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Language Statistics Explains Spatial-Numerical Association of Response Codes

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The spatial-numerical association of response codes (SNARC) has shown that parity judgments with participants' left hands yield faster response times (RTs) for smaller numbers than for larger numbers, with the opposite result for right hand responses. These findings have been explained by participants perceptually simulating magnitude on a mental number line. In three RT experiments we showed that the SNARC effect can also be explained by language statistics. Participants made parity judgments of number words (Experiment 1) and Arabic numerals (Experiment 2). Linguistic frequencies mirrored the SNARC effect, explaining aspects of processing that a perceptual simulation account could not. Experiment 3 investigated whether high- and low-frequency non-numerical words would also elicit a SNARC effect. Again, RTs were faster for high-frequency words for left-hand responses with the opposite for right-hand responses. These results demonstrate that what has only been attributed to perceptual simulation should also be attributed to language statistics.

Keywords: SNARC; numerical cognition; perceptual simulation; embodied cognition; number processing; symbol interdependency

Many cognitive scientists have argued cognition is fundamentally perceptual in nature (Barsalou, 1999; Glenberg, 1997; Pecher & Zwaan, 2005; Semin & Smith, 2008). This even seems to hold true for processing numerical information. When asked to make a parity judgment for small/large numbers, participants process small numbers faster with their left hand and large numbers faster with their right hand, suggesting that comprehenders perceptually simulate numbers on a mental number line. This finding is commonly known as the spatial-numerical association of response codes (SNARC) effect (Dehaene, Bossini, & Giraux, 1993; Fisher & Brugger, 2011; Restle, 1970; Wood, Nuerk, Willmes, & Fischer, 2008).

The SNARC effect is well understood and quite robust, with physical manipulations of the participant (e.g., crossing hands, grasping) and handedness failing to influence its direction (Andres, Ostry, Nicol, & Paus, 2008; Dehaene et al., 1993). SNARC also holds when participants are presented with two-digit numbers (Dehaene et al., 1993; Reynvoet & Brysbaert, 1999) and number words (Fias, 2001). In fact, SNARC extends to other sequence-based mental organizational systems such as alphabetic letters, large and small object words, and other types of ordinal information (Gevers, Reynvoet, & Fias, 2003; Ren, Nicholls, Ma, & Chen, 2011; Shaki & Gevers, 2011; Shaki, Petrusic, & Leth-Steensen, 2012).

Several theories have been proposed to explain the SNARC effect in terms of perceptual simulations. Dehaene et al. (1993) suggested that numbers are spatially organized on a mental number line according to their magnitude, where small numbers are on the left side and large numbers are on the right side. Others proposed the SNARC effect might instead be a learned embodied association between numbers and actions (e.g., common patterns of motor activation utilize the fact that the left side of a keyboard has only small numbers whereas the right has large numbers; Gevers, Caessens, & Fias, 2005). Fischer (2008) and Fischer and Brugger (2011) even suggest that finger counting may be the origin of the SNARC effect. All these theories share the idea that the SNARC effect is the consequence of perceptual simulation of a number line.

However, there are some findings that raise questions about a perceptual simulation account. For instance, the original parity task has also shown vertical (Ito & Hatta, 2004), and right to left effects (Shaki, Fischer, & Petrusic, 2009; Zebian, 2005), indicating that the mental number line is not canonical. In addition, illiterate Arabic speakers fail to show any SNARC effect (Zebian, 2005), suggesting that SNARC might have less to do with perceptual simulation and more with linguistic abilities. Fischer, Shaki, and Cruise, (2009) found that spatial representation is not inherent in the numbers themselves, but is caused by directional reading conventions and the direction of recent spatial processing, with Israelis, who read text from right to left and numbers from left to right, showing no SNARC effect. Fias (2001) demonstrated that SNARC is not limited to Arabic numerals, but can also be found for number words. These findings suggest that perceptual simulation might not be the only explanation for the SNARC effect, and hint at the possibility of a linguistic explanation.

Recent literature has considered linguistic explanations for experimental findings that originally supported perceptual simulation accounts. Several psycholinguistic theories have argued that cognitive processes can be explained by both embodied factors (e.g., perceptual simulations) and symbolic factors (e.g., statistical linguistic frequencies) (Louwerse, 2007; 2008; 2011; Paivio, 1986; Simmons, Hamann, Harenski, Hu, & Barsalou, 2008). For instance, the Symbol Interdependency Hypothesis proposes that language encodes perceptual relations, allowing language users to take advantage of language statistics in cognitive processing (Louwerse, 2007; 2008; 2011). Evidence has shown that experimental findings attributed to perceptual simulations can be explained at least as well as or even better by language statistics

(Louwerse, 2008; 2011; Louwerse & Connell, 2011; Louwerse & Jeuniaux, 2010). These findings allow for the possibility that the SNARC effect too might be attributed to non-perceptual factors, such as statistical linguistic frequencies. That is, even though a perceptual simulation account (i.e., mental number line representations) can explain the SNARC effect, such an account might be complementary to one that considers statistical linguistic frequency. To test for this possibility, we conducted three experiments.

Two experiments used the methods and analysis of the original SNARC experiments with number words (Dehaene et al., 1993; Fias, 2001; Nuerk, Iversen, and Willmes, 2004) (Experiment 1) and Arabic numbers (Dehaene et al., 1993) (Experiment 2). We predicted a strong negative correlation between number magnitude and number (or number word) frequency. We also hypothesized that both word frequency and number magnitude would explain response times in a SNARC-like fashion in Experiments 1 and 2. In Experiment 3 we used non-number words with a relatively high or low frequency to determine whether a SNARC-like effect could be obtained based entirely on word frequency, such that participants would process frequent words faster with their left hand and infrequent words faster with their right hand.

EXPERIMENT 1

Experiment 1 tested the effect of number magnitude and number-word frequency on response times, to determine whether SNARC can be explained both perceptually and linguistically. If the SNARC effect has a linguistic basis, we should be able to first and foremost find the effect in number words. We therefore followed the method for the standard parity task reported in Dehaene et al. (1993) for number words.

Method

Participants. Fifty-seven right handed native English-speaking undergraduate students at the University of Memphis participated for course credit. Randomly assigned response conditions instructed subjects to respond to respond to even numbers with their left hand and odd numbers with their right hand (*n*=27), or to odd numbers with their left hand and even numbers with their right hand (*n*=30).

Stimuli. Each experiment consisted of 130 trials, with each trial including one number word, ranging from one to nine (excluding five, following Tzelgov, Meyer, and Henik, 1992). In addition, trials were paired such that each number was paired with every other number, in both orders (e.g., participants saw a trial of *one* followed by a trial of *three*, as well as a trial of *three* followed by a trial of *one*).

Procedure. In both conditions, number words were presented in the center of an 800x600 resolution screen. Once a participant responded, the next trial would commence after the fixation symbol '+' appeared for 1000 ms. A short beep followed every two trials. Trial pairs were randomly presented to negate order effects. Participants saw every combination of number word pairs in each condition. Six practice trials preceded the experiment.

Results and Discussion

Five participants were removed because >14% of their answers were incorrect. The remaining 52 participants were equally distributed between conditions. The average error rate was 5%. Outliers were identified as responses slower than 1500 ms and faster than 200 ms, following Shaki, et al. (2009). Errors and outliers were removed from the analysis, affecting 6.5% of the data.

As in Dehaene et al. (1993) and Fias (2001), median RT per number word per response side was separately computed per participant.[1] Median left hand responses were subtracted from median right hand responses. A mixed-effects regression was conducted on RT with response side and magnitude and frequency as fixed predictors and participant and item as random predictors (Baayen, Davidson, & Bates, 2008). 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 chance of Type I error (Littell, Stroup, & Freund, 2002). Critically, we included a frequency factor to the analysis that was operationalized as the log frequency of the number word from the Web 1 trillion word 5-gram corpus (Brants & Franz, 2006).

A main effect was found for response side with faster RTs for right hand responses, F (1, 5815.85) = 6.57, p = .01, R^2 = .0002. This result is not surprising, as all participants were right handed. More interestingly, the SNARC effect stems from the interaction between faster left hand responses for smaller numbers, and faster right hand responses for larger numbers. This interaction was found, with response side by magnitude reaching significance, F (1, 5816.93) = 3.26, p = .04, R^2 = .15, replicating the SNARC effect. The resulting RTs were fitted using a linear model (Figure 1).

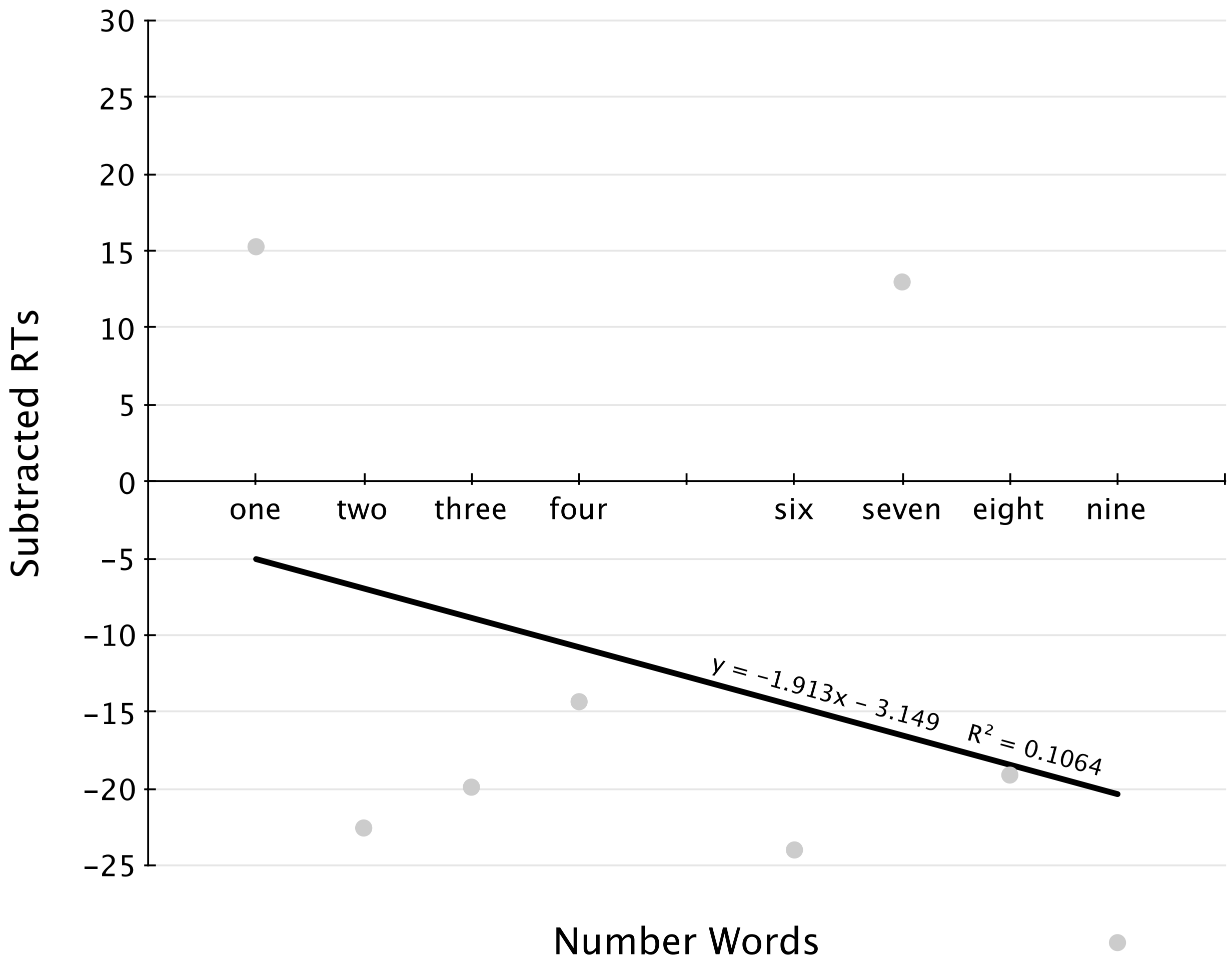

Figure 1. Linear fitting of the SNARC effect for Experiment 1 (number words).

As predicted, there was a strong negative correlation between magnitude and frequency, $r = -.98$, $p < .001$ (cf. Dehaene & Mehler, 1992). This correlation at least allows for the possibility that the SNARC effect can also be explained by word frequencies. In order for this possibility to apply, word frequency should not affect the RTs, but an interaction is predicted between response side and frequency. That is, the SNARC effect predicts that small numbers are processed faster with the left hand; if word frequency alone affected RTs, we would expect to see faster processing of frequent words regardless of response side. We found frequency itself not explaining RTs, F (1, 5587.95) = .01, $p = .93$, $R^2 = .02$, but, analogous to the SNARC effect, an interaction was found between response side and frequency, F (1, 5586.16) = 3.23, p = .04, R^2 = .78 (Figure 2).

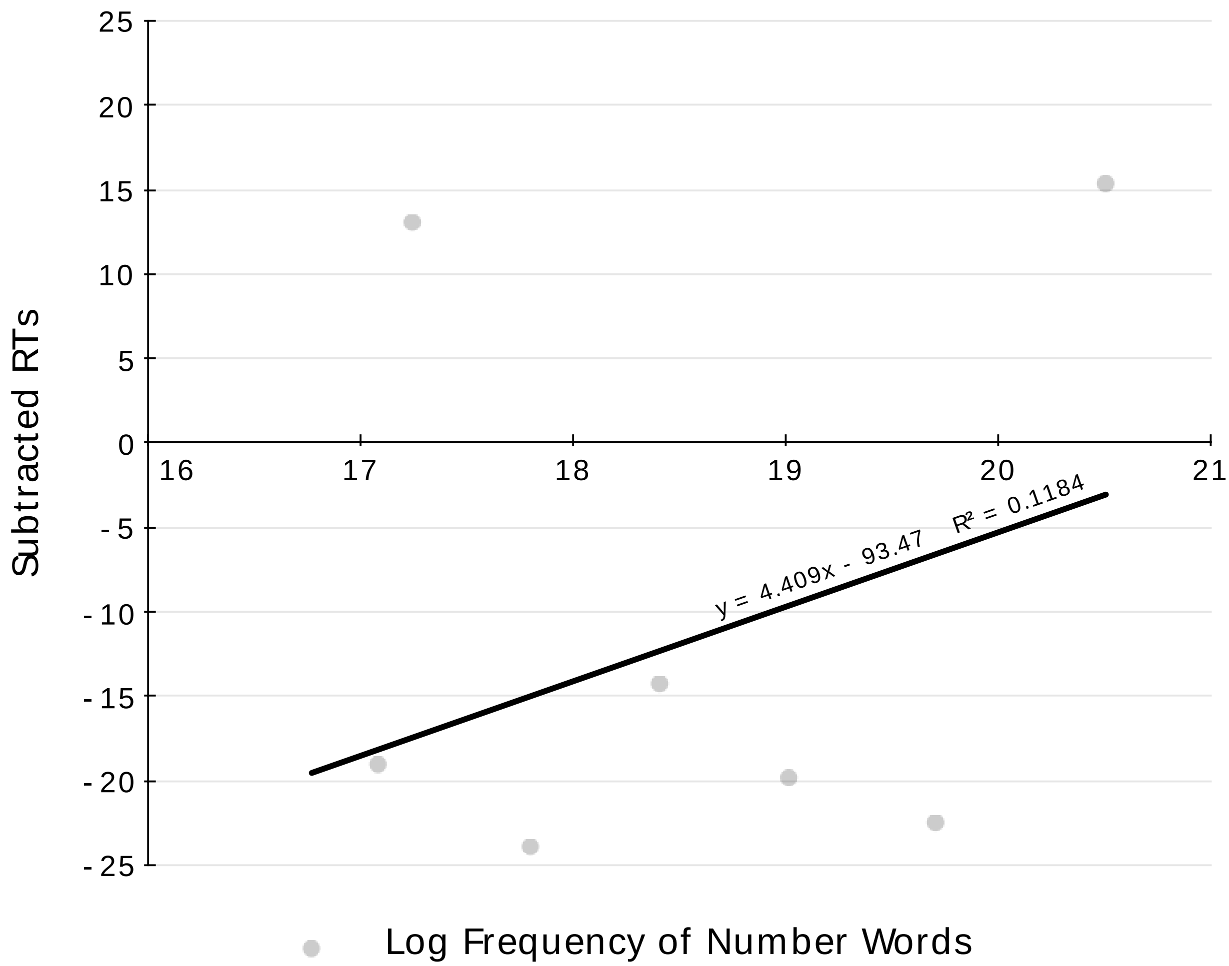

Figure 2. Linear fitting of the statistical linguistic frequencies for Experiment 1 (number words).

The question of whether the linguistic system simply provides redundant information derived from the perceptual system is still left open, because that which is explained by language statistics can also be explained by magnitude. To test whether linguistic frequencies might independently explain the experimental findings, we further analyzed the collocation frequencies of paired number words (the number word presented in trial n and the number word presented in trial *n*+1) After all, if statistical linguistic frequencies of word pairs explain RTs, this finding would be difficult to attribute to perceptual simulations because collocation frequencies cannot simply be explained by the magnitude of the second number word. There was no correlation between the collocation frequencies and the second number's magnitude, $r = -.15$, $p = .20$. In a mixed effects model, bigram frequency significantly explained RTs of the second word in the pair, F (1, 3072.72) = 4.12, $p = .04$, $R^2 = .001$, with higher frequencies yielding lower RTs. As before, we subtracted the left hand response from the right hand response[1]. A significant interaction was found between response side and frequency, F (2, 3082.32) = 3.54, $p = .03$, $R^2 = .21$. These collocation results thus mirror the traditional SNARC findings while they are difficult to explain with a perceptual simulation account, providing evidence for a statistical frequency account.

EXPERIMENT 2

In Experiment 2, we again followed the methods in Dehaene, et al. (1993) but used Arabic numerals instead of number words. Different than Experiment 1, we included the number 0, whose low magnitude, yet low frequency allowed for comparing a perceptual account (number magnitude explains the SNARC effect) and a frequency account (number frequency explains the SNARC effect).

Methods

Participants. Forty-four right handed native English speaking undergraduates participated for extra course credit. Participants were again evenly split between conditions.

Stimuli and procedure. Each experiment had 162 trials, including one Arabic numeral ranging 0-9 (as before, excluding 5). The procedure was identical to Experiment 1, except subjects were presented with Arabic numerals. A short beep followed every two trials. Trial pairs were randomly presented to negate order effects and the instructions told participants ‘0’ was an even number.

Results and Discussion

Eight participants were removed because >30% of their answers were incorrect. A software error incurred a loss of 2.2% of the data. As in Experiment 1, we removed responses slower than 1500 ms and faster than 200 ms resulting in data loss of 2.43%.

To determine if word frequency might also explain RTs, we conducted an analysis in the same way as in Experiment 1 where median RT per number word per response side was separately computed per participant.[1]

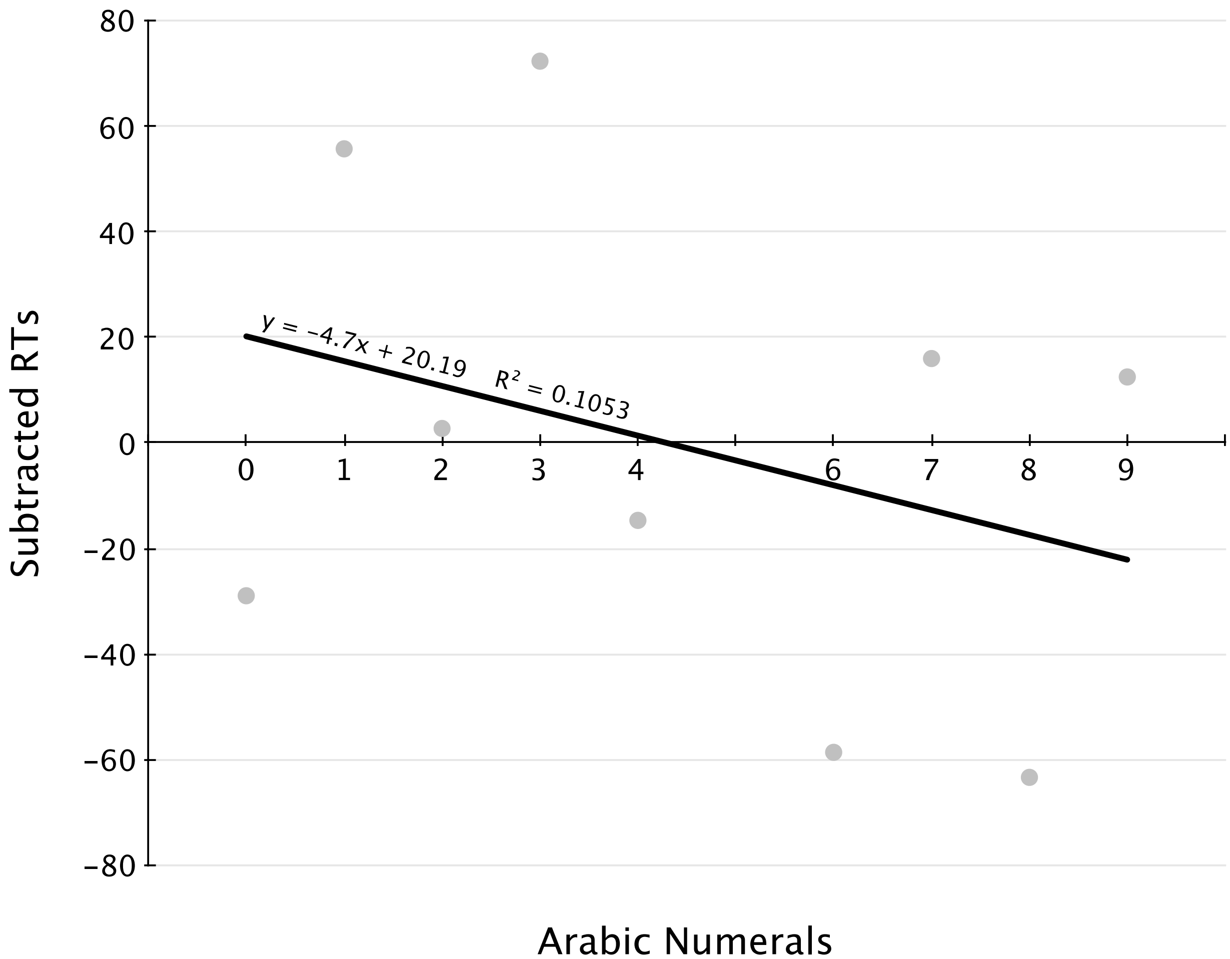

Figure 3. Linear fitting of the SNARC effect for Experiment 2 (Arabic numerals).

As in Experiment 1, response side did not significantly contribute to this model, F (1, 4973) = 1.20, p < .001, R^2 = .02, nor did magnitude, F (1, 4973) =.42, p = .52, R^2 = .007. An interaction between response side and magnitude, however, was significant, F (1, 4973) = 13.88, p < .001, R^2 = .23 (Figure 4).

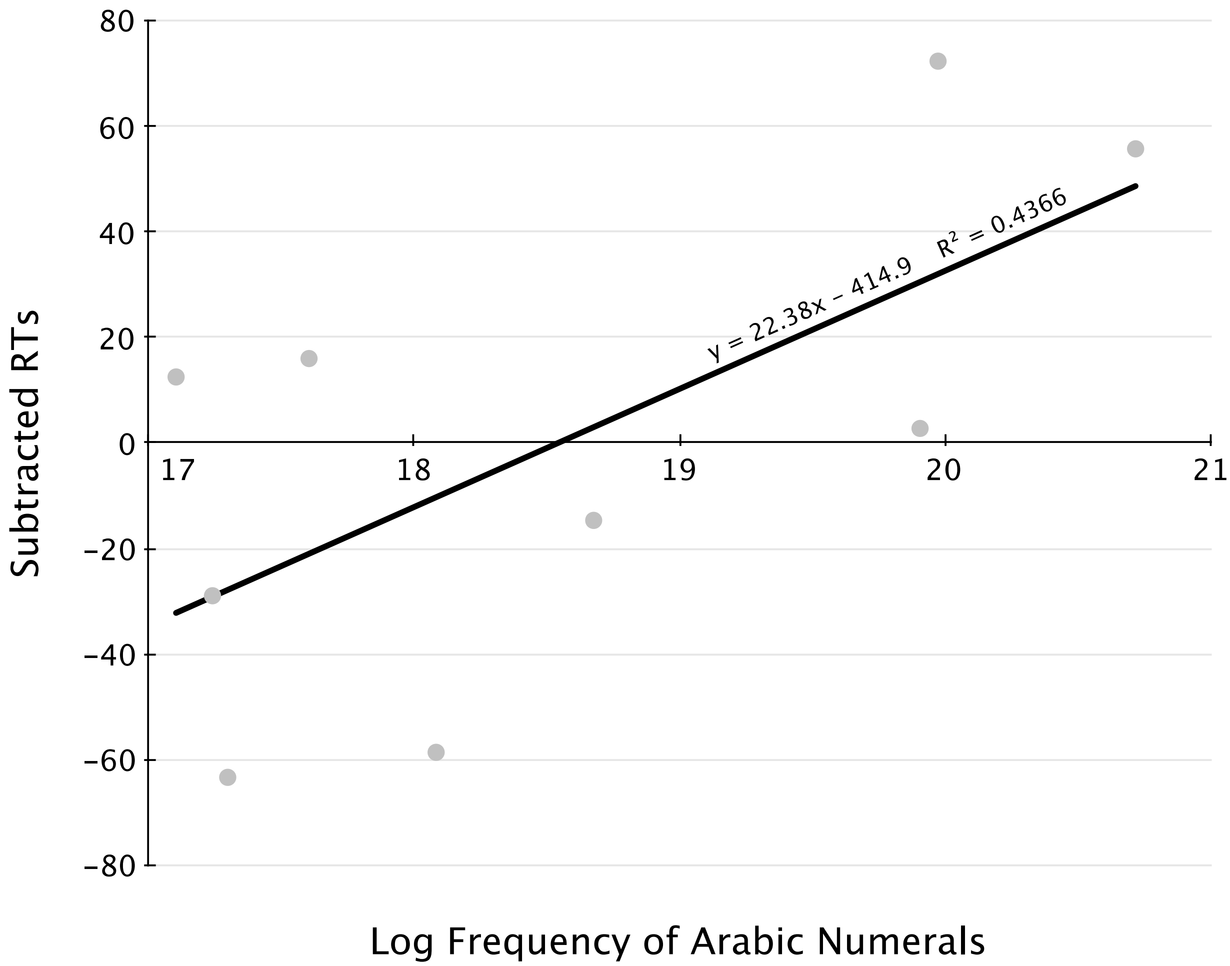

Figure 4. Linear fitting of the statistical linguistic frequencies for Experiment 2 (Arabic numerals).

As in Experiment 1, there was an expected negative correlation between the number words and their frequencies, $r = -.60$, $p < .001$. Note the correlation is weaker than in Experiment 1, because we included ‘0’, an infrequent, but small number. Without the inclusion of ‘0’, the correlation between magnitude and frequency is stronger, $r = -.98$, $p < .001$. A mixed-effect model was conducted on RTs with response side and frequency as fixed predictors and participant and item as random predictors. Frequency did not affect RTs, F (1, 4973) = .05, $p = .81$, $R^2 = .001$, but a response side by frequency interaction was again significant, F(1, 4973) = 14.60, $p < .001$, R^2 =

.24. Response side did not significantly predict RTs, $F(1, 4973) = .41$, $p = .52$, $R^2 = .007$ (Figure 3).[2]

As before, we assessed frequency collocations for number word pairs to determine whether bigram frequency alone impacted RTs. Bigram frequency was computed for each number pair. Bigram frequency did not significantly explain RTs, F (1, 2098) = .03, $p = .88$, R^2 = .001. As before, left hand responses were subtracted from right hand responses per number pair. A response side by frequency interaction was significant, F (1, 2098) = 42.22, $p <.001$, $R^2 = .53$, as was a main effect of response side, F (1, 2098) = 9.29, $p < .01$, $R^2 = .12$. Bigram frequencies did not correlate with the magnitude of the second word in the pair, $r = .08$, suggesting that frequencies indeed contributed to the SNARC effect, a finding that cannot be explained by a perceptual simulation account.

Including the number ‘0’ in the stimuli allowed us to investigate the perceptual simulation and the frequency accounts further, because this number has a low magnitude yet a high frequency. Left hand responses for ‘0’ were slower (M = 670 ms) than right hand responses (M = 641 ms), albeit not significantly so, t (555.65) = -1.5, $p = .13$. To determine whether RT findings for ‘0’ provided support for a frequency or perceptual account, we compared RTs for items ‘0’ and ‘1’. If magnitude explains responses, because ‘0’ and ’1’ both share a low magnitude, no significant difference is expected to be found between the two numbers. But if word frequency explained the responses, because ‘1’ is quite frequent and ‘0’ is less frequent, subtracted RTs for these two items are predicted to be divergent, which was indeed what we found, t (10.75) = -4.5, $p < .001$. The problem is that the differences between ‘0’ and ‘1’ might be explained by a learned perceptual relationship, because ‘0’ on a keyboard is placed on the far right. To support such an explanation, it would be necessary for RTs to ‘0’ to be faster with the right hand, but they were not, t (555.65) = -1.5, p = .13..

Experiment 1 and 2 demonstrated evidence of a non-perceptual explanation for the SNARC effect. This evidence does not exclude the possibility that participants perceptually simulate a number line, because we did find an independent effect of magnitude on RTs. At the same time, however, there are at least two arguments that favor a frequency account. First, when the number zero was included (Experiment 2), a number that has both low magnitude and low frequency and is therefore different than other low magnitude numbers, no SNARC effect was found even though a statistical linguistic frequency effect was obtained. Second, bigram frequencies explained RTs, whereas such an explanation is lacking for a perceptual simulation account.

EXPERIMENT 3

There are two problems with a frequency account. First, number magnitude and number frequency are so strongly correlated, it is difficult to disentangle whether frequency or magnitude is driving the SNARC effect. Experiment 3 therefore examined word frequency independently from magnitude by using stimuli without an associated number magnitude (i.e., non-number words). This allowed us to determine if frequency alone (high or low) would explain the effect.

A second problem with a frequency account concerns direction. Whereas number-line representation explains why left-hand responses are faster for low-magnitude items and right-hand responses are faster for high-magnitude items (for instance, because we count 1, 2, 3…), the rationale might not be so obvious for high-frequency numbers eliciting faster left-hand responses and low-frequency items eliciting faster right-hand responses. Markedness, however, is able to explain this pattern. Greenberg (1966) argued that for any pair of words the one that is more frequent is the unmarked (i.e., most natural, simplest, first learned) and the one that is less frequent is the marked member of the pair, with unmarked members preceding marked members (see also Louwerse, 2008; Louwerse & Jeuniaux, 2010). In other words, for two words for which there is a frequency asymmetry, the frequent word precedes the infrequent word. This general linguistic theory can be easily demonstrated for the number words in Experiment 1. When the bigram frequency is taken for two number words in a 5-word window in a large corpus of the English language (Brants & Franz, 2006), frequent number words precede infrequent number words more often than vice versa, $F(1, 70) = 31.25$, $p < .001$.

Based on the findings in Experiment 1 and 2 that SNARC can be attributed to a frequency account, and given the frequency asymmetry of word pairs, we predicted that high frequency words are processed faster with the left hand, and low frequency words are processed faster with the right hand.

Method

Participants. Forty-nine undergraduate students participated in this experiment for extra course credit. Twenty-two participants were randomly assigned to respond to animate words with their left hand and inanimate words with their right hand, and 27 to respond to inanimate words with their left hand and animate words with their right hand.

Stimuli. Each experiment consisted of 60 one-word trials. Words extracted from the MRC Psycholinguistic Database were either frequent or infrequent, $t(69) = -17.10$, $p < .001$, and were matched on word length. Half of the words described to animate concepts whereas the other half described inanimate concepts, in order for the participants to make animacy judgments (rather than parity judgments as in Experiment 1 and 2).

Procedure. The procedure was identical to Experiments 1 and 2 except the stimuli were words instead of numbers. Words were presented in the center of an 800x600 resolution screen. Participants were asked to indicate if a word that appeared on the screen represented something animate or inanimate. Once a participant responded, the next trial would commence after the fixation symbol '+' appeared for 1000 ms. Participants were told to answer as quickly and as accurately as possible. Words were randomly presented to negate order effects. Six practice trials preceded the experiment.

Results and Discussion

Seven subjects were removed from the analysis as they responded to greater than 14% of the trials with an incorrect answer. Because the RT data were skewed even after a logarithmic transform of the data, we removed outliers greater than 3 SD from the mean per subject per condition or faster than 200 ms. Removing all outliers resulted in loss of 2.1% of the data. The average error rate was 6.9%.

As before, median RT per word per response side was separately computed per participant.[1] Median left hand responses were subtracted from median right hand responses. As before, a mixed-effects regression was conducted on RT with response side and word frequency (high or low) as fixed predictors and participant and item as random predictors.

Response side significantly predicted RTs, $F(1, 1856) = 3.73$, $p = .05$, $R^2 = .14$, with right side responses being faster, as subjects were right handed. Frequency approached significance, $F(1, 1856) = 3.24$, $p = .07$, $R^2 = .12$. Most importantly, a response side by frequency interaction was significant, F (1, 1856) = 7.23, $p < .01$, $R^2 = .27$. These findings indicate that high frequency words are processed faster on the left, whereas low frequency words are processed faster when presented on the right (Figure 5).

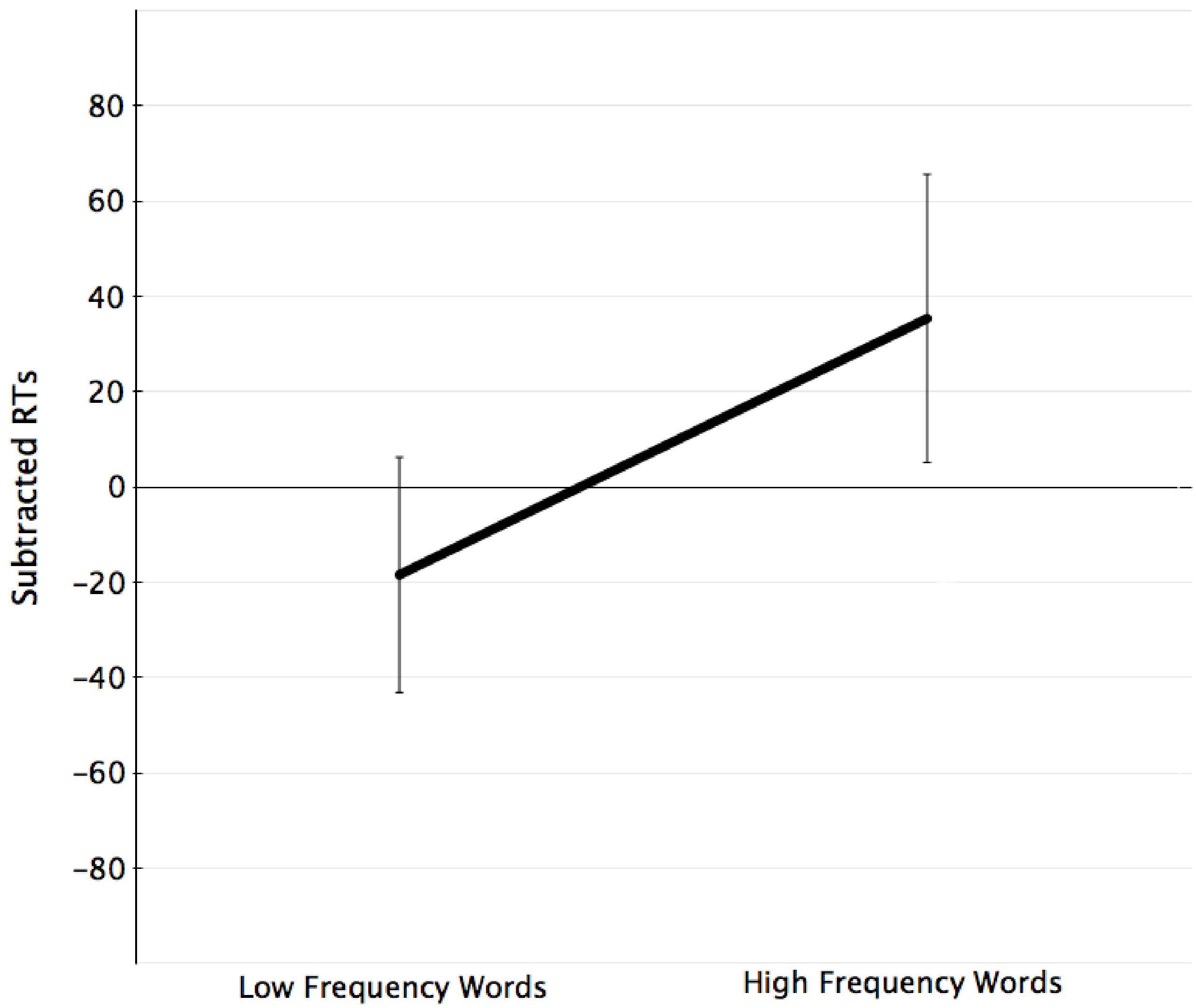

Figure 5. Linear fitting of the statistical linguistic frequencies for Experiment 3 (high and low frequency words).

General Discussion

The SNARC effect showing that left-hand responses are faster for low magnitude numbers whereas right-hand responses are faster for high magnitude numbers adds to the large body of literature that suggests that cognition is fundamentally perceptual in nature. Yet several studies have now demonstrated that statistical linguistic frequencies explain experimental results originally attributed to an embodied cognition account at least as well if not better (Louwerse, 2008; Louwerse & Connell, 2011; Louwerse & Jeuniaux, 2010). The results from the current paper add to these findings. Not only does a frequency account explain the experimental findings originally attributed to a perceptual account (Experiment 1 and 2), when collocations were taken into account, frequencies were able to explain RTs while a perceptual account could not (Experiment 1 and 2). Also, RTs from the number 0, a number with both low magnitude and frequency, supported the frequency account, and not the perceptual account (Experiment 2). Finally, when words were randomly selected on the basis of their low and high frequency, a SNARC-like effect was found, except that magnitude or perceptual simulation could not be the explanation (Experiment 3).

The finding that linguistic frequencies explain the spatial-numerical association of response codes does not dismiss a perceptual simulation account. On the contrary, the association of high frequency words with left-hand responses and low-frequency words with right-hand responses still suggests a spatial-numerical association of response codes. However, the current study suggests that the source of the spatial-numerical association is not necessarily magnitude but (also) linguistic frequency, and the nature of the SNARC effect might not be so much a mental number line that gets perceptually simulated, but a markedness effect with frequent items preceding infrequent items.

The notion of frequencies playing a role in numerical cognition is not a new one. Deheane et al. (1993) evaluated the interactions between number and word representations and showed that treating them as entirely separate processes does not provide an accurate description of number processing. This conclusion is reminiscent of the conclusion drawn by Louwerse and Jeuniaux (2010) that the nature of conceptual processing is both symbolic and perceptual. Whereas effects such as SNARC are commonly attributed solely to perceptual simulation processes, we have demonstrated that a language statistics account is a good, and perhaps even better, explanation. Language statistics facilitates cognitive processes, because language encodes perceptual (i.c., magnitude) information. This is true for encoding of modality (Louwerse & Connell, 2011), social relations (Hutchinson, Datla, & Louwerse, 2012), geography (Louwerse & Zwaan, 2009), and iconicity (Louwerse & Jeuniaux, 2010), and is no different for numbers.

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Endnote

1. The same analysis using the mean RT per number word per response side per participant where mean (rather than median) left hand responses were subtracted from mean right hand responses yielded similar results for all three experiments.

	EXP. 1		EXP. 2		EXP. 3	
	df	F	df	F	df	F
magnitude	5816.93	1.01	4973	0.1		
frequency	5587.95	0.18	4973	2.37	1856	3.24
response-side x magnitude	5816.93	12.52**	4973	13.88**		
frequency x magnitude	5586.16	8.67**	4973	14.6**	1856	7.33**
bigram frequency x response side	3082.32	13.77**	2098	18.34**		

2. 2. The same analysis excluding 0 had an insignificant main effect of response side, F (1, 4408) = .26, p = .61, R^2 = .005, and frequency, F (1, 4408) = .24, p = .62, R^2 = .005, and a significant interaction between response side and magnitude, F (1, 4408) = 17.14, $p < .001$, R^2 = .32.