected button in the parity–judgment task. RTs were subjected to a 4 x 2 x 2 x 2 x 2 repeated measures ANOVA with four within–subject factors: magnitude bin (4: 1/2, 3/4, 6/7, 8/9), response–side (2: left vs. right), tone (2: low vs. high) and SOA (2: short vs. long) and one between–subjects factor: group (2: right responses to odd digits: group one vs. right responses to even digits: group two).

Results

Manual Responses (Task–1): Response Times

Mean RT was 687 ms. Fastest responses were given to the magnitude bin 1/2 (679 ms) and slowest RTs to 6/7 [692 ms, 3/4: 689 ms, 8/9: 688 ms; $F(3,102) = 4.56$, $MS_e = 2014.39$]. Moreover, right–hand responses (681 ms) were faster then left–hand responses [692 ms; $F(1,34) = 4.20$, $MS_e = 7763.19$]. Also, responses in trials with long SOA (739 ms) were slower than in trials with short SOA [634 ms; $F(1,34) = 199.18$, $MS_e = 16021.91$]. Most relevant to this study, we observed a SNARC effect [$F(3,102) = 11.57$, $MS_e = 3331.84$; see Figure 5a] which in turn was not further modulated by any other factor, such as SOA [$F(3,102) = 0.80$, $MS_e = 1228.23$, $p = 0.80$]. Regression analyses of right–hand minus left–hand RT (dRT–Task–1) on the numerical magnitude presented revealed that per magnitude bin the RT difference decreased by –17.40 ms [$t(35) = -4.22$, $SEM = 4.12$; see Figure 5c].

Manual Responses (Task–1): Error Rates

Participants answered 2.23 % of all trials incorrectly. More errors were made following a short SOA (2.90 %) than after a long SOA [1.56 %; $F(1,34) = 22.72$, $MS_e = 0.0143$]. Moreover, we found a SNARC effect for error rates: with smaller numbers more error were made when right–side responses were required and vice versa for larger numbers [$F(3,102) = 5.73$, $MS_e = 0.0242$; see Figure 5b].

None of the other effects was found significant. Regression analysis of right–hand minus left–hand error rates on numerical magnitude bin confirmed this SNARC effect. The difference of right–hand and left–hand error rates decreased by 1.37 % per magnitude bin [$t(35) = -2.99$, $SEM = 0.0125$;[4] see Figure 5d].

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[4] The t–value and SEM refer to transformed error rates.

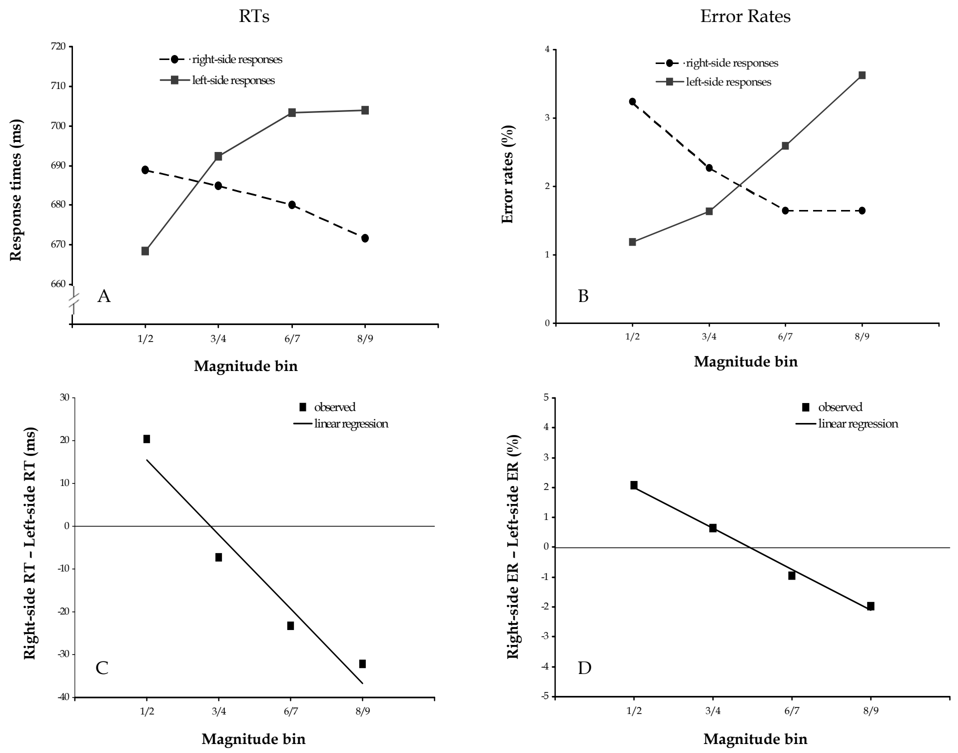

Figure 5
a. RT: Mean response times (in ms) for right-side (dots) and left-side (squares) responses as a function of magnitude bin.
b. RT: Observed differences (squares) of right-side and left-side RTs (in ms) and regression of RT differences (dRT) on the magnitude bin presented (solid line).
c. Error Rates: Mean error rate (in %) for right-side (dots) and left-side (squares) responses as a function of magnitude bin.
d. Error Rates: Observed differences (squares) of right-side and left-side error rates (in %) and regression of error rate differences (dER) on the magnitude bin presented (solid line).

Vocal Responses (Task-2)

Mean vocal RT equaled 814 ms. Two main effects were found: first, vocal responses which followed the magnitude bin 1/2 (806 ms) in Task-1 were faster compared to responses following the other magnitude bins [3/4: 818 ms, 6/7: 819 ms, 8/9: 815 ms; $F(1,34) = 3.11$, $MS_e = 3068.25$]. Second, responses after a short SOA (877 ms) were slower than responses after a long SOA [751 ms; $F(1,34) = 372.95$, $MS_e = 12251.93$]. Most important for the present study, we found a SNARC-like effect: tones following compatible digits in Task-1 were responded to faster than tones following incompatible digits [$F(3,102) = 4.94$, $MS_e = 5041.88$]. Thus, the combinations of small numbers/left-hand response and large numbers/right-hand response in Task-1 led to shorter vocal RTs in Task-2, relative to the other, incompatible combinations. This SNARC-like effect was of the same size for short and long SOA [$F(3,102) = 0.78$, $MS_e = 3111.21$, $p = .50$; see Figures 6a,b].

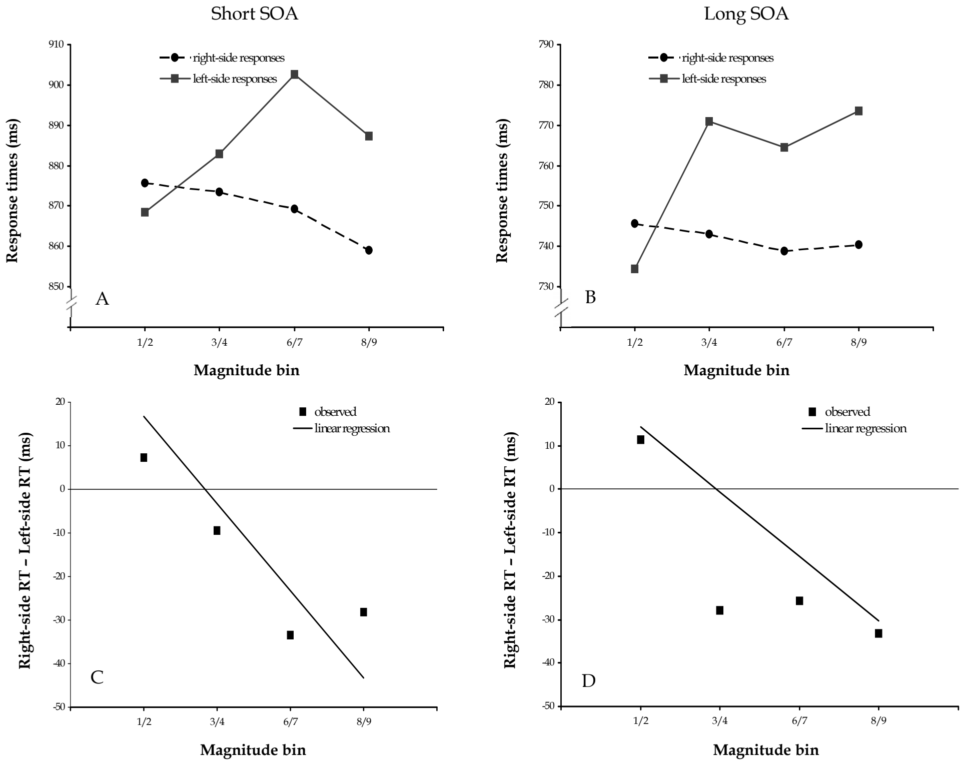

Figure 6
Vocal RTs as a function of the magnitude bin presented and button pressed in the parity-judgment task.

a. Short SOA: Mean vocal response times (in ms) after right-side (dots) and left-side (squares) responses as a function of magnitude bin.
b. Long SOA: Mean vocal response time (in ms) after right-side (dots) and left-side (squares) responses as a function of magnitude bin. (Note that the origins of the scales of Figures 6a and 6b differ).
c. Short SOA: Observed differences (squares) for vocal RTs (in ms) after right-side and left-side responses and regression of RT differences (dRT) on the magnitude bin presented (solid line).
d. Long SOA: Observed differences (squares) for vocal RTs (in ms) after right-side and left-side responses and regression of RT differences (dRT) on the magnitude bin presented (solid line).

To further quantify the SNARC-like effect we regressed the vocal RT to tones preceded by right manual responses minus vocal RT to tones preceded by left manual responses (dRT-Task-2) on the corresponding magnitude bin in Task-1. For the short SOA, the vocal RT difference in Task-2 decreased by 13.04 ms per numerical magnitude bin [$t(35) = -3.14$, $SEM = 5.66$; see Figure 6c]. Similarly, for the long SOA, the vocal RT difference decreased by 13.13 ms per magnitude bin [$t(35) = -2.48$, $SEM = 5.30$; see Figure 6d]. Regression slopes did not differ [$t(35) = 0.015$, $SEM = 5.92$, p = .98].

Comparison of the standard SNARC effect and the SNARC-like effect

In the present Experiment we observed a SNARC-like effect which suggests that the standard SNARC effect in Task-1 arises at the perceptual or central stage of information processing. A potential qualification of this tentative conclusion is that further, additional components of the SNARC effect might arise during the execution of the response in Task–1. To check for this potential contribution, we contrasted the RT differences to tones in Task–2 as a function of Task–1 characteristics and right minus left RTs obtained in Task–1. That is, dRT–Task–1 and dRT–Task–2 were subjected to a 4 x 2 x 2 x 2 repeated measures ANOVA with three within–subject factors: magnitude bin (4: 1/2, 3/4, 6/7, 8/9), task (2: parity–judgment task vs. tone–discrimination task), SOA (2: short vs. long), and one between–subjects factor: group (2: right responses to odd digits vs. right responses to even digits). Because right minus left RT differences served as dependent variable, the magnitude bin main effect would describe the SNARC effect.

We found a significant magnitude bin main effect; i.e., confirmed an overall SNARC effect [$F(3,102) = 8.49$, $MS_e = 13580.26$]. Importantly, this SNARC effect did not interact with task; i.e., the standard SNARC effect and the SNARC–like effect obtained in the same way in the parity–judgment Task–1 and in the tone–discrimination Task–2 [$F(3,102) = 1.23$, $MS_e = 1069.44$, $p = .30$]. None of the other effects was found significant.

Discussion

In Experiment 2 we aimed to distinguish between a perceptual/central stage and a motor stage origin of the SNARC effect. We presented an odd or even digit which was rapidly followed by a high or low tone. Participants were asked to first manually indicate the parity status of a digit and then to vocally indicate the pitch of the tone. We first discuss the results of the parity–judgment task, although our main focus was on the latencies of the vocal responses.

In the parity–judgment task, we obtained faster responses but more errors for the short SOA compared to the long SOA. The central bottleneck model could explain this unexpected finding with the additional assumption that at the short SOA participants sometimes perceived the tone as a response signal and emitted premature responses, leading to shorter RTs but more errors. The central capacity sharing model (e.g., Tombu & Jolicœur, 2003, 2005) assumes that processing capacity between the two tasks can be shared. As a consequence, RT_1 is predicted to decrease as SOA increases, so that RT_1 is slowed down less by sharing part of the capacity with Task–2 (see Tombu & Jolicœur, 2005, p. 792). This prediction is opposite to the RT_1 pattern found in the present study, although it does qualitatively correspond the pattern of error rates, at least when more capacity sharing (i.e., shorter SOA) is assumed to translate into an increase of error rate. Clearly, the present data do not permit us to draw any firm conclusion ruling out the one or other of these accounts.

Most important in the present context, we observed a robust SNARC effect: smaller numbers were responded to faster with left-side responses and vice versa for larger numbers. Error rates complemented these RT findings, yielding a clear SNARC effect on error rates. For the purpose of our study, it is critical that a robust standard SNARC effect obtains because we specifically aimed to evaluate vocal RTs in Task-2 as a function of this effect.

For Task-2 we found the characteristic RT slowing as a function of SOA: tones were responded to 126 ms faster in trials with a long SOA, compared to tones in trials with a short SOA. We also obtained a SNARC-like effect in Task-2: vocal RTs were shorter when a preceding small (large) number was responded to with the left (right) hand than vocal RTs to the incompatible digit/hand combination in Task-1. We found this pattern to hold in a similar way for both SOAs. On the basis of our predictions, this result suggests that the SNARC effect arises when the digit is identified or when the response is centrally selected. Thus, the time to encode the numerical stimuli and to select the response is shorter for compatible digits compared to incompatible digits. As a consequence, the selection of the response for the tone-discrimination Task-2 can be initiated earlier with compatible digits than with incompatible digits. To further strengthen this conclusion and to check if an additional component of the SNARC effect originates at the stage of response execution, we compared the standard SNARC effect of Task-1 to the SNARC-like effect in Task-2. If the motor-stage additionally contributes to the SNARC effect, we predicted that the SNARC-like effect in Task-2 should be smaller than the standard SNARC effect in Task-1. Alternatively, similar results of the standard SNARC effect and the SNARC-like effect would suggest that this effect fully arises during the perceptual encoding of a digit or when the response is selected, with no further contribution from a later, motor-related stage. We found virtually identical results for manual and vocal responses: the standard SNARC effect fully propagates onto vocal RT. This outcome suggests that the response execution stage does not additionally contribute to the formation of the SNARC effect. Further evidence for this view comes from a study by Schwarz and Keus (2004) who reported that eye movements in SNARC effect compatible trials were initiated earlier than in incompatible trials. However, the "temporal and spatial characteristics of the actual eye movements themselves [did] not exhibit magnitude-related effects" (p. 659). Our and Schwarz and Keus' (2004) findings are in contrast to the results reported by Fischer (2003) in a pointing task. Fischer (2003) showed that the movement time in a pointing task to compatible digits is shorter than the movement time to incompatible digits. One possible explanation is that the characteristics of a saccadic task and that of a manual pointing task differ greatly, e.g., with respect to their response complexity. For example, Fischer (2003) found RTs of up to 800 ms with his pointing task whereas Schwarz and Keus (2004) reported saccadic latencies of about 400 ms.

It is noteworthy that the SNARC-like effect for the short and the long SOA was of very nearly the same size. We expected that at the long SOA, vocal RTs should be less affected by the parity-judgment task. The reason is that the selection of the appropriate response in Task-1 should then often be completed before the perceptual stage of Task-2 is finished. Our findings, however, suggest that the perceptual encoding and selection of the response in the parity-judgment task persists for at least 400 ms. This figure is indeed quite compatible with movement onset latencies of 450 ms recently reported by Fischer (2003) in a SNARC-like manual pointing task. Given that the RTs in a dual-task situation are generally prolonged compared to single tasks, it seems likely that the stimulus encoding and response-selection in the parity-judgment task can exceed 450 ms. For example, Sigman and Dehaene (2005) concluded that in a number-discrimination task the time to select the response consumed about 70% (about 550 ms) of the total RT in a given trial whereas only 30% of the total RT was required to first identify the digit and to finally execute the response. These findings suggest that the standard SNARC effect can influence vocal RTs in Task-2 even at relatively long SOAs, yielding a SNARC-like effect. This tentative conclusion is also in line with our finding that in Task-1 RT with the long SOA is about 100 ms longer than with the short SOA. This outcome maximizes the potential for the standard SNARC effect to affect the vocal responses also at long SOA.

General Discussion

The purpose of our study was to identify or at least to delimit the functional locus of the SNARC effect. Previous studies (cf. Miller & Reynolds, 2003; Sigman & Dehaene, 2005) have demonstrated convincingly that the so-called PRP paradigm is a useful and sensitive tool to localize the processing stage(s) which an experimental manipulation affects. In our first experiment, we adapted the standard SNARC setting to the locus-of-slack paradigm: a tone was presented first which was, either after a short or long SOA, followed by a digit. We found, for both SOAs, an equally robust SNARC effect.

From the predictions derived from the central bottleneck model, we concluded that the SNARC effect arises when the parity status of a digit is mapped onto a specific response (response-selection; central stage) or when this response is executed (motor stage). At the same time, our results seem hard to reconcile with a perceptual locus of the effect. In our second experiment, we used the effect-propagation paradigm: in a given trial, the presentation of a digit preceded the presentation of a tone. Our main focus was on the vocal RTs in Task-2 as a function of the standard SNARC effect obtained in the parity-judgment Task-1. We found clear evidence of a SNARC-like effect; for example, tones preceded by small digits and left hand Task-1 responses yielded faster vocal RTs in Task-2 than tones preceded by small digits which were responded to with the right hand. The standard SNARC effect obtained in Task-1 and the SNARC-like effect in Task-2 were of the same basic signature and magnitude. On the basis of the central bottleneck model these results suggest that the SNARC effect emerges while a digit is perceptually encoded and identified or when the response to this digit is selected. Moreover, our findings indicate that the stage of the response-execution does not further contribute to the formation of the SNARC effect. Logically, then, the joint pattern of our findings implies that the SNARC effect arises while the appropriate response to an already-identified digit is selected. At the same time our results argue against an early perceptual and also against a late motor-related locus of the SNARC effect.

Previous and the present findings suggest the following tentative model for the formation of the SNARC effect (Figure 7; see also Gevers et al., 2006). During an early stage of information processing (stage P) the digit is encoded, and its properties, such as its numerical magnitude and its parity, are identified. Specifically, the numerical magnitude of the digit automatically preactivates a spatial code according to its relative location on the mental number line. In a similar dual-task setting, Oriet et al. (2005) looked at the numerical distance effect and found this effect to affect the early and central stage of information processing. These authors concluded that in an early stage, digits are automatically precategorised as being “large” or “small” which in terms of the SNARC effect should also include the activation of a spatial code. Moreover, Fischer et al. (2003, p. 556) found “that mere observation of numbers obligatorily activates the spatial representations associated with number meaning”. The duration of this early stage is, for example, affected by the notation of a digit, as recently shown by Sigman and Dehaene (2005; see also Dehaene, 1996; Pinel, Dehaene, Rivière, & Le Bihan, 2001), although this stage does in itself not seem to contribute to the SNARC effect. This conclusion fits in well with results of Nuerk, Wood, and Willmes (2005; see also Nuerk, Iversen, & Willmes, 2004) who reported a notation main effect on RT (e.g., responses to Arabic digits were faster than responses to number words) but no interaction of the SNARC effect with the notation. Moreover, the encoding and identification of a digit seems to be automatic and fast under specific circumstances, such as when the relevant (e.g., parity, orientation of a line segment) and irrelevant feature (numerical magnitude) of a stimulus share common neural circuits (Fias et al., 2001; but see also Hubbard et al., 2005). Our results suggest that this neural overlap between the relevant and irrelevant feature is a necessary condition for the SNARC effect to show up but may in itself not directly cause the chronometric SNARC effect. The relevant feature is then encoded and identified in parallel with the irrelevant numerical magnitude, as depicted in Figure 7.

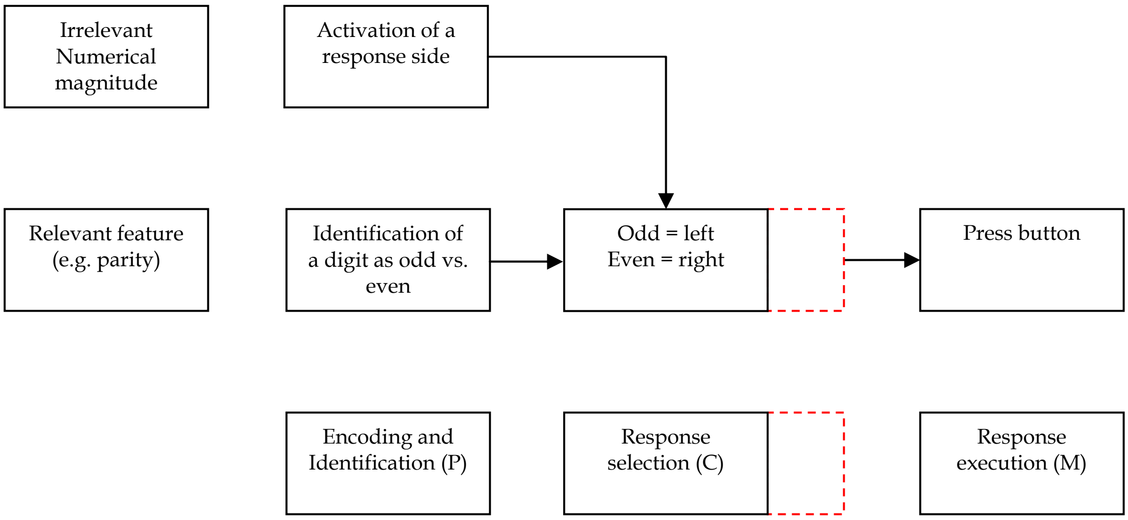

Figure 7
Schematic model for the formation of the SNARC effect: Digits are perceptually encoded and identified two-fold: First, with regard to the relevant (e.g., parity) feature such as a digit being odd or even. Second, the irrelevant numerical magnitude is encoded and preactivates a spatial side according to the digits place at the mental number line. In the second step the appropriate response to the relevant attribute is centrally selected which is facilitated or inhibited (illustrated by the dotted line) by the preactivated spatial code. Finally, the response is executed; i.e., the left or right button is deflected.

During the next stage, the specific response that is associated with the digit's relevant feature is centrally selected. Our data suggest that the SNARC effect arises at this stage, due to a magnitude-dependent preactivation of a spatial code of the digit which facilitates or inhibits the selection of the response to the digit's relevant feature. For example, a small digit, such as 1, preactivates a left-side response after it is perceptually encoded. If the parity status “odd” also requires a left-side response, then this preactivation will facilitate the selection of the appropriate response. That is, correspondence of the spatial side of the numerical magnitude on the mental number line and the required response side for the relevant feature speeds up the selection of the overt response. On the other hand, if odd digits require a right–side response, then the selection of the response is inhibited because a conflict arises between the preactivated spatial side and the required response side (see Schwarz & Ischebeck, 2003). After the response is selected, the motor program is initiated and executed (stage M). The present findings, and previous results reported by Schwarz and Keus (2004), indicate that this stage does not separately contribute to the SNARC effect (but see Fischer, 2003).

To summarize, our results indicate that the standard SNARC effect arises when the response to an already–identified digit is selected, with little or no separate contributions from early perceptual or from later motor stages. These conclusions are in line with previous ERP–studies which also point to a functional locus of the SNARC effect during the response–selection stage (cf. Keus et al., 2005; Otten et al., 1996). At the same time, the present study supports the view that the PRP paradigm yields sensitive and useful diagnostics that can help in localizing the functional origin of basic effects in the area of numerical cognition (Miller & Reynolds, 2003; Sigman & Dehaene, 2005).

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CHAPTER 5

"1–2–3": IS THERE A TEMPORAL NUMBER LINE? EVIDENCE FROM A SERIAL COMPARISON TASK

Abstract

Evidence suggests that numbers are intimately related to space (Dehaene et al., 1993; Hubbard et al., 2005). Recently, Walsh (2003) suggested that numbers might also be closely related to time. To investigate this hypothesis we asked participants to compare two digits which were presented in a serial manner, i.e., one after another. Temporally ascending digit pairs (such as 2–3) were responded to faster than temporally descending pairs (3–2). This effect was in turn qualified by a local SNARC effect and a local semantic congruity effect (SCE). Moreover, we observed a global numerical SCE only for temporally descending digit pairs. However, we did not observe a global SNARC effect; i.e., an interaction of numerical magnitude and the right/left response hand. We discuss our results in terms of overlearned forward–associations ("1–2–3") as formed by our ubiquitous cognitive routines to count off objects or events.

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Introduction

Numbers are often assumed to be represented in a continuous manner, which is usually conceptualized as mental number line (Dehaene, 1997; Hubbard, Piazza, Pinel, & Dehaene, 2005). Important evidence supporting the concept of the mental number line comes from the numerical distance effect (Moyer & Landauer, 1967, for summary see Dehaene, 1997), from the magnitude effect (Brannon & Terrace, 1998; Gallistel & Gelman, 1992, 2000), and from the Stroop–like interaction of physical and numerical digit size (Schwarz & Ischebeck, 2003).

The spatial orientation of the mental number line: The SNARC effect

Dehaene, Bossini and Giraux (1993) provided the first direct evidence that the mental number line is spatially oriented from left–to–right by asking their participants to indicate the parity status of a digit. They found that, although numerical magnitude information per se was task–irrelevant, it was automatically activated and systematically influenced performance: smaller numbers were responded to faster with the left hand and larger numbers were responded to faster with the right hand. This effect has been labelled as the spatial numerical association of response codes (SNARC) effect. Using a target detection task Fischer, Castel, Dodd, and Pratt (2003) extended these results and showed that the mere observation of small vs. large numbers activates an attentional shift to the spatial hemifield associated with that magnitude. Related neuropsychological evidence for a spatial left–to–right ordering of numbers comes, for example, from a number bisection task with neglect patients (Zorzi, Priftis, & Umiltà, 2002; for recent overviews see e.g., Fias & Fischer, 2005 and Hubbard et al., 2005).

The present study

Walsh (2003) hypothesized that numbers may be associated not only to space but also to time. Specifically, numbers may be ordered along a temporal mental number line. For example, we often say that the digit 2 comes *before* digit 3. As Walsh (2003) observed, numerical information, time, and space are all partly processed in the inferior parietal cortex and could be closely interrelated (ATOM – A Theory of Magnitude; see also Hubbard et al., 2005). The standard parity judgment task to induce the SNARC effect, however, does not allow for a direct test of the association of number and time; in this standard task the temporal dimension is not involved. One way to examine this association is the use of serial comparison tasks in which one digit is centrally presented and is after some time replaced with a second digit (e.g., Kaan, 2005). Participants are then asked to choose either the larger or the smaller of the two digits. In contrast, in the standard comparison task the two digits are spatially separated and simultaneously presented on the left and right side of the screen (e.g., Shaki & Petrusic, 2005).

Recently, Turconi, Campbell, and Seron (2006) asked participants to indicate the spatial numerical order of two spatially presented digits. The authors observed systematically faster responses to spatially ascending pairs (e.g., left 2 – right 3) as compared to spatially descending pairs (e.g., 3 – 2). In their view, this effect arises because spatially ascending pairs match the left–to–right ordering of our mental number line. Similarly, in a serial comparison task faster responses to temporally ascending digit pairs compared to temporally descending pairs would indicate a corresponding temporal aspect of the mental number line (Kaan, 2005). Furthermore, it is not known whether serial comparison tasks induce a global SNARC effect. For example, Shaki and Petrusic (2005) observed a global SNARC effect in a standard comparison task: smaller digit pairs were responded to faster with the left hand and vice versa for larger digit pairs. On the other hand, participants might "zoom in" on each single digit pair, and respond faster with the right (left) hand to ascending (descending) pairs ("local SNARC effect"). For example, Dehaene et al. (1993) found faster right–hand responses to the digit 5 within a range of 0 to 5, but faster left–hand responses to the same digit when it was presented within a range of 4 to 9. Together, according to a global view the temporally ascending digit pair 2–3, which is small compared to the other digit pairs, should be responded to faster with the left hand. According to a local view, however, this digit pair should be responded to faster with the right hand even though, for example, when, under the instruction "choose smaller", participants have to respond to the digit 2.

Another important finding observed in standard comparison tasks with consecutive[1] digit pairs is the numerical semantic congruity effect (SCE): for small digit pairs (e.g., 2–3) responses under a "choose smaller" instruction are faster than responses under a "choose larger" instruction whereas for larger digit pairs (e.g., 7–8) the opposite holds (Banks, Fujii, & Kayra–Stuart, 1976). According to the semantic coding model (Banks et al., 1976) each digit pair is categorized as small or large. If this categorization matches the question of the instruction then responses speed up; however, if they do not

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[1] Pairs are called consecutive if the two digits to be compared are separated by the distance one (i.e., n/n+1 or n+1/n; see also Turconi et al., 2006).

match then responses slow down. In the present study, we asked if this numerical SCE also holds in a serial comparison task. According to a local view, it might also be possible to observe a local SCE (in analogy to the local SNARC effect): ascending digit pairs might be responded to faster under the instruction "choose larger" and descending digit pairs might be responded to faster under the instruction "choose smaller".

The present study tests if there is a genuine association between number and time in a serial comparison task. In our model task, a digit was centrally presented which after 1000 ms was replaced with a fixation cross. Following further 1000 ms this cross was again replaced with a second digit. In some blocks, participants were asked to indicate which of the two digits was the smaller, in other blocks which was the larger one. In principle, our task could also be conceptualized as a number comparison task in which the first digit serves as a variable standard. In contrast, in standard comparison tasks, a fixed standard (e.g., 5) is defined prior to a session, and in each trial only the to-be-compared digit (rather than two digits) is presented (e.g., Dehaene, 1989; Nuerk, Bauer, Krummenacher, Heller, & Willmes, 2005).

Utilizing a serial comparison task, we first address if there is any reliable association of number and time at all. If there is, then it should manifest itself in a way quite analogous to the spatial domain: faster responses to temporally ascending pairs such as 2–3 as compared to temporally descending pairs such as 3–2. Second, we asked if other typical number-related findings such as the SNARC and the numerical SCE also obtain in a serial comparison task. That is, we asked if the standard numerical effects typically found under spatial conditions translate to the temporal domain. Third, we explore if the temporal numerical order influences or interacts with other number-related effects mentioned above. For example, in the spatial domain, Turconi et al. (2006) obtained a reversed numerical distance effect for spatially ascending digit pairs: consecutive ascending digit pairs were responded to faster than pairs with a distance of two.

Method

Participants Twenty-four participants (19–27 years; mean age 21.5 years) took part in this study. All gave their informed consent, had normal or corrected-to-normal eye vision and either received 12 Euro or course credit.

Stimuli and Apparatus Digits ranging from 1 to 9 were centrally presented in Times New Roman font (height 1.4 deg) in white against a dark background on a VGA monitor. We included six consecutive pairs for further analyses, namely: 2–3, 3–4, 4–5, 5–6, 6–7, and 7–8. Each pair was presented in a temporally ascending (e.g., first 2 then 3, 2–3) or descending order (e.g., first 3 then 2, 3–2), resulting in 12 ordered pairs. In addition, the two ordered filler pairs 2–1 and 8–9 were used which made it impossible to predict the stimuli following the digit 2 or the digit 8. Thus, altogether 14 ordered pairs were presented.

Buttons were horizontally separated by approximately 40 cm and responses were given manually with the corresponding left or right index finger.

Procedure The task of the participants was to indicate which of two serially presented digits was the larger or the smaller. This instruction was fixed within a block and changed across blocks in an LSSLLS or SLLSSL fashion (L = "choose larger"; S = "choose smaller"). Participants performed two sessions on two different days which differed in the response–assignment. In the first session half of the participants deflected the left button if the first digit matched the given instruction of the block, and the right button if the second digit matched the instruction. For example, when under the "choose larger" instruction the digit pair 3–2 is presented, and thus the first digit, 3, matches the instruction, participants pressed the left button. Alternatively, when under the same instruction the digit pair 2–3 is presented, participants pressed the right button. This response–assignment is henceforth called L–R assignment. In a second session this response–assignment was reversed; i.e., participants responded with the right button if the first digit correctly matched the given instruction of the block and with the left button if the second digit matched this instruction (R–L assignment). For the other participants the order of assignments across sessions was reversed.

Each single trial started with a central presentation of a fixation cross lasting for 1000 ms. The fixation cross was replaced with a single digit for 1000 ms which was then again replaced with the fixation cross. After another 1000 ms the second digit, which was response terminated, was centrally presented. Response time (RT) was defined as the time from the onset of the second digit to the deflection of a button. If a response was incorrect, the word "Error" appeared for 500 ms; the next trial started about 1500 ms thereafter.

One session lasted about 60 minutes and consisted of six blocks each of which comprised 84 trials. Within each block each of the 14 ordered pairs was presented six times. Each block was followed by a self–paced break of at least 30 seconds.

Data Analyses We discarded all trials in which RT was shorter than 150 ms or longer than 1200 ms (5.15 %).[2] Across all correct trials and for each participant, mean RTs were calculated and then subjected to a 6 x 2 x 2 x 2 repeated measures ANOVA with four within-subject factors: digit pair (6: 2–3, 3–4, 4–5, 5–6, 6–7, 7–8), temporal numerical order (2: ascending vs. descending), instruction (2: "choose smaller" vs. "choose larger"), and response-location (2: left vs. right). In this factorial setup, an interaction of digit pair and instruction indicates the numerical global SCE. Similarly, the interaction of digit pair and response-location represents a global SNARC effect. The interaction of numerical order and instruction refers to a local SCE; the interaction of numerical order and response-location represents a local SNARC effect. Finally, the L-R vs. R-L response-assignment is captured by the triple interaction of temporal numerical order, instruction, and response-location.

Block order did not exert any effect and was therefore not considered in further analyses. For inferential statistics mean error rates were first transformed to arcsin ($\sqrt{p}$) values to stabilize the variances (Bishop, Fienberg, & Holland, 1975, p. 367), and then subjected to an ANOVA of the same design as RT. However, descriptive statistical summaries refer to untransformed error rates.

To further quantify the global SNARC effect we regressed, for each participant separately, right-hand RT minus left-hand RT on the minimum of a digit pair presented (Lorch & Meyers, 1990). Similarly, to measure the global SCE we regressed the RT under the "choose larger" instruction minus RT under the "choose smaller" instruction on the smaller digit presented. We then tested if the means of the individual regression slopes differed from zero. In both cases, the means of the slopes are sensitive and efficient indices of the SNARC effect and numerical SCE (Fias, Brysbaert, Geypens, & d'Ydewalle, 1996). All effects were tested at a significance level of $\alpha = 0.05$.

Results

Response Times

Overall mean RT equaled 517 ms. All four main effects were significant. First, RT increases as the size of the pair increases [$F(5,115) = 2.73$, $MS_e = 1638.92$]. RT to the smaller

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[2] These outlier criteria were used to be in maximal correspondence with the criteria of related other studies evaluating the SNARC effect and SCE (Dehaene et al., 1993; Fias et al., 1996; Fischer, 2003). Moreover, other outlier criteria led to virtually identical results.

digit pairs was 12 ms shorter than RT to the larger digit pairs; i.e. we obtained a magnitude effect, the numerical analog to the psychophysical Weber effect (see e.g. Dehaene, 2003). Second, we observed a time–number congruency main effect: responses to digit pairs in ascending order were faster (510 ms) than responses to digit pairs presented in descending order [524 ms; $F(1,23) = 10.22$, $MS_e = 5353.26$]. Third, responses to "choose larger" (511 ms) were faster than responses to "choose smaller" [523 ms; $F(1,23) = 4.48$, $MS_e = 8832.01$]. Fourth, right–hand responses were 23 ms faster than left–hand responses [$F(1,23) = 15.59$, $MS_e = 9971.00$].

These main effects were qualified by four significant interactions. First, we found a global SCE: the numerical magnitude of the pair interacted with the instruction [see Figure 1a; $F(5,115) = 2.76$, $MS_e = 1742.62$]; this effect is further analyzed below.

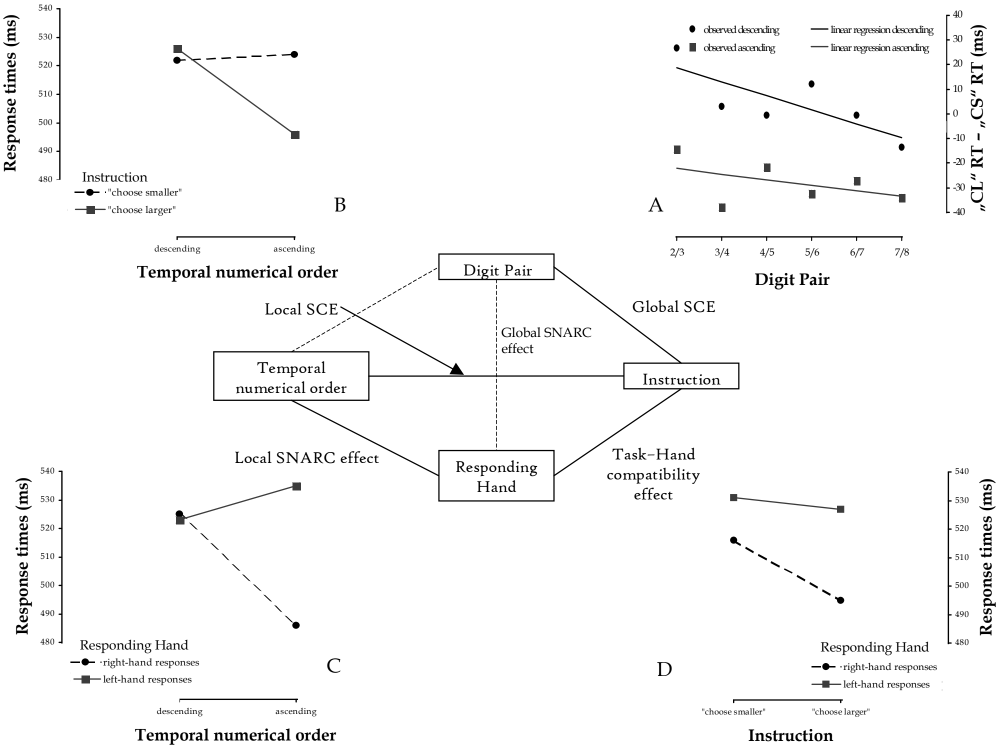

Figure 1
The central part of the Figure shows the factors involved in the present design. The solid lines represent significant interactions. The dotted lines refer to non–significant effects (such as the global SNARC effect).

a. Global SCE: Observed differences of descending (squares) and ascending (circles) digit pairs and corresponding regression of the RT differences (dRT) of "choose larger" (CL) and "choose smaller" (CS) instruction on the digit pair presented.
b. Local SCE: Mean "choose smaller" and "choose larger" response times (ms) as a function of temporal numerical order (descending/ascending).
c. Local SNARC effect: Mean left and right hand response times (ms) as a function of temporal numerical order (descending/ascending).
d. Task–hand compatibility effect: Mean left and right hand response times (ms) as a function of the instruction ("choose smaller/larger").

Second, the instruction "choose smaller/larger" interacted with the temporal numerical order of the digit pair [see Figure 1b; $F(1,23) = 7.01$, $MS_e = 10784.62$]. For descending pairs RTs for "choose larger" (522 ms) and "choose smaller" (524 ms) were nearly identical. However, for ascending pairs, responses to "choose larger" (496 ms) was 30 ms faster than responses to "choose smaller" (526 ms; local numerical SCE). Third, we observed a local SNARC effect: the temporal numerical order of the digit pair interacted with the response-location [see Figure 1c; $F(1,23) = 10.95$, $MS_e = 16443.81$]. For descending digit pairs left and right-hand responses were equally fast (523 ms and 525 ms, respectively) whereas for ascending digit pairs right-hand responses (486 ms) were considerably faster than left-hand responses (535 ms). Fourth, we obtained an interaction of instruction and response-location; i.e., a task-hand compatibility effect [see Figure 1d; $F(1,23) = 8.72$, $MS_e = 2436.59$]. That is, the advantage of right-hand responses over left-hand responses was larger for the instruction "choose larger" (32 ms) than for the instruction "choose smaller" (15 ms). We did not obtain a global SNARC effect; i.e., an interaction of digit pair and response-location [$F(5,115) = 0.46$, $MS_e = 1663.25$, $p = .88$].

One might have expected participants to be faster with an L–R assignment as compared to the opposite R–L assignment. Note that with the L–R assignment the temporal dimension first/second digit maps onto the spatial dimension left/right button (i.e., press the left button if the first digit answers the question posed in the instruction, and the right button if the second digit answers it). In our design, the L–R vs. R–L assignment is described by the triple interaction of temporal numerical order, instruction, and response-location. However, this interaction was far from significant [$F(1,23) = 1.04$; $MS_e = 166487.20$, $p = .32$], indicating that responses under the L–R assignment and R–L assignment were equally fast.

To further quantify the global SCE, we regressed, for each participant separately, the difference of "choose larger" RT minus "choose smaller" RT on the minimum of the digit pair presented (see Figure 1b). The difference of the two instructions decreased 3.94 ms per pair size [$t(23) = -2.07$, $SEM = 1.91$]. For ascending pairs, the regression slope was not significantly different from zero [$b = -2.18$; $t(23) = -1.02$, $SEM = 2.12$, $p = .32$]. For descending pairs, the difference of the RTs under the two instructions decreased by 5.71 ms per digit pair [$t(23) = -2.92$, $SEM = 2.49$].

Similarly, we regressed right-hand RT minus left-hand RT on the magnitude of the digit pair. The results of the regression analyses confirmed the ANOVA finding that there is no SNARC effect, a result that holds true for ascending and descending pairs separately (all $t < 1$).

Error Rates

Overall, 3.23 % of all trials were answered incorrectly. Not all RT effects showed up as error effects, but conversely all error effects complemented the analogous RT effects. We found a time–number congruency effect: more errors were made with descending pairs (3.77 %) as compared to ascending pairs [2.69 %; $F(1,23) = 7.52$, $MS_e = 0.0322$]. Additionally, we obtained a local SNARC effect; i.e. temporal numerical order interacted with the response–location as well as an interaction of instruction and response–location [$F(1,23) = 8.43$, $MS_e = 0.0470$ and $F(1,23) = 11.69$, $MS_e = 0.0175$, respectively]. For descending pairs, participants made fewer errors when left–hand responses were required as compared to right–hand responses. For ascending pairs this pattern was reversed. Similarly, under the instruction "choose smaller" left–hand responses produced fewer errors than right–hand responses; conversely, for the instruction "choose larger", right–hand responses were less error–prone than left–hand responses. We did not obtain a SCE nor did we find a SNARC effect for error rates [$F(5,115) = 1.47$, $MS_e = 0.0178$, $p = .21$ and $F < 1$, respectively].

Discussion

The aim of the present study was to explore the association of numbers and time, and to investigate the SNARC effect and the numerical SCE in a serial comparison task. To this end, participants were asked to indicate which of two serially presented digits was smaller/larger.

Overall, our participants responded faster to temporally ascending digit pairs in which the smaller digit was presented first (e.g. 2–3) as compared to when the larger digit was first (e.g., 3–2). However, this main effect of temporal numerical order was in turn qualified by a local SNARC effect (i.e., interaction of numerical order and response–location) and also by a local SCE (i.e., interaction of numerical order and instruction): it holds only for right hand responses, and for the "choose larger" instruction. Therefore, our conclusions need to reflect the boundary conditions implied by these interactions. On the one hand, our results clearly suggest that judgements about numbers reflect, in addition to their well–established spatial associations, also the temporal numerical order in which they are presented, as has been suggested earlier by Walsh (2003; see also Kaan, 2005, but see Dormal, Seron & Pesenti, 2006). On the other hand, our results also indicate that this influence of temporal numerical order is in turn modified by the specific task and response requirements.

These conclusions are further substantiated by the distinct way in which temporal numerical order modulates other important number-related effects, for example, by our finding of a global numerical SCE for descending but not for ascending digit pairs. For descending, but not for ascending, digit pairs the instruction "choose smaller" led to faster responses for numerically smaller digit pairs whereas the instruction "choose larger" led to faster responses for numerically larger digit pairs (global SCE). This finding is reminiscent to that of Turconi et al. (2006) who observed a reversed distance effect for ascending digit pairs but a regular standard distance effect for descending digit pairs. Similarly, Jou (2003) obtained a reversed distance effect for numbers in a three-item comparison task which he interpreted as suggesting that the computation of numerical order ("serial search mechanism") may be more efficient than a magnitude-based comparison process. Further, Turconi et al. (2006) argue that the representation of consecutive digit pairs might activate an associative serial "rote" representation; i.e., a highly overlearned forward-association which supersedes a genuinely magnitude-based comparison process. According to this view, our universal serial counting routines used to number off objects lead to a strong association of consecutive, ascending digits (see also Marcel & Forrin, 1974, Experiment 4 and Figure 4, for a related priming study). Participants might then be able to select the smaller or larger digit in a purely associative manner, without actually accessing a magnitude representation. On the other hand, descending digits might not be that closely related (i.e., we rarely count-down), and be compared to each other on the basis of an explicit magnitude-based representation. Only this magnitude-based representation facilitates the encoding of the digit pair as being small or large "with respect to their general position on the continuum" (Banks, White, Sturgill, & Mermelstein, 1983, p.561), yielding a global numerical SCE. It seems, however, that numerical order is more salient for temporally as for spatially ordered digits. Thus, Shaki and Petrusic (2005) observed a standard numerical SCE for both spatially descending and ascending digit pairs. In line with this, Turconi et al. (2006) only observed a numerical order effect when participants explicitly had to identify the numerical order ("was it ascending vs. descending?") but not when they simply had to compare the spatially presented digit pairs ("which digit is larger?").

The characteristics of the numerical SCE also suggest that magnitude information can be dissociated from numerical order representation. For example, Turconi and Seron (2002; see also Delazer & Butterworth, 1997) describe a patient who could perform a standard number comparison task but had severe problems in a numerical order task. Electrophysiological studies also found a markedly distinct time course for numerical order and quantity activation (Kaan, 2005; Turconi, Jemel, Rossion, & Seron, 2004).

It was concluded above that the numerical SCE for descending digit pairs relies on a magnitude-based representation of these pairs as small or large. Presumably, this representation should then also yield a global SNARC effect for descending digit pairs. However, contrary to this prediction we did not observe a global SNARC effect. This finding suggests that in the present task the global magnitude information was dissociated from its global spatial information. Similarly, Ito and Hatta (2004) did not observe a global SNARC effect in a standard comparison task (indicate whether a digit is smaller/larger than 5). Our study does not unequivocally specify the mechanism(s) which prevented a global SNARC effect in the present data. Clearly, the boundary conditions which lead to a spatial-numerical association will need closer attention in future research (see also Fias, Lauwereyns, & Lammertyn, 2001).

In the present serial comparison task we obtained a local SNARC effect: the advantage of right-hand responses compared to left-hand responses was larger for ascending than for descending digit pairs, a finding that held similarly across all numerical magnitudes. Two explanations of this spatial pattern are conceivable: first, this local SNARC effect might reflect a general association of order and space. For example, Gevers, Reynvoet and Fias (2003; but see Zorzi, Priftis, Meneghello, Marenzi, & Umiltà, 2006) report evidence that the letters of the alphabet as well as the months of a year are spatially represented. They conclude that the SNARC effect is generally induced by ordinal sequences and is not limited to numerical magnitude information per se. Second, participants might be able to "zoom in" on a small subsection of the mental number line for each pair. For example, Dehaene et al. (1993) observed faster left-hand responses for the digits 4 and 5 within a range from 4 to 9 but faster right-hand responses for these same digits when the range was from 0 to 5. This finding strongly points to a flexible and context-specific rather than to a rigid association of numbers and space. These two possible explanations of the local SNARC effect are by no means mutually exclusive. Indeed, the joint effect of both mechanisms might best explain our results. For each digit pair, participants focus and zoom in on the relevant section of the mental number line.

Assume, for example, that the digit two is presented first. Its presentation induces a spreading forward-association to the digit three; i.e., forward and to the right along the mental number line. Thus, participants respond especially fast when the digit three is presented second, as compared to trials in which the digit one is presented second. This interpretation is further supported by the reversed distance effect of ascending but not descending digit pairs observed by Turconi et al. (2006; see also Jou, 2003). Given that we also associate numbers with space, the induced right step leads to especially fast responses when an ascending digit pair has to be responded to with the right hand. This condition (ascending digit pair and right-hand response) thus perfectly matches both – the orientation of our forward-oriented temporal number line and of our rightward-oriented spatial number line.[3] Similarly, this spread of activation towards the subsequent larger digit facilitates the response selection to the instruction "choose larger"; i.e., a local numerical SCE.

This forward-association is apparently not activated in standard comparison tasks which generally yield equally fast RTs to numbers smaller and larger than the fixed standard (Dehaene, 1989; Dehaene, Dupoux, & Mehler, 1990; Nuerk et al., 2005). Thus, the presentation of two digits in close temporal succession seems to be a necessary condition to obtain the forward spread of activation described above.

Taken together, the local SNARC effect and the local numerical SCE both indicate that the presentation of the first digit automatically evokes a forward-association to the right along the mental number line towards the larger neighbouring digit. Thus, participants exhibit fast responses when this local activation is compatible with the response requirements, i.e., with the response-location (local SNARC effect) or the response instruction (local SCE).

The association of quantity and space is, however, in so far a global effect as we also found a larger advantage of right-hand responses over left-hand responses for the instruction "choose larger" than for "choose smaller" (see also Turconi, et al., 2004). Notice, though, that this effect is not related to numerical magnitude per se. Therefore, it

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[3] Further evidence for this forward association of digits towards the larger digit located at the right on the mental number line comes from the task-hand compatibility effect. As stated above, the variable of response-assignment is included in the present analysis as the three-way interaction of temporal numerical order, instruction, and response-location. Each main effect and each interaction found in the presented analysis can be mapped one-to-one into a corresponding effect which includes the factor response-assignment rather than response-location. For example, the interaction of instruction and response-location (task-hand-compatibility) reflects, in terms of the factor response-assignment, the interaction of temporal numerical order and response-assignment. Thus, the task-hand compatibility effect indicates that responses to ascending digit pairs are relatively faster with the L-R assignment, whereas responses to descending digit pairs are relatively faster with the R-L assignment. This finding, therefore, further supports that there exists a correlation between the temporal (forward) orientation of the number line and its spatial (rightward-oriented) counterpart. We are grateful to an anonymous reviewer that s/he made this point clear to us.

seems to represent a more general quantity–related classification effect that is not limited to any specific stimulus attribute or dimension. In particular, the same effect should also show up when stimuli other than numbers are judged. This conclusion is similar to that of Walsh (2003) who argues that the SNARC effect might be a special case of a more general SQUARC effect describing the association of quantity and spatial response codes.

In summary, our results reveal that in comparison tasks temporal numerical order is activated and has a substantial and systematic impact on other prominent effects, such as the numerical SCE and SNARC effect. Therefore, studies examining effects related to numerical magnitude need to take into account not only the spatial but also the temporal numerical order when eliciting and interpreting these effects.

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CHAPTER 6

GENERAL DISCUSSION:
A NUMB3R OF FINAL WORDS

When you have mastered numbers, you
will in fact no longer be reading numbers,
any more than read words when reading
books. You will be reading meanings.

W.E.B. Du Bois

General Discussion

The common aim of the studies presented in this thesis is to explore the nature of the SNARC effect, which was first described by Dehaene, Bossini, and Giraux (1993). In a parity–judgment task small numbers are responded to faster with the left hand/key whereas responses to large numbers are faster with the right hand/key. This spatial–numerical association has been interpreted in terms of a spatially oriented mental number line with small numbers being located on the left side and large numbers on the right side.

Automatic activation of numerical magnitude?

Most studies, including the present ones, utilize a parity–judgment task to induce the SNARC effect. Although irrelevant for performing the task, numerical magnitude is automatically activated, much like color word in a STROOP task. This numerical magnitude provides a spatial code which facilitates or inhibits the selection of the appropriate response (see Chapter 4). At present it is still a question of debate under which conditions the numerical magnitude information is automatically activated. For example, even less mandatory tasks such as phoneme monitoring (Fias, Brysbaert, Geypens, & d'Ydewalle, 1996) induce a SNARC effect. Moreover, Fias, Lauwereyns, and Lammertyn (2001) observed the SNARC effect when participants indicated the spatial orientation of lines superimposed in digits. On the other hand, they did not observe a SNARC effect when participants specified the color of digits. Fias et al. (2001) argue that the neural overlap between the relevant (e.g., color, parity) and the irrelevant (i.e., numerical magnitude) dimension determines the occurrence of the SNARC effect. Because numerical magnitude information is represented in the parietal cortex (see Hubbard, Piazza, Pinel, & Dehaene, 2005 for an overview) the likelihood to obtain a SNARC effect should increase as the role of the parietal cortex for the processing of the relevant information increases. A recent study of Claeys et al. (2005) showed that the parietal cortex is also involved in color tasks. Moreover, some grapheme–color synaesthetes experience achromatic numbers as colored (see e.g., Cohen–Kadosh et al., 2005). Posner, Sandson, Dhawan, and Shulman (1990) argue that the interference seen in synaesthetes is caused by interconnected anatomical systems. Given these facts, the neural overlap hypothesis predicts that the SNARC effect should also obtain when participants are asked to indicate the color of digits. Another possible explanation for the non-occurrence of the SNARC effect in color-judgment tasks comes from relative speed accounts (Schwarz & Ischebeck, 2003). According to this view the influence of an irrelevant dimension on the relevant dimension depends on the relative speed with which both dimensions are activated. Taken together, the debate about the specific experimental conditions, which do and which do not induce an automatic activation of numerical magnitude is far from being resolved; it certainly deserves closer attention in further studies.

The SNARC effect and the writing and reading system

Another issue frequently raised is whether the spatial orientation of the mental number line is a direct consequence of the writing system the participants had acquired (ontogenetic view; e.g., Dehaene et al., 1993; Zebian, 2005). According to a strong ontogenetic interpretation, the SNARC effect should only obtain with effectors closely related to the process of writing and reading such as hands and eyes. However, in our first study (Chapter 2) we observed a pedal SNARC effect which did not differ in its size from the SNARC effect obtained for manual responses. Our finding is hard to reconcile with a strong ontogenetic view. Instead, it could be taken to support either a phylogenetic view or a weak ontogenetic view. In our second study (Chapter 3) we investigated the characteristics of the SNARC effect with vertically and horizontally arranged buttons. For vertically arranged buttons the nature of the SNARC effect was influenced by the task context created: with a hand-related instruction the SNARC effect reflects an association of left/right hand to small/large numbers. With a button-related instruction the SNARC effect reflects an association of bottom/top button (i.e., extracorporal space) to small/large numbers. For horizontally arranged buttons, however, the extracorporal component of the SNARC effect overrides a hand-related instruction: small numbers are responded to faster with the left button and large numbers with the right button irrespective of the actual hand pressing that button. One likely interpretation of these complex findings is that the nature of the SNARC effect is influenced by the writing and the reading system participants are adapted to. It could be argued that a horizontal representation is our default representation of numbers, and, thus, more stable than a vertical representation. Furthermore, note that with horizontally arranged buttons and crossed hands the spatial information of the participants' hands is ambiguous: the right hand is on the anatomical right side but in relative terms it is on the left side. Thus, under this condition the association of extracorporal space and numbers stably reflects the direction of our writing system. Given this explanation and the results of the first study, the weak ontogenetic interpretation of the SNARC effect gathers from our findings. According to this view, the general disposition to develop a mental number line per se has a phylogenetic origin but its spatial orientation is determined by the participants' direction of writing. That does not preclude that the SNARC effect generalizes to other effectors, such as feet, which are not related to writing and reading.

Strong evidence for a phylogenetic basis of our mental number line comes from animal and infant studies (see Chapter 1). Further support for the influence of the writing system on the orientation of the mental number line comes from a recent study of Zebian (2005). Arabic Monoliterates, adapted to a right-to-left writing system, exhibit faster responses in a same-different numerical judgment task when the larger digit was presented on the left side and the smaller digit on the right side (e.g., 9-2) compared to the reversed presentation (e.g., 2-9). On the other hand and in line with the left-to-right writing system, English participants respond systematically faster to spatially ascending pairs (e.g., 2-3) as compared to spatially descending pairs (e.g., 3-2) in a numerical order task (Turconi, Campbell, & Seron, 2006). According to the weak ontogenetic view participants, adapted to a top-to-bottom writing system, should associate small/large numbers to top/bottom locations. However, Japanese participants show a reversed association with small/larger numbers to the bottom/top button (Ito & Hatta, 2005). It could be argued, that Japanese students are strongly influenced by the western writing system (e.g., via the internet, or books written in English) which might alter their spatial-numerical association. Therefore, studies relating the SNARC effect to cultural influences should carefully control for variables which might have potential influence on the SNARC effect, such as the exposure to different writing systems.

The flexible SNARC effect

As pointed out above, the results of our second study (Chapter 3) also suggest that the SNARC effect with vertically arranged buttons is influenced by the task context created. Another context dependency of the SNARC effect was found in our last study (Chapter 5). In this study participants were asked to indicate the smaller or larger number of serially presented consecutive digits, such as 2-3. Under this condition, we observed a local SNARC effect for each presented digit pair. Specifically, the advantage of right-hand responses was larger for temporally ascending pairs (e.g., 2-3) compared to descending pairs (e.g., 3-2). Thus, it appears that for each digit pair, participants "zoomed in" on the mental number line. Taken together, our findings suggest that the SNARC effect reflects a flexible rather than a rigid association of numbers to space. Put differently, absolute small one-digit numbers or pairs (e.g., 1 and 2) are not necessarily responded to faster with the left hand and absolute large one-digit numbers or pairs (e.g., 8 and 9) are not necessarily responded to faster with the right hand. For example, Bächtold, Baumüller, and Brugger (1998) observed faster right-hand responses to small digits (e.g., 3) and faster left-hand responses to large digits (e.g., 9) when participants were asked to imagine the face of an analog clock. Moreover, numbers are not only represented along a horizontally spatially oriented mental number line. Rather, numbers are also represented in a vertical fashion: our second study (Chapter 3) showed that small numbers are represented at the bottom whereas large numbers are associated with the top (see also Schwarz & Keus, 2004).

Fischer, Dewulf, and Hill (2005) tested the practical implications of numerical representations. They observed that the understanding of diagrams depends on the spatial orientation of the numerical information: a vertical orientation of bar graphs facilitates the understanding of the implied numerical information compared to horizontal bar graphs. Thus, humans' spatial-numerical associations and their flexibility should be considered when creating ergonomic displays to facilitate the processing of numerical information.

SNARC effect induced by ordinal sequences or numerical magnitude information?

The results of our last study (Chapter 5) posed the question whether the SNARC effect is based on numerical magnitude or induced by the ordinal sequence of digits. For example, Gevers, Reynvoet, and Fias (2003) observed an association of months of a year to space. Therefore, they argued that the SNARC effect reflects a general association of ordinal sequences to space and is not caused by, and limited to, numerical magnitude information. It should be noted, though, that months of a year also represent numbers ranging from 1 to 12. Moreover, it is conceivable that months are circularly represented because the first month (January) follows the last month (December). Recently, Rusconi, Kwan, Giordano, Umiltà, and Butterworth (2006) reported that pitch height is also spatially represented: high-frequency pitches were associated with a top location whereas low-frequency pitches were associated with a bottom location; the effect has been named *Spatial Musical Association of Response Codes (SMARC) effect*. Taken together, these findings suggest that non-numerical ordinal sequences can also induce SNARC-like effects. On the other hand, in a neuropsychological study with neglect patients Zorzi, Priftis, Meneghello, Marenzi, and Umiltà (2006) found different bisection patterns for numerical and non-numerical sequences, such as letters. The bisection results of numerical sequences pointed to a spatial representation of numbers in a fine graded, spatial, and continuous manner whereas letters were categorically coded. These results have been interpreted to reflect different representational systems of simple ordinal sequences and numerical magnitudes. The authors concluded "that the spatial layout characterizing numerical representations (i.e., a mental number line) constitutes as specific property of numbers, as postulated by Dehaene et al. (1993), rather than a general characteristic of ordered sequences" (Zorzi et al., 2006, p. 1067). Thus, the debate whether the SNARC effect is based on ordinal meanings or on numerical magnitude information is by no means settled. It should be also noted that the common associations of numbers and other ordinal dimensions to space does not necessary imply that the "sensorimotor transformations in the cognitive system" (Rusconi et al., 2006, p.227) are, therefore, identical. More studies are certainly required which evaluate the actual translation of presented numerical and ordinal sequences into spatial codes.

One possible way to shed light on this issue comes from functional imaging. As pointed out in the introduction (Chapter 1), the HIPS is essential for the abstract representation of numerical meaning (Dehaene, Piazza, Pinel, & Cohen, 2003). Studies using functional imaging showed the HIPS to be not activated when involved in other tasks such as animal naming (see Dehaene et al., 2003, for an overview). However, as yet no studies have tested for an activation of the HIPS during the processing of ordinal dimensions.

The SNARC effect as a categorical vs. continuous effect

The usual way, also used in the present studies, to quantify the size of the SNARC effect is to utilize linear regression. Here, for each participant the right hand minus the left hand response time is regressed on the numerical magnitude presented. By definition this regression model is continuous, and this seems to suggest that the advantage of right-hand over left-hand responses continuously increases as numerical magnitude increases. However, one may ask whether the SNARC effect reflects rather a categorical representation of numbers.

Using an Eriksen flanker task Nuerk, Bauer, Krummenacher, Heller, and Willmes (2005) evaluated the fit of a continuous vs. a categorical regression. A categorical SNARC effect did explain more variance than a continuous regression: numbers smaller than 5 were responded to faster with the left hand and numbers larger than 5 were responded to faster with the right hand. Within these categories the slope was flat; e.g., the advantage of left-hand responses over right-hand responses was not larger for the digit 1 compared to the digit 4. Recently, Ishihara et al. (2006) displayed digits ranging from 0 to 9 on five different locations (far left – left – middle – right – far right) on the screen. Whenever an odd digit was presented participants were asked to point to the digit. They observed faster reaction times to the digit 1 when presented far left compared to the left position. Reactions to the digit 5 were fastest when presented in the middle of the screen. Finally, reactions to 9 were fastest when presented far right. These results favor a continuous association of numbers and space rather than a categorical representation. As described above, the results of Zorzi et al. (2006) also suggest a continuous coding of numerical magnitudes. It should be noted that the tasks in the studies differed which might have influenced the nature of the spatial-numerical associations. Therefore, more studies are needed to specify the factors or task demands which induce a categorical or a continuous SNARC effect.

The SNARC effect as a response-related effect

In their pointing task Ishihara et al. (2006) recorded the reaction time as well as the movement time. As described above they found that the reaction time varied as a function of the numerical magnitude and the location. However, the movement time did not vary as a function of the numerical magnitude and the location. In contrast, Fischer (2003) observed faster left-side movements for small numbers and faster right-side movements to large numbers. This finding seems to suggest that the SNARC effect arises while the response is executed. The finding of Ishihara et al. (2006) is well in line with our own results observed in a dual-task study (Chapter 4). We concluded that the SNARC effect origins while the response is selected. Our results were hard to reconcile with the assumptions that the SNARC effect is purely perceptual or arises while the actual movement is executed (see also Keus & Schwarz, 2005). Recently, Keus and Jenks (2006) observed that the effect of movement time, as found by Fischer (2003), disappears when so-called initial errors are excluded. More specifically, small numbers automatically initiate a movement to the left whereas large numbers initiate a movement to the right. For example, the digit 9 should correctly be responded to with a movement to the left but initially participants move to the right and then change their moving direction. After deleting these irregular trials, movement time did not exert any influence on the SNARC effect anymore. Taken together, the most recent results converge in suggesting that the SNARC effect arises while participants select the response.

A temporal mental number line?

In our last study (Chapter 5) we tested for a potential association of numbers and time. It should be noted that, in line with the other studies of this thesis, we also examined the SNARC effect. As pointed out by Walsh (2003) time is partially processed in the parietal lobule as are numbers and space; therefore the processing of temporal and numerical information might be related. We observed in a serial comparison task that temporally ascending digit pairs were responded to faster than temporally descending pairs. This effect was further qualified by a local SNARC effect and a local SCE. This pattern suggests that numbers are also temporally ordered reflecting an overlearned forward-association of numbers ("1-2-3") as formed by our ubiquitous cognitive routines to count off objects or events.

At the present state of research only a few studies focused on the relation of numbers and time (e.g., Kaan, 2005). The conditions and nature of this relation might be of great interest in further studies. However, research along these lines has to keep in mind that temporal processing is subdivided into different time scales relying on different neural mechanisms (Buonomano & Karmarkar, 2002). For example, temporal intervals in the millisecond range are thought to be automatically processed in the cerebellum (Ivry & Spencer, 2004). Timing ranges of seconds, though, have to be processed consciously involving the parietal cortex (Lewis & Walsh, 2002). Given that multi-second intervals are partly processed in the parietal cortex, Walsh (2003) further argued that time and space should also be related. He also suggests that the SNARC effect might reflect a specific case of a more general spatial-quantity association: *Spatial Quantity Association of Response Codes (SQUARC) effect*. If this were true other quantitative dimensions, such as lengths or mass, should also elicit SNARC-like effects; i.e., a SQUARC effect.

Further research objectives and practical implications

What are the practical implications of an investigation into the nature of a spatially oriented mental number line? In the Introduction (Chapter 1) it has been argued that the mental number line is an evolutionary primitive which humans share with other species. The mental number line "underlie[s] our intuition of what a given numerical number size means, and of the proximity relation between numbers." (Dehaene et al., 2003, p. 489). Thus, it is very likely that the mental number line influences performance in arithmetical tasks. An abnormal representation of numbers might therefore be one factor in developmental dyscalculia. However, only a few studies have as yet been conducted to investigate the mental representation of numbers and, more specifically, the SNARC effect in clinical populations.

Bachot, Gevers, Fias, and Roeyers (2005) compared the SNARC effect of children with visuospatial disabilities and control children. The clinical population showed deficits in complex arithmetic tasks and visuospatial tasks. In a magnitude comparison task the standard SNARC effect was not found for these children whereas it was obtained for a matched control group. Bachot et al. (2005) concluded that children with visuospatial disabilities do have problems in "mapping numbers on a mental number line representation" (Bachot et al., 2005, p. 182). It should be noted, though, that the study by Bachot et al. (2005) only established a correlation between visuospatial disabilities and the SNARC effect, not a direct causal relationship. More specifically, it is not possible to infer that the abnormal mapping of numbers to space causes the visuospatial disabilities or vice versa. Therefore, more and especially longitudinal studies should be performed.

With regard to developmental dyscalculia most studies focused on the correlation of dyscalculia with other cognitive domains rather than on the basic numerical representation (see Landerl, Bevan, & Butterworth, 2004, for a summary). Landerl et al. (2004) provided first evidence that "the most likely cause of dyscalculia is a congenital failure to understand basic numerical concepts, especially the idea of numerosity, a capacity independent of other abilities" (Landerl et al., 2004, p. 122). If a regular representation of numerical information along a mental number line is essential for the development and understanding of arithmetic, an investigation of the exact nature of the mental representation of numbers in dyscalculia might help in developing diagnostic tools to identify later disabilities related to computation and mathematical reasoning.

Given that the mental number line is spatially oriented from left to right, spatial metaphors might facilitate the understanding of the ordinal ordering of numbers (Goswami, 2006), enabling the children to master more complex task. For example, Wilson, Dehaene, Pinel, Revkin, Cohen, and Cohen (2006) developed an adaptive computer game called "The number race" for the remediation of children with dyscalculia. Here, children learn the concept of the mental number line by the usage of spatial metaphors. First results indicate that the game fosters the development of numerical concepts (Wilson, Revkin, Cohen, Cohen, & Dehaene, 2006). In Dutch primary schools the concept of an “empty number line” (i.e., a line with no numbers; see Figure 1) has been introduced to help children by visualizing their calculation strategies (e.g., Bobis & Bobis, 2005; Klein, Beishuizen, & Treffers, 1998), for example in addition or subtraction two-digit numerals (see Figure 1). Treffers (1991; see also Klein et al., 1998) showed that the visualization of the calculation process indeed leads to an improvement of the children’s solution strategies. At the present state of research more controlled studies are certainly needed to investigate how the utilization of the mental number line can help to master more abstract numerical manipulations.

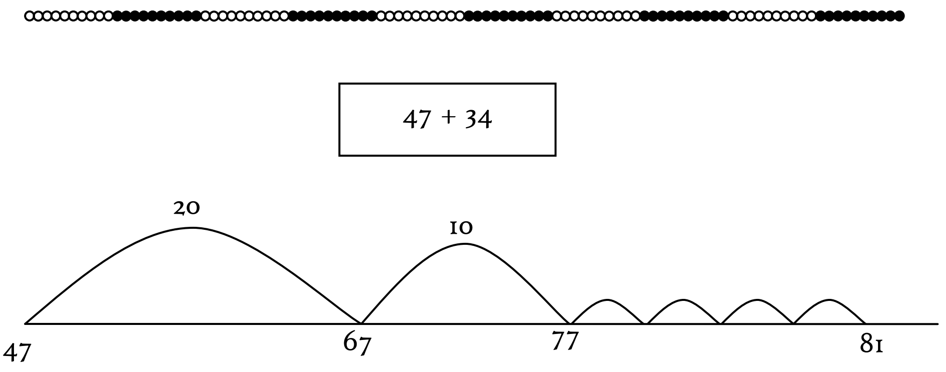

Figure 1
Example for an “empty number line”: The children are supposed to calculate 47 + 34. One summand (usually the larger one) serves as the starting point and is written on the left of the empty number line. Then jumps are used to visualize the calculation process. At the beginning, a chain of circles on base-10 serves as visualising the numbers from 1-100. Similar to addition, subtraction problems can be solved. Here the starting point is on the right and children subtract by jumps to the left. This empty number line utilizes the ordering of numbers along a mental number line spatially oriented from left-to-right.

These studies on dyscalculia and on the development of numerical abilities in normal children all utilize and further investigate the concept of the mental number line. They also illustrate that research into the nature of the mental number line has direct practical implications for education and diagnostic. However, given the numerous research questions still unanswered in the young field of numerical cognition, practitioners will certainly benefit from further research into numerical abilities and the nature of the representation of numbers within the human brain.

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