Situated Influences on Spatial-Numerical Associations

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Introduction: Spatial influences are ubiquitous and flexible

In our cultural world, numerical information can be organized in multiple ways. For instance, rulers and modern computer keyboards adopt a default left-to-right direction of number ordering, which we also use when writing down consecutively increasing numbers. However, humans are much more flexible in their usage of numerical information. We invented negative numbers, whose direction on a conventional axis reverse the direction for natural numbers. We can also memorize or process numbers randomly distributed in space or make systematic use of circular, vertical or diagonal directionality while using mobile phones, clocks or thermometers. How does our mind flexibly adopt not only one but multiple different formats for representing numbers in space?

The ability to form *spatial-numerical associations* (SNA) constitutes one of the basic traits of the human mind (e.g. Hubbard, Piazza, Pinel, & Dehaene, 2005; de Hevia, Vallar, & Girelli, 2008a; Fischer M., & Shaki, 2014; Cipora & Nuerk, 2013; Cipora et al., 2016; for reviews; see Cipora, Patro, & Nuerk, 2015 and Patro, Nuerk, Cress, & Haman, 2014 for a taxonomy of different SNAs). While the origin of this ability is a highly contested issue (for biological innate views, see de Hevia, Izard, Coubart, Spelke, & Streri, 2014; Rugani, Vallortigara, Priftis, & Regolin, 2015; for more culturally-oriented views see Nuerk et al., 2015; Núñez & Fias, 2015), the literature is fairly consistent in that SNAs are directly or indirectly modulated by the direction of our reading habits (Shaki, Fischer M., & Petrusic, 2009; Zebian, 2005; Fischer M. & Shaki, 2015 for review). The reading habit account offers an explanation for default organization of numerical sequences being ordered from left to right in Western cultures, but not in Arab or Hebrew cultures. In cognitive experiments, participants from Western cultures are usually more likely to associate small numbers with the left-hand side and larger numbers with the right-hand side, while participants from Middle-Eastern cultures show the reverse or null effect (see Shaki, Fischer M., & Göbel, 2012; Fischer M. & Shaki, 2014).

While there is a general default for cultural spatial habits, it is also obvious that we live in a world that provides us with a multiplicity of directional spatial instructions and arrangements in different situations. For instance, bilingual speakers of English and Hebrew or English and Arab can switch between different reading directions quickly and with great ease. Is such spatial-directional flexibility also relevant for SNAs? When considering this question, it is essential to acknowledge that spatial influences and their cultural modulations are not restricted to reading (Nuerk et al., 2015). Many other situations or spatial activities strongly influence the way that we mentally associate numbers with space and learn SNAs (Newcombe, Levine, & Mix, 2015). Even though many of these spatial activities are not directly related to numbers (e.g., shifting an

object from left to right), they can determine in which direction spatial-numerical information will be processed in a particular situation (Patro, Fischer U., Nuerk, & Cress, 2016a, for a controlled training study). The processes underlying such number line formation have been described by Nuerk et al. (2015) and Patro, Nuerk, and Cress (2016b) in details.

Most current research, however, is concerned with fixed SNAs rather than with their flexibility. Here, we focus on flexibility, which is perhaps the more interesting and the more telling attribute of how human number cognition works. We will argue that *the situated influences on spatial-numerical associations* may be a key factor in understanding human SNAs and thus deserves more attention.

A general distinction of spatial-numerical processing: Extension and Directionality

Situated influences operate in a particular framework of spatial-numerical processing, which will be introduced here first as a theoretical background. Generally, at least two types of SNA can be distinguished: one based on extension and another on directionality (Patro et al., 2014; Cipora et al., 2015). The first one refers to the phenomenon wherein larger numbers are more readily associated with larger extensions in space (length, surface, spatial intervals; see also Walsh, 2003 for ATOM theory). Such an association can be observed already in infants and school children, and it can be used for embodied training of basic arithmetic skills in kindergarten and school children (e.g. de Hevia & Spelke, 2010; Fischer M. & Brugger, 2011; Siegler & Opfer, 2003; Moeller, Neuburger, Kaufmann, Landerl, & Nuerk, 2009; Ramani & Siegler, 2008; Link, Moeller, Huber, Fischer U., & Nuerk, 2013; Link, Nuerk, & Moeller, 2014; Fischer U., Moeller, Bientzle, Cress, & Nuerk, 2011). Extensive reviews about this relationship can be found elsewhere (Newcombe et al., 2015; Dackermann, Huber, Bahnmueller, Nuerk, & Moeller, 2015).

However, our multidirectional spatial experience, to which we just referred above, appears to be more relevant for the second type of SNA - a directional relation between numbers and space. One of the most thoroughly investigated SNAs from this category is the *Spatial Numerical Association of Response Codes* (SNARC effect; Dehaene, Bossini, & Giraux, 1993; Wood, Willmes, Nuerk, & Fischer M, 2008 for meta-analysis). In the most typical experimental procedure (parity judgement task), participants classify numbers presented on the screen as odd or even using lateralised keys. After half of the experiment, the assignment of response keys is changed, so that for each number, there is a response with the left-hand key and one with the right-hand key. In Western cultures (cf. Shaki et al., 2009), participants typically respond more quickly to small magnitude numbers using the left key, and to large numbers with the right key. Behaviourally similar results are also observed in a magnitude comparison task. There are several variants of

the SNARC effect. The most common variant (described above) is referred to as horizontal SNARC because numbers are associated with the horizontal (left-right) dimension. However, numerical magnitudes may also be mapped onto other spatial dimensions (e.g. the vertical SNARC; faster responses to small/large magnitude numbers in the lower/upper space). The latter is considered to be more universal, consistent across cultures, and less shaped or modulated by cultural experience (Shaki & Fischer M., 2012). The SNARC effect has also been described in the sagittal dimension (i.e., small magnitude numbers are associated with space close to the body and large magnitude numbers with space farther from the body; Winter, Matlock, Shaki, & Fischer M, 2015, for review).

The horizontal SNARC effect is quite ubiquitous. It has been observed in unimanual setups (i.e., binary responses with two fingers of the same hand), in tasks requiring responses with one finger, feet, directional saccades, and for stimuli other than symbolic numbers, such as letters, days of the week, non-symbolic number magnitudes and object sizes (Ren, Nicholls, Ma & Chen, 2011 for object sizes; Fischer M. & Shaki, 2014, for extensive review), and even in Go-NoGo tasks in which no spatial response location is assigned for different responses (Fischer M. & Shaki, 2016). So far, SNARC research has largely been descriptive or demonstrative, i.e., it has shown that the SNARC effect can be observed for another stimulus choice, another response choice, another experimental setting. However, in our review, we will show that the SNARC effect seems not to be modulated equally for all conditions. In particular, we will show that there are situated constraints driving or interfering with directional SNAs.

Bidirectional relations between numbers and space

A standard question for SNAs is whether spatial processing influences number processing or vice versa, i.e., where links between numbers and space originate from. An overview of the possible patterns of directional relationships between numerical and spatial processing is depicted in parts I and II of Figure 1 (Fischer M. & Shaki, 2014, for current overview).

First, processing numerical magnitudes causes biases in spatial processing. Regarding directionality, it was shown that perceiving small magnitude numbers causes covert shifts of attention to the left side, while perceiving large magnitude numbers causes attention shifts to the right side (Fischer M., Castel, Dodd, & Pratt, 2003 but see Fattorini, Pinto, Rotondaro, & Doricchi, 2015). Shaki and M. Fischer (2014; Exp 1) showed that random numbers generated while walking in an empty room influenced the direction of subsequent turns (left/right turns were more likely after small/large magnitude numbers). In sum, representing number magnitude causes spatial shifts of attention or motion in the direction predicted by SNA directionality. Such numerical influences have also been documented for processing non-

directional spatial extension like, for instance, estimation of a line's midpoint flanked by small or larger numbers (Fischer, 2001, de Hevia & Spelke, 2009, de Hevia Girelli & Vallar, 2006, de Hevia, Girelli, Bricolo & Vallar, 2008b)

As we have mentioned above, spatial processing (e.g., performing motion in space) might also influence numerical processing. For instance, random number generation can be influenced by the direction of head movements. While performing leftward head movements, participants generate smaller numbers than when performing rightward movements (Loetscher, Schwarz, Schubiger, & Brugger, 2008). Additionally, changes in body posture, and leftward/rightward turns while walking influence estimation of numerical values accordingly (Eerland, Guadalupe, & Zwaan, 2011; Shaki & Fischer M., 2014, Exp 2).

To summarize, there is now ample evidence that SNAs represent a bidirectional link between numbers and space.

A framework of embodiment influences on SNAs: Groundedness, Embodiedness and Situatedness

The evidence we presented suggests that SNAs, including its exact directionalities, are hard-wired. This claim is congruent with typical accounts of SNA. On the other side, much evidence suggests that SNAs can also be influenced by situational factors. These influences (see part III of Figure 1) are the main point of interest for the current work.

Figure 1. Overview of relationships between numbers and space.

M. Fischer (2012, see also M. Fischer & Brugger, 2011) proposed a general theoretical framework on how our experience may shape numerical processing. This hierarchical

framework includes groundedness, embodiedness and situatedness, which are hypothesized to play a role in establishing SNAs. *Groundedness* refers to universal constraints of cognition that express invariance in the external world, like gravity. In regards to numerical cognition, smaller numbers would be associated with lower space and larger numbers with upper space (vertical SNARC) since larger piles that are comprised of more elements are typically higher than smaller piles. *Embodiedness* refers to performance signatures reflecting bodily (sensory and motor) constraints of our bodies. These sensory and motor experiences are incorporated into the structure of knowledge, and can be evoked by activation of several concepts (even abstract ones). In terms of numerical cognition, such influences include universal cultural experiences such as reading in one direction (Wasner, Moeller, Fischer U., & Nuerk, 2014), which may affect horizontal SNARC (which also falls into this category). *Situatedness*, the last level of this hierarchy, refers to the situational constraints on the availability of knowledge that are exerted by the state of one's body and its environment. They may also refer to perceptual and bodily (i.e., somatosensory and motor) influences of the ongoing (e.g., experimental) situation. Such a modulation of the SNARC effect is not due to long-lasting internalized bodily experiences like reading direction, but to the sensory and bodily constraints of the experimental situation in that moment, which can be referred to as *situated influences*. As M. Fischer (2012) proposes, situated influences may easily interfere with embodiedness. Altogether, this distinction, followed by empirical evidence, emphasizes that associations of numbers and space do not obligatorily originate from stable representations but rather may be considered as effects of interaction between long-term cognitive structures and the current situation or task demands. Nevertheless, data collected up to date showing such interactions come from varied experimental procedures, which possibly influence different stages of processing and still need to be systematized.

		SNARC measurement	
		t	
		Pre-experimental manipulation	
		Intra-experimental manipulation	
Mode of manipulation		Reading-related	Reading-unrelated
Perceptual		✓	?
		✓	✓
		✓	✓
Representational		×	?
		✓	✓
Action		?	✓
		?	✓

Figure 2. Overview of proposed types of situated influences on the SNARC effect. Large tics (✓) represent strong evidence for effects of given manipulation type. Small tics (✓) represent poor evidence for effect of given manipulation type. Question mark (?) represent manipulation types that are not yet tested, whereas x sign (×) denotes manipulation types that were not successful.

A taxonomy of situated influences on directional SNAs

Typically, the SNARC effect was considered to be a signature of stable mapping of number representations on spatial locations (points on a directional mental number line; Dehaene et al., 1993). However, to date, the literature has documented several instances of situated influences on SNARC effect. Surprisingly, studies have found that even very short manipulations may lead to prominent changes in the SNARC effect, showing that embodied and situated factors can dominate even long-standing sensory-motor habits. Nevertheless, manipulations that lead to temporal changes in typically observed SNAs varied largely at both technical and, even more importantly, conceptual levels. Therefore, we wish to go beyond a review of all available situated influences and present a new systematization and taxonomy of situated influences (see Figure 2 and Table 1). We hope that this taxonomy will clarify our understanding of the SNARC effect and

guide further studies to improve our understanding of how situational factors may change typical associations between abstract and concrete concepts. Note that we restrict our taxonomy to situated influences on horizontal SNARC. We decided not to include the vertical SNARC effect for the following theoretical and practical reasons in this review. The theoretical reason is that vertical SNARC is, as we already mentioned, classified as a signature of groundedness in cognition. It is theoretically postulated (Fischer M., 2012) that this phenomenon is more stable than the horizontal effect and therefore, situated influences are likely more difficult to detect, however, there is still not much evidence supporting that claim. The practical reason is related and may have its source in the above theoretical considerations: Published studies of situated influences on vertical SNA mapping are very scarce. Nevertheless, we must make a note here that there is some evidence that vertical spatial mapping of numbers may also be modified by situated linguistic factors. Göbel (2015) has recently demonstrated that counting direction in a vertical array may be influenced by reading direction. In her study, Cantonese speakers (who read from left to right as well as from top to bottom) counted objects arranged in a square in the direction depending on the directionality of a text presented to them just before. Note, however, that this study did not test the vertical SNARC effect per se, only counting direction. This one study might suggest that situated influences may also play an important role for vertical SNAs. Furthermore, M. Fischer (2013) reports unpublished studies showing modulations of the vertical SNARC effect. However, given the lack of literature, it is too early to make a definitive judgement.

Table 1. Overview of situational influences on the SNARC effect.

Mode of manipulation	Time of manipulation	
	Pre-experimental	Intra-experimental
Perceptual	<p>How to cook SNARC – large/small magnitude numbers placed at the beginning / end of text lines (R-R) [Fischer M. et al., 2010]</p> <p>Bilingual participants reading a paragraph of a text written from left to right / right to left before a parity judgment task (R-R) [Shaki & Fischer M., 2008; Exp 1]</p>	<p>Bilingual participants reading number words written from left to right / right to left (R-R) [Fischer M. et al., 2009; Exp 1]</p> <p>Simon compatibility of stimulus-response location influences the SNARC effect (R-U) [Keus & Schwarz 2005; Gevers et al., 2005; Tlauka, 2002#; Mapelli et al., 2003#]</p> <p>SPARC-SNARC interaction: auditory numbers are superadditively slow when both SNARC and SPARC are</p>

		incompatible (e.g., large number is in low pitch and on the left side) (R-U) [Weis et al., 2016]
Representational	Bilingual participants listening to a passage of text in a given language (R-R) [Shaki & Fischer M., 2008; Exp 2] #	<p>Bilingual participants being auditorily presented with number words in a given language (R-R) [Fischer M. et al., 2009; Exp 2]</p> <p>Imaging numbers as placed on the clock face versus on the ruler (R-U) [Bächtold et al., 1998]</p> <p>Neglect patients asked to imagine numbers as positions on a clock face process large magnitude numbers – which are placed on the left-hand side – less efficiently (R-U) [Vuilleumier et al. 2004; Exp. 4].</p> <p>The SNARC effect depends on number range present in the task (R-U) [Dehaene et al., 1993; Exp 3; Fias et al., 1996; Exp 1]</p> <p>The SNARC effect depends on the magnitude of criterion number the number is to be compared with in magnitude classification (R-U) [Ben Nathan et al., 2009]</p> <p>Distortion of the SNARC effect caused by the presentation of descending number sequences (R-U) [Lindemann et al., 2008]</p> <p>Distortion of the SNARC effect caused by working memory load (R-U) [Herrera et al., 1998, van Dijck et al. 2009]</p> <p>SNARC for order in sequences stored in working memory (R-U) [van Dijck & Fias., 2011; Ginsburg et al. 2014; Ginsburg & Gevers, 2015; Huber et al., 2016]</p> <p>Verbal labels instead of spatial locations determine the direction of the SNARC effect (R-U) [Gevers et</p>

		al., 2010, Imbo et al., 2012; Georges et al., 2015]
Action	Rapid construction of SNA in preschoolers (R-U) [Patro et al., 2016a]	<p>Varied response key distance does not influence the SNARC effect (R-U) [Schiller et al., 2016] #</p> <p>Direction of unimanual SNARC depends on hand orientation: palm up versus palm down (R-U) [Riello & Rusconi, 2011]</p> <p>SNARC effect with crossed hands depends on reference frames (R-U) [Dehaene et al., 1993; Exp 6, Fischer M. & Hill, 2004, Wood et al., 2006a #, Müller & Schwarz, 2007, Viarouge et al., 2014b]</p> <p>Direction of the SNARC effect changed by spatial compatibility of stimuli successful only when the same effectors are used for both tasks – spatial and numerical (R-U) [Notebaert et al., 2006]</p> <p>SNARC disappears [Tan & Dixon, 2011] or is significantly reduced [Pfister et al., 2013] when calculated from RTs to number stimuli that were preceded by identical numbers. (R-U).</p> <p>SNARC is weaker when it is calculated for RTs to number stimuli that were preceded by SNARC-incompatible response (R-U) [Pfister et al., 2013]</p>
R-R – reading related manipulation R-U – reading-unrelated manipulation # sign denotes non-successful manipulations		

To theoretically and practically structure situated influences on this specific instance of SNA, we organize our review around three categorical distinctions that are illustrated in Figure 2. More detailed description of each type of situated influences is presented in Table 1. All these

distinctions refer directly to the SNARC effect. However, we believe they can be, at least partly, extended to other directional SNA types.

- (i) ***Mode of manipulation:*** This is a primary distinction in our model, because it directly refers to stages of processing that seem to be involved in SNA formation. We distinguish three modes of manipulation: perceptual, representational and action-related.
 - a. *Perceptual manipulations* refer to alterations of stimuli that are biased so that perception itself includes spatial-directional component.
 - b. *Representational manipulations* are those in which a spatial-directional component is to be produced or processed mentally (i.e., perceptual input does not involve directionality). For instance, when a reading material is presented auditorily, the directional component may only be activated at a representational but not perceptual level.
 - c. *Action-related manipulations* refer to changes in the type of motor/effector responses that are performed prior to the task or within a given task. Action and perceptual components are often congruently interconnected. Nevertheless, under some conditions, they may be contrasted against each other. To illustrate this distinction, one may imagine typing text on a typical computer keyboard. The motor activity during typing on the keyboard is by no means directional. However, the perceptual properties observed by the person who is typing are directional (i.e., letters appear in a sequence from left to right).¹
- (ii) ***Time of manipulation:*** Our secondary distinction specifies that within each mode, applying manipulations may vary in time. We will see that this is an important factor for the reliability of situated influences.
 - a. *Pre-experimental manipulation:* Is introduced before the task measuring the SNARC effect is administered. For instance, a text in a given direction (e.g., an instruction) has to be read, before the SNARC task with Arabic numerals is administered.
 - b. *Intra-experimental manipulation:* The manipulation is applied during the task that is used to measure the SNARC effect. For instance, bilingual participants are tested with number words of languages with different reading directions within the experiment itself.

¹ However, evidence exist that emotional valence of words can be biased by position of letters given word consist on the QWERTY keyboard (so-called QWERTY effect; Jasmin & Casasanto, 2012). We would like to thank Martin Fischer for pointing this to us.

- (iii) ***Reading relatedness:*** After categorizing the reviewed manipulations regarding mode and time, we propose to further divide them into two additional types, depending on whether they are reading-related or not.
- a. *Reading related:* The manipulation refers to reading, for instance, the reading direction of presented number words.
 - b. *Reading-unrelated:* The manipulation does not refer to reading, such as the presentation of an analog clock face.

Our taxonomy is not based on similarity of groups (e.g., bilinguals) or task procedures. We might assume that converging results on SNARC changes due to a given manipulation type could shed some light on the nature of underlying processes. Although most of the published studies report successful situated manipulations of SNARC, in our overview, we also include null results (i.e., failures to manipulate the SNARC effect within a given manipulation type), and mark them with the # sign. Such null results may be due to technical details of utilised procedures as well as the fact that a given processing stage / representation form is less prone to changes caused by situational factors. The latter would be more likely if null results were found using multiple tasks (i.e., task-overlapping construct validity).

The manipulations we discuss can be generally categorized in two groups. First, there might competing representations which may be activated concurrently. For instance, when the SNARC effect is examined with crossed hands the right responding hand is on the left side while the right response code (i.e. the response key) is on the left side. One question is whether directional SNAs follow the response codes or the response hands or both (cf. Wood, Nuerk, & Willmes., 2006b). Second, the existing space-to-number mapping may be distorted. For instance the standard mapping of larger numbers to the right space may be disturbed if numbers in a cooking recipe appear on the left or right side of the text (Fischer M., Millis, & Shaki, 2010).

Characteristics of situated influences on the SNARC effect

Perceptual manipulations

Pre-experimental

Manipulations present at the perceptual level, applied directly before the SNARC-relevant task, may strongly influence the magnitude of the effect or even cause it to disappear. Several such manipulations can be found in the literature, and the majority of them are reading-related.

M. Fischer et al., (2010) exposed participants to numbers placed within the lines of cooking recipes in the way that was either congruent or incongruent with the left-to-right reading

direction (e.g., small numbers on the left side vs. on the right side). This kind of manipulation was pre-experimental since the reading task was irrelevant to subsequent parity judgment. The placement of numbers in the text lines was also irrelevant to both reading and parity judgment tasks. This manipulation was perceptual, because a text had to be perceived, while motor actions were not modulated. It led to significant changes in SNARC: the incongruent condition reduced the effect in monolingual English speakers and induced its reversal in monolingual Hebrew speakers.

In another experiment, Shaki and M. Fischer (2008; Exp 1) tested bilingual Russian-Hebrew speakers. The participants were pre-experimentally primed with a short paragraph written in Hebrew or in Russian. After reading a paragraph in Hebrew (i.e., right to left script) the SNARC effect was significantly reduced.

In sum, pre-experimental situated perceptual manipulations can influence the SNARC effect, at least when they are reading-related. By the term *reading-related* we mean that the studies refer directly or indirectly to the direction of the reading process in a given culture or a given subject in a certain experimental condition. We do not claim that reading-related effects stem from the reading process itself.² Rather they could also stem from attentional function directly or indirectly influenced by the reading process. This is evident in cultural habits and activities that are performed mostly in reading-consistent direction (see Nuerk et al., 2015 for such examples).

Intra-experimental

M. Fischer, Shaki, and Cruise (2009; Exp 1) demonstrated that the SNARC effect can be effectively reduced by intra-experimental perceptual manipulation. They tested bilingual participants (Russian and Hebrew speakers). Each trial consisted of two sequentially presented stimuli. First, a number word written in either Russian (script from left to right) or Hebrew (script from right to left) was presented and the participants were asked to assess its parity status. Subsequently, an Arabic number was presented, the parity status of which was also to be assessed. Having applied such manipulation, the authors observed that the SNARC effect was significantly reduced in trials containing a Hebrew number word and in the following digit trials. This result suggests that to alter the SNARC effect in bilinguals (i.e., in case there are concurrent, relatively stable number to space mappings), pre-experimental warm-up in a given scanning/reading direction is not needed.

The SNARC effect is thus susceptible to manipulations applied intra-experimentally on a perceptual level, and can be changed by reading direction even on a trial-by-trial basis.

² We would like to thank Martin Fischer for raising this important issue.

Nevertheless, to the best of our knowledge, this is the only reading-related study that falls into this category.

However, there are reading-unrelated studies for both the visual and auditory modality. As regards visual modality, Keus and Schwarz (2005) observed that the SNARC effect is present in Simon incongruent conditions (i.e. number presented on the left and response given on the right) but not in Simon congruent conditions (see also Gevers, Caessens, & Fias, 2005). On the other hand, some studies did not demonstrate the interaction between SNARC and Simon (Tlauka, 2002; Mapelli, Rusconi, & Umiltà, 2003). In the same vein, Weis, Estner, van Leeuwen, & Lachmann (2016) observed a superadditive interaction between the SPARC effect (Spatial Pitch Association of Response Codes i.e., higher pitches are associated with the right response code and low pitches with the left response code; Lijdl, Kolinsky, Lochy, & Morais, 2007) and the SNARC effect. The SNARC effect was more pronounced for incongruent SPARC mappings. So, when experimental situations are complex and require resolution of perceptual incongruencies the SNARC effect is more pronounced.

Summary – perceptual manipulations

Perceptual manipulations can strongly influence the SNARC effect irrespective of whether they are applied prior to or during the task measuring the SNARC effect. We wish to note that perceptual manipulations may or may not be related to mental changes at the conceptual or representational level. Nevertheless, the results of the studies discussed above suggest that directional perceptual activity (usually but not necessarily related to reading; Padakannaya, Devi, Zaveria, Chengappa, & Vaid, 2002; Nuerk et al., 2015 for diverging views) plays an important (and most likely causal) role in the formation of the SNARC effect.

Representational manipulations

A representational manipulation was intended to influence directionality at a representational level without directional stimuli (e.g., script in left-to-right reading) being actually perceived. A good example is a study from Shaki and M. Fischer (2008), in which verbal material was presented auditorily. The verbal material was from two languages with different reading directions, but the reading direction was only mentally represented, because no written material was presented.

Pre-experimental

Experiment 2 from the study by Shaki and M. Fischer (2008) is, to the best of our knowledge, the only study in which a representational manipulation was administered before the task aimed at

measuring the horizontal SNARC effect. Bilingual participants (Russian and Hebrew speakers) listened to a short text passage in Hebrew or in Russian. Afterwards, the participants performed a typical parity judgment task. There was no difference in the magnitude of the SNARC effect between two language conditions. Therefore, an attempt to prime the concurrent reading-related mapping associated with given language, but without explicit reference to scanning direction, failed to influence the SNARC effect.

Thus, pre-experimental manipulation of reading direction representations was *not sufficient* to modulate subsequent SNARC experiments. This does not rule out the possibility that reading-unrelated, but number-related pre-experimental representational manipulations (e.g., direction of the number line) may modulate the SNARC effect. This should be examined in future studies.

Intra-experimental

Most of situated influences on the SNARC effect we identified belong to this category. Furthermore, the vast majority of these manipulations are not related to reading. The only study we identified that referred to reading direction, but in an implicit way, was Experiment 2 by M. Fischer et al. (2009). Number words were presented binaurally in Hebrew or in Russian, in a randomised order, and participants were to assess their parity status. The SNARC effect differed significantly between trials presented in the two languages. As predicted, the effect was significantly reduced for Hebrew number words. This result clearly indicates that the bias caused by represented reading direction in a given language may significantly influence spatial mapping of number representations. Contrary to pre-experimental manipulation, where explicit reference to reading direction is necessary, in intra-experimental manipulations, implicit references to the representation of reading direction are sufficient to induce the SNARC effect. What is more, these data are a nice demonstration that the distinction between pre-experimentally cued direction and intra-experimentally activated direction is important for whether SNARC manipulations can be observed.

Several representational manipulations not related to reading also caused changes in the SNARC effect, providing several insights into the nature of the SNARC effect. Bächtold, Baumüller, and Brugger (1998) in the training phase, asked one group of participants to *imagine* numbers as placed on a clock face (where large numbers are placed to the left of small numbers). Another group was asked to imagine these numbers as placed on the ruler (where large numbers are placed to the right of small numbers). Afterwards, all participants performed magnitude classification and had to imagine the clock face or the ruler throughout the whole experiment.³

³ Note that the manipulation started pre-experimentally here because the participant had to imagine the clock face / the ruler before the experiment but it persisted intra-experimentally because the participant

The instruction stated that they were to assess whether each presented number referred to earlier or later than 6 o'clock / longer or shorter than 6 centimetres. Contrarily to the ruler condition where the regular SNARC effect was found, in the clock face condition, the SNARC effect was reversed. Therefore, situated factors that were intended to evoke alternative number-space mapping successfully influenced the observed SNARC effect. Note that in this experiment, the manipulation was again aimed at evoking concurrent and stable spatial representations rather than on-line building of such. This result was further confirmed by Vuilleumier, Ortigue, and Brugger (2004; Exp. 4). The authors demonstrated that neglect patients, who normally neglect the left side of representational (incl. numerical) space (Zorzi, Priftis, & Umlità, 2002), processed large numbers less efficiently when required to imagine them on a clock face. Note that like in the famous Piazza del Duomo study in neglect patients (Bisiach & Luzatti, 1978), clock faces were not perceived in this experiment, but only imagined. Therefore, such experiments show that – as in neglect – not only perception, but also mental representation of directional stimuli modulates human cognition.

A seminal study by Dehaene et al. (1993, Exp 3; see also Fias, Brysbaert, Geypens, & d'Ydewalle, 1996, Exp 1) demonstrated that the SNARC effect depends on the context in which a given number appears. Therefore, the spatial mapping may be created during an ongoing task instead of being permanent. The researchers used two numerical intervals (0-5 and 4-9) presented in separate blocks. They were most interested in results for numbers 4 and 5 because these were present in both intervals. The response pattern for these numbers was characteristic of large magnitude numbers (i.e., right hand advantage) when the numbers appeared in the interval 0-5. The opposite was true when the same numbers appeared in the interval 4-9 (i.e., left hand advantage). Therefore, the task set largely modifies the pattern of the SNARC effect. Similar to this approach, Nathan, Shaki, Salti, and Algom (2009) examined trial-to-trial changes in the SNARC effect. They used a magnitude comparison task with a varied criterion value changing from trial to trial. In each trial, the participant was first instructed about the criterion value (e.g., 4 / 7) to which the target number (e.g., 6) was to be compared. Depending on the criterion, each target number could be classified as larger or smaller. The pattern of results (i.e., right or left hand advantage) for a given number depended on the relative magnitude of a number (i.e., whether it was smaller or larger than the criterion; see also Vuilleumier et al., 2004) rather than its absolute value. In sum, this shows that the SNARC effect is not absolute, but rather relative to the mental set within an experiment.

had to imagine the clock face or the ruler throughout the whole experiment. Therefore, it was not classified as a pre-experimental only manipulation. In fact the manipulation was both pre- and intra-experimental.

Lindemann, Abolafia, Pratt, and Bekkering (2008) presented participants with ascending, descending or disordered (i.e., with no monotone order) number sequences and asked them to memorize these sequences. Subsequently, the participants were to assess the parity status of a presented number and, at the end, to recall the memorized sequences. Interestingly, SNARC was only present after ascending and disordered sequences, but disappeared after descending sequences. Moreover, an effect of SNARC alternation was observed only when all sequences in a block were of the same type. This observation is complementary to bilingual studies reported above, when activation of a directional mapping caused changes in the SNARC effect. The difference between these two tasks (apart from the presence of a reading component) is that here, the directionality was created (or rather disturbed) online and had to be kept in active working memory, whereas in bilingual experiments, the prime word evoked a reading-related directionality that was already established in long-term memory in the participants.

This early experiment of Lindemann et al. (2008) converges with another line of research, which demonstrated that loading working memory while performing a SNARC task modulated SNARC effects. Herrera, Macizo, and Semenza (2008) demonstrated that the SNARC effect measured with a magnitude classification task is reduced when participants have to maintain visuospatial information (i.e., Corsi block-tapping task sequences) in their memory. This reduction in the SNARC effect was not present in the parity judgment task. Van Dijck, Gevers, and Fias (2009) replicated this finding and provided evidence for further dissociation between parity judgment and magnitude classification by showing that the SNARC effect measured with the former is reduced when verbal working memory is loaded. These results provide evidence for the claim that working memory is important for the situated mapping of numbers to space. This would explain why the pattern of the SNARC effect depends largely on the task set.

A spectacular demonstration of the role of working memory resources for the appearance of the SNARC effect was shown by van Dijck and Fias (2011). They asked participants to memorize a sequence of numbers. Subsequently, the participants performed parity judgment on this material (and were to refrain from assessing parity of numbers that were not present in the sequence). At the end of such a block, they were to reproduce the sequence. The observed SNARC effect could theoretically be dependent on either the number's magnitude or its position in the sequence. For instance, in the sequence 9 2 4 6 1, the largest magnitude number is placed in a leftmost (first) location and the smallest magnitude number is placed in the rightmost location. The results show that the SNARC effect depended on number position, not on number magnitude. In a subsequent experiment, van Dijck and Fias (2011) used sequences of vegetable and fruit names. Participants were to memorize these sequences and to perform binary fruit-vegetable classification. The authors again observed a significant SNARC-like effect depending

on the element's position in a sequence. This implies that order can drive SNARC-like effects not only for numbers, which have ordinal characteristics, but even for naturally unordered categories like fruits and vegetables.

The working memory account may also explain the appearance of SNARC in typical tasks, when there are no situational manipulations. The basic assumption behind that explanation is that the numbers of an experimental set are also stored in working memory. However, ordered discrete items are stored in the most salient serial order. For numbers, this means that the smallest number is stored at the first position and the largest at the last position. For letters and other ordered sequences, the first element is mentally stored at the first serial order position. As a general principle, the first element is – in our culture – always associated with the leftmost space and the last element with the rightmost space. Therefore, in line with this account, the SNARC effect could be considered as a signature of the working memory function (Fias & van Dijck, 2016) and is a special case of broader phenomenon of spatial coding of ordinal position in a working memory sequence (Abrahamse, van Dijck, & Fias, 2016).

A subsequent study by Ginsburg, van Dijck, Previtali, Fias, and Gevers (2014) demonstrated that the effect of ordinal sequence (instead of SNARC effect depending of number magnitude) is present only when participants are required to retrieve the sequence from memory. Therefore, WM retrieval, and not information maintenance, seems to be related to the SNARC effect. The authors also conclude that there might be multiple mechanisms underlying effects for numerical magnitude and ordinal position. They also speculate that the SNARC effect may originate from temporal activation of long-term memory representations. Similar conclusions can also be drawn from later studies by Ginsburg and Gevers (2015) and Huber, Klein, Moeller, and Willmes (2016). Therefore, although the WM account can explain SNARC and its situated changes to some extent, it is not the only possible mechanism responsible for these effects.

Another linguistic representational manipulation modulating the SNARC effect was described by Gevers et al. (2010). According to these authors, the SNARC effect can be explained by verbal coding of response sides. Namely, small magnitude numbers are associated not with the left side of space but rather with the verbally coded concept “left,” whereas large magnitude numbers are associated with the “right” concept. Effects depending on spatial location and abstract verbal concepts can be contrasted and tested against each other. Gevers et al. (2010; Exp. 3) instructed participants to perform parity judgment by pressing the keys labelled with “right” and “left”. The keys could be placed on the right or left hand side of the display. Interestingly, the observed SNARC effect depended on the verbal codes ascribed to the response keys, but not to the spatial locations of keys. This was also replicated in 9-11 year-old children (Imbo, De Brauwer, Fias, &

Gevers, 2012). Nevertheless, a recent study shows that when spatial aspects are emphasized in the task instructions (i.e., “press the button on the left / right side of the display”), the number-space associations depend both on verbal-spatial and visuospatial mechanisms (Georges, Schiltz, & Hoffmann, 2015). However, Georges et al. (2015) used a magnitude classification task that is thought to rely more on visuospatial than verbal processing in general (van Dijck et al., 2009). In sum, linguistic influences might be dominant in the parity judgement task, while spatial aspects may be more salient in the magnitude comparison task. However, this depends on the focus of the task instructions.

Summary – representational manipulations

As the SNARC effect is thought to originate from a representational level, manipulations on this level seem to be a natural way of influencing this effect. Note that only manipulations which were also applied intra-experimentally (c.f. Bächtold et al., 1998) were found to be successful. However, there was large variety of these manipulations, including imagery, manipulating the task set, working memory load, etc. One of these manipulations was reading-related, but it referred to text directionality in an associative way (meaning of the word as well as its phonological properties associated with a given language and its reading direction). The other did not involve a reading component.

Unsurprisingly, it seems that the SNARC effect originates mostly from a representational level and multiple components seem to modulate or even trigger it in a rather flexible, possibly even trial-by-trial basis. In fact, the effect seems to largely originate from dynamic changes and representations that are actively constructed during task performance. Evidence for such online construction of number representation (i.e., on a trial-by-trial basis) was found in neglect patients as well (Hoeckner et al., 2008). Typically, when a regular task set (whole range of one-digit numbers) and instructions are presented, the online construction seems to lead to what we observe and ascribe as a stable SNARC effect. Otherwise, the construction leads to observed distortions in the typical pattern of results.

Action manipulations

Action manipulations refer to experimental settings where motor actions or body postures per se are manipulated. Obviously, there is a close link between perception and action, which we do not wish to ignore. Thus, when we change perceptual stimuli (e.g., written number words of different reading directions), we might also trigger particular actions of participants. Vice versa, if participants are instructed to perform particular motor actions, they might also perceive them visually or somatosensorily. Here, we focus on manipulations that target motoric or bodily

movements or postures per se. Determining the extent to which such manipulations work in part or as a whole because they are also perceived via multiple modalities remains an important question for the future.

Pre-experimental

Patro et al. (2016a) trained preschool children to play a non-numerical spatial game in which they had to move an object leftward or rightward. Just a few minutes of this directional training evoked SNAs: children trained with the rightward movement formed left-to-right SNA, and those trained with leftward movement formed right-to-left SNA. However, as outlined above, although motor action was the agent of manipulation here, children also perceived accompanying congruent spatial changes (i.e., the spatial trajectory of movement observed on the screen; cf. Patro et al., 2016b). Future experiments must clarify whether the motor action manipulation is still successful when visual perception is prohibited or even interfered with (e.g., in appropriately designed virtual reality experiments).

One must also keep in mind that the only evidence for this type of manipulation comes from preschoolers. It remains unknown whether action manipulations would cause the same effects in adults. We believe this also should be addressed in future studies.

Intra-experimental

In several situations, the SNARC effect is not susceptible to situated influences related to changes in effectors. As we have already mentioned, this can be observed in unimanual setups. Typically, participants asked to assess parity status of presented numbers by using two fingers of the same hand respond faster with the finger located on the right/left to large/small magnitude numbers (Priftis, Zorzi, Meneghello, Marenzi, & Umlità, 2006). Riello and Rusconi (2011) show that when hands are in prone position, a significant SNARC effect can be observed only in case of right-hand responses. In contrast, when hands are in supine position, a significant SNARC can be observed only in left-hand responses. The explanation for this effect is that SNARC may be observed only when the direction of the Mental Number Line is congruent with individual's finger-counting routine. The authors propose that finger series provide a relevant frame of reference in the external space that may be necessary for the SNARC effect to appear. Furthermore, as it has been recently demonstrated, in bimanual setups the distance between response keys does not influence the SNARC effect (Schiller, Eloka, & Franz, 2016).

On the other hand, several studies have shown that modifying the way the participants respond in the SNARC task lead to changes in the observed pattern of results. In general, these manipulations are based on body frame adjustments by contrasting relative (depending on

individual's body / limb) and absolute positions or directions. In the first study demonstrating the SNARC effect, Dehaene et al. (1993; Exp. 6) found that when participants respond with their hands crossed, the effect depends on the position of a key, not on the responding hand. A similar procedure was utilised by M. Fischer and Hill (2004). Parity judgment of auditorily presented numbers was performed both with crossed and uncrossed (parallel) hands. Furthermore, in one condition, the participants were allowed to look at their hands and in the other condition they were not. In this first condition, the SNARC effect depended on the position of responses in external space (i.e., small/large numbers associated with given left/right spatial location) irrespective of whether hands were crossed or uncrossed. However, when the participants were blindfolded, the effect was present only in the crossed hands condition. The authors' interpretation was that in the crossed hands condition, the proprioceptive input was stronger, which led to the building of a stronger frame of reference that produced the SNARC effect. Müller and Schwarz (2007) also support the claim that the SNARC effect depends on spatial location of the response button and not on the responding hand. They found that SNARC depended on spatial location even when the instruction emphasized parity-to-hand mapping (which was constant across session), whereas hand-to-button mapping was altered (crossed and parallel hands blocks).

Wood et al. (2006a) attempted to replicate this finding by testing a larger sample and using different materials (Arabic numbers, written and auditory number words, and dice patterns). The participants were instructed to respond with the right and left key. The authors failed to replicate the effect in any condition. According to the interpretation by Wood et al. (2006b), both body-centred and hand-based associations may be activated when a subject performs the task. These associations are contrasted against each other in the crossed hands condition. In the study by Wood et al. (2006a), they referred more to the responding hand (left/right hand) rather than the response side (left / right side), because blocks with crossed hands were performed after blocks with parallel hands. In the study by M. Fischer and Hill (2004), the stimuli were presented auditorily and this (especially in the blindfolded condition) did not induce external frames of reference. The authors provide evidence that individuals may rely on different frames of reference in terms of their SNAs. These frames are stable intra-individually, but differ across individuals. Therefore, the effects of motor manipulations aimed at changing the SNARC effect may also depend on frames of reference, which a given participant preferentially activates.

Viarouge, Hubbard, and Dehaene (2014) provide further support for the claim that multiple reference frames provide situated influences on the SNARC effect when addressed intra-experimentally. They differentiate between global, body-centred and object-related frames. Influence of each frame may be manipulated by the experimental context (constituted by

response locations, response set or visual feedback provided by the response set). The authors argue that in a typical situation, a global left-right reference frame is activated. They also postulate that several situated influences on the SNARC effect may be caused by activations of concurrent reference frames (i.e., focusing the instructions on participants' hands instead of focusing on directions in space).

Action manipulations may also take other forms, which do not depend on altering body-centred to absolute frames of reference. Notebaert, Gevers, Verguts, and Fias (2006; Exp. 1) found that the SNARC effect may be influenced by a concurrent task in which participants are to respond in a SNARC-incompatible way. SNARC effect in the orientation judgment trials (upright vs. tilted) was largely influenced by the type of inducer task (e.g., it was reversed in participants who were to respond to small / large magnitude numbers with right / left hand) within a concurrent task. In the second experiment, Notebaert et al. (2006) demonstrated similar results with a spatial inducer task. However, this kind of action manipulation is effective only if the same effectors are used in both inducer trials and trials that are used to measure the SNARC effect (Notebaert et al., 2006; Exp. 4). Therefore, an action defined as performing a concurrent task that requires SNARC-incompatible bimanual decisions may lead to distortion in the observed SNARC effect. Action manipulation does not need to involve concurrent inducer tasks. The effect varies largely from trial to trial. Namely, the SNARC effect calculated based on trials that were preceded by the same numbers disappears (Tan & Dixon, 2011) or is significantly reduced (Pfister, Schroeder, & Kunde, 2013). Furthermore, a significant reduction in SNARC is also observed when it is calculated on trials preceded by trials requiring spatially incompatible (left / right to large / small magnitude number) responses (Pfister et al., 2013). Apart from overall reduction in the SNARC effect, the effect also seems to be more disorganized. Namely, there was a larger error term in the regression model indicative of SNARC (i.e., the data points were more dispersed). It seems that action (i.e., given type of preceding response given by the participant) was sufficient to impact the SNARC effect.

Summary – action manipulations

Regarding action manipulations, the pattern of results must be carefully differentiated. The distance or extension of left and right response codes does not alter the SNARC effect. Whether responses are bimanual or unimanual and whether there are small or large distances between response hands does not seem to play a major role in the effect. Like for the mental set of numbers in an experiment in the representational manipulations, the spatial reference frames for different physical distances again seem to be relative, rather than related to absolute distance.

However, the picture changes dramatically if action reference frames are reversed or induced. When hands are crossed, the SNARC effect can be eliminated, possibly because the body-centered action reference frame and the default representational reference frame for numerical sequences point into opposite direction. In such scenarios, instruction seems to be crucial, i.e., whether it focuses on external response keys or body-centered effectors such as response hands. Reversal of action direction can even pre-experimentally reverse the SNARC effect, at least in preliterate children.

To summarize, absolute distance of action parameters does not modulate the SNARC, but the reversal of directionality of action modulates the SNARC at least with appropriate instructions.

Conclusions

Our review suggests that SNAs and in particular, the SNARC effect, consist of a highly flexible, situated spatial mapping of numbers. It operates at different levels of human information processing (perceptual, representational, action), in different temporal frames (pre-experimentally activated mappings or online activated mappings during the experiment), and is triggered by different informational content (reading direction, reading-unrelated action direction, mental numerical set). We will briefly elaborate on the most important points of this conclusion.

- **Flexibility:** All the phenomena described above consistently show that our cognitive system can easily adjust to different ways of mapping numbers to space. Depending on the situation, the system can immediately switch between concurrent mappings, suppress dominant representations or create a new representation just from the beginning. Flexibility can be triggered before the experiment (e.g., by reading texts before or performing actions in particular direction) or during the experiment (e.g., by presenting number words in different scripts). Importantly, it cannot only change for one experiment, but also on a trial-by-trial basis.
- **Situatedness:** The SNARC effect is situated in the context of the experiment or even of a given trial. We hope to have convinced the reader that the default SNARC effect is just a base for SNARC research, because it can be modulated by multiple situational contexts within or even before the experiments. Perceptions, representations and actions as well as reading-related and reading-unrelated content can all modify or reverse the SNARC effect.
- **Different levels of information processing:** The variety of situated influences on the SNARC seems to suggest that this effect cannot be considered only as stimulus-response compatibility effect, present at the response selection stage of processing (e.g. Gevers,

Ratinckx, De Baene, & Fias, 2006). The SNARC effect can be modulated by manipulations at a perceptual, representational, or action level. Moreover, most of these manipulations do not only modulate the SNARC when the response is given, but also modify the reference frames in which space and numbers are mapped even before the experiment. Since the SNARC can be induced even without directional response selection (Fischer M. & Shaki, 2016), a pure response selection account cannot explain all results. However, this does not rule out the possibility that SNARC operates at multiple levels, response selection being one of them.

- ***Different temporal frames:*** The SNARC effect can be modulated both prior to and during SNARC measurement procedure. Moreover, effects of manipulations vary depending on the time they are applied. This is theoretically important, because it seems to suggest that different temporal reference frames with different durations can be activated. When we outlined the flexibility above, we highlighted that spatial reference frames can be flexibly altered over a very short duration, even less than a second on a trial-to-trial basis. However, spatial reference frames do not need to be altered or to dissolve during such a short period of time. Pre-experimental, representational and action-related manipulations, trigger directionality of spatial reference frames, which at least persist during the subsequent experiment without any additional updating of those reference frames. Whether different temporal reference frames can operate in parallel, or whether just one reference frame can be activated over different durations remains an open question for future research.
- ***Different informational content:*** When embodied and situated modulations of the SNARC effect are discussed, it is mostly discussed with reference to reading direction. However, we hope to have shown that script and written words are just one of many types of information that can alter the SNARC effect. Mental imagery, reversal of motoric codes, and training of directional action can all modulate the SNARC effect in a similar way as particular reading-related content. We conclude that spatial-numerical mappings can be modulated and induced (cf. Nuerk et al., 2015) without reading-related content.

To conclude: Gevers and Lammertyn (2005) titled their review paper on the SNARC effect “The hunt for SNARC,” emphasizing the difficulties in examining this phenomenon. Our review shows that successful SNARC hunting requires operating at several information processing levels. Apart from isolating and investigating separate mechanisms that influence the SNARC effect, future effort should focus on testing the interplay between these mechanisms. It seems that what we observe as a typical SNARC effect should be considered not as a unitary phenomenon but rather as an effect of a situated interplay between very specific configurations of relevant

factors. Without such a multi-componential approach, the SNARC effect averts our understanding just like the Snark averts being found in Lewis Carroll's "The Hunting of the Snark" poem.

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