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Abstract

The spatial-numerical association of response codes (SNARC) effect provides evidence for perceptual simulation of symbols. That is, parity judgments with one's left hand are faster for lower numbers than for higher numbers (with one's right hand, judgments are faster for higher numbers than for lower numbers). A perceptual simulation account of the SNARC effect leaves little room for a non-embodied explanation, even though recent studies have demonstrated that statistical linguistic data can explain findings from various embodied cognition studies. The current study explored whether such linguistic factors could also explain the SNARC effect. In a response time experiment, participants were asked to make parity judgments of number words. Frequencies of those number words explained the results just as well as a perceptual simulation explanation. Moreover, collocation frequencies (the previous number word and the following number word) also explained response times, further demonstrating that linguistic factors might play an important role in number processing. The results of this experiment show that language encodes information that could also be attributed to perceptual simulations. Consequently, language users might well be using these linguistic cues during number processing.

Keywords: SNARC; numerical cognition; mental number line; mental representations; perceptual simulation; embodied cognition; number processing

Introduction

Intuitively, number manipulation seems more symbolic than perceptual in nature. The computing of numbers, after all, does not require references to the symbols being manipulated or a visual representation of the manipulation process. Nevertheless, a spatial representation of numbers is often thought to facilitate our understanding (Semenza, 2008). When participants are presented with small (1, 2, 3, 4) and large (6, 7, 8, 9) numbers, and are asked to make a parity judgment, they are faster to respond to small numbers with their left hand, and large numbers with their right. This finding is known as the SNARC (spatial-numerical association of response codes) effect (Dehaene, Bossini, & Giraux, 1993; Wood, Nuerk, Willmes, & Fischer, 2008) and suggests that comprehenders perceptually simulate the representation of numbers. Importantly, subjects are not making judgments that would call attention to number magnitude, but instead, they are making a speeded parity judgment. Purportedly, the SNARC effect occurs because participants use mental representations to spatially represent numbers on a number line. Furthermore, the SNARC effect always seems to occur in the same direction as the directional reading conventions of the subject's culture (i.e., English speakers show a left-to-right SNARC effect while Arabic speakers show the reverse effect) (Shaki, Fischer, & Petrusic, 2009).

Researchers have replicated and modified the original SNARC experiment to also demonstrate vertical effects (Ito & Hatta, 2004), as well as right-to-left effects (i.e., opposite of what is expected for English speakers) (Shaki et al., 2009; Zebian, 2005) for other language groups. In fact, Israelis, who read text from right-to-left and who read numbers from left-to-right, show no SNARC effect at all (Shaki et al., 2009). In addition, illiterate Arabic speakers fail to show any SNARC effect (Zebian, 2005). Andres, Ostry, Nicol, and Paus (2008) have shown that physical manipulations of the subject (e.g., crossing hands, or using grasping motions) do not influence the direction of the effect. Yet others have found that the SNARC effect holds when subjects are presented with two-digit numbers (Dehaene et al., 1993; Reynvoet & Brysbaert, 1999) and number words (Fias, 2001), however it is noted that in some cases number word processing may increase response times (RTs) relative to Arabic numeral processing (Dehaene et al., 1993). Furthermore, although the effect may exist for numbers, no such magnitude-based mental organizational system is found for alphabetic letters (e.g., *A, B, C,* etc.) (Zorzi, Priftis, Meneghello, Marenzi, & Umilta, 2006). Interestingly, the SNARC effect does seem to be influenced by processing strategies employed during the experimental task. Subjects asked to imagine distance on a ruler demonstrate a typical SNARC effect, whereas those who instead imagine numbers representing time on a clock face show no such effect (Suzuki, Sugimoto, Tsuruo, Bachtold, Baumuller, & Brugger, 1998).

Apart from simply expanding upon instances in which the SNARC effect occurs and does not occur, various theories explaining the effect have been offered. As number representation is thought to be somewhat independent of other language processes (Semenza, 2008), many researchers have proposed a spatial representation explanation of the SNARC effect. In other words, the SNARC effect occurs because the mental representations of numbers are spatially organized according to number magnitude (i.e., numbers are placed on a mental number line with small numbers on the left and large numbers on the right) (Zorzi, Priftis, & Umilta, 2002). Although such an explanation is succinct and even empirically supported through neurological research (Zorzi et al., 2006), it fails to account for how numbers are represented for language users of specific groups that fail to show any SNARC effects (e.g., Israelis and illiterate Arabic speakers).

Dehaene and colleagues (1993) have suggested that instead of spatial representation being inherent in the numbers themselves, the SNARC effect may be caused by directional reading conventions. Further development of this theory hypothesizes that the direction of recent spatial processing be considered in addition to culturally constrained conventional reading directions (Fischer, Shaki, & Cruise, 2009).

Proctor and Cho (2006) claimed that the SNARC effect occurs through the consideration of stimuli polarity. According to a theory of number representation, small numbers have a negative polarity whereas large numbers have a positive polarity. Thus words and numbers are represented along a positive-negative dimension in space. In the instance of SNARC, the right side and large numbers are associated with a positive polarity and the opposite is true for the left side and small numbers. Bächtold, Baumüller, and Brugger (1998) have posited that the SNARC effect might be due to a learned embodied association between numbers and actions (i.e., common patterns of motor activation make use of the knowledge that the left side of a keyboard possesses only small numbers whereas the right possesses large numbers).

Even others suggest that two different processing routes (a top-down conditional route and an automatic unconditional route) work together simultaneously to help us understand the stimuli being presented, therefore accounting for RT differences among various numbers (Gevers, Cassens, & Fias, 2005; Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2005). It is important to note that despite differences between theories, most agree the SNARC effect is, at least in some way, further evidence for perceptual simulation during cognition.

Symbolic and Embodied Cognition

Many studies have demonstrated that cognition is embodied (Barsalou, 1999; Glenberg, 1997; Pecher & Zwaan, 2005; Semin & Smith, 2008). Proponents of the embodied cognition account suggest that concepts and percepts are understood through perceptually simulating external experiences. In other words, according to this view, mental representations are thought to be modality specific neural reenactments of perception and action. Further, embodiment theorists argue there is little room for the utilization of symbolic representations during conceptual processing, such as statistical linguistic variables, because mental representations must always be grounded in bodily experiences (Glenberg & Kaschak, 2002; Lakoff, 1987).

A number of perceptual features have been found to facilitate conceptual comprehension. Implied perceptual features such as shape, location, modality, orientation, and direction (Glenberg & Kaschak, 2002; Šetić & Domijan, 2007; Stanfield & Zwaan, 2001; Zwaan & Yaxley, 2004) that facilitate language comprehension have led to views of embodied cognition that reject symbolic accounts (Glenberg & Kaschak, 2002; Lakoff, 1987; van Dantzig, Pecher, Zeelenberg & Barsalou, 2008). The ready dismissal of non-perceptual explanations in cognition is somewhat surprising, given the evidence summarized in Paivio's (1986) Dual Coding Theory. Paivio and colleagues demonstrated in a range of experimental studies that cognitive processes involve both verbal and non-verbal representations. Accordingly, words may be stored in memory as a set of embodied simulations or as a set of abstract linguistic representations, based on a variety of factors (e.g., individual differences, concreteness, task demands, etc.).

Louwerse (2007; 2010) proposed the Symbol Interdependency Theory. According to this theory language encodes perceptual relations (Louwerse, 2008), and language users take advantage of these linguistic cues during cognition. For shallow processing, language users primarily rely on linguistic representations, whereas for deep processing they rely more on perceptual simulations (Louwerse & Jeuniaux, 2010). For instance, Louwerse (2008) tested whether the finding that the word pair *flower-stem,* presented one above the other, yielded faster response times because participants were perceptually simulating the word pair, or because of the word order. Spatially higher items were found to precede lower items (the frequency of word pairs such as *flower-stem* is significantly higher than word pairs *stem-flower*), and the linguistic frequencies explained response times better than perceptual ratings. Louwerse (2008) replicated the effect for linguistic frequencies when the two words were presented horizontally, next to each other.

The experimental evidence supporting the Symbol Interdependency Theory allows for the possibility that the SNARC effect could also be attributed to statistical linguistic factors. To test for this possibility, we conducted a SNARC response time study. As in most SNARC studies, we asked participants to evaluate whether numbers were even or odd, by responding using their left or right index finger. However, instead of presenting Arabic numerals we opted for number words.

The rationale for using number words was that a) if the SNARC effect could have a linguistic basis, we should be able to first and foremost find it in words and b) although making parity judgments regarding number words may seem to be more difficult than making parity judgments about Arabic numerals, still number words have shown to yield a SNARC effect (Fias, 2001).

Admittedly, there is evidence that number words and Arabic numerals are processed in different ways (Damian, 2004; Fias, 2001). However, past research has suggested that number word presentation shows few differences from traditional Arabic numeral presentation in a SNARC experiment (Nuerk, Iversen, & Willmes, 2004). Furthermore, as we exclusively presented number words, any variations in RTs should be systematic across all parity judgments, and are thus of little consequence.

Because language encodes embodied representations, we hypothesized a strong correlation between the perceptual ordering of the numbers and their frequencies. Moreover, we hypothesized that these frequencies would explain the results as well as (or better than) a perceptual simulation account. Finally, we hypothesized that if linguistic factors explain the SNARC effect, the collocation frequencies of paired number words (e.g., *one* preceding *two*, *one* following *two*) would also impact processing time.

Experiment

The current experiment investigated whether linguistic factors could be considered as a possible alternative explanation for the SNARC effect. Subjects participated in a standard SNARC experiment by making parity judgments about number word stimuli while their response times with their left and right hand were recorded.

Methods

Participants

Fifty-seven University of Memphis undergraduate students participated for extra credit in a psychology course. All participants had normal or corrected vision, were right handed, and were native English speakers. Twenty-seven participants were randomly assigned to respond to even numbers with their left hand and to odd numbers with their right hand, and thirty participants were randomly assigned to respond to odd numbers with their left hand and to even numbers with their right hand.

Stimuli

Each experiment consisted of 130 trials, with each trial including one number word. Number words included ranged from one to nine, but, as is convention in SNARC experiments, five was excluded (Tzelgov, Meyer, & Henik, 1992). Importantly, trials were paired such that each number word was paired with every other number word, in both orders (i.e., participants would see *one* followed by *three*, as well as *three* followed by *one*).

Procedure

In both conditions, number words were presented in the center of an 800x600 resolution computer screen running E-prime software (Psychology Software Tools, Inc., Pittsburgh, PA). Participants were asked to make a parity judgment as quickly and as accurately as possible after each number word was presented on the screen. Depending on which condition they were assigned to, participants responded to either even or odd number words with the left index finger (by pressing the 'F' key) and with the right index finger (by pressing the 'J' key).

Once a participant responded, the symbol '+' would appear as a fixation point in the center of the screen for 1000 msecs, then the next number word would appear. Trials consisted of two separate number word presentations followed by a short beep. Participants were instructed to press the spacebar when they heard the beep to progress to the next trial pair. Number words within an experimental session were randomly presented for each participant in order to negate any order effects. Each participant saw every combination of number word pairs one through nine (excluding five) in each condition. To ensure participants understood the task, a session of six practice trials preceded the experimental session.

Results

Five participants were removed from further analysis because >14% of their answers were incorrect. The total of 52 participants were now equally distributed between the response conditions, with 26 participants in each condition. The average error rate was 5%. In addition, outliers were identified as 2.5 SD above the mean RT per participant per condition. Errors and outliers were removed from the analysis, affecting 6.5% of the initial data.

A mixed-effect regression model was conducted on RT with response side and number magnitude as fixed predictors and subject and item as random predictors (Baayen, Davidson, & Bates, 2008; Richter, 2006). The model was fitted using the restricted maximum likelihood estimation (REML) for the continuous variable (RT). F-test denominator degrees of freedom were estimated using the Kenward-Roger's degrees of freedom adjustment to reduce the chances of Type I error (Littell, Stroup, & Freund, 2002).

A main effect was found for response side with faster response times for right handed responses compared to left handed responses, $F(1, 5815.85) = 6.57$, $p = .01$. This result is not surprising, given that all participants were right-handed.

As described earlier, the SNARC effect stems from the interaction between faster responses for lower numbers with the left hand, and faster responses for higher numbers with the right hand. This is exactly what was found. An interaction between response side (left or right handed response) and number magnitude (*one*, *two*, *three, … nine*) reached significance, $F(1, 5816.93) = 3.26$, $p = .04$.

As in Fias (2001), for each subject, the median RT per digit per response side was separately computed for all correct answers. Median left hand responses were subtracted from median right hand responses. The resulting RTs were then fitted using a 3rd degree polynomial model. ($y=a+bx+cx^2+dx^3$), where x is the digit the number word represents (see figure 1). Coefficients for the model are presented in Table 1.

The linguistic factor was operationalized as the log frequency of the number word (e.g., *one, two,* etc.) obtained using the large *Web 1T 5-gram* corpus (Brants & Franz, 2006). There was an almost perfect negative correlation between the selected number words (one-nine) and their frequencies, r = -.98, p < .001. This makes it at least a possibility that the perceptual representation of the words in the SNARC effect is affected by word frequency. In order for this possibility to apply, the frequency of the number words should not affect the response times, but an interaction is predicted between response side and word frequency. This is indeed what the results demonstrated.

The SNARC effect predicts that small numbers are processed faster with the left hand; so if word frequency alone impacted RTs, we would have expected to see faster processing of frequent words regardless of response side. Instead we found that the log frequency did not explain RTs, $F(1, 5587.95) = .01$, $p = .93$), but, as expected an

Table 1: Correlation coefficients, standard errors, and parameter coefficients for all three fittings

	RT	Linguistic Frequencies	Bigram Frequencies
R	0.78	0.76	0.55
SE	14.21	14.73	20.73
a	-58.160	46850.540	-28.161
b	58.380	-7646.834	-5.082
c	-12.947	415.294	2.970
d	0.841	-7.502	-0.240

interaction was found between response side and log frequency, $F(1, 5586.16) = 3.23$, $p = .04$. See Table 1 for model coefficients and Figure 2 for the fit of the polynomial model.

The argument could be made that it is the magnitude of the number rather than the log frequency that is responsible for the effect on response times (as magnitude and log frequency were so highly correlated). We assessed frequency collocation for number pairs to determine whether linguistic frequency (as opposed to number magnitude) indeed had an impact on response times. Number word order frequency was thus computed for number pairs (e.g., *one* preceding *two*, *one* following *two*). In a mixed model, log frequency of the word pair

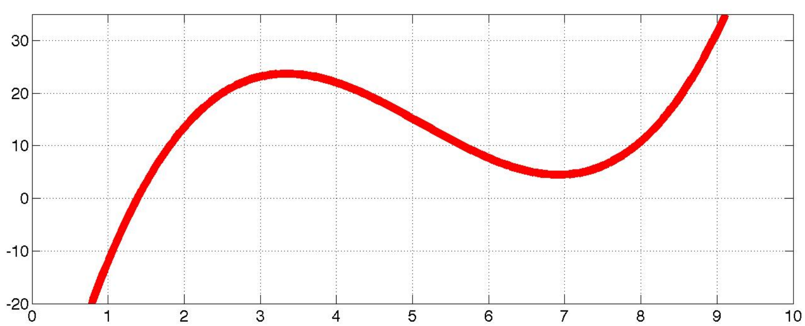

Figure 1: RT results (right-hand results – left-hand results) curve-fitted to a 3rd degree polynomial model. Numbers 1-9 are plotted sequentially along the x axis.

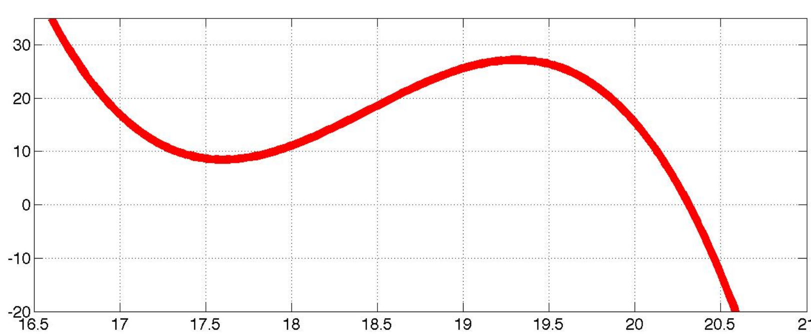

Figure 2: RT results (right-hand results – left-hand results) curve-fitted to a 3rd degree polynomial model. Log frequencies are plotted sequentially along the x axis.

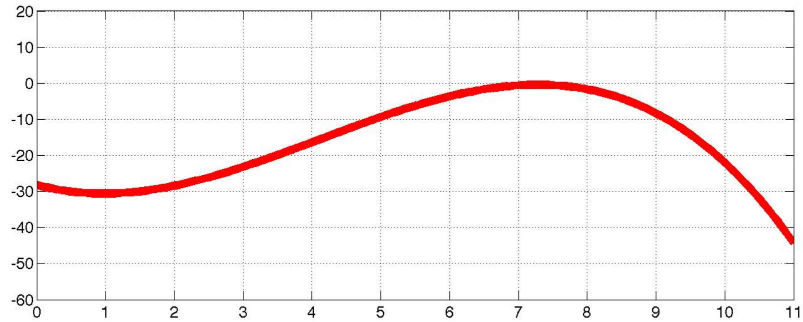

Figure 3: RT results (right-hand results – left-hand results) curve-fitted to a 3rd degree polynomial model. Ten percentiles of the log frequencies are plotted sequentially along the x axis.

significantly explained response times, $F(1, 3072.72) = 4.12$, $p = .04$, with higher frequencies yielding lower response times. Also, a significant interaction was found between response side and word pair frequency, $F(2, 3082.32) = 3.54$, $p = .03$. As before, we subtracted the left-hand response from the right-hand response per word number pair. The log frequencies were then averaged in ten percentiles, and the same curve fitting method was applied as before (see Figure 3). Table 1 presents the fit, the standard errors, and the values for the four variables. Figures 2 and 3 appear to mirror the SNARC results but by using log frequencies, indicating that it is at least a possibility that, in addition to perceptual simulation, linguistic features might also explain the SNARC effect.

Discussion

The current study aimed to determine if linguistic factors might explain the outcome of the SNARC effect. The reported results suggest that word log frequencies can explain performance on the experimental task. The SNARC effects were replicated, specifically, the RTs for small numbers were faster when the left hand was used to respond, and the RTs for large numbers were faster when the right hand was used to respond. Our current data suggest that the notion that the SNARC effect is evidence for perceptual simulation alone must be reconsidered. If linguistic representations were irrelevant to numeral processing we would have expected linguistic features to show no relationship to outcomes from the SNARC experiment. They do, however, explain both response side and response times suggesting that a linguistic explanation can therefore not be dismissed.

We not only replicated SNARC findings, but number word frequencies were able to explain the SNARC effect as well as a perceptual simulation account. Also, because response side and word pair frequencies showed an interaction, we can conclude that magnitude alone does not explain the results, suggesting further that linguistic factors may play a part in the representation of numbers.

Embodiment theorists should be careful not to overlook the impact of linguistic factors during conceptual processing. As Paivio (1986) argued, linguistic and perceptual information both can be used to represent incoming information, and it appears that this may also be true for the comprehension of numbers. Although there is much evidence supporting embodied accounts of mental representations, there remains value in theories that consider symbolic representations. The current project demonstrated that an effect that was previously explained through embodied mechanisms can be explained through linguistic means as well. Further study must investigate under what conditions numbers are represented using linguistic or perceptual means in order to better understand when and how different types of representations are utilized. For example, because the direction of the SNARC effect varies for different cultures (Ito & Hatta, 2004; Shaki et al., 2009; Zebian, 2005) but numbers have intrinsic statistical frequencies that are constant across cultures (Dehaene & Mehler, 1991), it would be of interest to determine whether the SNARC effect (or lack thereof) could be explained by linguistic frequencies for these other language groups as well.

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