SNARC: An Effect of the Alignment of the Egocentric and Allocentric Reference Frames

by

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Your file Votre référence
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To my parents

Abdul Kader Mourad

and

Nada Karabala

Abstract

Dehaene and colleagues (1993) discovered an association of smaller numbers with the left motor responses, and larger numbers with the right motor responses, which they termed the SNARC effect. They attempted to explain the occurrence of this effect in terms of a mental number line representation. Recent evidence, however, has challenged the mental number line notion and thus the SNARC effect still stands short of a comprehensive explanation. Based on McNamara and colleagues' model of spatial cognition (Kelly, & McNamara, 2003; McNamara, Rump, & Werner, 2003; Mou, Fan, McNamara, & Owen, 2008; Mou, Li, & McNamara, 2008; Mou, & McNamara, 2002; Mou, McNamara, Valiquette, & Rump, 2004; Mou, Zhang, & McNamara, 2004; Shelton & McNamara, 2001), this thesis proposes that the SNARC effect in fact involves both the allocentric and the egocentric spatial reference frames. Several assumptions regarding the SNARC effect were specified in terms of constraints involving the alignment of the two types of reference frames. These assumptions were then tested in three experiments. In Experiment 1, a SNARC effect was found for a learned sequence that was associated with increasing perceptual magnitudes and not for other learned sequences involving magnitude information that were either decreasing in size or completely absent. This result indicates that the sequence needs to have a salient intrinsic directionality in order for a SNARC effect to occur. In Experiment 2, the SNARC effect disappeared when its allocentric and egocentric composites were dissociated from each other through imagery and response codes alignment manipulations. Namely, a standard SNARC effect was found for the horizontally aligned allocentric and egocentric axes. As for the vertically aligned axes, a gender effect was unexpectedly found where only the male participants displayed a SNARC effect. Finally, in Experiment 3, it was demonstrated that the

allocentric and egocentric axes should overlap at their subjective midpoint of the former and midline of the later in order for the SNARC effect to occur. The results showed that new associations of the response codes with left and right were formed depending on the position of the midpoint standard within the sequence. These experiments contribute to the understanding of the SNARC effect by presenting it as an effect of the interaction of multiple allocentric and egocentric spatial representations.

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﴿ الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ ﴾

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Introduction

A curious phenomenon was discovered by Dehaene and colleagues (Dehaene, 1992; Dehaene, Bossini, & Giraux, 1993; Dehaene, Dupoux, & Mehler, 1990) when they found that people were faster at identifying a smaller digit with their left hand and a larger digit with their right hand. They coined this phenomenon the Spatial Numerical Association of Response Codes (SNARC). Though the underlying mechanism of this phenomenon is still a mystery, many of its characteristics have been identified in the literature such as the fact that the SNARC effect can be found for negative numbers (Fischer & Rottmann, 2005; Shaki & Petrusic, 2005), as well as for letters of the alphabet, months of the year, and days of the week (Gevers, Reynvoet, & Fias, 2003, 2004). It reverses for Middle-Eastern cultures which have an opposite orthographic direction to English (Dehaene et al., 1993, Experiment 7; Zebian, 2005; Shaki, Fischer, & Petrusic, 2009), it becomes orthogonal for Far-Eastern cultures which have a vertical orthographic system (Ito & Hatta, 2004), and it disappears in illiterates (Zebian, 2005) and children under the age of 9 (Berch, Foley, Hill, & Ryan, 1999). It reverses when an hour face is used as context for a number comparison task (Bachtold, Baumuller, & Brugger, 1998), it is unaffected by crossing the arms (Dehaene et al., 1993, Experiment 6), and it has also been found in blind people (Castronovo & Seron, 2007).

In the majority of SNARC studies, an underlying assumption is that the magnitude of the numbers is being automatically activated and represented spatially in terms of a mental number line, even if the task itself does not require magnitude retrieval (such as for odd-even parity judgments). Though this explanation may account for some of the SNARC effect's characteristics, it does not account for all of them. For example, it does not explain why this effect reverses for different contexts such as when the numerical representation has been specified in terms of an hour face rather than a ruler. It does not explain why illiterates do not have this spatial association, neither does it explain why this association effect is also found for non-numerical concepts such as letters of the alphabet or the months of the year.

In this thesis, I propose that the SNARC effect is not necessarily dependent on numerical magnitude and a mental number line per se but, rather, it is the consequence of the abstract conception of a salient sequence of elements (numbers or otherwise) that has been spatially represented in relation to the body. Given the inherent directional flexibility of the SNARC effect, it will be maintained that the exact nature of the empirical manifestation of such an effect depends on the manner in which internal sequence-based allocentric frames of reference and external response-based egocentric frames of reference become aligned. Importantly, I will also propose that these reference frame representations must align at their subjective midlines in order for the spatial codes of the respective elements within a sequence to become activated. This alignment results in a phenomenon that can be likened to what has been referred to as the *memory alignment effect* and the *sensorimotor alignment effect* in the spatial cognition literature. The aforementioned alignments are, hence, hypothesized to be brought about depending on the nature of the judgment tasks used to examine the SNARC effect.

Namely, whenever participants have to compare a target element within a salient sequence as to whether it is larger or smaller than a standard, the sequence is retrieved from memory allocentrically along the direction of the axis in which it was originally encoded. Therefore, the mental spatial representations for both elements that are to the left or to the right of the standard and the left or right response locations are co-activated, respectively. For example, in a sequence of numbers from 1 to 9, with a standard 5, the digit 8 would co-activate both a conceptual spatial representation of right and the sensorimotor areas in the brain used to make a response on the right side of (the relevant) egocentric space. Hence, the co-activation of spatial representational codes for both the stimuli and the response results in faster reaction times (RTs) to the right for elements that are to the right of the standard and, similarly, faster RTs to the left for elements to the left of the standard. The nature of the spatial representations underlying the SNARC effect will be explored in the 'Frames of Reference' section. But first, some of the properties of the SNARC effect will be reviewed in the following chapter.

The SNARC Effect

In this section, I will introduce the classic SNARC effect and some of its empirical properties that have been established in the literature. After reviewing some initial main findings involving this effect, the first subsection will focus on how numbers can induce a spatial bias. Next, I will discuss how the SNARC effect's directionality is naturally found to be different for different cultural contexts. The third subsection concerns how this directionality can be artificially reversed depending on context. Fourth subsection is about the fact that non-numerical concepts can also lead to SNARC effects will be reviewed in the fourth subsection. Finally, I will introduce an overview of the main models of the SNARC effect in the fifth subsection.

The SNARC effect reflects an association between numerical magnitudes and spatial codes for left and right. First discovered by Dehaene and colleagues (Dehaene, 1992; Dehaene et al., 1993; Dehaene et al., 1990), the SNARC effect refers to the phenomenon that left-hand responses are faster than right-hand responses for small numbers, whereas the converse is true for large numbers. Dehaene et al. (1993) asked subjects to judge numbers from 0-9 as either 'even' or 'odd' and they found that the SNARC effect was present for this task. They therefore concluded that this effect was independent of the parity judgment, suggesting that the number's corresponding magnitude information is automatically retrieved. They proposed that people have a mental representation of number magnitudes in terms of a number line, where on the left are the smaller numbers extending rightward as they increase until they reach a magnitude of 9.

Dehaene et al. (1993, Experiment 3) also tested whether the nature of the response code association depends on absolute characteristics of the numbers or whether it depends on the relative magnitude of the numbers with respect to some pre-specified interval. They administered two parity judgment experiments, one with numbers in the interval 0-5 and one with numbers in the interval 4-9. The associations of both the numbers 5 and 4 changed depending on their relative magnitude within the sequence. That is, they were associated with the right hand when they were the largest in the sequence 0-5 but with the left hand when they were the smallest in the sequence 4-9. Dehaene et al. (1993) concluded that it is the relative magnitude of a number within a given interval that exerts an important influence on the observed spatial associations.

As well, the possibility that these effects are due to the linguistic overrepresentation of the smaller digits over the larger ones was ruled out. Although in many languages, the word 'one' is more frequent than the word 'two', and the word 'two' is more frequent than the word 'three', in these experiments the number 0 had the fastest RT by 27 ms, in spite of being less frequent both as a number word *zero* and as an Arabic numeral 0 (Dehaene et al., 1993, Experiment 3).

The general SNARC effect has now been replicated many times for both the parity task and comparisons of single digit magnitude (e.g., Gevers, Caessens, & Fias, 2005). Its theoretical significance is that it strongly implies that numerical magnitudes have a spatial representation, such as a mental line, that orients from left to right. Further evidence for the automatic nature of this effect was provided by a study in which the SNARC effect was examined in an orientation-discrimination task involving either a triangle or a line superimposed on a digit, where participants had to respond with the left or right hand (Fias, Lauwereyns, & Lammertyn, 2001). In this case, the authors observed a SNARC effect which they posited shows that numerical magnitude is processed automatically, along with its associated spatial representation. However, when they also administered shapes and colors for binary classification instead of orientations, the SNARC effect was diminished. In all of these tasks, participants were instructed to ignore the digit in the background. The authors suggest that neural substrates for orientation and numerical information are shared or overlapping but not for either color or shape information. They also concluded based on other functional neuro-imaging and electrode recording results, that the representations of number and space have a shared location in the parietal cortex neural loci.

Spatial biases invoked by numbers

Although it has been shown that the SNARC effect is not restricted to number sequences, it is still likely to be stronger and more salient for numbers because of their special role in spatial cognition. There is in fact a body of behavioral, cognitive, and neuroscientific evidence that supports the proposed intimate shared relations between numbers and space. The notion of measurements, dimensions, Cartesian coordinates, even the imaginary latitude and longitude lines that separate the earth's spaces into equal parts and angles are all examples that reveal how dependent people are on number representations to make sense of their spatial information.

In a simple experiment that demonstrated how numbers can invoke spatial biases (Calabria & Rosseti, 2005; Fischer, 2001), participants were asked to bisect a line composed of either 'X's or digits. When the line was composed of 'X's, participants were fairly accurate on average. However, when they had to bisect a line made up of numbers, their bisection was biased to the right when the line was composed of the digit 9 or its French word 'neuf'. Conversely, bisection was biased to the left when the line was composed of a smaller digit such as 2 or its French word 'deux'. The authors suggested that such biases are automatically generated. In this case, the spatial location of the corresponding digit on the mental line might have been the cause of the bisection bias.

Fischer, Castel, Dodd, and Pratt (2003) provided supporting evidence for the role of numerical bias in spatial attentional shifts. They administered a simple detection task consisting of a circle appearing randomly on either the left or right side of the screen. The target circles were preceded randomly by one of four digits (1, 2, 8, or 9). Their results showed that circles in the left visual field were detected faster when preceded by a low digit (1 or 2) relative to being preceded by a high digit (8 or 9), and circles in the right visual field were detected faster when preceded by a high digit relative to being preceded by a low digit. Such results imply that number magnitudes have spatial associations that can influence the allocation of attention in the visual field, thus inducing a spatial attentional bias.

An important aspect to note in regard to the orienting of spatial attention is that directing it towards the left/right can be either conscious or unconscious. The unconscious orienting of spatial attention is referred to as exogenous and it is typically characterized as being more automatic than the conscious orienting known as endogenous, which is more deliberate and strategic (Petrusic, W.M., Harrison, D.H., & Baranski, J.V. (2004). Long-term memory for elementary visual percepts: Memory psychophysics of context and acquisition effects. *Perception & Psychophysics, 66* (3), 430-445.

Posner, 1990). In a typical cue-target paradigm experiment, Bartolomeo, Zieren, Vohn, Dubois, and Sturm (2008) explored different aspects of spatial attention orientation. Surprisingly, they asserted that endogenous direction of attention can occur subconsciously, meaning that attention can be directed to a certain side of peripheral vision in anticipation of the stimulus without the participant being able to report that they were aware of doing so. Their findings indicated that people who were able to report on their strategy (verbalizers) and people who were not aware that they were using such a strategy (non-verbalizers) performed similarly well, in terms of RTs, on the cue-target detection task. These findings are important because the SNARC effect might similarly be related to unconscious endogenous direction of attention in anticipation and preparation of a response.

Directionality of the SNARC effect

An important property of the SNARC effect for North American and European participants is that it implies a certain directionality of the spatial representation of numbers. Because many researchers have proposed that the nature of the directionality manifested in the SNARC effect stems from reading and writing systems, studies investigating how it naturally occurs in different cultures have been conducted.

Dehaene et al. (1993, Experiment 7) tested the idea of cultural biases on number conceptualization using a group of French natives and Iranians who had lived in France for differing amounts of time. Both groups participated in a parity judgment task and an individual analysis of the Iranian participants revealed that those who had long been in

France and who had learned French early in life presented results similar to their non-Iranian French counterparts. Thus, they showed faster RTs for large numbers with right-hand responses and for small numbers with left-hand responses. However, the Iranians participants who were trained to read and write in their native country showed much less of an association between number size and hands, which was more consistent with their right-to-left cultural conventions for reading, writing, and number conceptualizing.

Dehaene reflected in his discussion of these results that indeed culture could have a pervasive influence on our spatial-numerical associations. He gave examples of how series of numbers are written in an order where the smallest is on the left increasing rightwards on rulers, calendars, mathematical diagrams, library bookshelves, and so on. He further observed that influences of the spatial conceptualization of numbers are found in American children who tend to explore sets of objects from left to right, whereas the converse is true for Israeli children (Tversky, Kugelmass, & Winter, 1991).

Zebian (2005) expanded Dehaene's research a step further by investigating the SNARC effect for Arabic monoliterates and illiterate Arabic speakers as the main interest groups, as well as for English monoliterates and Arabic-English biliterates. Zebian administered a number matching test to her participants in which they had to respond orally as to whether two digits that appeared on a computer screen were either the same or different. The key condition of interest being the left-right ordering of 'different' pairs (i.e., [4, 5] vs. [5, 4]). The results supported the idea that people think spatially about number concepts in terms of a mental line which is influenced by the directionality of reading and writing. The Arabic monoliterates group showed a reversed SNARC-like effect such that the mental line had a right-to-left directionality (e.g., they were faster to respond 'different' to the pair [5, 4] than to the pair [4, 5]). The biliterates group showed a similar but weakened effect and the illiterate group showed no significant effect. The author argued that it is the visuo-motor skills involved in reading and writing in a right-to-left direction that is manipulating the direction and the strength of this effect for the Arabic participants. However, Zebian did not observe any effect for her English monoliterates speakers, which she speculated might be due to the fact that they did not resort to accessing semantic magnitude codes, but rather compared the two presented digits perceptually when performing this judgment task. Nonetheless, Zebian's research has served to strengthen the hypothesized link between reading and writing direction, and SNARC's directionality.

In another very recent study, Shaki et al. (2009) examined the nature of the SNARC effect for three groups who performed a parity judgment task: Arabic-speaking Palestinians, English-speaking Canadians, and Hebrew-speaking Israelis. A reversed SNARC effect was confirmed for the first group of Arabic-speaking Palestinians who write Arabic and Arabic-Indic numbers from right to left. The Canadian English-speaking group displayed the standard SNARC effect. In the third group, however, the SNARC effect was insignificant and inconsistent. The researchers attributed this last result to the dependent nature of SNARC on the two opposing directional habits of writing Hebrew and using numbers in Israel as part of cultural conventions.

Not only does the mental number line orient from left to right in Western cultures and right to left in Middle-Eastern cultures, but it also orients vertically from top to bottom in Far-Eastern cultures (Hung, Hung, Tzeng, & Wu, 2008; Ito & Hatta, 2004). However, it is worth mentioning that whenever Arabic numbers have been used with the

Far-Eastern cultures, the number line orients from left to right again just as for Western participants.

Reversing the SNARC effect

As mentioned, SNARC has been found to naturally reverse directionality in cultures that use a reversed spatial reference frame for their writing systems. However, artificial experimental manipulations have also been successful in reversing the effect, implying that it is inherently flexible and can be very sensitive to contextual demands. This flexibility has led some researchers to suggest that the SNARC effect is merely an instance of strategic problem solving involving task relevant spatial reference frames (e.g., Fischer, 2006; Lindemann, Abolafia, Pratt, & Bekkering, 2008) and *not* an automatically activated mental number line.

Indeed, the spatial bias invoked by numbers has been found to be influenced by the context within which the numbers are currently being represented. Bachtold et al. (1998) presented numbers from 1 to 11 in the center of the visual field. They asked participants to identify them as smaller or larger than 6, while they conceived of the numbers as distances on either a ruler or a clock face. When participants conceived of the numbers as distances on a ruler, a standard SNARC effect was observed (i.e., they had faster left-hand RTs to identify smaller numbers and faster right-hand RTs to identify larger numbers). When they conceived of the numbers as units on a clock face, however, a reverse SNARC effect was observed. Responses to hours after 6 o'clock now had faster left-hand RTs and responses to hours before 6 o'clock had slower left-hand RTs. Bachtold and his colleagues attributed these patterns to a 'stimulus-response compatibility effect' whereby there is an association between the nature of the representational space currently associated with the numbers and not with number magnitudes per se.

Subsequently, Ristic, Wright, and Kingstone (2006) have obtained experimental evidence suggesting that the spatial attentional bias invoked by numbers that was demonstrated by Fischer et al. (2003) can be attributed to top-down processing of the mental number line conceptualization. When they explicitly asked participants to conceive of the number line as starting from the right, the RT effects for the left and right target stimuli reversed (i.e., participants now had faster detection RTs when smaller digits preceded right targets, and faster detection RTs when larger digits preceded left targets). Moreover, when targets were presented at four possible locations (top, down, left, or right) the digit's left-right association effect was completely abolished. Ristic et al. (2006) concluded that attentional shifting due to digit cues is mediated by strategic top-down factors. They argued that this explanation was especially compelling given that the mental number line effect only emerges quite slowly at 700 ms from the first appearance of the digit cue, which is much slower than the reflexive RT effects (which take less than 200 msec to emerge) of other cues such as arrows or the gaze direction of schematic faces. Therefore, numerical attention shifting effects are both slow and extremely sensitive to changes in top-down mental set.

It is also possible to reverse the SNARC effect by manipulating the usage of the response mappings within both magnitude-relevant and -irrelevant judgment tasks. For instance, Notebaert, Gevers, Verguts, and Fias (2006, Experiment 1) forced an opposite association between numbers and response codes by instructing participants to respond with the left key to numbers larger than 5 and with the right key to numbers smaller than

5 in a magnitude comparison task. A mixed-block paradigm was used whereby the magnitude judgment trials were presented along with number orientation judgment trials. A reversed SNARC effect was observed for the number orientation task even though magnitude was irrelevant for this task.

Bae, Choi, Cho, and Proctor (2009, Experiment 1) provided a replication of the Notebaert et al. (2006) results, except that instead of a mixed-block paradigm, they used a transfer paradigm involving a magnitude comparison task followed by a parity judgment task. They obtained a reversed SNARC effect for the parity judgments when the response's spatial mappings were reversed (i.e., left/large and right/small) for the initial magnitude task. For both of these studies, though, the reverse SNARC condition yielded slightly longer RTs than a control group who used the SNARC-congruent mapping (i.e., left/small and right/large) in the magnitude task (and note that RTs were also longer in the clock than the ruler condition in Bachtold et al., 1998). Such a result suggests that an association of left/small and right/large is the default, and when a reversed response mapping has been imposed, additional processing is required resulting in a reversed correspondence effect along with longer overall RTs.

Non-numerical SNARC effects

When considering the underlying spatial associations of numbers with response codes, it is important to note that if this association was a result of numerical magnitude activation, it would be exclusive to numbers. However, this is not the case. In fact, Gevers et al. (2003, 2004) have found SNARC effects for letters of the alphabet, days of the week, and months of the year. For each stimulus type, participants performed an order-relevant task and an order-irrelevant task. In the first task, they had to decide if the stimulus presented came before or after a standard (the letter O, the day Wednesday, and the month of July). In the second condition, they performed a consonant-vowel classification task (e.g., "Does November end in R?"). In both tasks, a SNARC effect was found, implying that those types of ordered information also have an internal spatial coding and that this ordering can be processed automatically even if it is irrelevant to the task.

Furthermore, Dodd, Van der Stigchel, Leghari, Fung, and Kingstone (2008) showed that letters of the alphabet, days of the week, and months of the year yielded SNARC-like attentional cuing but only when participants were also asked to explicitly determine the position of the cue items compared to a middle item within the sequence (Experiment 2). In an initial experiment (Experiment 1), when the same items were used as cues at fixation point for an upcoming target on either the left or right side of the display, but without explicit reference to their serial orderings, results revealed that only number cues resulted in an automatic shifting of attention to the left or right visual field. The authors attributed this discrepancy between the processing of numbers and other concepts to different visuo-spatial processing mechanisms in the brain, though they mention that the saliency of the sequences might play a role.

Not only do spatial orderings yield SNARC effects, but a similar association has been found for temporally ordered numbers too. Muller and Schwarz (2008) administered a magnitude judgment task for pairs of numbers that were presented temporally in a serial manner, one by one. They presented these numbers in either a descending or ascending numerical order and participants had to judge which of the numbers (i.e., the first or the second) was either the larger or smaller. They found a

SNARC-like effect for judgments involving ascending orders only (such as 2-3) where responding was faster with the right hand but not for descending orders (such as 3-2). This result suggests that the numbers' association with space is one of an ordinal nature caused by over-learned forward associations (1-2-3). If the numbers' association with space was magnitude-based in nature, then the order in which the pairs were presented should not have mattered.

An unexpected type of spatial stimulus-response association has also been found for temporal auditory stimuli. Ishihara, Keller, Rossetti, and Prinz (2008) administered periodic auditory clicks every 500 ms followed by an auditory probe click on the eighth period that occurred either a bit earlier or a bit later than the timing of the previous clicks. The participants' task was to make a judgment about whether the administered probe click was either 'earlier' or 'later' than the prior periods of the clicks. A spatial temporal association was found for these temporal judgments whereby judgments for 'earlier' responses were made faster with the left hand, and judgments for 'later' responses were made faster with the right hand.

Another type of dimension for which a spatial association to response codes has been found is pitch (Rusconi, Kwan, Giordano, Umilta, & Butterworth, 2006). Akin to a parity judgment paradigm, participants had to decide whether musical sounds differing in pitch were played by a wind or a percussion instrument. A group of musically naïve and a group of musicians participated in this study and the responses were selected using either vertical or horizontal keys. The authors found that although the pitch height was irrelevant to the instrument identification task, higher pitches were spatially associated with the upper vertical key and lower pitches were associated with the lower vertical key.

In addition, musicians also showed an association of the horizontal keys with pitch height (right key with high pitches and left key with low pitches).

Very recently, Previtali, Dolores de Hevia, and Girelli (2010) have also found a SNARC effect for word and image sequences. After extensively learning the serial order of a set of 11 words and images, participants were asked to respond whether a presented stimulus word from the ordering came either before or after a middle standard. Previtali and colleagues' findings showed a typical SNARC effect, hence, providing a clear generalization of this effect to non-numerical sequences. Moreover, they concluded that their results suggested that a left-to-right spatial arrangement of information in long-term memory is the preferential way to organize ordinal learning.

Such non-numerical SNARC effects evidently show that this effect is not exclusive to numerical magnitude, but rather, that other mechanisms are involved as well. Furthermore, neurological disorders also lend support to a distinction between magnitude and order information.

Magnitude and ordinal dissociations in neurological disorders

Neuropsychological approaches have unveiled a dissociation between ordinal and magnitude representations. Perhaps the most pronounced order dysfunction is observed in the Gerstmann Syndrome. Gerstmann Syndrome has the characteristics of dysgraphia, agraphia, alexia, acalculia, finger agnosia, and right-left confusion (Turconi & Seron, 2002). In a case study of a patient (CO) who had this disorder as a result of having suffered a bilateral parietal lesions (Turconi & Seron, 2002), order knowledge disruption was one of his symptoms. However, his assessment confirmed that he had no lateral neglect and preserved picture naming. This patient had difficulties in the sequencing and ordering of both numerical and non-numerical elements, though his semantic knowledge of the series was intact (e.g., he knew that there is no school on Saturdays and Sundays) and he was able to recite them. He was tested on series such as numbers, days, months, and letters in tasks where he had to judge if an element came before or after a standard. For example, if presented with numbers, he would not know if 7 came before or after 5; if presented with months, he would not know if June came before or after August; and so on. Interestingly, his magnitude concept was preserved and he was able to perform arithmetic and number comparisons.

The Gerstmann Syndrome has a reverse dissociation condition in which the patient can process sequences and orders correctly, but has lost the concept of magnitude. For example, a patient SE had suffered a left frontal infarct and was unable to access the cardinal meaning of numbers. He showed a severe impairment in calculation tasks and in applying arithmetic principles, along with an inverse distance effect in number comparison, whereas the sequence meaning of numbers such as which numbers come before or after was preserved (Turconi & Seron, 2002).

Another neurological condition related to ordinal sequences is synaesthesia. In this condition, ordinal sequences are explicitly experienced in elaborate spatially extended patterns (Price & Mentzoni, 2008). A feature of the condition is that any verbal or visual cue can trigger an involuntary explicit sequence either in imagined or peripersonal space. These sequences have been reported to be anything that can have an ordinal arrangement such as shoe sizes, numbers, letters, school grades, and days of the month, etc.

Price and Mentzoni (2008) examined the SNARC effect in people with the neurological condition of synaesthesia. The rationale behind testing the SNARC effect for such participants is that if the effect is caused by sequence and spatial interactions in the normal population, then it should be exaggerated in people with synaesthesia. Such a trend was indeed found for comparing the months of the year. Their 16 normal control participants did not show a SNARC effect in a before/after judgment task involving months. In contrast, a substantial SNARC effect did occur for the 4 synaesthetes participants. Interestingly, for two of the synaesthetes participants, their vivid visions of the calendar sequence were in terms of a circular layout with the early months on the right whereas the converse was true for the other two synaesthetes. Therefore, for the synaesthetes whose visions of the months have the early months on the right side of space, their results revealed a reversed SNARC effect. The synaesthetes also showed a SNARC effect in a second task where they had to indicate whether a presented month had a numerical calendar position that was odd or even (e.g., January is odd, February is even). Again, for this task the controls showed no SNARC effect. Hence, this study illustrates how the size of the SNARC can be exaggerated for people who have an explicit experience of sequences in space.

In sum, it has been demonstrated in this literature review that the SNARC effect has a directionality that is variable across cultures and susceptible to contextual manipulations. Also, the SNARC effect has been found in the ordering of many concepts other than numbers, suggesting that it is not exclusive to number magnitude. In reinforcing this conclusion, neuropsychological conditions have revealed a dissociation between number orderings and number magnitude in the Gerstmann syndrome, and an association between orders and an exaggerated SNARC effect in the synaesthesia condition.

Models of the SNARC effect

Two main theoretical accounts for this effect that are currently available in the literature are the polarity correspondence model espoused by Proctor and Cho (2006) and the computational model developed by Gevers, Verguts, Reynvoet, Caessens, and Fias (2006). The Proctor and Cho (2006) polarity correspondence model proposes that the formation of associations between the stimuli and responses in all types of binary classification tasks is dependent solely on structural similarities and not necessarily perceptual or conceptual similarities. Structural similarities refer to a propositional-based categorization of both stimulus and response attributes in terms of negative and positive polarities (i.e., - and +). According to Proctor and Cho (2006), such relational codings are applied to all kinds of perceptual and conceptual attributes (including spatial ones) and underlie all of the stimulus-response compatibility effects that are observed in the literature. For example, in the case of the SNARC effect, according to this model both smaller numbers and the left side of the response space are coded as having a negative polarity, whereas both larger numbers and the right side of the response space are coded as having a positive polarity. When there is a correspondence in polarity for the stimulus and response, faster response selection can be achieved.

An alternative and fairly influential model of the SNARC effect is the Gevers et al. (2006) computational connectionist model which has been used to model the processing that is occurring in both magnitude and parity tasks. This model assumes three layers of processing units, the first of which contains both a number field used to represent each number in the range of numbers being judged and a standard field used to represent the identity of the standard referent defined by the task instruction. The second layer receives its input from the first and can be used to code a number as small or large. This layer can also be used, in parallel, to code parity information (i.e., whether the number is odd or even), and/or any other arbitrary numerical coding. The third layer represents the left and right responses.

The model assumes two operative processing routes, one automatic and one controlled, where the automatic route essentially incorporates learned stimulus-response mappings and serves to facilitate responding when the mapping currently being invoked in the controlled route is compatible with those learned associations and interferes with responding when the mapping currently being invoked in the controlled route is incompatible with those learned associations. A key aspect of Gevers and colleagues' model that results in the SNARC effect is that it supposes an inevitable (i.e., regardless of the nature of the task) categorical classification of number magnitudes at the second layer as 'small' or 'large' (where such magnitude coding is occurring relative to an explicit standard for the magnitude comparison task but relative to an implicit standard for parity judgments). Within the automatic processing route, it is these notions of small and large that are assumed to be associated, in a fairly hard-wired fashion with left and right response codes, respectively.

Each of those models has contributed to the understanding of the SNARC effect, and each one of them has its own strengths with respect to accounting for the data trends obtained from the various tasks that produce the SNARC effect. The Proctor and Cho (2006) polarity model is especially relevant to results obtained in tasks that involve various kinds of binary categorizations of the stimuli (e.g., judgments of small/large, before/after, or close/far). The Gevers and colleagues model, on the other hand, can provide nice accounts for the pattern of SNARC effects obtained in the both parity and magnitude task s, but unlike the polarity model, it has not been applied to other kinds of non-numerical sequences. However, neither of these two models addresses the fact that the underlying basis for the SNARC effect might indeed be spatial in nature. The next section will introduce a spatial model that assumes that this effect arises out of the interaction between different spatial frames of reference. Such a view can then provide a more natural account for the flexible nature of the effect, such as its reversal and its association with different effectors.

Frames of Reference

For number representations (or those of any type of item within a sequence) to be spatially localized entails that they need a frame of reference, that is, they must be mentally represented relative to other entities. As such, a frame of reference is a system that represents the spatial location of entities with respect to something else (Medina, 2007). There are two types of frames of reference that a spatial representational system could use, namely, an allocentric or an egocentric frame of reference. To illustrate, if the position of the numbers on the mental number line are represented with respect to absolute location (e.g., the number 3 is to the East), then their representational system could be said to have an allocentric frame of reference. In this work, however, the allocentric system pertains to the mental arrangement of the items in a sequence as they relate to each other (e.g., the number 3 is before the number 8). If on the other hand, the number positions are represented with respect to the body, then their representational system can be said to have an egocentric frame of reference (e.g., the number 3 is to my left). Both of these reference frames may also involve reference axes along which location can be represented.

The allocentric frame of reference generally refers to the system that represents the coordinates of things independently of the subjective body. It establishes a correspondence between an entity's spatial position (e.g., the position of the school in a district) with respect to other physical entities (e.g., left of the community center), the environment (e.g., in the valley), or absolute coordinates of North, South, East, and West. Its relevance for ordered concepts is that it pertains to mapping out the relationships between the items that are forming the sequence. For example, a sequence of months could be conceived of as 'May' is before 'July' but 'November' comes after, and similarly for other types of sequences.

The egocentric frame of reference, on the other hand, concerns coordinates that are derived by the sensory modalities exclusively relative to the body. Research has demonstrated the presence of multiple egocentric frames of reference such as eye-centered, head-centered, shoulder-centered, body-centered, and hand-centered (e.g., Colby, 1998; Colby & Goldberg, 1999). For example, retinotropic areas in the brain encode stimulus location information in coordinates provided by the eye. Hence, the location of the object can be encoded relative to the eye itself, which is called an eye-centered reference frame, but in addition, retinotropic areas also encode the same location relative to the head, shoulders, hand, body, and so forth, which are called head-centered, shoulders-centered, hand-centered, and body-centered frames of reference, respectively. Therefore, each sensory brain area encodes location information with respect to every body part, thus generating multiple egocentric frames of reference of the object's location.

In the present work, however, the egocentric frame of reference will refer to the totality of the body-centered coordinates of left-right/up-down extracorporal space. In this sense, the relation of ordered elements in a sequence to physical response codes is considered to be an egocentric representation (e.g., if 3 is smaller than 5, press the left key). On the other hand, the relation of ordered elements with respect to each other in a sequence are considered to be an allocentric spatial representation given that no matter where the elements are physically perceived in relation to the body, they are by default mentally represented with respect to their position within the sequence (e.g., 3 is before 5, *not* 3 is to my left).

With respect to the work that is proposed in this thesis, there is a quite well-respected theoretical stance related to this general allocentric-egocentric view which has been posited by McNamara and colleagues in their spatial cognitive model (Kelly & McNamara, 2008; McNamara, Rump, & Werner, 2003; Mou, Fan, McNamara, & Owen, 2008; Mou, Li, & McNamara, 2008; Mou, & McNamara, 2002; Mou, McNamara, Valiquette, & Rump, 2004; Mou, Zhang, & McNamara, 2004; Shelton & McNamara, 2001). Although all of their work on spatial frames of reference has been empirically conducted with geophysical locations of objects, their theoretical account is indeed relevant to the SNARC effect. Therefore, this thesis will extend the main tenets of the McNamara et al. spatial model to encompass abstract conceptions of sequences.

McNamara and colleagues' spatial model

Consistent with the spatial memory literature (Avraamides & Kelly, 2010; Easton & Sholl, 1995; Holmes & Sholl, 2005; Kelly, Avraamides, & Loomis, 2007; Mou et al., 2004; Waller & Hodgson, 2006), McNamara and colleagues' model postulates the presence of two spatial representational systems based on the egocentric and the allocentric frames of reference. The egocentric-based system is responsible for the mental representation of the body's direct interaction with the environment. The model's assumptions regarding the egocentric frame of reference are that it (a) is sensorimotor in nature and is supported by perceptual processes, (b) involves the generation and use of transient short-term memory codes regarding the relative locations of objects in the immediate environment with respect to the current position of the body, and (c) helps to govern performance in on-line spatial tasks by mediating task-relevant actions towards or away from such objects. The allocentric-based system on the other hand, supports the mental representation of the spatial relations between objects in the environment. The assumptions underlying this system are that it (a) is purely memory or imagery based, (b) involves the retrieval and use of more enduring and stable long-term memory codes regarding relative object-to-object locations independent of the current position of the body, and (c) supports reasoning in off-line spatial tasks concerning the spatial relations of objects not currently being experienced (e.g., route planning). The allocentric spatial system upholds some advantages over the egocentric frame of reference such that it allows for the representation of spaces that have never been experienced, for new spatial relations to be construed, and for previous object relations to be retrieved and even modified (Vosgerau, 2007).

The key aspect that distinguishes McNamara and colleagues' model is its important contribution regarding the nature of the allocentric system. Their model assumes that learned allocentric representations of actual environmental layouts are encoded in memory with respect to a major intrinsic reference axis whose orientation can be determined by factors such as (a) salient aspects of the environmental structure of the layout (such as the walls of a room; Shelton & McNamara, 2001), (b) the nature of a reference axis that participants were explicitly instructed to use when learning a spatial layout (Mou & McNamara, 2002), or (c) the manner in which the layout was experienced egocentrically when it was learned (Mou et al., 2004; Kelly et al., 2007). Evidence for this stance has been provided by a number of studies which have shown that performance on spatial reasoning tasks involving the relative directions of objects with respect to a current imagined perspective is enhanced whenever that perspective is aligned, rather than misaligned, with the presumed intrinsic reference axis.

The correspondence between an imagined perspective and the presumed intrinsic reference axis of an allocentric representation can result in what is referred to as a memory alignment effect. On the other hand, the correspondence between an imagined perspective and the egocentric representation of the body's current location in space can result in what is referred to as a sensorimotor alignment effect. Accordingly, it is hypothesized in this thesis that the SNARC effect could represent a manifestation of both memory and sensorimotor alignment effects. Namely that, in accordance with the memory alignment effect, the most natural way of processing the relations between the items in a numerical, or in any other sequence is along perspectives that are aligned with the intrinsic allocentric spatial reference frames used to encode the sequence information in memory. Moreover, in accordance with the sensorimotor alignment effect, responding that is made on the basis of perspectives that are aligned with the current egocentric frame of reference are facilitated.

The memory alignment effect

The memory alignment effect refers to the facilitation that occurs whenever an imagined perspective of a layout corresponds with the spatial arrangement of the environmental constituents in long-term memory (Kelly et al., 2007). For example, for teachers who have taught a class in a specific room, the easiest way for them to imagine the layout of that classroom is as if they were standing facing the same direction that they taught in, that is, at the front of the room looking towards the back. In this case, the imagined perspective of the layout is compatible with the actual direction from which they had taught in the classroom, thus resulting in a memory alignment effect. However, if they imagine themselves standing in a different location from which they had taught, then there would be a misalignment between their imagined perspective and their actual experience of the classroom layout.

However, the memory alignment effect is not exclusively dependent on viewpoint-based learning of a layout by individuals. Studies by McNamara and colleagues suggest that accurate judgments of the relative direction of an object in space can depend on a memory alignment with a learned orientation that is intrinsic to the objects' layout. For example, Mou and McNamara (2002) presented participants with an array of objects from a viewpoint that was 315° from the intrinsic angle defined by the actual layout of the room (0°). To elaborate, the 315° viewpoint ran along the columns that were made up of the objects (pan, wood, lamp) and (book, shoe, clock), whereas the 0° viewpoint ran along the intersecting columns that were made up of the objects (book, wood), (shoe, lamp), and (jar, clock). Importantly, the 0° viewpoint was aligned with the walls of the room. Participants were then asked to learn the spatial layout either from their actual viewpoint (315°) or from the intrinsic room-defined viewpoint (0°).

After learning the spatial layout, they moved to a different room where they were asked to imagine that they were standing at particular locations facing particular objects and then point to another (e.g., "Imagine you are at *A* and facing *B*. Point to *D*.").

Participants were better able to perform the pointing task for imagined headings that were aligned with the learned heading. The authors concluded that such results indicate that the allocentric spatial representation of objects is stored in memory with reference to an intrinsic axis that is consistent with the one used to learn the layout.

In another similar study, Shelton and McNamara (2004) had participants memorize a layout of objects and then describe them to another person from a different point of view. The participants were then tested on their memory of the layout in two tasks involving either scene recognition or relative direction judgment (where the latter was analogous to the pointing task in Mou & McNamara, 2002). The results showed a dissociation for the two tasks, such that performance in the scene recognition task depended on the viewpoint of the participant but performance on the relative judgments depended on whether the alignment of the imagined heading was parallel to the described view. The latter finding indicates that the intrinsic reference axis of the stored representation of the objects' layout was heavily influenced by the requirement to describe it from that point of view.

With respect to the SNARC effect, it seems that when a sequence is retrieved from long-term memory, it is automatically aligned along an intrinsic direction with its items spatially mapped out in the order that they have been learnt in. Consequently, within a sequence, this representation preserves the items' relations to each other such that for numerical sequences the number 3 is always two units after the number 1 and two units before the number 5, for example. Importantly, there is consensus in the literature that for individuals from North America and Europe, the intrinsic directionality of this axis orients from left to right in accordance with cultural conventions.

The sensorimotor alignment effect

The correspondence between an imagined perspective of a layout and the current egocentric frame of reference can lead to what is known as the sensorimotor alignment effect. For example, if you close your eyes and imagine the layout of the furniture around you from your current position, and then tried to imagine it from a heading that is rotated 180°, you would notice the extra mental effort needed to imagine the layout in the latter case.

Empirical support for the sensorimotor alignment effect comes from a number of studies (e.g., May, 2004; Mou et al., 2004; Presson & Montello, 1994; Rieser, 1989). Recently, Kelly et al. (2007) were able to demonstrate sensorimotor alignment effects (Experiment 1) by first having participants stand in the middle of a virtual room and learn virtual object positions around them. In the test phase, the objects were removed and participants had to either stay in that room or 'walk' three meters ahead to another virtual room and then (in both cases) rotate 90° either to their left or right side. Participants were then presented with statements of the form: "Face:*x*, Find:*y*", where they had to imagine the location of (*x*) from memory and while facing it point to the other object (*y*). With respect to the sensorimotor alignment effect, their results showed that when the participants stayed in the same room for the test phase, pointing responses were faster and more accurate for imagined perspectives that were aligned with their current heading compared to misaligned ones. Interestingly, this sensorimotor alignment effect was not present when the participants moved to a novel room but could be recovered if they returned to the learning room (Experiment 2) or if they were prompted to imagine themselves anchored in the learning room relative to the objects (Experiment 3). The authors concluded that the egocentric reference system is supported by online perceptual-motor mechanisms as predicted by Mou et al.'s (2004) spatial model. Therefore, only when participants were able to relate either physically or imaginally to the objects in the room did the sensorimotor effect naturally appear.

Sensorimotor alignment and the SNARC effect

The mere presence of the SNARC effect for lateralized left-right responses strongly implicates the involvement of egocentric frames of reference. Correspondingly, Gevers and Lammertyn (2005) went on to suggest that whatever egocentric frame of reference the SNARC effect depends upon, it cannot be hand-centered because, if so, it should reverse by crossing the hands, which is not the case as demonstrated by Dehaene et al. (1993; although some recent work by Muller & Schwarz, 2007, indicates that hand-centered SNARC-like associations can indeed occur under special circumstances in which the responses are aligned vertically and the task-set emphasizes responding with respect to hands). It also seems evident that the frame of reference cannot be eye-centered because the SNARC effect has been found in blind people (Castronovo & Seron, 2007). In addition, the SNARC effect has also been found for pedal responses (Schwarz & Muller, 2006). Hence, although exceptions can be found, it seems to be the case that the egocentric frame of reference that is contributing to this effect is one that is relative to the totality of the egocentric coordinates, that is, to an abstract representation of the left and right sides in extracorporal space (Dehaene et al., 1993; Muller & Schwarz, 2007).

Although much research has established the robustness of the SNARC effect for participants responding bimanually with the index fingers of the left and right hands, few studies have attempted to manipulate the nature of the egocentric frame of reference for the responses. One exception is Kim (2004) who manipulated the egocentric frame of reference in a series of experiments involving the interchanging of different effectors in different spatial positions. Such egocentric manipulations can directly illustrate the nature of the sensorimotor alignment constraints underlying the SNARC effect.

In his Experiment 1.1, Kim had participants judge number magnitudes unimanually with their index and middle fingers and the use of the right and left hands counterbalanced across blocks. He found a SNARC effect consistent with a left-to-right directionality of the mental number line, where participants responded faster to smaller numbers (1-4) with the middle finger of the left hand and index finger of the right hand (i.e., the left keys) but faster to larger numbers (6-9) with the index finger of the left hand and middle finger of the right hand (i.e., the right keys). However, in another condition (Experiment 1.2) in which the hands were rotated 180° (i.e., palm up), the SNARC effect was found to reverse direction depending on which hand was used first (where a standard SNARC effect occurred only for participants who started with their right hand). In these experiments, the sensorimotor spatial correspondence with the sequence became lateralized across the index and middle fingers of one hand rather than across the index fingers of the left and right hands.

In another sensorimotor alignment manipulation, Kim (2004, Experiment 2.1) also had participants judge number magnitudes unimanually with their index and middle fingers, except that this time the response keys were aligned vertically (with the palms facing the participants). He found an association of smaller numbers with the top effector (i.e., the index finger) and larger numbers with the bottom effectors (i.e., the middle finger). However, when the palms were rotated 180° in Experiment 2.2 (such that the palms were now facing away with the middle finger on top), this vertical SNARC effect was drastically attenuated.

His Experiment 3 was a replication of Experiment 2.1 but with responding to the vertical axes manipulated as in Bachtold et al. (1998) by asking participants to visualize numbers either in terms of a vertical scantron sheet (where numbers increase from top to bottom) or an elevator (where numbers increase from bottom to top). It was found that the nature of the SNARC effect indeed depended on the imagery condition, such that for the scantron sheet condition, the top response was associated with the smaller numbers and the bottom response was associated with the larger numbers and vice versa for the elevator condition.

Additionally, Kim found that there was no hand dominance differences in the SNARC effect for right-handed or left-handed participants (in his Experiment 5) and also that no SNARC effect occurred when responding was made to two left and right keys (positioned 5 cm apart from body midline) using a single response finger (Experiment 6; although he did find a slight SNARC-like trend effect that favored an association of smaller numbers with the left key only).

These different research outcomes of Kim's (2004) strongly suggest that there is a favorable arrangement of the allocentric frame of reference for the numerical magnitudes and the egocentric frame of reference for the responses that allows the SNARC effect to occur. Manipulations of the egocentric response frame of reference outside of this optimal arrangement resulted in a diminished SNARC effect or in a different type of spatial congruity compatibility. In general, Kim attributed his results to the dependency of the SNARC effect on the effectors' relation to the gravitational coordinates (he refers to the left, right, up and down allocentric coordinates as gravitational coordinates) as well as to their relation to the body.

However, Kim's (2004) finding of a non-significant slight SNARC-like trend effect in his Experiment 6 is questionable because his results run counter to those found by Fischer (2003) who did indeed obtain significant SNARC effects for left and right unimanual pointing responses to a touch screen. Therefore, the only constraint on the nature of the egocentric representation of the response space seems to be the presence of lateralized left and right responses rather than two response effectors.

Three Assumptions Underlying the SNARC Effect

In light of the McNamara and colleagues' spatial cognitive model, I am proposing that the SNARC effect arises as a consequence of the alignment of the allocentric and egocentric frames of reference. Just as for the spatial layout of physical objects, the influence that the spatial layout of abstract concepts has on guiding action in terms of response times (RTs) happens only when it is embedded within an egocentric representation (Vosgerau, 2007). The mental spatial layout of the sequence gets embedded egocentrically when the SNARC task forces an egocentric lateralization that triggers the neural association of the subjective left- and right-side of the sequence with the left- and right-side of the body's extracorporal space.

In this vein, three underlying assumptions regarding the SNARC effect will be experimentally tested in this thesis. The first assumption is that allocentric spatial representations of sequences have intrinsic reference axes that determine the default directionality of any related SNARC effects. The second assumption is that, in order to obtain a SNARC effect, the allocentric intrinsic axis needs to be aligned with the egocentric representational axis. Finally, the third assumption is that the nature of the SNARC effect that will occur depends on the alignment of the allocentric and egocentric representations at their respective subjective midlines.

First assumption: The intrinsic directionality of the allocentric frame of reference

It is posited in this thesis that the integral process behind the SNARC effect is the alignment between sequence-based allocentric and response-based egocentric representations. For number sequences, one aspect that determines the nature of this alignment is the fact that the allocentric mental representation of the number sequence has an implicit directionality along an intrinsic axis corresponding to the mental number line. This directionality is inherent to the way that the items within that sequence have been learned. Subsequently, when the sequence is retrieved from memory, it lends itself to be ordered along the learned axis naturally aligning itself with the body's left/right axes.

This intrinsic directionality assumption will be tested in Experiment 1 of this thesis. To do so will require the learning of a novel sequence. Hence, in this experiment, participants will learn to associate six symbolic consonant-vowel-consonant (CVC) nonsense names with different square sizes. The key manipulation will be the spatial manner in which the squares will be presented during the learning phase. In the first condition, the squares will always be presented, over learning trials, in the middle of the screen. In the second and third conditions, the squares will be presented from left-to-right across the screen during learning in either an increasing or decreasing order, respectively, with respect to their sizes. In the testing phase, single CVCs will be presented in the middle of the screen and participants will have to decide whether they refer to either one of the three smaller or one of the three larger squares. The first condition of this experiment will allow for a determination of the manner in which the ordering of stimulus items naturally aligns along an intrinsic reference axis. The second and third conditions will test whether inducing an explicit spatial directionality on the sequence ordering will affect the manner in which the SNARC effect becomes manifested.

Second assumption: The alignment of the allocentric and egocentric axes

As it has been hypothesized above, within the context of the SNARC effect, allocentric spatial representations for both numerical and non-numerical ordered sequences can have intrinsic reference axes. Subsequently, alignment effects are expected to occur when the current egocentric spatial representation of the stimulus-to-response mappings corresponds with the allocentric reference axis. Importantly, studies such as Bachtold et al. (1998) clock-face experiment have shown that the nature of such effects can depend on the alignment of the egocentric frame of reference with an intrinsic reference axis consistent with an instructed imagined allocentric perspective (as also in Kim, 2004, Experiment 3).

Hence, according to the view espoused in this thesis, the presence of numerical SNARC effects should be severely compromised by the adoption of an imagined allocentric perspective that is completely misaligned (i.e., orthogonal to) the orientation of the egocentric frame of reference. In this vein, the participants in Experiment 2 will be instructed to visualize a number sequence in terms of either a vertical array of floor numbers in an elevator or a horizontal array of numbered boxes while performing a numerical magnitude task. Such a manipulation is analogous to that used by Kim (2004; Experiment 3) to examine the effect of imagined perspectives on the vertical SNARC effect. Unlike Kim however, in this present study, the responses for both types of visualization conditions will be made using either vertical bottom and top or horizontal left and right response keys. To my knowledge, no previous experiment has tried to examine the nature of the SNARC effect that would occur under such circumstances.

Third assumption: The alignment of the allocentric and egocentric reference axes at their subjective midlines

Given the notion that casting allocentric sequential relations in terms of an egocentric frame of reference represents an important aspect of the SNARC effect, a key issue is the manner in which the items within the sequence become associated with spatial codes. The essence of the mental number line hypothesis underlying the SNARC effect is that there is a direct correspondence between the left-right positions of the numbers on this line and the positions of the responses which then facilitates responding for cases in which these positions are congruent (Santens & Gevers, 2008).

One interesting phenomenon though is that left and right egocentric spatial associations are not bound to specific numbers. For example, Dehaene et al. (1993) found that the association between certain numbers and left-right response codes depended on the range of numbers used (e.g., 0-5 or 4-9; see the earlier discussion of this work). Hence, that finding suggests that the spatial codes associated with numbers might in fact be based on their relative position with respect to either a standard or, more generally, the subjective midpoint of the specific range of digits.

One aspect regarding the issue of the nature of the sensorimotor alignment that could underlie the SNARC effect that has not been explored in the literature is the effect of changing the effective location of the standard (or subjective midpoint) on the nature of the SNARC effect. Hence, the influence of the location of the subjective midpoint within the range of digits on the SNARC effect obtained for magnitude comparisons will be explored in Experiment 3 of this thesis by moving the midpoint position to different locations within a constant range of numbers. Such an exploration will allow for a determination of whether the SNARC effect results from an association of left-right response codes with specific numbers (within a constant range of numbers) or, alternatively, from associations that are derived relative to the subjective midpoint of the sequence (e.g., consider the digit 6 within the range 1-9 with a standard of 7). Once more note that, to my knowledge, the nature of the SNARC effects that would be obtained for different positions of the standard has never before been examined.

Experiment 1: The intrinsic directionality of the allocentric frame of reference

This experiment was designed to test the implicit directionality of the intrinsic axis of the allocentric representation for a novel sequence of ordered items. The task consisted of binary magnitude decisions involving symbolic items (i.e., CVCs) from a sequence of items whose ordering had been learned by explicitly associating them with different perceptual magnitudes (i.e., squares of increasing sizes). Importantly, there was no explicit serial learning of this item sequence. Hence, this work allowed for a determination of the extent to which SNARC effects extend to the representation of ordered sequences not learned in a serial fashion. In addition, it entailed conditions intended to manipulate the left-right directionality of the intrinsic axis of the allocentric representation of the learned sequence.

The first part of this experiment represented a control condition, whereby each of the squares were displayed at the center of the computer screen during learning (i.e., there was no induced directionality). Therefore, the directionality of any SNARC effects observed in this condition could be assumed to provide an indication of the natural spatial alignment of the allocentric representation of the sequence. In the second condition, however, the squares were displayed in an increasing size order (i.e., smaller to larger) from left to right across the computer screen during learning. The opposite situation occurred for the third condition, whereby the squares were displayed in a decreasing size order (i.e., larger to smaller) from left to right across the computer screen during learning. If the directionality of the intrinsic axis of the allocentric sequence representation is related to the spatial layout present during learning, then standard SNARC effects should occur in the second condition but reverse SNARC effects should occur in the third condition. Such effects would be expected to occur because in both cases the intrinsic axis of the learned sequence should automatically orient with the positional information regarding the smaller and larger squares that was present while their CVC names were being learned.

Experiment 1A

Method

Participants. Twenty-four participants (16 females and 8 males) aged from 17 to 45 years old were recruited from the Carleton University Psychology Department subject pool and participated for course credit. They were run individually for 90 minute sessions.

Apparatus. Using a program written in Turbo Pascal, stimuli were presented on the computer screen of a 486 PC running in DOS mode. Responses during the initial learning phase were collected using a computer mouse but responses during the subsequent test phase were collected using a response box.

Procedure. In the initial learning phase, participants learned to associate six CVC labels (i.e., TOG, BIX, NAK, GUF, ZOC, or PEM) with six squares ranging in size from 18, 23, 30, 39, 50, and 63 pixels in width and height (where the increasing size differences as the squares became larger accommodated for the fact that subjective size can become compressed with increasing magnitude). On each trial of the learning phase, one of the six squares was displayed in white (against a black background) in the centre of the screen. Each square was accompanied by the six CVC labels arrayed horizontally (in a random order across trials) in boxes at the bottom of the screen. One of these boxes was highlighted in red. Participants were required to use the mouse to move the red highlighting to the box with the correct CVC label and then provide a left click response on the mouse (before a 5s time limit was up where responses made after that limit were regarded as errors). At first, participants did not know what the correct labels were but gradually learnt them throughout the course of the learning phase by receiving feedback at the end of each learning trial. To provide feedback, the red highlighting either moved (on its own) to the correct CVC label or stayed put if the response had been correct. The feedback always lasted for 2 s and the next trial was initiated 1 s after that. The learning phase ended whenever participants had responded with the correct CVC label to each stimulus five times in a row or had performed 300 learning trials without reaching this learning criterion. At the end of each learning phase, though, each participant was given three additional over-learning trials per stimulus.

In the subsequent test phase, participants were presented with a single randomly determined CVC label (in the center of the screen) on each trial and were required to indicate whether the square associated with that CVC label had been either one of the three smaller or one of the three larger squares (note that during learning the participants were not aware that they would subsequently be tested in this fashion). Responses were made using the index fingers of each hand to press lateralized left- and right-sided response buttons. Halfway through the test phase, the mapping of the smaller and larger responses to the left and right response keys was flipped (with the nature of the mappings used first and second counterbalanced across participants). Each block in the test phase was 60 trials long and involved 10 replications for each of the six CVC stimuli. Three blocks of trials per response mapping was performed (i.e., six full blocks of test phase trials in total) with a shorter practice block of 40 trials given before the first and fourth blocks. In the test phase, no feedback was provided and the length of the inter-trial interval was 2 s. Participants initiated each new block in the test phase by pressing the space bar and were informed that they could take breaks between each block.

Results

Analyses of the test phase data were performed by calculating for each of the 24 participants the difference between mean correct RTs for non-practice-block responses made with the right hand minus those made with the left hand for each of the six CVCs corresponding to increasing remembered square magnitudes. These differences were then regressed against the square magnitudes (in pixels) separately for each participant and one-sample t-tests run on the resulting unstandardized and standardized regression coefficients (Lorch & Myers, 1990). Note that in such an analysis, standard SNARC effects are marked by a significantly negative mean slope value (i.e., faster left-hand RTs for smaller stimulus magnitudes but faster right-hand RTs for larger ones). Before running these analyses, both error responses (where note that the overall error rate was only 1.6%) and any participant RTs more than 3 SDs from their mean in either of the smaller-larger and larger-smaller response mapping conditions were removed (2.9% of the RT data in total). Note, as well, that the mean number of trials to reach the learning criterion in the initial learning phase was 208 (with a standard deviation of 61 learning trials).

The one-sample t-test on the unstandardized regression coefficients revealed that their mean of 1.03 (SD = 5.10) was not significantly different from 0, $t(23) = .990$, $p <$ .332, $d = 0.20$. In fact, 11 of 24 of these coefficients were negative and 13 were positive. In increasing order, these coefficients were -6.50, -6.02, -3.23, -3.18, -3.11, -1.95, -1.84, -1.78, -1.40, -0.81, -0.40, 0.76, 0.92, 1.39, 1.83, 1.97, 2.13, 2.75, 3.27, 3.30, 3.90, 5.63, 8.87, and 18.20. As well, the overall right minus left mean correct RT differences were -26.27, -13.96, -55.55, 42.01, 26.17, and -0.51 for each increasing square size, respectively. A plot of these mean differences is provided in Figure 1, their mean of 0.048 was not significantly different from 0, $t(23) = .460$, $p < .668$.

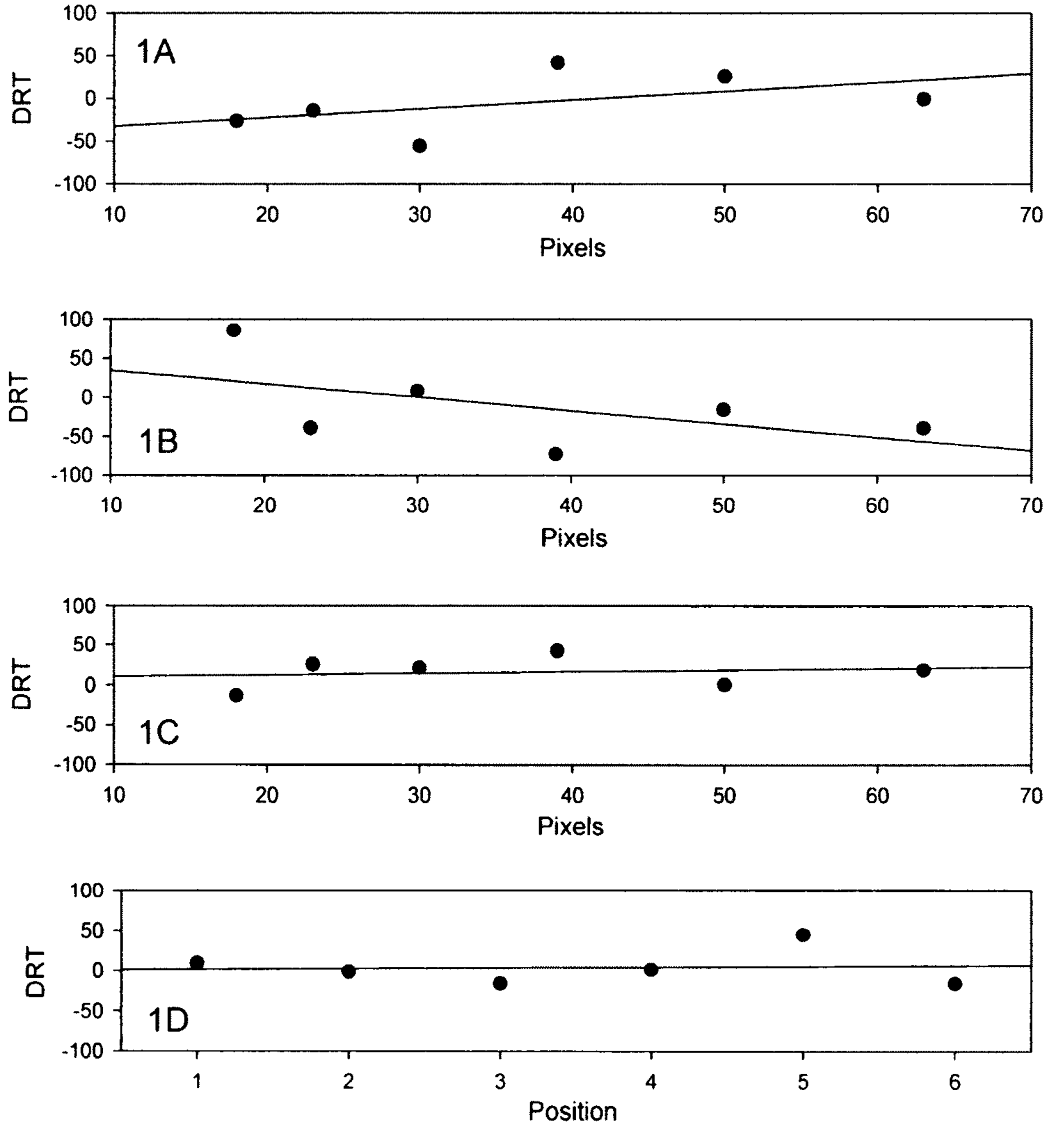


***Figure* 1. Right – Left mean correct RT differences (DRT) in the test phase as a function of square pixel size (Experiments 1A, 1B, and 1C) or ordinal position (Experiment 1D).**

Experiment 1B

Method

Twenty-four new participants (17 females and 7 males) aged from 18 to 36 years old were recruited in the same manner as in Experiment 1A. The apparatus and procedure for both the learning and the test phase were exactly the same as for Experiment 1A except for the fact that during the learning phase, the squares were each presented in one of six horizontally arrayed spatial locations across the computer screen (with the smallest square always displayed in the left-most spatial location, the next smallest square always displayed in the second left-most spatial location, etc.).

Results

Analyses of the test phase data were performed in the exact same manner as in Experiment 1A. In this experiment, 2 participants were not used in the analysis because their error rate was very high (i.e., 33% each). The overall error rate for the remaining 22 participants was 4.0%. As before, all error responses and any participant RTs more than 3 SDs from their mean in either of the smaller-larger and larger-smaller response mapping conditions were removed (5.9% of the RT data in total). For these 22 participants, the mean number of trials to reach the learning criterion in the initial learning phase was 141 (with a standard deviation of 76 learning trials; note that the 2 participants with high error rates in the test phase learned in 150 and 180 trials, respectively).

The one-sample t-test on the unstandardized regression coefficients revealed that their mean of -2.07 (SD = 7.12) was not significantly different from 0, $t(21) = -1.366$, $p <$ .186, d = 0.29. In fact, 10 of 22 of these coefficients were negative and 12 were positive. In increasing order, these coefficients were -14.89, -13.77, -13.33, -11.24, -11.03, -9.42, -

3.63, -3.40, -0.59, -0.45, 0.20, 0.22, 0.26, 0.99, 1.50, 1.68, 2.30, 2.44, 4.50, 5.20, 7.84, and 9.02. As well, the overall right minus left mean correct RT differences were 85.56, -39.02, 8.15, -73.11, -15.74, and -39.44 for each increasing square size, respectively. A plot of these mean differences is provided in Figure 1. The one sample *t*-test on the standardized regression coefficients also revealed that their mean of -0.076 was not significantly different from 0, $t(21) = -0.722, p < .478$.

Experiment 1C

Method

Twenty-four new participants (17 females and 7 males) aged from 17 to 29 years old were recruited in the same manner as in the previous two experiments. The apparatus and procedure for both the learning and the test phase were exactly the same as before except for the fact that during the learning phase, the squares were each presented in one of six horizontally arrayed spatial locations across the computer screen (but now with the largest square always displayed in the left-most spatial location, the next largest square always displayed in the second left-most spatial location, etc.).

Results

Analyses of the test phase data were performed in the exact same manner as for the previous two experiments. In this experiment, 3 participants were not used in the analysis because their error rate was very high (i.e., 32, 34, and 36%, respectively) and 1 other participant could not be used because no data was recorded for one of the response mapping conditions due to computer failure. The overall error rate for the remaining 20 participants was 2.4%. As before, all error responses and any participant RTs more than 3 SDs from their mean in either of the smaller-larger and larger-smaller response mapping conditions were removed (4.4% of the RT data in total). For these 20 participants, the mean number of trials to reach the learning criterion in the initial learning phase was 130 (with a standard deviation of 51 learning trials; note that the 3 participants with high error rates in the test phase learned in 156, 144, and 42 trials, respectively).

The one-sample t-test on the unstandardized regression coefficients revealed that their mean of 0.20 (SD = 5.52) was not significantly different from 0, $t(19) = 0.161, p < .874, d = 0.036$. In fact, 10 of 20 of these coefficients were negative and 10 were positive. In increasing order, these coefficients were -11.07, -9.76, -9.17, -2.49, -2.37, -1.86, -1.45, -0.13, -0.05, -0.02, 0.27, 1.34, 1.95, 2.25, 4.20, 4.68, 4.92, 5.35, 6.89, and 10.47. As well, the overall right minus left mean correct RT differences were -13.13, 26.15, 21.87, 42.36, 0.28, and 18.68 for each increasing square size, respectively. A plot of these mean differences is provided in Figure 1. The one sample t-test on the standardized regression coefficients also revealed that their mean of 0.098 was not significantly different from 0, $t(19) = 0.695, p < .495$.

Discussion of Experiments 1A, 1B, and 1C

Surprisingly, no SNARC effects were found in any of the first three conditions of this experiment (note that a fourth condition is up-coming). A number of possible reasons for not finding any SNARC effects here can be entertained. First, such a result could suggest that the representation of the stimulus items used during the test phase (i.e., the CVCs) did not actually involve an ordering of those items in memory. Indeed, some researchers (viz., Baranski & Petrusic, 1992; Petrusic, Baranski, & Kennedy, 1998; Petrusic, Harrison, & Baranski, 2004) have argued that after learning a set of CVC-percept associations, subsequent processing of the CVC items is analogous to processing the remembered percepts themselves. In support of this notion, those researchers have shown that quite fine discriminations can be made when comparing remembered sizes with actual sizes (i.e., CVC-percept comparisons), although such discriminations are invariably much noisier than those involving two actual percepts. Hence, it is possible that the participants were actually judging the smallness and largeness of the actual remembered square sizes themselves in the test phases of these three conditions. Although SNARC effects have been obtained for certain kinds of perceptual stimuli (as reviewed earlier), the presence of SNARC effects for the perceptual size dimension has never, to my knowledge, been demonstrated.

Second, it is possible that participants did indeed generate allocentric spatial representations of the CVC ordering but with a directionality that differed across individual participants (cf., Wood, Nuerk, & Willmes, 2006a, 2006b). If so, the present results could indicate that the direction of the intrinsic axis of the allocentric representation for this type of stimulus ordering is not as predetermined as that for other types of order representations that have been learned serially (such as days of the week, months of the year, letters of the alphabet, and serially learned word lists). Such a state of affairs, however, would then certainly serve to complicate attempts to study the SNARC effect because the presence of such effects in different directions across individuals would tend to cancel out on average. Before considering this latter possibility more fully though, it seems important to determine whether a consistent SNARC effect can be obtained for a set of items for which it could generally be assumed a learned ordering of them does indeed exist in memory. For this purpose, a final condition was ran in which participants learned an ordering of names for a set of six people (who were assumed to differ in height from shorter to taller) within a linear syllogistic reasoning paradigm.

Experiment 1D

Experiment 1D was designed to test whether the lack of SNARC effects in the previous three conditions was due to the fact that participants did not generate a linear ordering of the stimulus items in memory. Therefore, the paradigm used here is one for which it is quite well accepted that its use leads to a linear ordering of items. In previous work by Leth-Steensen and Marley (2000), participants had to infer the relative heights of six imaginary people (ordered a priori) by being presented with the five pairs of adjacently ordered names during learning. The fact that participants do seem to resort to creating an ordering of the set of items in order to learn this task is evident from the fact that after learning they are easily able to respond to all of the other possible pairs (i.e., they display transitive reasoning). In the test phase of the experiment performed here, though, participants made shorter or taller judgments about single names (analogous to the test phases in the previous three experimental conditions).

Method

Participants. Twenty participants (10 females and 10 males) aged from 17 to 47 years old were recruited from the Carleton University Psychology Department subject pool and participated for course credit. They were run individually for 75 minute sessions.

Apparatus. Using a program written in MEL 2.0, stimuli were presented on the computer screen of a 486 PC running in DOS mode. Responses were made by pressing either the "Z" or "/" response keys on each side of the bottom row of the computer keyboard.

Procedure. In the initial learning phase, participants learned the ordering of six imaginary "people" (i.e., Dan, Ted, Jim, Pat, Bob, and Mel) assumed to differ in height. During learning, participants were presented with each of the five comparison pairs consisting of the stimuli that were adjacent to each other in the ordering. Each comparison trial began with a blank screen for 1000 ms. Then the relevant comparative instruction ("Taller?" or "Shorter?") was displayed for 1000 ms just above a plus sign, which acted as a temporary fixation point for the location of the name stimuli. The participants were then presented with two of the six names side by side in the centre of the computer screen (in MEL System48 font size). They had to choose which person (i.e., the name presented on the left or the name presented on the right) was either the shorter or, respectively, the taller of the pair. They were asked to use the index fingers on their left and right hands to make their responses.

The participants were not expected to know the relative heights of the stimuli at the very start of the experiment and, hence, would initially be guessing. After each response in the learning phase, though, feedback was immediately provided on the computer screen that indicated whether the response had been correct or incorrect and also showed the correct name for that comparison trial. This feedback helped the participants eventually learn which person was the taller and which was the shorter in each pair. They were able to examine this feedback for as long as they wanted and could initiate the next trial with a press of the space bar. Both the comparative instruction and the pair of names remained on the screen throughout the trial (including during the presentation of the feedback).

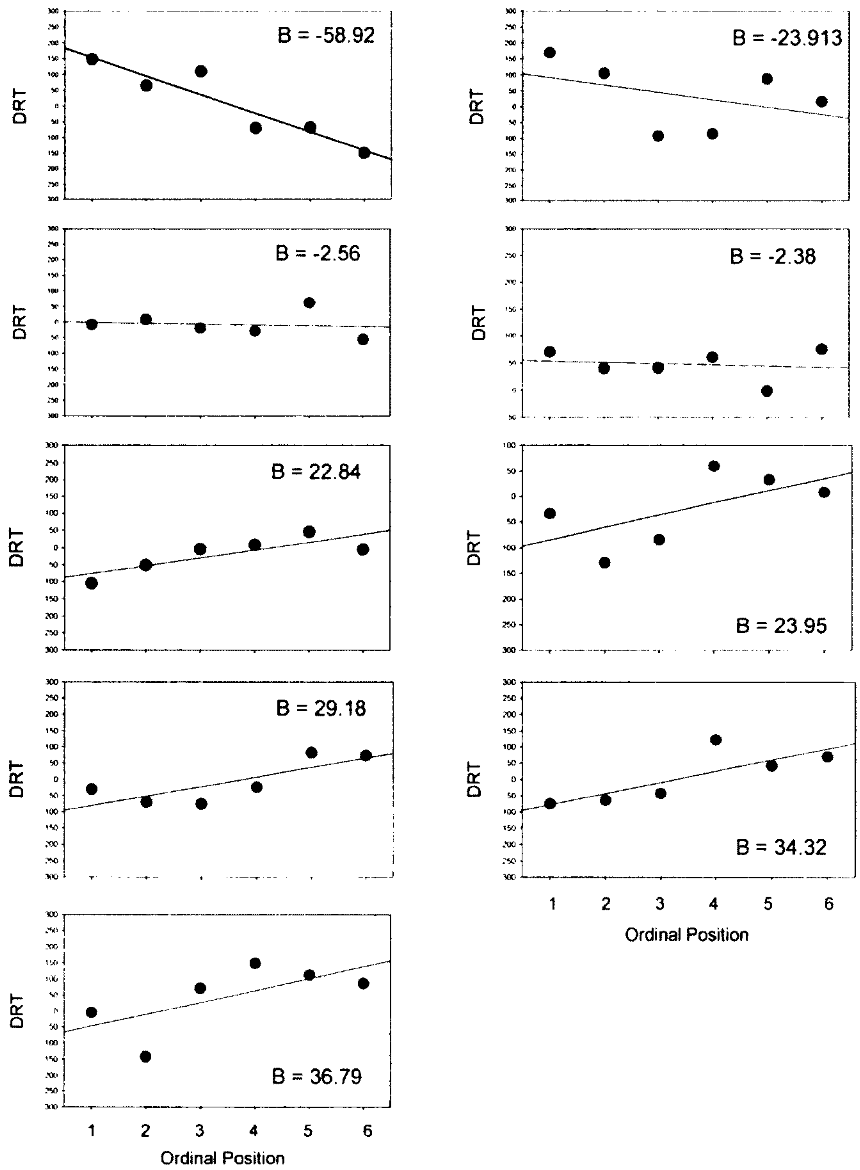
Learning trials were presented in blocks of 20 trials (i.e., five pairs with each of the two instructions in each of the two left-right spatial presentation of the pairs) with breaks after the first 2 learning blocks only. In the first 2 blocks, the pairs were presented in an ordered fashion (e.g., four trials with Dan and Ted followed by four trials with Ted and Jim, etc.) but then presented randomly across trials within the remaining blocks. The learning phase took anywhere from 15 to 30 minutes to perform and was completed when the participant had been correct for a full block of 20 learning trials (up to a maximum of 10 blocks at which point the learning phase was stopped).

In the subsequent test phase, participants were presented with a single randomly determined stimulus name (in the center of the screen) on each trial and were required to indicate whether it referred to one of the three shorter people or one of the three taller people (note that during learning the participants were not aware that they would subsequently be tested in this fashion). Responses were made using the index fingers of each hand (the response keys were the same as for the learning task). Halfway through the test phase, the mapping of the shorter and taller responses to the left and right response keys was flipped (with the nature of the mappings used first and second counterbalanced across participants). Each block in the test phase was 60 trials long and involved 10 replications for each of the six name stimuli. Three blocks of trials per response mapping was performed (i.e., six full blocks of test phase trials in total) with a shorter practice block of 24 trials given before the first and fourth blocks. In the test phase, no feedback was provided and the length of the inter-trial interval was 2 s. Participants initiated each new block in the test phase by pressing the space bar and were informed that they could take breaks between each block.

Results

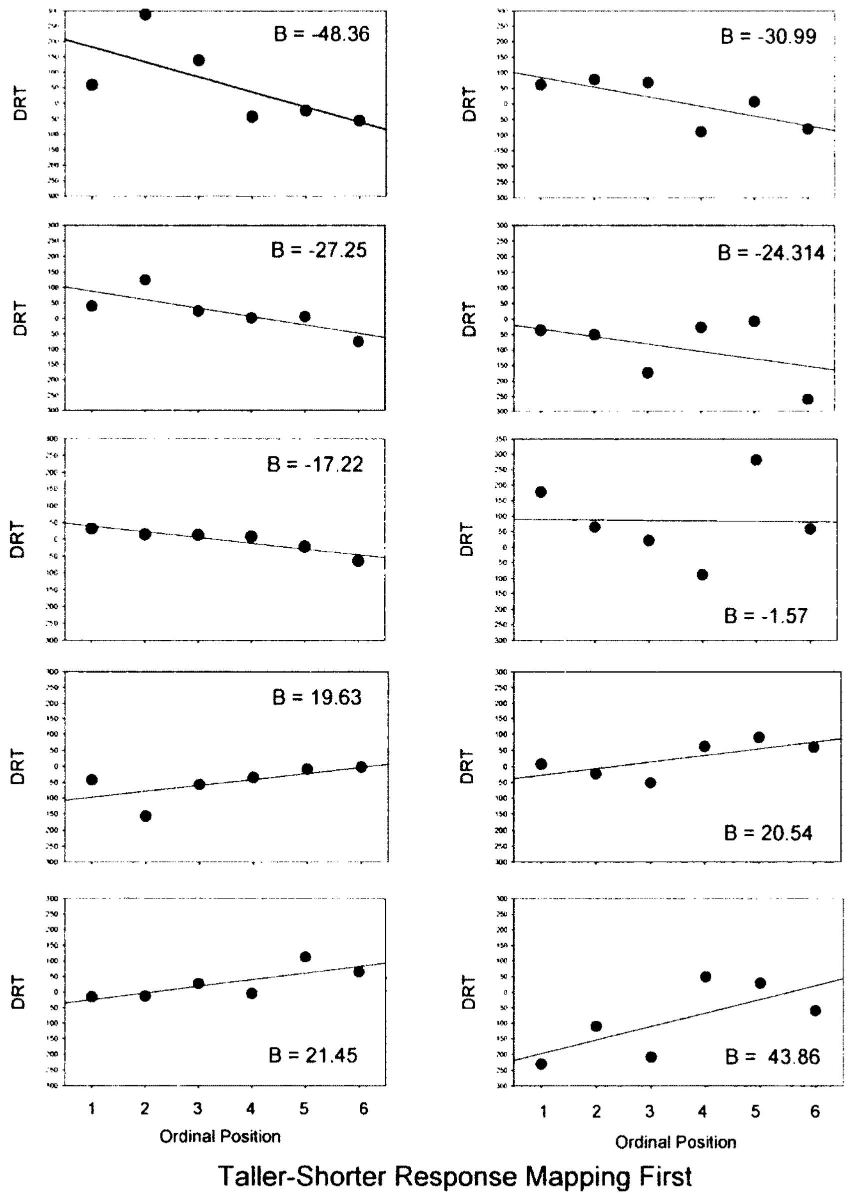
In this experiment, 1 participant was not used in the analysis because his error rate was 50%. The overall error rate for the remaining 19 participants was 3.3%. Analyses of the test phase data were performed by calculating for each of the 19 remaining participants the difference between mean correct RTs for non-practice-block responses made with the right hand minus those made with the left hand for each of the six names. These differences were then regressed against the positional order of the names (i.e., 1, 2, 3, 4, 5, and 6) separately for each participant and one-sample t-tests run on both the resulting unstandardized and standardized regression coefficients (Lorch & Myers, 1990). Note, again, that in such an analysis, standard SNARC effects are marked by a significantly negative mean slope value. Before running these analyses, both error responses and any participant RTs more than 3 SDs from their mean in either of the shorter-taller or taller-shorter response mapping conditions were removed (5.3% of the RT data in total). Note, as well, that the mean number of learning blocks performed in the initial learning phase was 6.8 (with a standard deviation of 2.9 blocks; Min = 3 and Max = 10).

The one-sample t-test on the unstandardized regression coefficients revealed that their mean of 0.82 (SD = 30.35) was not significantly different from 0, $t(18) = 0.118$, $p <$ .902, $d = 0.027$. In fact, 10 of 19 of these coefficients were negative and 9 were positive. In increasing order, these coefficients were -58.92, -48.36, -30.99, -27.25, -24.14, -23.13, -17.22, -2.56, -2.38, -1.57, 19.16, 20.54, 21.45, 22.84, 23.95, 29.18, 34.32, 36.79, and 43.80. As well, the overall right minus left mean correct RT differences were 9.67, -1.17, -15.46, 1.45, 45.19, and -15.76 for each increasing ordinal position, respectively. A plot of these mean differences is provided in Figure 1. Corresponding plots for all 19 participants are provided in Figure 2 (below). The one sample t-test on the standardized regression coefficients also revealed that their mean of 0.064 was not significantly different from 0, $t(18) = .406$, $p < .689$.



Shorter-Taller Response Mapping First

Plot 1



Plot 2

Figure 2. **Right – Left mean correct RT differences (DRT) in the test phase as a function of ordinal position plotted for each participant in Experiment 1D.**

Plot 1 – Participants who used the shorter-left, taller-right response mapping first. Plot 2 – Participants who used the taller-left, shorter-right response mapping first.

Further discussion of Experiments 1A, 1B, 1C, and 1D

As before, no overall SNARC effect was observed in Experiment 1D. Because it is quite commonly accepted (Leth-Steensen & Marley, 2000) that the task used in this latter condition should indeed have served to induce a linear ordering of the stimulus items (and note that no perceptual referents at all were available in Experiment 1D), the lack of the SNARC effect for this condition cannot be attributed to the fact that the participants might not have linearly aligned the stimulus items in memory. Even so, it is possible that one requirement for the emergence of an intrinsically aligned, allocentric spatial representation might be that some sort of serial learning of the ordering has taken place. In other words, perhaps it is the case that ordered information only becomes spatially configured if it is clear that such information represents an actual sequence. Another potential consideration concerns the nature of the learning occurring in the learning task. Except for the two end items, each of the other four items in the middle of the ordering was responded to as being either the taller member of a pair or the shorter member of another pair an equal number of times. Hence, the fact that these items had been associated with being both the shorter item and the taller item during learning may have lessened the strength of any spatial associations that would have arisen based on the absolute sizes of these items within the ordering.

On the other hand, the results for the individual SNARC effects shown in Figure 2 seem also to provide some evidence for the presence of a great deal of individual differences in the directionality of the SNARC effect for a stimulus ordering of this nature (cf., Wood et al., 2006a, 2006b). Indeed, about six participants in Experiment 1D showed a clear preference for ordering the shortest to tallest stimulus items from left to right (i.e., negative regression slopes) and about nine other participants showed a clear preference for ordering the shortest to tallest stimulus items from right to left (i.e., positive regression slopes). Hence, given these results, the possibility that similar individual directionality differences were occurring in the previous three CVC conditions seems more tenable. What is not clear, however, is why such directionality differences occurred in Experiments 1B and 1C where explicit attempts were made to induce a specific directionality. In regards to this point, it could likely have been the case that the participants were indeed focusing mostly on the square size information while learning the CVC associations and ignoring the location information that was also being provided (note that whereas the size information was an explicit attribute for learning, the location information was really only implicit in nature). As well, unlike the left-right numerical spatial associations that become built up across a lifetime of being exposed to them, the amount of learning provided in the Experiment 1B and 1C was not very extensive.

Given the potential presence of individual directionality differences in the manner in which the allocentric representation of the order information in these four conditions is aligned in memory, it seems important to try to determine why such differences might have occurred. Hence, some subsequent regression and *t*-test analyses were performed to determine whether either the age or the gender of the participants might predict the individual unstandardized regression slopes observed within each of the four conditions of this experiment (see Table 1 for these results). The only other individual characteristic collected here was the left or right handedness of the participants but no handedness analyses were run given that only two of the participants in all of these four conditions self-reported as being left handed. Unfortunately, the native language of these participants was not asked for here (although such information was indeed collected as part of the next set of experiments).

An additional set of analyses that were run examined whether the individual regression slopes were related to the number of learning trials taken by each participant in the initial learning phase, but no such relation seemed to be present either (see Table 1). Finally, one aspect of the design itself that could possibly have had an effect on the observed directionality of the SNARC effects was the order of the response mappings used (i.e., whether the small-left and large-right mapping was performed first or second). However, a set of t-tests involving mapping order did not yield any significant results for three of the four conditions. The exception was Experiment 1A where the mean slope for the participants who performed the small-left and large-right mapping first was 3.276 whereas the mean slope for the participants who performed the small-left and large-right mapping second was -1.215.

Table 1. Analyses of Individual Differences in Regression Slopes for Experiment 1.

Variable	Experiment 1A	Experiment 1B	Experiment 1C	Experiment 1D
Age	$r = .13, p < .55$	$r = .18, p < .46$	$r = .02, p < .95$	$r = .38, p < .11$
Gender	$t = 0.50, p < .62$	$t = -1.10, p < .28$	$t = 0.03, p < .98$	$t = -0.76, p < .46$
Learning Trials	$r = .29, p < .17$	$r = .01, p < .98$	$r = .20, p < .40$	$r = .05, p < .84$
Mapping Order	$t = 2.36, p < .03$	$t = 0.14, p < .89$	$t = 1.12, p < .28$	$t = 0.79, p < .44$

One issue related to the fact that a consistent SNARC effect did not occur in Experiment 1D is the fact that a clear overall SNARC effect, in the standard direction, was indeed obtained by Van Opstal, Fias, Peigneux, and Verguts (2009) after training 14 participants on a task that was essentially analogous to that in Experiment 1D. There were some key methodological differences between that study and Experiment 1D, however, that could have accounted for the difference in findings. First, their participants spent seven sessions learning the same ordering (the stimuli were six abstract figures) before performing the SNARC task. Second, the sequential nature of the ordering was emphasized right from the start given that it was learned by having the participants judge which of the items in each pair was the hindmost in the ordering. Moreover, in the SNARC task, their participants were asked to judge whether a single presented stimulus items came either before or after the middle of the ordering. Finally, they did not actually obtain regression slopes as part of their analysis of the results for the SNARC task but simply compared overall RT for the before-left and after-right SNARC-congruent mapping with the after-left and before-right SNARC-incongruent mapping.

Interestingly, in an experiment that was quite similar to Experiment 1D, Pardo, Van der Henst, and Noveck (2008) found a SNARC effect for a set of stimuli consisting of a description of a row of seating arrangements for six friends (e.g., Anne is to the left of Louise, Claire is to the left of Eve, Maud is to the left of Anne, etc.). Here, learning was not too extensive, unlike in Van Opstal et al. (2009). Rather, participants were given only one session to learn the spatial arrangement of the stimuli. In it, though, they were allowed as much time as they needed to learn, and they were even able to take notes. However, it is important to note that these researchers only obtained a significant SNARC effect after removing the middle stimuli in order to further lateralize the sequence.

In line with Pardo et al. (2008), the presence of SNARC effects involving only the two end terms was examined for all of the conditions in the present Experiment 1. In these analyses, a SNARC effect was now found for condition 1B, in which the perceptual magnitudes had been presented in an increasing fashion from left-to-right during learning. The unstandardized regression coefficients' mean value of -28.558 (*SD* = 64.595) was significantly different from 0 for this condition $t(21) = -2.074$, $p < .05$. Therefore, it can be concluded based on this latter result that the SNARC effect can occur for the end terms of a derived ordered sequence when an intrinsic directionality has been provided. However, when no such a direction stands out, McNamara et al. (2003) have suggested that the potential frames of reference that are actually used are chosen on the basis of intrinsically salient features in spatial memory. Hence, the variability between participants that was observed in Experiment 1C may be attributed to the fact that some used decreasing perceptual magnitude as a possible left-right frame of reference (i.e., consistent with how the stimuli had been presented during learning), whereas other participants may have used a standard left-to-right increasing directionality of the sequence as their intrinsic reference frame. In Experiments 1A and 1D, however, no obvious intrinsic directionality features were available. These latter points will be revisited more thoroughly in the General Discussion section below.

With respect to the two alternative models of the SNARC effect, these findings could also be regarded as not being compatible with the tenets of either or both of them. First, the fact that it was so difficult to obtain any SNARC effects in Experiment 1 is not very consistent with the polarity correspondence view. After learning the CVC-percept associations, participants were then asked to classify the CVCs as representing smaller or larger perceptual magnitudes. According to the polarity correspondence view, any kind of stimuli that has been classified as small should also be negatively polarity coded and, hence, show facilitation when responded to the left response (which would also be assumed to be negatively polarity coded by Proctor & Cho, 2006). Indeed, one major aspect of this model is that it explicitly invokes a general polarity correspondence principle that should then apply across any type of magnitude comparison. Similarly, the same point could apply to the Gevers et al. (2006) model, given that it also invokes the notion of smaller and larger categorical codings of stimulus magnitude which then have hardwired connections to left and right responses, respectively. To be fair, though, this latter model has restricted itself to the processing of numerical magnitude and, hence, the extent to which its predictions would then extend to the processing of non-numerical magnitude is not completely clear. As well, in general, it is hard to draw strong conclusions about the validity of any model in the absence of significant experimental results. Nonetheless, it is meaningful that significant results were found for Experiment 2B only when restricting the analyses to the end-point stimuli. Because the difference between this condition and Experiments 1A and 1C involves a purely spatial manipulation of the manner in which the set of CVC-percept associations were learned, such a result does suggest a spatial basis for the presence of this result.

Experiment 2: The alignment of the allocentric and egocentric axes

This experiment was designed to test for the occurrence of SNARC effects when the intrinsic reference axis of the allocentric representation of the sequence is aligned, compared to misaligned, with the egocentric representation of the spatial reference frame for the responses. It is expected that instructing participants to adopt an imagined orientation of the allocentric representation that is different from the orientation of the egocentric response-based representation would result in their misalignment. The abolishment of the SNARC effect for the misaligned condition compared to the aligned one would indicate that an alignment of these two spatial reference frames is indeed a requirement for the SNARC effect to occur.

Two sets of experimental conditions, each comprised of a control and a manipulated condition, were run for this experiment. In the control condition of first set, the allocentric mental number sequence was imagined along the horizontal axis, and the egocentric response-based representation was aligned horizontally as well (i.e., the horizontally compatible or HH condition). In the other condition of this set, the orientation of the allocentric mental number sequence was manipulated such that participants were asked to imagine it along the vertical axis, while the egocentric response-based representation was kept horizontal (i.e., the VH condition). Similarly, in the control condition of the second set, the allocentric mental number sequence was imagined along the vertical axis, and the egocentric response-based representation was aligned vertically as well (i.e., the vertically compatible or VV condition). In the other condition of this set, the orientation of the allocentric mental number sequence was manipulated such that participants were asked to imagine it along the horizontal axis, while the egocentric response-based representation was kept vertical (i.e., the HV condition).

In this experiment, it was expected that a SNARC effect would be present in the control conditions with compatibly aligned spatial representations (i.e., HH and VV), but that this effect would be abolished with incompatibly misaligned spatial representations in the manipulated conditions (i.e., VH and HV respectively).

Experiment 2A (HH)

Method

Participants. Thirty participants (14 females and 16 males) aged from 17 to 26 years old were recruited from the Carleton University Psychology Department subject pool and participated for .5% of course credit. They ran individually for 30 min sessions in room A530A LA.

Apparatus. Using a program written in SuperLab 2.0, stimuli were presented in the centre of the computer screen of a PC running in Windows XP. Responses were collected on the computer keyboard.

Procedure. In this condition, prior to testing, participants were asked to take a minute to close their eyes and imagine a number sequence from 1 to 9 aligned horizontally in a row from left to right, just as they would be if they represented nine small numbered boxes lined up in a row on a table in front of them. In a subsequent magnitude comparison task, the stimuli were randomly presented digits from 1 to 9 (excluding 5) displayed in the center of the screen. Participants then responded either with a left or right keypress (of the '*Z*'or '/' keys), using their left or right index fingers, respectively. They provided left (right) keypresses if the stimulus was larger (smaller) than 5. This mapping was reversed halfway through the experiment, with the order of usage of each mapping counterbalanced across participants. For each half of the experiment, participants performed 16 practice trials and 160 experimental trials (i.e., two blocks of 10 replications of each number stimulus).

Results

In this experiment, one participant was removed from the analysis because her unstandardized regression coefficient (see the following) was more than 3 *SD*s from the group mean, and another participant was removed because he was only 76% accurate (and only 50% correct with the larger-left and the smaller-right response mapping). For the remainder of the group, the overall error rate was 2.9%. Analyses of the magnitude comparison data were performed by calculating, for each of the remaining 28 participants, the difference between the mean correct RTs for non-practice-block responses made with the right hand minus those made with the left hand for each of the eight digits. These differences were then regressed against the digits separately for each participant and one-sample *t*-tests run on both the resulting unstandardized and standardized regression coefficients (Lorch & Myers, 1990). Note, again, that in such an analysis, standard SNARC effects are marked by a significantly negative mean slope value (i.e., faster left-hand RTs for smaller numerical magnitudes but faster right-hand RTS for larger ones). Before running these analyses, both error responses and any participant RTs more than 3 *SD*s from their mean in either of the small/large or large/small response mapping conditions (1.9% of the correct RT data) were removed.

The one-sample *t*-test on the unstandardized regression coefficients revealed that their mean of -17.455 (SD = 34.22) was significantly different from 0, $t(27) = -2.699$, $p < .012$, $d = 0.51$. In fact, 19 of 28 of these coefficients were negative and 9 were positive.

In increasing order, these coefficients were -133.914, -90.059, -72.148, -52.817, -37.845, -33.486, -25.202, -17.238, -16.347, -14.695, -14.528, -13.467, -12.042, -11.196, -10.143, -7.781, -6.492, -2.990, -.720, 2.168, 2.394, 4.387, 4.417, 6.449, 10.951, 13.211, 14.230, and 26.155. As well, the overall right minus left mean correct RT differences were 51.36, 40.75, 24.21, 51.69, -74.56, -55.23, -60.61, and -63.17 for each increasing digit, respectively (see Figure 3). The one sample *t*-test on the standardized regression coefficients also revealed that their mean of -.343 was significantly different from 0, $t(27) = -2.923$, $p < .007$.

Experiment 2B (VH)

Method

Participants. Thirty participants (18 females and 12 males) aged from 18 to 34 years old were recruited from the Carleton University Psychology Department subject pool and participated for .5% of course credit. They ran individually for 30 min sessions in room A530A LA.

Apparatus. The apparatus was the same as in Experiment 2A.

Procedure. Everything was the same as in Experiment 2A, except that prior to testing in this condition, participants were asked to take a minute to close their eyes and imagine the buttons 1 to 9 in an elevator of a building with nine floors starting from the bottom button upwards. Importantly, as in Experiment 2A, responses were still made using left or right keypresses (i.e., the '*Z*' or '/' keys) with the left or right index fingers, respectively.

Results

In this experiment, three participants were removed from the analysis because they had very high error rates of 50, 74, and 75%, respectively. Analyses of the mean correct RTs were conducted in the same way as before according to the Lorch and Myers (1990) individual regression technique (the overall error rate was 3.0%). Also as before, both error responses and any participant RTs more than 3 *SD*s from their mean in either of the small/large or large/small response mapping conditions (2.0% of the correct RT data) were removed before running these analyses.

As expected, no SNARC effects were found for this condition. The one-sample *t*-test on the unstandardized regression coefficients revealed that their mean of -5.113 (SD = 16.530) was not significantly different from 0, $t(26) = -1.607$, $p < .120$, $d = 0.30$. Nonetheless, 18 of 27 of these coefficients were negative and 9 were positive. In increasing order, these coefficients were -54.080, -29.579, -26.532, -23.199, -19.061, -17.360, -12.727, -8.688, -8.004, -6.385, -5.879, -5.858, -5.046, -4.914, -4.803, -4.753, -3.693, -.501, 1.051, 6.119, 6.449, 8.576, 11.179, 13.010, 14.346, 16.828, and 25.440. As well, the overall right minus left mean correct RT differences were 12.59, 12.67, -17.23, -24.14, -45.98, -15.27, -32.02, and -26.11 for each increasing digit, respectively (see Figure 3). The one sample *t*-test on the standardized regression coefficients revealed that their mean of -.156 was not significantly different from 0, $t(26) = -1.268$, $p < .216$.

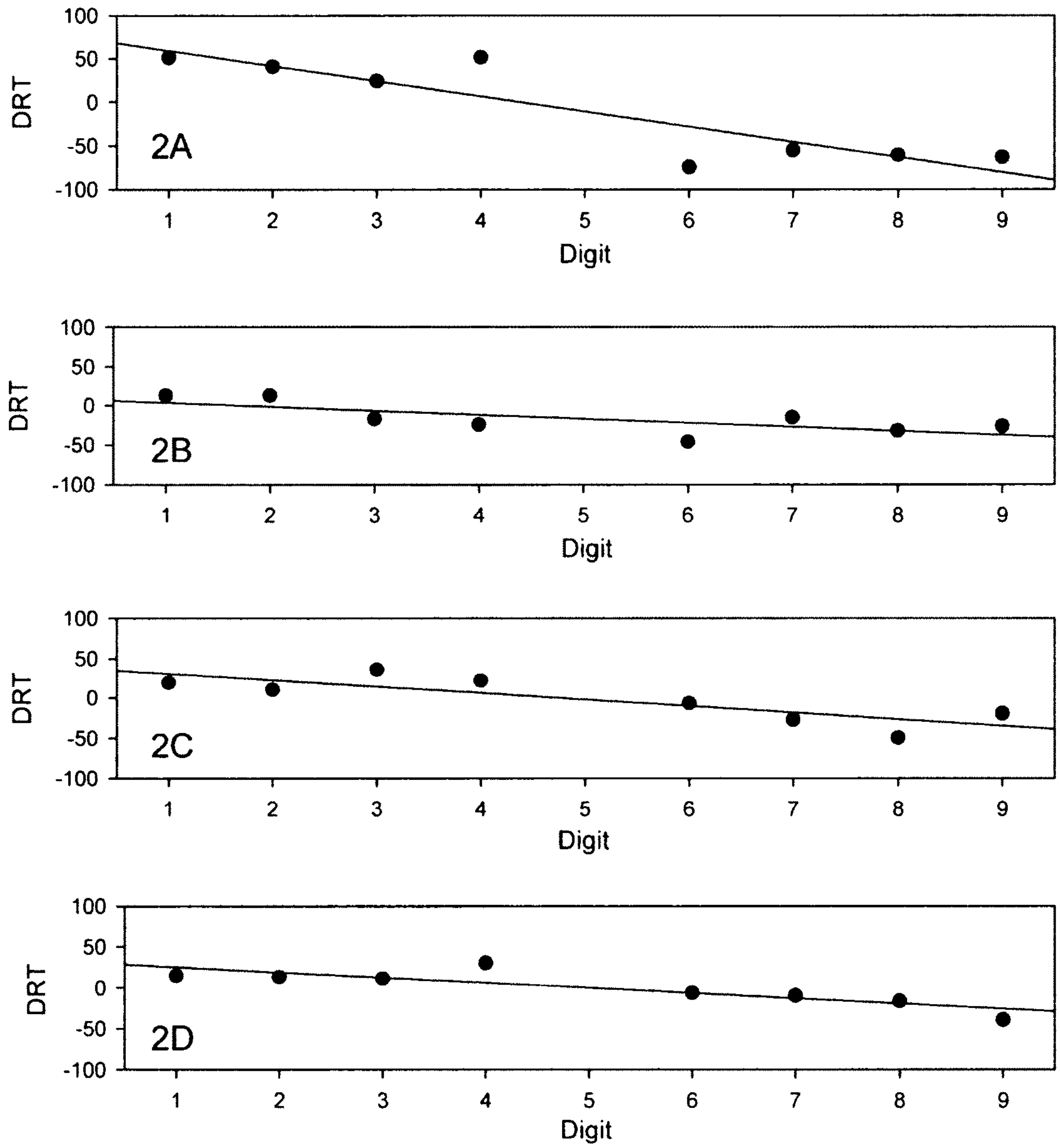


Figure 3. **Right – Left mean correct RT differences (DRT) as a function of digit size in Experiments 2A – 2D.**

Experiment 2C (VV)

Method

Participants. Thirty participants (19 females and 11 males) aged from 17 to 27 years old were recruited from the Carleton University Psychology Department subject pool and participated for .5% of course credit. They ran individually for 30 min sessions in room A530A LA.

Apparatus. The apparatus was the same as in the previous Experiments 2A and 2B.

Procedure. Everything was the same as in the previous Experiments 2A and 2B except that participants were now instructed to respond using either a top or bottom key press (i.e., the '*6*' or '*B*' keys) where the top key was to be pressed using their right index finger and the bottom key with their left index finger. Prior to testing (as in Experiment 2B), participants were asked to close their eyes and imagine the buttons from 1 to 9 in an elevator starting from the bottom upwards.

Results

Two participants were removed from the analysis, one because of a computer malfunction and the other because she had a regression coefficient that was more than 3*SD*s from the group mean. The results were analyzed in the same way as in the previous experiments (the overall error rate was 3.0%). Importantly, though, note that right minus left difference RTs now refer to top- minus bottom-key RT differences, with negative slopes now indicating that small digits are responded to faster with the bottom key and large digits are responded to faster with the top key. Before running these analyses, both error responses and any participant RTs more than 3 *SD*s from their mean in either of the small/large or large/small response mapping conditions (1.8% of the correct RT data) were removed.

Unexpectedly, the one-sample *t*-test on the unstandardized regression coefficients revealed that their mean of -8.145 ($SD = 25.554$) was not significantly different from 0, $t(27) = -1.687, p < .103, d = 0.318$. In fact, 17 of 28 of these coefficients were negative and 11 were positive. In increasing order, these coefficients were -74.882, -66.663, -42.855, -42.100, -26.928, -24.323, -23.313, -15.002, -14.297, -12.353, -11.523, -10.338, -7.233, -4.161, -3.260, -2.522, -1.202, 4.032, 4.412, 9.056, 10.353, 10.750, 12.855, 13.889, 13.943, 17.962, 19.262, and 38.373. As well, the overall right minus left mean correct RT differences were 19.07, 10.40, 35.99, 21.90, -6.57, -27.28, -49.41, and -19.50 for each increasing digit, respectively (see Figure 3). The one sample *t*-test on the standardized regression coefficients also revealed that their mean of -.142 was not significantly different from 0, $t(27) = -1.133, p < .267$.

Experiment 2D (HV)

Method

Participants. Thirty participants (19 females and 11 males) aged from 17 to 26 years old were recruited from the Carleton University Psychology Department subject pool and participated for .5% of course credit. They ran individually for 30 min sessions in room A530A LA.

Apparatus. The apparatus was the same as in the previous Experiments 2A, 2B, and 2C.

Procedure. Everything was the same as in the previous Experiments 2A, 2B, and 2C, except that prior to testing, as in Experiment 2A, participants were asked to close their eyes and imagine a number sequence from 1 to 9 in the form of nine numbered boxes aligned horizontally in a row from left to right. As in Experiment 2C, participants then responded with either a top or bottom keypress (i.e., the '*6*' or '*B*' keys) using their left or right index fingers, respectively (in the same manner as before).

Results

Two participants were removed from the analysis, one because of a computer malfunction and the other because he had a regression coefficient that was more than 3 *SD*s from the group mean. The results were analyzed in the same way as in the previous experiments (the overall error rate was 2.0%). Before running these analyses, both error responses and any participant RTs more than 3 *SD*s from their mean in either of the small/large or large/small response mapping conditions (2.0% of the correct RT data) were removed.

As expected, the one-sample *t*-test on the unstandardized regression coefficients revealed that their mean of -7.111 (SD = 32.907) was not significantly different from 0, $t(27) = -1.144, p < .263, d = 0.21$. In fact, 16 of 28 of these coefficients were negative and 12 were positive. In increasing order, these coefficients were -89.654, -85.397, -53.709, -30.643, -26.745, -25.337, -22.311, -16.598, -14.474, -13.577, -9.376, -7.880, -7.140, -6.918, -1.477, -.507, .760, 3.553, 4.154, 4.950, 9.028, 12.499, 13.298, 13.643, 18.283, 22.150, 31.067, and 79.236. As well, the overall right minus left mean correct RT differences were 14.92, 13.40, 11.48, 30.44, -6.17, -9.51, -16.28 and -39.11 for each digit, respectively (see Figure 3). The one sample *t*-test on the standardized regression coefficients also revealed that their mean of -.144 was not significantly different from 0, $t(27) = -1.217, p < .234$.

Discussion of Experiment 2

Experiment 2 was designed to test for the effect of an alignment versus misalignment of the allocentric and egocentric spatial representations on the SNARC effect. Conditions HH and VH (i.e., Experiments 2A and 2B, respectively) supported the hypothesis that representational alignment is necessary in order to produce the SNARC effect. A standard SNARC effect was found for the HH condition, where the imagined sequence of numbers horizontally aligned with the response keys. On the other hand, when the vertical array of the imagined sequence was misaligned with the horizontal placement of the response keys in the VH condition, a significant SNARC effect was not obtained. Note that as in the previous Experiment 1, additional sets of analyses were run (for all four conditions) in order to inspect whether the age, gender, or mapping order (i.e., whether the small-left and large-right mapping was performed first or second) had any relation to the SNARC effect (see Table 2).

Table 2. Analyses of Individual Differences in Regression Slopes for Experiment 2.

Variable	Experiment 2A (HH)	Experiment 2B (VH)	Experiment 2C (VV)	Experiment 2D (HV)
Age	$r = -.28, p < .14$	$r = .25, p < .20$	$r = .20, p < .30$	$r = -.27, p < .16$
Gender	$t = 0.21, p < .83$	$t = -0.35, p < .72$	$t = 2.31, p < .02$	$t = 2.72, p < .01$
Mapping Order	$t = -3.16, p < .005$	$t = 0.79, p < .43$	$t = -0.48, p < .63$	$t = 0.003, p < .99$

These analysis revealed the presence of a mapping order effect on the SNARC effect in the HH condition such that a SNARC effect was not present when the small-left, large-right mapping order was performed first, $t(14) = -.283$, p < .781 ($M = -.99$, $SD =$

13.49) but was present when this same response mapping was performed second, $t(12) = -3.195$, $p < .008$ ($M = -36.46$, $SD = 41.15$). As well, a complete listing of the native languages of each of the participants along with their corresponding regression coefficients are given in Table 3. In this table, the regression coefficients have been presented in an increasing in order and no systematic associations of any particular language with either the positive or the negative slopes is at all evident. Because no systematic effects were evident in this table, no follow-up statistical analyses were performed on the native languages.

Table 3. Each participant's Regression Slope and Native Language for Experiment 2.

HH		VH		VV		HV	
Native Language	Slope	Native Language	Slope	Native Language	Slope	Native Language	Slope
English	-133.914	Persian	-54.080	English	-74.882	English	-89.654
English	-90.059	Serbian	-29.579	English	-66.663	Turkish	-85.397
English	-72.148	Arabic	-26.532	English	-42.855	English	-53.709
English	-52.817	Arabic	-23.199	Vietnamese	-42.100	English	-30.643
Spanish	-37.845	Russian	-19.061	English	-26.928	Polish	-26.745
Chinese	-33.486	Arabic	-17.360	English	-24.323	English	-25.337
English	-25.202	Urdu	-12.727	English	-23.313	English	-22.311
Mandarin	-17.238	English	-8.688	English	-15.002	English	-16.598
English	-16.347	English	-8.004	English	-14.297	English	-14.474
English	-14.695	English	-6.385	English	-12.353	Russian	-13.577
English	-14.528	English	-5.879	Chinese	-11.523	Arabic	-9.376
English	-13.467	English	-5.858	Somali	-10.338	English	-7.880
English	-12.042	Russian	-5.046	English	-7.233	Bosnian	-7.140
Vietnamese	-11.196	English	-4.914	**	-4.161	Cantonese	-6.918
English	-10.143	English	-4.803	English	-3.260	English	-1.477
English	-7.781	Spanish	-4.753	Philippines	-2.522	Arabic	-.507
Arabic	-6.492	English	-3.693	English	-1.202	English	.760
English	-2.990	Chinese	-.501	English	4.032	English	3.553
English	-.720	English	1.051	English	4.412	English	4.154
English	2.168	Arabic	6.119	English	9.056	Urdu	4.950
Serbian	2.394	Chinese	6.449	English	10.353	English	9.028
English	4.387	English	8.576	English	10.750	English	12.499
Chinese	4.417	French	11.179	English	12.855	English	13.298
Russian	6.449	English	13.010	English	13.889	English	13.643
English	10.951	English	14.346	Somali	13.943	Chinese	18.283
English	13.211	Vietnamese	16.828	Bosnian	17.962	Urdu	22.150
Chinese	14.230	French	25.440	English	19.262	English	31.067
Mandarin	26.155			Arabic	38.373	English	79.236

In the other set of experimental conditions, again no SNARC effect was obtained in the HV misaligned condition but, surprisingly, neither was it obtained in the VV aligned condition. Interestingly, though, a gender difference was found for both the VV and the HV conditions. A subsequent analysis for each gender group in the VV condition separately indicated that a SNARC effect was present for the males, $t(9) = -2.816$, $p < .020$, $d = 0.89$ ($M = -22.069$, $SD = 24.782$), but not for the females, $t(17) = .075$, $p < .941$, $d = 0.017$ ($M = -.409$, $SD = 23.121$). In increasing order, the coefficients for the males were -66.663, -42.855, -42.100, -26.928, -24.323, -23.313, -11.523, -7.233, 10.353, and 13.889. For the females, the coefficients were -74.882, -15.002, -14.297, -12.353, -10.338, -4.161, -3.260, -2.522, -1.202, 4.032, 4.412, 9.056, 10.750, 12.855, 13.943, 17.962, 19.262, and 38.373. The same kind of trend was also observed for the other vertical response condition. Namely, in the HV condition, a subsequent analysis for each gender group separately indicated that a marginally significant SNARC effect was present for the males, $t(8) = -2.223$, $p < .057$ ($M = -29.220$, $SD = 39.440$), but not for the females, $t(18) = .612$, $p < .548$ ($M = 3.361$, $SD = 23.932$). In increasing order, the coefficients for the males were -89.654, -85.397, -53.709, -30.643, -16.598, -13.577, -.507, 4.950, and 22.150. For the females, these coefficients were -26.745, -25.337, -22.311, -14.474, -9.376, -7.880, -7.140, -6.918, -1.477, .760, 3.553, 4.154, 9.028, 12.499, 13.298, 13.643, 18.283, 31.067, and 79.236.

The fact that there was a gender difference in the results of the VV and HV condition is a novel finding. Such a gender difference has not been reported in other studies that have tested the SNARC effect along either the vertical or horizontal axis (e.g., Hung et al., 2008; Ito & Hatta, 2004; Kim, 2004; Schwarz & Keus, 2004; Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006; Muller & Schwarz, 2007). Moreover, in a recent meta-analysis on the SNARC effect by Wood, Willmes, Nuerk, and Fischer (2008), although the effect of individual differences on the size of this effect was examined across various ages, no mention of any potential gender differences was made.

In comparing the present findings to other vertical SNARC studies in the literature, it can be noted that the only study to show a vertical SNARC effect for a magnitude comparison task was Kim (2004), who found both a SNARC and a reversed SNARC effect in his Experiment 3 (unfortunately, no information regarding the gender of these participants was provided). There were some methodological differences, however, between that experiment and the vertical response conditions in the present experiment. The main difference being the fact that Kim used vertical response keys aligned along the up-down gravitational axis instead of the top and bottom (i.e., '*6*' and '*B*') keyboard response keys used in this study. Such a response arrangement in Kim's study might have made the egocentric response layout more physically compatible with the imagined vertical elevator layout, thus leading to a stronger co-activation of the two representations.

In the rest of the literature, the only other vertical SNARC effects that have occurred have been obtained for parity judgment tasks. One of the first published instances of a vertical SNARC effect for manual responding was by Ito and Hatta (2004) who obtained it for a parity judgment task with Japanese participants. With respect to this SNARC effect, small numbers were found to be more closely associated with bottom responses and large numbers with top ones. Of relevance was the fact that responding in their Experiment 2 was made using response buttons arrayed "vertically" on a table top (where they also showed that the use of either the left or right index finger to respond to the top or bottom buttons did not matter with respect to eliciting the SNARC effect).

This finding of a vertical SNARC effect orienting from bottom-to-top for a parity judgment task was subsequently replicated by Muller and Schwarz (2007). These researchers found a vertical SNARC effect when they emphasized the number's association to vertically aligned table-top response keys (in their Experiment 1) but not when they emphasized the number's association to the left and right responding hands (i.e., in their Experiment 2). According to these authors, their results implied that either extracorporal spatial or spatio-anatomical components can influence the SNARC effect depending on the experimental context.

Nonetheless, the sensitivity of the vertical effect to the egocentric extracorporal space has been illustrated by Schwarz and Keus (2004, Experiment 2) who found a vertical SNARC effect for eye-movement responses. Upon the presentation of a central digit on a computer screen, their participants had to saccade either up or down (in a counterbalanced fashion) in response to odd or even digits. This finding was important because it provided further evidence for the fact that the same spatial representational mechanisms seem to underlie both the vertical and horizontal (as per Fischer, Warlop, Hill, & Fias, 2004, where eye movements showed a horizontal association) processing of parity information.

In contrast, a similar conclusion cannot be unequivocally drawn for numerical magnitude information at this point although, as mentioned, there were some gender differences present in Experiment 2C and 2D such that vertical SNARC effect were found for the males in both of those samples. Importantly, if it can be assumed from other studies, that females do manifest vertical SNARC effects for parity judgment tasks, the fact that they did not occur here for a magnitude judgment task implies that their representation of numbers might not be as consistent as that for males.

Finally, the inability to find significant overall SNARC effects in three of the four conditions of Experiment 2 could be regarded as not being very consistent with what might have been expected on the basis of the polarity correspondence view. Namely, one presumed strength of this view is that it can easily account for both horizontal and vertical SNARC effects simply by assuming that bottom responses (like left ones and small magnitudes) have a negative polarity coding and that top responses (like right ones and large magnitudes) have a positive polarity coding. Hence, (quite consistent) SNARC effects should have been obtained in all four conditions. Nonetheless, Proctor and Cho (2006) have suggested that such polarity coding might be overwritten by imagined co-ordinate spatial representations whenever participants have been instructed to image a particular reference frame. Such an explanation was needed by them to explain the reverse-SNARC effects obtained in the Bachtold et al. (1998) clock-face experiment and could also be applied to the current Experiment 2 given the explicit imagery instructions used there.

The results for the Experiment 2B could have some implications for the Gevers et al. computational model as well. In this model, the influence of a vertical imagined perspective could be modeled by assuming the presence of an alternative number field that instantiates the elevator representation. However, given that such a representation should still have resulted in a small and large categorical coding of the number stimuli at the second level of the model, a standard SNARC effect would still likely have been expected in the VH condition. With respect to the two vertical SNARC conditions (VV and HV), to my knowledge no clear predictions are available from the Gevers et al. model for these cases as it has not yet been extended to the presence of vertical responding (although in accordance with the standard vertical Y-axis of the number line - and elevator buttons - smaller categorical codes would likely be associated with bottom responses and larger categorical codes with top responses).

Experiment 3: The alignment of the subjective midpoint of the allocentric reference axis with the midline of the egocentric reference axis

This experiment was designed to examine the pattern of SNARC effects that occur for magnitude comparisons when the standard referent occupies one of several different positions within the sequence. If it can be demonstrated that the associations between the response codes and the digits depend on the location of the standard, it would indicate that the SNARC effect arises when the subjective allocentric midpoint of the sequence has been superimposed upon the egocentric midline determined by the lateralization of the responses. An effect of this nature would dissociate the previously encoded sensorimotor associations (of the left side with the 1, 2, 3, 4 digits and the right side with the 6, 7, 8, 9 digits, say) and induce new associations of left and right with the digits. Such a finding would provide support for the hypothesis that it is the position of the standard that is responsible for the association of the specific numbers with the left or right egocentric coordinates as opposed to the range of the sequence as was suggested by Dehaene et al. (1993, Experiment 3).

In this experiment, participants were randomly assigned to one of three groups and presented with the digits from 1 to 8. Experiment 3A was the control condition and this group was told to consider the digits 1, 2, 3, and 4 as being small and 6, 7, 8, and 9 as being large. The group in Experiment 3B was instructed to regard the digits 1 and 2 as small and 3, 4, 5, 6, 7, and 8 as large. Lastly, for the third group in Experiment 3C, the digits 1, 2, 3, 4, 5, and 6 were to be regarded as small and the digits 7 and 8 as large. If differential SNARC effects are found in these conditions, it would indicate that different associations with left/small and right/large have been formed for each of them.

In addition, subsequent to the magnitude task, a parity task was also administered for the digits from 1 to 8. If the numerical associations with the response codes in this subsequent task were influenced by any associations that were previously formed in the initial magnitude task, such a finding would indicate that the same numerical representation was being used for both the magnitude and parity tasks. If, on the other hand, no transfer of the associations from the previous task is observed in the parity task, this finding would suggest that different representations might, in fact, be operating for the magnitude and parity processing tasks.

Experiment 3A

Method

Participants. Twenty-seven participants (16 females and 11 males) aged from 16 to 23 years old were recruited from the Carleton University Psychology Department subject pool and participated for 1% of course credit. They ran individually for 60 minutes sessions in room A530A LA.

Apparatus. Using a program written in SuperLab 2.0, stimuli were presented in the centre of the computer screen of a PC running in Windows XP. Responses were collected on the computer keyboard by pressing either the 'Z' key (using the index finger of the left hand) or the '/' key (using the right index finger).

Procedure. Participants had to decide if randomly presented digits were either small (i.e., 1, 2, 3, and 4) or large (i.e., 5, 6, 7, and 8). They completed two consecutive blocks of 80 trials each, followed by another two blocks with a counterbalanced mapping of the left-right response keys (i.e., the 'Z' and '/' keys) to the smaller and larger responses. Each set of blocks was preceded by a short practice block of 24 trials.

This magnitude task was followed by a parity task consisting of odd and even judgments for the numbers from 1 to 8. As in the magnitude judgment task, participants completed two consecutive blocks of 80 trials each, followed by another two blocks with a counterbalanced mapping of the odd and even response keys (i.e., the 'Z' and '/' keys). Again, each set of blocks was preceded by a practice block consisting of 24 trials.

Results

In this experiment, one participant was removed from the analysis of the magnitude task because of a very high error rate of 50%. The overall error rate after this participant's removal was 2.0%. Analyses of the test phase data were performed by calculating for each of the remaining 26 participants the difference between mean correct RTs for non-practice-block responses made with the right hand minus those made with the left hand for each of the eight digits. These differences were then regressed against the digits separately for each participant and one-sample *t*-tests run on both the resulting unstandardized and standardized regression coefficients (Lorch & Myers, 1990). Note, again, that in such an analysis, standard SNARC effects are marked by a significantly negative mean slope values (i.e., faster left-hand RTs for smaller stimulus magnitudes but faster right-hand RTS for larger ones). Before running these analyses, both error responses and any participant RTs more than 3 *SD*s from their mean in either of the small/large or large/small response mapping conditions were removed (1.8% of the correct RT data in total).

The one-sample *t*-test on the unstandardized regression coefficients revealed that their mean of -16.500 ($SD = 36.468$) was significantly different from 0, $t(25) = -2.307$, $p < .030$, $d = 0.452$. In fact, 17 of 26 of these coefficients were negative and 9 were positive. In an increasing order, these coefficients were -92.547, -92.447, -65.444, -62.387, -52.968, -36.660, -29.016, -23.322, -21.803, -20.083, -19.340, -16.614, -14.279, -13.505, -12.568, -8.730, -8.229, 1.454, 3.310, 3.426, 5.397, 7.364, 11.570, 11.784, 51.037, and 66.590. As well, the overall right minus left mean correct RT differences were 12.02, 32.43, 29.13, 40.05, -73.70, -61.23, -61.12, and -64.20 for each increasing digit, Figure 4. The one sample *t*-test on the standardized regression coefficients also revealed that their mean of -.226 was significantly different from 0, $t(25) = -2.077, p < .048$.

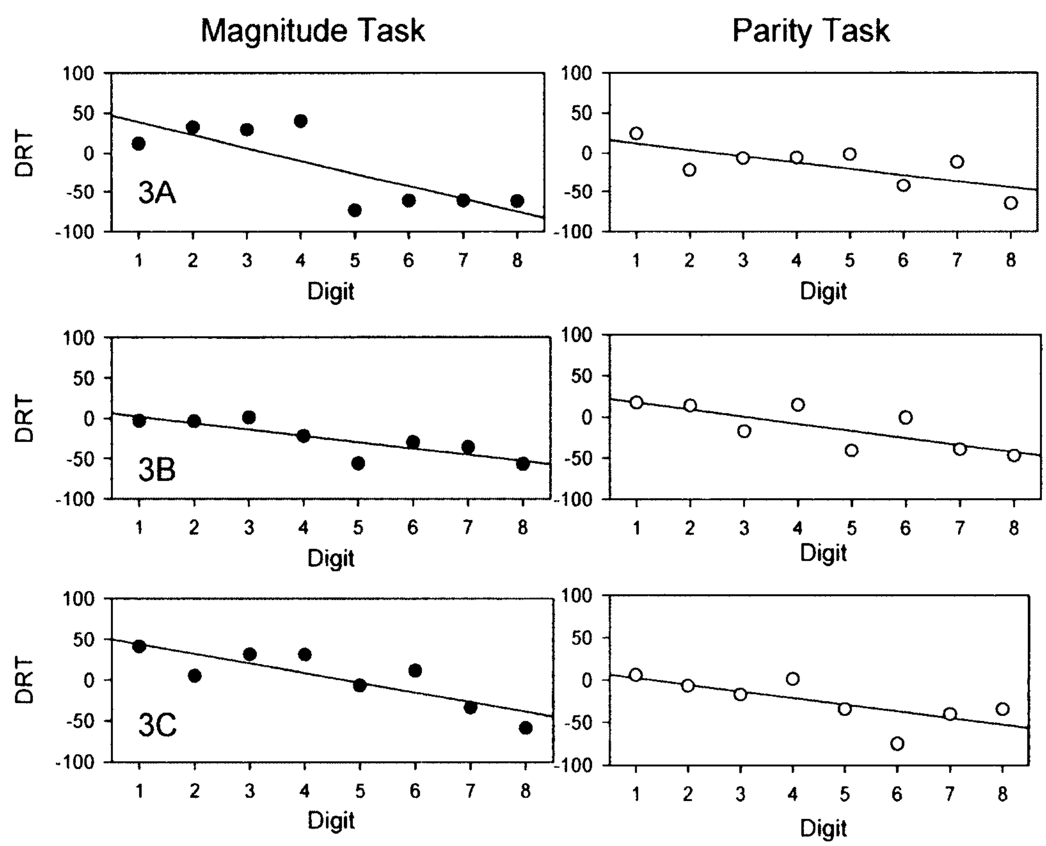


Figure 4. **Right – Left mean correct RT differences (DRT) as a function of digit size for both the magnitude (left plots) and the parity (right plots) task in Experiments 3A – 3C.**

The parity task analysis was performed in the same manner as the magnitude task analysis. The overall error rate was 3.0%, and the overall outliers removed were 2.0% of the correct RT data in total. The one-sample *t*-test on the unstandardized regression coefficients revealed that their mean of -8.039 (SD = 23.907) was not significantly different from 0, $t(26) = -1.747$, $p < .092$, $d = 0.336$. In fact, 17 of 27 of these coefficients were negative and 10 were positive. In an increasing order, these coefficients were -64.064, -57.399, -52.655, -37.484, -26.824, -16.844, -16.318, -12.053, -10.035, -9.338, -8.636, -5.769, -5.691, -4.557, -4.361, -4.301, -2.813, .939, 2.385, 4.800, 5.406, 8.739, 9.112, 9.987, 14.549, 17.233, and 48.927. As well, the overall right minus left mean correct RT differences were 24.13, -21.35, -6.34, -5.56, -1.47, -41.69, -11.47, -64.83 for each increasing digit, respectively (see Figure 4). The one sample *t*-test on the standardized regression coefficients revealed that their mean of -.154 was also not significantly different from 0, $t(26) = -1.911$, $p < .067$.

Experiment 3B

Method

Participants. Thirty participants (13 females and 17 males) aged from 17 to 41 years old were recruited from the Carleton University Psychology Department subject pool and participated for 1% of course credit. They ran individually for 60 min sessions in room A530A LA.

Apparatus. The apparatus was the same as in Experiment 3A.

Procedure. The procedure was the same as in Experiment 3A except that a different assignment of digits to small and large was used, such that the digits 1 and 2 were to be considered small and the digits 3, 4, 5, 6, 7, and 8 were to be considered large. Moreover, because this manipulation involved a non-centered standard condition, each of the two smaller digits were presented 19 times in a block whereas the other six digits were presented 7 times each. This manipulation ensured an approximately equal number of smaller and larger responses per block. The subsequent parity task, however, was still run in the exact same manner as in Experiment 3A.

Results

The same statistical analysis was used as in Experiment 3A. Two participants' data were removed from the analysis of the magnitude task, one because of a regression coefficient that was more than 3 *SD*s from the group mean and the other due to computer malfunction. The overall error rate for the group after removing those two participants was 3.0%, and the overall outliers removed were 1.8% of the correct RT data in total.

The one-sample t-test on the unstandardized regression coefficients revealed that their mean of -7.874 ($SD = 21.818$) was not significantly different from 0, $t(27) = -1.910$, $p < .067$, $d = 0.36$. Nonetheless, 19 of 28 of these coefficients were negative and 9 were positive. In an increasing order, these coefficients were -43.212, -40.171, -39.187, -38.593, -32.699, -25.449, -21.793, -20.108, -19.890, -16.579, -15.177, -12.935, -12.045, -10.624, -5.081, -3.473, -3.319, -3.074, -.341, 1.193, 3.660, 4.474, 8.469, 11.385, 15.022, 22.880, 27.758, and 48.440. As well, the overall right minus left mean correct RT differences were 4.30, -3.63, 7.04, -20.09, -50.82, -32.68, -30.18, and -47.41 for each increasing digit, respectively (see Figure 4). The one sample t-test on the standardized regression coefficients revealed that their mean of -.208 was significantly different from 0, $t(27) = -2.228$, $p < .034$.

The parity analysis was performed in the same way as the magnitude analysis. The same two participants that were removed from the analysis of the magnitude task were also removed from this analysis (because of the same reasons as before). As well, one other participant was removed from the parity task analysis due to a high error rate. The overall error rate was 5.0%, and the overall outliers removed were 1.9% of the correct RT data in total. The one-sample t-test on the unstandardized regression coefficients revealed that their mean of -8.570 (SD = 20.648) was significantly different from 0, $t(26) = -2.157, p < .040, d = 0.41$. In fact, 20 of 27 of these coefficients were negative and 7 were positive. In an increasing order these coefficients were -59.075, -46.565, -39.819, -26.084, -22.583, -22.478, -21.842, -20.773, -17.705, -14.687, -11.848, -6.597, -6.474, -6.319, -5.121, -4.595, -4.078, -3.785, -2.409, -.468, .066, 6.399, 17.376, 18.605, 18.933, 22.191, and 28.318. As well, the overall right minus left mean correct RT differences were 17.49, 13.76, -16.98, 14.61, -40.59, -.61, -38.97, and -46.83 for each increasing digit, respectively (see Figure 4). The one sample t-test on the standardized regression coefficients revealed that their mean of -.206 was significantly different from 0, $t(26) = -2.899, p < .008$.

Experiment 3C

Method

Participants. Twenty-seven participants (18 females and 9 males) aged from 18 to 32 years old were recruited from the Carleton University Psychology Department subject pool and participated for 1% of course credit. They ran individually for 60 min sessions in room A530A LA.

Apparatus. The apparatus was the same as in Experiment 3A and 3B.

Procedure. The procedure was the same as in Experiment 3A and 3B except that a different assignment of digits to small and large was again used, such that the digits 1, 2, 3, 4, 5, and 6 were to be considered small and the digits 7 and 8 were to be considered large. Moreover, because this manipulation involved a non-centered standard condition, each of the two larger digits were presented 19 times in a block whereas the other six digits were presented 7 times each. This manipulation ensured an approximately equal number of smaller and larger responses per block. Again, the subsequent parity task was run in the exact same manner as before.

Results

The same statistical analysis was used as in Experiment 3A and 3B. Two participants were removed from the analysis of the magnitude task, one because of a regression coefficient that was more than 3 *SD*s from the mean, and the other due to computer malfunction. The overall error rate after removing those two participants was 3.0%, and the overall outliers removed were 2.0% of the correct RT data in total. The one-sample *t*-test on the unstandardized regression coefficients revealed that their mean of -11.842 (SD = 17.062) was significantly different from 0, $t(24) = -3.470$, $p < .002$, d = 0.694. In fact, 20 of 25 of these coefficients were negative and 5 were positive. In an increasing order these coefficients were -52.002, -51.003, -38.520, -30.472, -22.988, -20.604, -20.365, -17.443, -13.214, -11.694, -9.621, -9.610, -7.389, -5.273, -5.121, -5.096, -4.640, -4.163, -3.039, -2.950, 2.230, 3.781, 8.674, 8.930, and 15.537. As well, the overall right minus left mean correct RT differences were 41.28, 5.21, 31.76, 31.13, -6.62, 11.32, -33.90, and -58.73 for each increasing digit, respectively (see Figure 4). The one sample *t*-test on the standardized regression coefficients revealed that their mean of -.313 was significantly different from 0, $t(24) = -3.623$, $p < .001$.

The parity analysis was performed in the same way as the magnitude analysis. Two participants were also removed from the analysis of the parity task, one because of a regression coefficient that was more than 3 *SD*s from the group mean, and the other due to computer malfunction (where the latter participant only was also removed from the magnitude task analysis). The overall error rate was 3.6%, and the overall outliers removed were 1.8% of the correct RT data in total. The one-sample *t*-test on the unstandardized regression coefficients revealed that their mean of -7.859 (SD = 18.949) was significantly different from 0, $t(24) = -2.074$, $p < .049$, $d = 0.414$. In fact, 18 of 25 of these coefficients were negative and 7 were positive. In an increasing order these coefficients were -61.658, -35.090, -31.164, -23.673, -17.877, -17.357, -16.048, -14.687, -13.991, -9.362, -7.502, -6.930, -6.126, -5.837, -4.707, -3.310, -2.372, -1.969, .084, 1.189, 5.021, 9.222, 10.063, 20.765, and 36.841. As well, the overall right minus left mean correct RT differences were 6.03, -6.45, -16.84, 1.57, -34.24, -74.53, -40.17, and -34.35 for each increasing digit, respectively (see Figure 4). The one sample *t*-test on the standardized regression coefficients revealed that their mean of -.221 was significantly different from 0, $t(24) = -3.175$, $p < .004$.

Direct comparison of the effect of the midpoint location on the SNARC effects in Experiments 3A, 3B, and 3C

To provide a better indication of the extent to which the nature of the SNARC effect for the magnitude task was differentially affected by the location of the midpoint in each of these three experimental conditions, individual regression analyses on the right-minus left-hand difference RTs were run for every participant for each of three different restricted digit ranges. These ranges contained the four digits surrounding the midpoint referents used for each of the three conditions. The mean of the unstandardized regression coefficients from these analyses are given in Table 4 for each of the

Experiment 3A, 3B, and 3C groups of participants (where similar results were found for the standardized coefficients).

Table 4. Mean Unstandardized Regression Slopes from the Magnitude Task for each of Three Restricted Ranges of Digits in Experiment 3.

Digit Range	Experiment 3A	Experiment 3B	Experiment 3C	
1 to 4	8.64	-5.12	-0.66	$F = 0.66, p < .52$[a]
3 to 6	-38.99	-12.56	-10.43	$F = 1.67, p < .19$
5 to 8	2.78	-0.89	-22.52	$F = 3.41, p < .04$

[a] dfs are 2, 76

For each range of digits, the most negative mean regression coefficient occurred in the experimental condition with the midpoint referent that fell in the middle of the corresponding digit range. These results indicate that for each range, SNARC effects generally tended to be the strongest in the corresponding midpoint condition (although significant differences in these coefficients between midpoint conditions occurred only for the 5 to 8 digit range).

Determination of subjective midpoints in Experiments 3A, 3B, and 3C

For each of the group regression curves in Figure 4, the point at which the regression line crosses the X-axis (i.e., where DRT = 0) was determined by computing the intercept/slope. These values are given in Table 5 and indicate the average digit magnitude at which the left-hand RT advantage turned into a right-hand RT advantage which, in essence, could be regarded as the effective subjective midpoint of the range of digits for that task and midpoint condition. Note that the actual categorical midpoints for Experiments 3A, 3B, and 3C were 4.5, 2.5, and 6.5, respectively.

Table 5. Locations of the Subjective Midpoints for each Task in Experiment 3.

Task	Experiment 3A	Experiment 3B	Experiment 3C
Magnitude	3.39	1.26	4.73
Parity	2.51	3.03	1.34

The first thing to note about the subjective midpoint values for the magnitude task in Table 5 is that their ordering is consistent with what would have been expected on the basis of the actual midpoints employed in each of these three conditions (although all subjective midpoint values seem to be undershooting those actual midpoints to some extent). The second thing to note in Table 5 is that the ordering of subjective midpoint values for the parity task are not consistent (i.e., and even opposite) to what would have been expected if the nature of the digit-response associations in the initial magnitude task had indeed transferred to the parity task.

Discussion of Experiment 3

In this experiment, significant SNARC effects were present in the results of the magnitude task for each midpoint condition (although only marginally so for the unstandardized regression coefficients in Experiment 3B given that the mean size of the SNARC effect was a bit smaller in that condition). Moreover, significant SNARC effects were also present in the results of the parity task for the two non-centered midpoint conditions (i.e., Experiments 3B and 3C) with a marginally significant SNARC effect (albeit of comparable size) occurring in the centered midpoint condition (i.e., Experiment 3A). Some subsequent analyses involving the results from the magnitude task provided some evidence to indicate that (a) for each of three digit ranges, the largest SNARC effect occurred in the condition with the midpoint that fell within the range, and (b) the subjective midpoints in each condition were shifted towards the objective categorical midpoints.

Hence, the results obtained Experiment 3 do demonstrate that the association of left and right response codes in the magnitude task is not specific to certain numbers, but rather, that it can depend on the location of the standard used to categorize the magnitudes of the digits. To illustrate, when the digits 3 and 4 were to be considered as small in the control condition (i.e., Experiment 3A), they tended to be responded to faster on the left (i.e., positive right – left mean difference RTs). On the other hand, when these same digits were to be regarded as being large in Experiment 3B, the nature of this spatial-numerical association was not the same (compare also the mean difference RTS for the digits 5 and 6 in Experiments 3A vs. 3C). As discussed previously, such results could be assumed to arise as a consequence of the midpoint of the allocentric frame of reference being superimposed upon the midline of the egocentric frame of reference.

On the other hand, it must be acknowledged that the Gevers et al. (2006) model can also provide a full account for the current results. Indeed, one key aspect of that model is that small and large number categorizations are achieved by comparing the relative size of the comparison number (in the number field) with the standard (in the standard field) where the identity of that standard is determined by the midpoint referent specified in the task instructions. For example, only numbers below the standard reference will be categorized as small and automatically facilitate left-sided responses. Hence, both this account and the account based on overlapping allocentric and egocentric reference frames posited in this thesis could be regarded as equally plausible accounts for the findings obtained in Experiment 3.

In addition, it seems fairly clear in the present results that the subjective midpoints for the magnitude task did not transfer over into the parity task given that the nature of the spatial-numerical associations revealed by the SNARC effect were quite different in each task. It must be noted that the lack of transfer effects in this experiment is somewhat at odds with the findings of Bae et al. (2009) who demonstrated that SNARC-incongruent mappings in an initial magnitude task did indeed transfer into reverse SNARC effects in a subsequent parity task. Their findings suggest that the nature of the mappings used in the magnitude task resulted in a wholesale reversal in the directionality of the effective allocentric representation of the number sequence used in the parity task.

Given those previous findings it is not clear at all why no trace of the midpoint alignments effects observed in the magnitude task were to be found in the parity task results (indeed, this was actually quite unexpected). Hence, the nature of the representational processing of the numerical sequence indeed seems somewhat dissociated for both types of tasks in the present experiment. Such a dissociation could arise either because the manner in which a common spatial-numerical representation is being processed differs across tasks or because the nature of the representation itself being processed differs across the two tasks. This issue will be revisited in the General Discussion.

General Discussion

The experiments that are presented in this thesis tested the SNARC effect in terms of McNamara and colleague's cognitive spatial model. More precisely, the three experiments in this thesis were designed to test the nature of the interaction between the allocentric and egocentric frames of reference which has been hypothesized to underlie the SNARC effect. The first experiment tested for the intrinsic directionality of a novel sequence of ordered items. The second experiment tested for the presence of SNARC effects when the allocentric representation of the number sequence and the egocentric representation of the responses were aligned versus when they were misaligned. Finally, the purpose of the third experiment was to show that SNARC effects depend on the manner in which the allocentric and egocentric representations overlap at the midpoint of the former and subjective midline of the latter.

Intrinsic directionality of the allocentric frame of reference

The premise behind the first experiment was that the SNARC effect is the result of the correspondence between the directionality of the intrinsic axis of the allocentric reference frame for the sequence and the directionality of the egocentric reference frame for the responses. In this experiment, CVC stimuli were associated with a fixed set of perceptual magnitudes in a non-serial fashion. Here, a SNARC effect involving end terms was found only for the condition in which the perceptual magnitudes were presented as increasing from left to right during learning (i.e., Experiment 1B). In the other conditions, for which the perceptual magnitudes were either always centered (in Experiment 1A) or presented as decreasing in magnitude from left to right (in Experiment 1C) during learning no SNARC effects were observed. Although such results were not completely as expected, they can still readily be explained McNamara and colleague's spatial model.

According to Shelton and McNamara (2001), the structure of the scene or environment itself can provide the salient reference frames that are then encoded in spatial memory. Moreover, Mou and McNamara (2002) showed that participants are able to learn a spatial layout according to a perspective that is aligned with a strong intrinsic axis present in the environment just as well as they are able to learn a spatial layout from a perspective that they are physically facing. Large scale spaces too seem to be similarly represented using reference frames that are underlined by some major features in the environment (McNamara et al., 2003). McNamara et al. (2003) concluded that, even for those large scale spaces, spatial relations are structured around the allocentric reference system but selected on the basis of egocentric experience. That is, depending on the observer's perspective, the most salient intrinsic reference frame gets selected (out of possibly many others) to encode the scene.

In this thesis, it has been hypothesized that spatial cognitive systems represent mental order relations similar to the manner in which the relations of physical objects in the environment are represented. In Experiment 1A, the items within the sequence were deliberately learned non-serially and presented without any left-right location information (i.e., no intrinsic reference frame was present), in order to test whether participants would naturally generate a directionality for the sequence, and if so, whether it would depend on perceptual magnitude or not. Interestingly, in the absence of a contextually determined intrinsic frame of reference, participants did not generate a common directionality for the sequence. However, in Experiment 1B when a salient left-to-right intrinsic reference frame involving increasing perceptual magnitudes was provided, a partial ordering of the sequence items along that same directionality was induced. On the other hand, reversing the directionality of the ordering of perceptual magnitudes in Experiment 1C did not result in a SNARC effect, suggesting that a decreasing magnitude ordering is less salient than one that increases in magnitude. Hence, given that the sequences in Experiments 1A and 1C were not learned according to a salient intrinsic directionality, participants were not able to apply a consistent allocentric frame of reference when judging the magnitude relations of the items. As a result, the sequence was not represented in a way that facilitated its association egocentrically (i.e., relative to the body) and, therefore, no SNARC effect occurred for these conditions.

In order to confirm that the lack of SNARC in Experiments 1A and 1C was not due to the lack of a generated ordering of the sequence, a transitive inference (TI) paradigm (Leth-Steensen & Marley, 2000) was used in Experiment 1D. Even then, no group SNARC effects were found (i.e., the ordering generated by the participants did not seem to have any default left-to-right directionality). When comparing the four Experiment 1 conditions to other studies that have found non-numerical SNARC in the literature (e.g., Gevers et al., 2003, 2004; Previtali et al., 2010), the main difference appears to be a matter of whether the participants had learned the sequence in a serial order or not. In the present Experiments 1A – 1C, the order of learning the CVC-percept associations within the sequence was random, whereas the other ordinal SNARC studies that have been reported in the literature have typically used a design involving stimuli that were either ordered naturally in long term memory or novel items whose sequence was learned in a fixed serial order. Therefore, it seems to be the case that it is necessary to learn the sequence items in a serial order for the generation of a consistent allocentric representation of the sequence (which would then align with the egocentric representation of the responses in a consistent manner).

In fact, fMRI studies have shown that the processing of sequences that have an obvious frame of reference, and in which the items have a distinct spatial positions in relation to each other (such as numbers or the letters of the alphabet) occurs in different brain areas than does the processing of those sequences whose items have been learned in a non-serial manner (such as in TI tasks). More specifically, processing numbers and letters has been found to activate the intraparietal sulcus (IPS; Fias, Lammertyn, Caessens, & Orban, 2007), whereas processing the stimuli in a TI task has been found to activate the left inferior frontal gyrus (left IFG) after extensive learning (Van Opstal et al., 2009). As mentioned, Van Opstal et al. used a TI task in their experiment that was very similar to the one used in the current Experiment 1D, and they did indeed find a SNARC effect, but only after extensive training. In that study, though, they observed that the initial brain activation that occurred while learning the set of stimuli (a set of arbitrary figures that resembles some kind of hieroglyphic alphabet) was present in the hippocampal-angular gyrus and then only extended to the left inferior frontal gyrus (left IFG) when learning was completed. Additionally, it is at the same stage of learning in which the left IFG was activated that the SNARC effect was observed. Van Opstal et al. (2009) have hypothesized that the difference between the location of the brain activation during sequence processing found in their study compared to that found in Fias et al.'s (2007) may be because the IPS is related to more abstract concepts, whereas the left IFG may be related to the use of language related strategies. They also mention that the left

IFG is involved in both language and non-language related sequences such as the processing of musical sequences and the imagery of motion.

However, it cannot be overlooked that these Experiment 1 results also point to the importance of intrinsic directionality and frames of reference. It is possible that when a sequence has a strong intrinsic directionality and its items have distinct spatial relations to one another, it is processed in the IPS and can become readily associated with the egocentric reference frames. On the other hand, when the sequence items are learned in a more random order, extensive exposure to the sequence is needed in order to sort out its spatial relations in terms of its axes and reference frames (cf., the double stages in the activation and the longer learning periods that were required in Van Opstal et al., 2009). This reckoning is supported by the current experimental results indicating that no SNARC effect was found except when an intrinsic left-to-right directionality was induced in the way of increasing perceptual magnitudes (i.e., in Experiment 1B).

The alignment of the allocentric and egocentric axes

The second experiment revealed additional constraints concerning the reference frames upon which the SNARC effect depends. In line with McNamara and colleague's spatial model, it was predicted that in addition to the requirement that the reference axis for the allocentric representation of a numerical sequence have an intrinsic directionality, it is also necessary for it to be spatially aligned with the reference axis for the response-based egocentric representation in order for the SNARC effect to occur. Indeed, as reviewed in the Introduction, McNamara and colleagues' have demonstrated that perspectives taken during spatial judgment tasks that are aligned with either intrinsic allocentric reference axes in memory or current egocentric reference axes resulted in facilitating spatial reasoning performance (i.e., memory and sensorimotor alignment effects). Similarly, the view taken in this thesis is that the SNARC effect depends on the instantiation in memory of a left-to-right intrinsic allocentric reference frame of increasing numerical magnitude coupled with a small-left and large-right response mapping in egocentric space which then results in response facilitation due to the compatibility of the two reference frames. Importantly, such spatial compatibility and, hence, response facilitation should also occur for bottom-to-top vertical allocentric reference frames coupled with a small-bottom and large-top response mapping. For any other configuration of these two reference frames, spatial compatibility will not be the case and no SNARC effect should be present.

This prediction was tested and supported for the first set of conditions in Experiment 2 where the results revealed a standard SNARC effect for the control condition (i.e., HH) for which both the internal representation of the sequence and the response keys were aligned horizontally. On the other hand, the effect was absent when the allocentric and egocentric representations were aligned perpendicular to each other in the manipulated condition (i.e., VH). In the second set of conditions in Experiment 2, though, with vertically aligned response keys, SNARC effects were absent in both the control and manipulated conditions (i.e., VV and HV, respectively). However, the results of these latter two vertical-response conditions came with a caveat. Namely, gender differences were present in both conditions such that males tended to show a standard SNARC effect, but females did not. This finding is an important one because not much attention has been paid to SNARC-related gender differences in the literature.

In order to remain consistent with the proposed allocentric–egocentric alignment hypothesis, the results for the latter two conditions would have to be explained as follows. First, the lack of vertical SNARC effects for the females in these two conditions would suggest that any vertical-based allocentric representations they were invoking were either non-existent or not very consistent across individuals. Although such a state of affairs might have been expected in the horizontal imagery (i.e., HV) condition, the female participants did not seem to be able to use the vertical imagery instructions in the VV condition to retrieve the corresponding vertical allocentric representation (which has been referred to as invoking image-based co-ordinate spatial relations by Proctor & Cho, 2006, and see the discussion of this issue in Wood et al,, 2008). On the other hand, the presence of quite substantial and consistent vertical SNARC effects for the males in both of these two conditions suggests that vertical-based allocentric representations were indeed being invoked by them regardless of the nature of the initial imagery manipulation. Presumably, such vertically aligned spatial representations are much more salient and easily accessible for males than females.

One further point, though, is that vertical SNARC effects have been observed in parity tasks with samples containing a large proportion of females (e.g., Ito & Hatta, 2004, Schwarz & Keus, 2004; but note that no gender information was provided by Muller & Schwarz, 2007). Hence, females do seem to be able to apply a vertical allocentric reference frame for numbers but only for tasks involving parity judgments (where magnitude is only an implicit attribute) and when not explicitly instructed to do so imaginally.

The alignment of the subjective midpoint of the allocentric reference axis with the midline of the egocentric reference axis

The final experiment supported the hypothesis that the overlap of the allocentric and egocentric spatial reference frames at their midpoints is what determines the nature of the SNARC effect. Indeed, in the results for the magnitude task, the SNARC effects that were observed within three different sub-ranges of digits were dependent on the actual midpoints employed. As well, the subjective midpoints determined by the observed spatial-numerical relations that were present for each condition were shifted towards the actual midpoints. Such results clearly indicate that the association between numbers and spatial codes depends on the numbers' position in the sequence relative to the subjective midpoint and not solely on their magnitude.

The results of this experiment are quite important in that they dispel the notion that specific numbers are associated with specific response codes. Additionally, they indicate that it is not even the range of the numbers that specifies this association as has previously been suggested (Dehaene et al., 1993). Rather, such associations arise as a consequence of the manner in which the allocentric and egocentric axes are aligned. In essence, the categorical midpoint defined by the task instructions serves to partition the allocentric spatial representation of the number sequence into two distinct left and right parts, each of which then becomes associated with the left and right sides corresponding to the response lateralization of egocentric space. In other words, it seems that the categorical midpoint of the sequence can act as a focal point from which the correspondences of the sequence items to the left and right of egocentric space get generated.

Finally, regarding the parity task in Experiment 3, although significant overall SNARC effects were obtained in two conditions (i.e., Experiments 3B and 3C), the nature of these effects were not at all consistent with those observed for the magnitude task in these same conditions. Namely, the lack of a relation between the subjective midpoints computed for each task indicates that the midpoint used in the magnitude task did not then subsequently seem to be used in the parity task. There are two possible reasons why no transfer effects occurred. First, participants might simply have abandoned the explicit use of the subjective midpoint from the magnitude task given that it was no longer relevant in (or salient to) the parity task. Second, it is possible that different numerical representations were being used for each type of task. The possibility of different representations for these two tasks, though, is an issue that has not received much attention in the numerical cognition literature. Other than Ito and Hatta (2004), who conjectured that parity information might be represented in terms of separate even (i.e., 2, 4, 6, 8, etc) and odd (1, 3, 5, 7, etc.) sequences in long-term memory, most researchers typically assume that the same mental number line representation is accessed for both types of tasks (albeit only implicitly in the parity task).

Summary of main findings and conclusion

In sum, the three experiments performed here have demonstrated, first, that it is important for a sequence to have a salient intrinsic directionality in order to obtain a consistent assignment of left and right spatial codes to the sequence items. Second, it is also important for the allocentric representation of the sequence and the egocentric representation of the responses to align together in order for the compatible spatial elements of each to become co-activated. Third, explicit midpoints can act as a focal point from which the spatial correspondence between the sequence items and the response codes gets established.

In conclusion, the experiments presented in this thesis contribute to the understanding of the SNARC effect from the perspective of the McNamara and colleagues' spatial model by assuming that the same spatial cognitive systems can underlie the representation of both physical and mental concepts. Given the adoption of this view, the SNARC effect can be generalized to many other conceptual attribute dimensions besides numbers due to the fact that the allocentric representations hypothesized by the model are general enough to include any ordered concepts.
In addition, the flexibility of the SNARC phenomenon both with respect to its directionality across tasks and individuals could fruitfully be explained in terms of interactions between allocentric and egocentric representation reference frames.

Some important future work could involve developing a neural model of SNARC that explicitly incorporates the processing of allocentric and egocentric representational information. As well, it seems important to incorporate the working of various kinds of allocentric frames of reference into models of SNARC such as Gevers et al. (2006) computational model. Indeed, the current work suggests that there seems to be more to the SNARC effect than simple stimulus-response correspondences based on either categorical or polarity codes.

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