Psychology Science, Volume 47, 2005 (1), p. 10 - 21

The hunt for SNARC

WIM GEVERS[1] & JAN LAMMERTYN[2]

Abstract

The SNARC effect specifically relates small magnitudes to the left hand side and larger magnitudes to the right hand side (e.g. Dehaene et al., 1990; Dehaene et al., 1993). It is certain that cultural characteristics define the SNARC effect: In western cultures small and large numbers are coded in a left-right direction while in Arabic countries magnitude information is coded from right to left (Dehaene et al., 1993; Zebian, in press). In this sense, reading and writing direction have been considered to be the main determinants of the SNARC effect. Indeed, a number of recent studies support the idea that the mastering of a language (and thus reading and writing direction) biases scanning habit in a favourable direction (e.g. Chatterjee et al., 1999; Padakanaya et al., 2002). If this is indeed the case, it is not surprising that the SNARC effect has been found with stimuli other than numbers (Gevers et al., 2004). Related to this, future research could address the question if magnitude and ordinal information are processed by the same mechanism or by different mechanisms with similar properties. However, reading and writing direction alone are not sufficient to explain all SNARC related findings. For instance, it does not allow for an explanation of a vertical SNARC effect as observed by Schwarz and Keus (2004). Apparently, other variables are important in the onset of an association between numbers and space. Furthermore, the existence of a SNARC effect in the vertical dimension could indicate that the number line can be conceptually extended to a number map.

Another puzzling question is to what reference frame the SNARC effect is based. Based on the finding of a SNARC effect with both unimanual (Fischer, 2003a) and oculomotor responses (Fischer et al., 2004; Schwarz & Keus, 2004) at this moment an egocentric allocation of the SNARC effect does not seem feasible.

On the other hand, both behavioural (e.g. Bächtold et al., 1998) and neuropsychological studies (Veuilleumier et al., 2004) point out that the mental representation of numerical information in itself is of major importance to the SNARC effect.

[1] Wim Gevers, Department of Experimental Psychology, Ghent University, Henri Dunantlaan 2, B-9000 Ghent, Belgium; Phone: ++32 9 2646398; Fax: ++32 9 2646496; E-mail: Wim.Gevers@ugent.be

[2] Department of Experimental Psychology, Ghent University, Belgium; E-mail: Jan.Lammertyn@ugent.be

One recent study provided a first step to relate the SNARC effect to other conflict tasks (Mapelli et al., 2003). Directly comparing the SNARC effect with the Simon effect resulted in additive relations between both effects. The question what the exact cause of this additive relation is remains an interesting topic. Furthermore, it could also be worthwhile to contrast the SNARC effect with other conflict tasks such as the Stroop task and the Eriksen Flanker task.

To conclude, 10 years of research on the SNARC effect have unravelled interesting issues regarding the spatial coding of numerical information, fingers crossed for the following 10.

Key words: SNARC-effect, Spatial Numerical Association of Response Codes, reading and writing direction, mental representation of numerical information

The birth of SNARC

People have and always had an above average interest in numerical issues. Many reasons can be given for this preoccupation, but one important reason is that numbers provide us a way to describe our environment, both in space (my office measures about 5 by 3 meters, has number 2.06 and you can find it on the second floor) and time (the year is 2003, there is only 30 minutes left to lunch-time, and the deadline for this manuscript is far too close). Notwithstanding the fact that numbers are a very handy tool for describing our surroundings this does not necessarily imply that numbers are spatial by nature. In 1880, Galton (1880a,b) was the first to notice the apparent relation between the representation of numbers and space. When asked to draw their number representation, participants did so with a large variety of spatially defined numerical representations. After the research done by Galton the matter was not raised anymore for long time, and it is only since ten years that evidence is gathering which directly proves the spatial-numerical relation.

In the early 1990's a first step was taken to further reveal the intimate link between numbers and space. In their study, Dehaene, Dupoux and Mehler (1990) made the participants classify numbers as "larger" or "smaller" than 65 by pressing a left or right response key. The results revealed a distance effect, meaning that reaction times varied as an inverse function of distance to the fixed standard. Put differently, if a target-number was far away from the standard, this resulted in faster responses compared to close-to-standard targets. More important to the present story, the authors reported a strange but fascinating phenomenon. Being a cautiously designed study, Dehaene and his colleagues had counterbalanced the response-mapping over participants, meaning that half of them pressed left for "smaller" and right for "larger" while the remaining participants did the reverse. To their surprise, participants assigned to the first mapping were consistently faster and made less errors compared to participants of the latter group. At the time, no real explanation was given for this phenomenon, but a few years later Dehaene, Bossini and Giraux (1993) studied the phenomenon in a more direct way. Instead of using a number comparison task, this time they chose to use a parity judgment task. Furthermore, this time they used a within-participants design meaning that all participants used both response-mappings. Again they replicated their previous results, namely faster left hand responses to small numbers and faster right hand responses to large numbers. Inspired by a mystical figure out of Carroll's poem "the hunting for the

Snark" (1876), they baptized this effect the SNARC-effect (Spatial Numerical Association of Response Codes; Dehaene, 1997). Historically seen, the study by Dehaene et al. (1993) was the first to unambiguously show that numerical information is spatially coded in a specified direction, confirming earlier reports by Galton (1880). Furthermore it marked a new era of intensive research in the field of numerical cognition, allowing us to reveal bit by bit how our cognitive system handles and represents numerical information. Although a lot is now known about the representation of numbers, some questions remain unanswered. For instance, Dehaene et al. (1993) investigated whether the association between numbers and space is specific to numbers or whether this association can also be extended to other ordinal structures lacking magnitude information. To this end, instead of numbers, letters of the alphabet were used. No association between letters and space was obtained. However, some methodological considerations were shown to be decisive on this matter. Recently, Gevers and colleagues (Gevers, Reynvoet, & Fias, 2003, Gevers, Reynvoet, & Fias, 2004) showed the SNARC effect to occur with letters of the alphabet, months of the year and days of the week. The question can be asked if non-numerical ordinal information and numerical information share the same processing mechanisms or, alternatively, use different mechanisms with similar properties.

How much is left?

The idea of a spatially coded number magnitude is not that far-fetched. Besides the seminal paper by Dehaene et al. (1993), other types of evidence also point towards a spatially-numerical connection. On the neuroanatomical level, Dehaene (1997) noticed that the spatial representation of numbers may rely on a visuospatial cerebral network in which the parietal lobes play a prominent role (Andersen, Snyder, Bradley, & Xing, 1997; Colby & Goldberg, 1999; Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000). Starting from this idea, the parietal lobes were put forward as plausible candidates for representing and processing number related material. A great number of brain imaging studies show that the inferior parietal lobes are indeed responsible for the processing of numerical and spatial information (Dehaene, Piazza, Pinel, & Cohen, 2003; Pesenti, Thioux, Seron, & De Volder, 2000; Chochon, Cohen, van de Moortele, & Dehaene, 1999; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003).

Besides that, neuropsychological studies also provide evidence pointing to a link between number-processing and space. For instance, the Gerstmann syndrome is a complex often observed after a left parietal lesion. Patients suffering from it typically show classical acalculia which is often associated with agraphia, finger agnosia and left-right confusion (Dehaene & Cohen, 1997; Mayer, Martory, Pegna, Landis, Delavelle & Annoni, 1999). Another interesting disorder in this sense is hemineglect. Patients who suffer from this disorder typically show a rightward bias when doing a line-bisection task. Zorzi, Priftis, and Umiltà (2002) extended this effect to the number field by showing that these patients also show a rightward bias in doing a number interval bisection task.

Some properties

We will now give an overview of the properties of the mental number line, as they have been revealed by extensive research during the last decade.

One property of the mental number line is that it is dynamic by nature. This means for instance that the orientation of its extensions depends on the current context. This idea has first been proven by Dehaene et al. (1993; see also Fias, Brysbaert, Geypens, & d`Ydewalle, 1996) by looking for the SNARC effect using two different but partially overlapping number intervals. In one block participants had to judge the parity of numbers within the 0 to 5 interval, while in the other block numbers of the interval 4-9 were used. The results showed clearly that magnitude is spatially coded relative to the used interval. When the numbers 4 and 5 were considered as largest of their range interval (0-5), they were faster responded to with a right-hand response, whereas the reverse was the case in the 4-9 interval. Concretely, this indicates that the spatial coding of magnitude on the mental number line can be dynamically adjusted to the current context.

If the spatial coding on the mental number line is indeed based on relative magnitude, one can ask the logical question if this also applies for numbers beyond nine. A first hint in this direction was provided by Dehaene, Dupoux, and Mehler (1990) who showed a response-side effect for two-digit numbers in a number comparison task (which can be regarded as a precursor of the SNARC effect). Furthermore, Brysbaert (1995) found positional effects in both a number comparison and a naming task. In these experiments, two 2-digit numbers were presented and the participants had to press a button at the side of the smallest number or alternatively name the number at which a central presented arrow was pointing. Both tasks showed a clear SNARC effect and taken together with the Dehaene et al. (1990) study these data support the view that 2-digit numbers are also represented on a mental number line. Thus, the question if 2-digit numbers are also represented on a mental number line seems to be answered positively. This however does not mean that all problems are solved. The debate still continues about how the mapping of 2-digit numbers on a mental number line is actually implemented. Two different views on this matter compete: Initially a holistic view was proposed (Brysbaert, 1995; Dehaene, Dupoux, & Mehler, 1990; Reynvoet & Brysbaert, 1999), but lately a compositional view on 2-digit processing has taken the lead (see for instance Nuerk, Weger, & Willmes, 2001; Fias et al., 2003; Ratinckx, Brysbaert, Fias, & Stevens, submitted). Ratinckx et al. (submitted) investigated how two-digit Arabic numerals are named by looking at the effects of masked primes on the naming latencies. They found that target numerals were named faster if prime and target shared a digit at the same position (e.g., when primes 18 and 21 were used together with target 28). In contrast, naming latencies were slower when prime and target shared one or two digits at non-corresponding places (e.g. primes 82, 86, or 72 for target 28). Ratinckx et al. (submitted) conclude that very early in the course of the recognition process, 2-digit Arabic numbers are syntactically organized in tens and units. This means that tens and units have distinct representations, and one could argue that this indicates a distinct number line for tens and units. Notwithstanding this apparent separate processing, both the representations of units and tens have to converge into one entity somewhere. One could argue that from this point in processing a holistic view is used, but the validity of this assumption is still not clear.

Less than zero

Another logical question regarding the representation of numbers concerns negative numbers. Does the number line indeed extend towards negative numbers with higher negative numbers extending more to the left, or are negative numbers processed and represented like their positive counterparts? Although some effort has already been put in trying to tackle this problem (Fischer, 2003b; Nuerk, Iversen, & Willmes, 2004) the studies done so far seem to contradict each other. While the results obtained by Fischer (2003b) support the view of an extended negative number line, the study conducted by Nuerk et al. (2004) did not find anything to support this notion. One difference between the study of Fischer (2003b) and the study done by Nuerk et al. (2004) is that the former required the participants to do a magnitude related task, while in the latter a parity task was used. In an effort to clarify things once and for all (there is hope), Fischer and Rottmann (this issue) did some experiments while keeping in mind previous attempts. In a first experiment parity judgment was used, while in the second experiment numbers had to be classified as being larger or smaller than zero. The results again proved to be ambiguous in a sense that in the first experiment it was clearly shown that no such thing as a negative number line exists, while the results of the second experiment nevertheless provided some arguments favoring extension of the number line to negative numbers. To summarize, up until now we do not have clear-cut evidence at our disposal promoting a negatively extended number line.

A bias in space?

Knowing that a directional bias exists in the processing of numerical information naturally leads to the question how this bias arises. Berch, Foley, Hill, and Ryan (1999) showed that the SNARC effect as found with a parity judgement task starts to appear around the third grade. However, further research is needed to determine whether this lack of SNARC before the third grade was due to the task at hand (e.g. parity judgment versus magnitude comparison) or not (for a more extended discussion on this matter see Fias & Fischer, 2005).

Working with adult participants, Dehaene and colleagues (1993) tried to exclude alternative interpretations in terms of handedness or hemispheric specialization as a possible cause of the SNARC effect. Indeed, the SNARC effect did not reverse when only left handed participants performed the parity judgment task (experiment 5). The idea of hemispheric specialization as a possible explanation also seems unlikely because the SNARC effect did not reverse when participants performed the task with the hands crossed (experiment 6). More important however, writing direction did seem to contribute significantly to the orientation of the SNARC effect. That is, French monoliterates who use a left-to-right writing system persistently showed a stronger SNARC compared to high skilled French-Persian biliterates who use both a left-to-right and a right-to-left writing system. More convincingly, Zebian (in press) not only replicated but also extended these findings using a slightly adjusted task. In this study participants had to decide with a verbal response whether two numerals had the same numerical value (e.g., 9 9) or not. From Dehaene and Akhavein (1995) it is known that such a comparison necessarily involves semantic activation of the magnitude component. A comparison was made between those trials where the small number was presented on the left (e.g., 1 9) or on the right (e.g., 9 1) (for earlier implementations of this kind of task see Brysbaert, 1995, experiment 3; Ratinckx & Brysbaert, 2002). Surprisingly, only a trend towards a SNARC effect was found for English monoliterates. Zebian (in press) attributes this lack of significance to methodological differences with the Dehaene and Akhavein (1995) study which possibly could have influenced the results. For instance, participants had to respond orally instead of bimanually, and only numeral-numeral pairs were included, while Dehaene and Akhavein (1995) included different combinations of numerals and number words. Furthermore, replicating previous findings from Dehaene et al., (1993), a trend towards a reversed SNARC effect was obtained with Arabic-English biliterate groups. Most importantly, the Arabic Monoliterate group revealed a complete reversal of the SNARC effect making a strong claim for the influence of writing direction on the orientation of the SNARC effect.

Summarizing these results it can be argued that the coding direction of numerical information is by default mapped to the direction of writing. Furthermore, it has also been shown that the SNARC effect can be reversed depending on the task requirements. Bächtold, Baumüller and Brugger (1998) asked participants to make speeded responses towards centrally presented digits (in the range from 1 to 11). When the participants were asked to conceive the numbers as distances on a ruler, a regular SNARC effect was found. In contrast, when the numbers had to be conceived as hours on a clock face, a reversed SNARC effect was observed. This could be taken as an indication that the left-right representation is not that solid, but can easily be interchanged for another representation depending on the task requirements. Problematic for this interpretation was the additional finding that overall reaction times were longer when participants had to conceive the numbers as hours on a clock face as compared to distances on a ruler, which suggests that participants still had difficulties to break with the default left-right orientation.

Why then is it hard to map numbers with an alternative direction? This could be explained if one assumes that not only numbers are represented from left to right, but that the world in general is represented in a left-to-right manner. This directionality would then be particularly driven by reading and writing habits. If this is indeed the case, a directional bias should also exist in different areas than the domain of numerical cognition. Indeed, the mental representation of imagined scenes while reading sentences has also been shown to be spatially biased from left to right in a study by Chatterjee, Southwood, and Basilico (1999). What these authors showed was that verbally communicated events are translated in a left-to-right direction with the subject of the sentence located to the left of the object. At first, hemispheric specialization was used as an explanation for this directional bias in sentence processing. However, a more recent study minimizes the influence of hemispheric specialization while favouring a stronger influence of scanning habit (Maass & Russo, 2003). In parallel to previous research regarding the SNARC effect, Maass and Russo compared Italian and Arabic participants. Subjects were asked to draw a picture of sentences they were confronted with (e.g. The girl pushes the boy). Italian subjects positioned the girl to the left of the boy whereas Arabic subjects positioned the girl to the right of the boy. This latter finding is in agreement with another study showing that Hebrew participants have a directional bias from right to left when doing item-naming and spatial-exploration tasks (Tversky, Kugelmass, & Winter, 1991). More recently, Padakannaya and colleagues (Padakannaya, Devi, Zaveria, Chengappa, & Vaid, 2002) presented picture arrays to different groups of readers. Arabic students (strictly R-L directional reading and writing) named or recalled the picture arrays in nearly 100% of the trials in a right to left direction. Bidirectional readers (Urdu: R-L directionality in both reading and writing and English) showed a decreasing right to left bias with increasing mastering of English, whereas illiterate Urdu adults showed no directional bias.

Hence, the left-right bias in the processing of numbers as evidenced by the SNARC effect is plausibly the result of a more general left-to-right scanning habit caused by cultural characteristics such as reading and writing direction. A recent study (Schwarz & Keus, 2004) implicitly suggests that scanning habit is not the only important variable causing a SNARC effect. Indeed, if reading and writing direction were the only relevant variables one should not expect a SNARC effect in any other direction than the one associated with reading and writing. More specific, a SNARC effect would not be expected in the vertical dimension. At most, because in western cultures a text is read or written from top to bottom, one would expect small numbers to be associated with top and large numbers with bottom. In contrast, Schwarz and Keus (2004), using saccade latency as dependent variable, showed that a SNARC effect exists within the vertical dimension but not in the expected direction. Eye movements were initiated faster to the bottom (top) when centrally a relative small (large) number was shown. Clearly, reading and writing direction are not the only relevant variables for a spatial numerical association to occur. What other factors lay at the base of the SNARC effect should be subject to further research.

SNARC needs a reference

Because the mental representation of numerical information is spatially organised, a reference frame is needed. This raises the question whether numerical information is coded with respect to the body (egocentric coding) or alternatively to some non-bodily object (allocentric coding).

First, consider the possibility that the spatial coding of numerical information is egocentric in nature. With regard to what body part would numerical information then be coded? Because the SNARC effect is generally studied in a bimanual response setting, one obvious candidate is that the hands serve as reference. This account, however, is incompatible with empirical findings showing that the SNARC effect did not reverse when participants had to perform a parity judgment task with the hands crossed (Dehaene et al., 1993). Apparently, spatial coding of numerical information as evidenced by the SNARC effect, is not the result of the hand in itself, but rather relies on the relative position of the response. Further evidence supporting the notion that the SNARC effect is not the result of a hand-based reference frame results from findings where the SNARC effect was found in a pointing task in which participants pointed with the finger of one hand to a left or right target position (Fischer, 2003a). Moreover, because the SNARC effect is also present in the time to initiate eye movements (Fischer, Warlop, Hill, & Fias, 2004; Schwarz & Keus, 2004), or in a naming task (Brysbaert, 1995, Zebian, in press) the SNARC effect does not seem to be effector specific at all. It is clear that spatial information is not coded with respect to a specific body part. This assumption is also supported by the findings of Bächtold et al. (1998), showing that the mental representation itself can influence the SNARC effect independent from the effector (e.g. reversed SNARC effect when participants had to imagine the numbers on a clock face). Further evidence against the notion of effector specific coding is provided by the patient literature. More specific, left hemineglect patients who typically show a rightward bias in line bisection tasks, also showed a rightward bias when performing a number bisection task (Zorzi, Priftis, & Umiltà, 2002). For instance, these patients named the number 6 as lying in the middle between the number 3 and 7. Moreover, confirming the relative importance of the mental representation, the directional bias with left neglect patients was also shown to reverse when the patients imagined the numbers on a clock face (Vuilleumier, Ortigue, & Brugger, 2004).

Remember that Schwarz and Keus (2004) obtained a SNARC effect with eye movements not only in the horizontal dimension but also in the vertical dimension (e.g. small numbers were associated with the bottom and large numbers with the top of the frame). Because the SNARC effect was of comparable size in both the horizontal and the vertical dimension, the authors raised the possibility that a mental number map instead of a mental number line exists. If such a map exists, so was argued, then differential SNARC effects are predicted in a diagonal direction with stronger SNARC effects when eye movements are initiated towards the upper-right and lower-left quadrants compared to the upper-left and lower-right quadrants of the map. This would be predicted because both left (right) and bottom (top) are associated with small (large) magnitudes. Investigating the role of reference frames for the SNARC effect, Wood and colleagues (Wood, Nuerk, & Willmes, submitted) showed numbers in a random order at 12 different clock-face positions (not visible to the participants). An inspection of the results provides no support for the prediction made by Schwarz and Keus (2004) that SNARC effects should be relatively strong in the upper-right and lower-left quadrant. Actually, when averaging the slope values in the respective quadrants, a numerical trend towards the opposite is evident. One could argue that the latter results reflect the reading and writing direction from the upper left to the lower right side of a page. Although further systematic research is needed on this topic, these preliminary findings indicate that, at least in a bimanual response setting, it is hard to transpose the findings of the SNARC effect in both the horizontal and vertical dimension to the SNARC effect in a diagonal dimension.

One important difference between both tasks, however, is that with the Schwarz and Keus study (2004), the manipulation was at the level of response whereas in the study of Wood et al. (submitted) the manipulation happened at the level of the stimulus. Further research is needed on this topic to unravel the basic characteristics of the influence of the relative position of both the stimulus and the response.

SNARC meets Simon

Typically, the SNARC effect is studied in a bimanual response setting where participants have to perform a parity judgment task on a centrally presented target number. As outlined in the introduction, the SNARC effect can also be studied within a magnitude comparison task (Dehaene et al., 1990). Nuerk, Bauer, Krummenacher, Heller, and Willmes (this issue) investigated how the SNARC effect is influenced by adding irrelevant flanking numbers when performing a magnitude comparison task (see Eriksen, & Eriksen, 1974, for a discussion on the flanker task). It was shown that a typical SNARC effect as well as a distance effect was found for the target number. Moreover, although the flanking numbers did not exhibit a SNARC effect on itself, their magnitude was processed in relation to the target number. For instance, 11311 was responded to faster than 33133 because in the former the flanking numbers are smaller than both the reference number 5 and the target number 3.

An alternative way to study the SNARC effect is to present the numbers laterally instead of centrally. By studying the SNARC effect in this manner it is possible to determine the relation between the magnitude of the number and the physical position where it is presented. From the Simon effect it is known that responses are both faster and more accurate when a task irrelevant physical position of the stimulus matches that of the response (Simon, 1969). From the perspective of Kornblums taxonomy (Kornblum, Hasbroucq, & Osman, 1990), the SNARC effect may be regarded as a variant of the Simon effect. According to this taxonomy, the Simon effect is the result of a dimensional overlap between the irrelevant stimulus dimension (location of the stimulus) and the response dimension (left and right key press). Similarly, the SNARC effect in a parity judgment task can be seen as the result of a dimensional overlap between the irrelevant stimulus dimension (magnitude information) and the response dimension (left and right key press). One important difference between both effects however, is the fact that for the Simon effect the irrelevant stimulus dimension is explicit (position on the screen) whereas for the SNARC effect it is implicit (magnitude information). Recently, Mapelli and colleagues (Mapelli, Rusconi, & Umiltà, 2003) directly investigated this possible link between the Simon- and the SNARC effect. Following the Sternberg logic (1969) it was reasoned that if both SNARC and Simon are the result of mutual underlying processing mechanisms interactive rather than additive relations between both effects should be found. Whereas both Simon and SNARC were found they combined additively leading to the conclusions that different underlying mechanisms are at work in Simon and SNARC. However, the authors also pointed out that the Simon and the SNARC effect showed different time courses. While the Simon effect typically decays with increasing time (Hommel, 1994) this was not the case for the SNARC effect. Further research regarding the time course of the SNARC effect is clearly needed. Another interesting issue would be to investigate the relative contribution of magnitude information when this component is made relevant for the task at hand (e.g. magnitude comparison).

References

Andersen, R.A., Snyder, L.H., Bradley, D.C., & Xing, J. (1997). Multimodal representation of space in the posterior parietal cortex and its use in planning movements. Annual Review of Neuroscience, 20, 303-330.

Bächtold, D., Baumüller, M., & Brugger, P. (1998). Stimulus-response compatibility in representational space. Neuropsychologia, 36, 731-735.

Berch, D.B., Foley, E.J., Hill, R.J., & Ryan, P.M. (1999). Extracting parity and magnitude from Arabic numerals: Developmental changes in number processing and mental representation. Journal of Experimental Child Psychology, 74, 286-308

Brysbaert, M. (1995). Arabic number reading: On the nature of the numerical scale and the origin of phonological recoding. Journal of experimental psychology: General, 124, 434-452.

Carroll, L. (1876). The hunting of the snark. London: MacMillan and Co.

Chatterjee, A., Southwood, M.H., & Basilico, D. (1999). Verbs, events and spatial representations. Neuropsychologia, 37, 395-402.

Chochon, F., Cohen, L., van de Moortele, P.F., & Dehaene, S. (1999). Differential contributions of the left and right inferior parietal lobules to number processing. Journal of Cognitive Neuroscience, 11, 617-630.

Colby, C.L., and Goldberg, M.E. (1999). Space and attention in parietal cortex. Annual Review of Neuroscience, 22, 319-349.

Corbetta, M., Kincade, J.M., Ollinger, J.M., McAvoy, M.P., & Shulman, G.L. (2000) Voluntary orienting is dissociated from target detection in human posterior parietal cortex. Nature Neuroscience, 3, 292-297.

Dehaene, S.(1997). The Number Sense. Oxford University Press.

Dehaene, S., & Akhavein, R. (1995). Attention, automaticity, and levels of representation in number processing. Journal of Experimental Psychology: Learning, Memory and Cognition, 21, 314-326.

Dehaene, S., & Cohen, L. (1997). Cerebral pathways for calculation: Double dissociation between rote verbal and quantitative knowledge of arithmetic. Cortex, 33, 219-250.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. Journal of Experimental Psychology: General, 122, 371-396.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital ? Analogical and symbolic effects in two-digit number comparison. Journal of Experimental Psychology: Human Perception and Performance, 16, 626-641.

Dehaene, S., Piazza, M., Pinel, P., & Cohne, L. (2003). Three parietal circuits for number processing. Cognitive Neuropsychology, 20, 487-506.

Eriksen, B.A., & Eriksen, C.W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. Perception and Psychophysics, 16, 143-149.

Fias, W., & Fischer, M.H. (2005). Spatial representation of number. In J.I.D. Campbell (Ed.), Handbook of mathematical cognition (pp. 43-54). New York: Psychology Press.

Fias, W., Brysbaert, M., Geypens, F., & d'Ydewalle, G. (1996). The importance of magnitude information in numerical processing: Evidence from the SNARC effect. Mathematical Cognition, 2, 95-110.

Fias, W., Lammertyn, J., Reynvoet, B., Dupont, B., & Orban, G.A. (2003). Parietal representation of symbolic and nonsymbolic magnitude. Journal of Cognitive Neuroscience, 15, 47-56.

Fischer, M.H. (2003a). Spatial representations in number processing – Evidence from a pointing task. Visual Cognition, 10, 493-508.

Fischer, M.H. (2003b). Cognitive representation of negative numbers. Psychological Science, 14, 278-282.

Fischer, M.H., & Rottmann, J. (this issue). Do negative numbers have a place on the mental number line? Psychology Science, Special Issue, "Brain and Number".

Fischer, M.H., Warlop, N., Hill, R.L., & Fias, W. (2004). Oculomotor bias induced by number perception. Experimental Psychology, 51, 91-97.

Galton, F. (1880a). Visualised numerals. Nature, 21, 252-256.

Galton, F. (1880b). Visualised numerals. Nature, 21, 494-495.

Gevers, W., Reynvoet, B., & Fias, W. (2003). The mental representation of ordinal sequences is spatially organised. Cognition, 87, B87-B95.

Gevers, W., Reynvoet, B., & Fias, W. (2004). The mental representation of ordinal sequences is spatially organised: Evidence from days of the week. Cortex, 40, 171-172.

Hommel, B. (1994). Spontaneous decay of response-code activation. Psychological Research, 56, 261-268.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility - A model and taxonomy. Psychological Review, 97, 253-270.

Maass, A., & Russo, A. (2003). Directional bias in the mental representation of spatial events. Psychological Science, 14, 296-301.

Mapelli, D., Rusconi, E., & Umiltà, C. (2003). The SNARC effect: an instance of the Simon effect? Cognition, 88(3), B1-B10.
Mayer, E., Martory, M.D., Pegna, A.J., Landis, T., Delavelle., J., & Annoni, J.M. (1999). A pure case of Gerstmann syndrome with a subangular lesion. Brain, 122, 1107-1120.
Nuerk, H.C., Bauer, F., Krummenacher, J., Heller, D., & Willmes, K. (this issue). The power of the mental number line: How the magnitude of unattended numbers affects performance in an Eriksen task. Psychology Science, Special Issue, "Brain & Number".
Nuerk, H.C., Iversen, W., & Willmes, K. (2004). Notational modulation of the SNARC and the MARC (Linguistic markedness of response codes) effect. Quarterly Journal of Experimental Psychology A, 57, 835-863.
Nuerk, H.C., Weger, U., & Willmes, K. (2001). Decade breaks in the mental number line? Putting the tens and units back in different bins. Cognition, 82, B25-B33.
Padakannaya, P., Devi, M.L., Zaveria, B., Chengappa, S.K., & Vaid, J. (2002). Directional scanning effect and strength of reading habit in picture naming and recall. Brain and Cognition, 48, 484-490.
Pesenti, M., Thioux, M., Seron, X., & De Volder, A. (2000). Neuroanatomical substrates of Arabic number processing, numerical comparison, and simple addition: A PET study. Journal of Cognitive Neuroscience, 12, 461-479.
Ratinckx, E., Brysbaert, M. (2002). Interhemispheric stroop-like interference in number comparison: evidence for strong interhemispheric integration of semantic number information. Neuropsychology, 16, 217-229.
Ratinckx, E., Brysbaert, M., Fias, W., & Stevens, M. (submitted). The mental representation of two-digit Arabic numerals examined with masked priming: 28 is rapidly decomposed into {{2}x {10}} + {8}.
Reynvoet, B., & Brysbaert, M. (1999). Single-digit and two-digit numerals address the same semantic number line. Cognition, 72, 191-201.
Schwarz, W., & Keus, I. (2004). Moving the eyes along the mental number line: Comparing SNARC effects with manual and saccadic responses. Perception and Psychophysics, 66, 651-664.
Simon (1969). Reaction toward the source of stimulation. Journal of Experimental Psychology, 81, 1974-1976.
Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. In W.G. Koster (Ed.), Attention and Performance II: Acta Psychologica (pp. 276-315). Vol 30.
Tversky, B., Kugelmass, S., & Winter, A. (1991). Cross-cultural and developmental-trends in graphic productions. Cognitive Psychology, 23, 515-557.
Vuilleumier, P., Ortigue, S., & Brugger, P. (2004). The number space and neglect. Cortex, 40, 399-410.
Wood, G., Nuerk, H.C., & Willmes, K. (submitted). Responding to visual numbers guided by mental numbers: multiple frames of reference and the SNARC effect.
Zebian, S. (in press). Influences of cultural artefacts and social practices on number conceptualisation in adults: experimental and ethnographic approaches to everyday numeric cognition. In: Ongoing themes in psychology and culture. Yogyakarta, Indonesia: Kanisius.
Zorzi, M., Priftis, K., & Umiltà, C. (2002). Neglect disrupts the mental number line. Nature, 417, 138-139.

Author's note

This research was made possible by Grant D.0353.01 of the Flemish Fund for Scientific Research. Correspondence concerning this article should be addressed to: Wim Gevers or Jan Lammertyn, Department of Experimental Psychology, Ghent University, Henri Dunant-laan 2, B-9000 Ghent, Belgium. E-mail: wim.gevers@ugent.be; Jan.Lammertyn@ugent.be