Making SNAP Judgments: Rethinking the Spatial Representation of Number

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Abstract

Interactions between number and space, exemplified by the SNARC (Spatial-Numerical Association of Response Codes) effect, are often taken as evidence for a privileged spatial representation of number. Naturally, research on the *spatial* representation of number has typically focused on *spatial* tasks. But in order to make inferences about numerical cognition more generally, one must take care to tease apart spatial *mental representation* from spatial *action*. The present study asked participants to judge the relative magnitude of numbers, and to respond by producing sounds of different *pitches*. There was a significant interaction between pitch and number magnitude, analogous to the interaction between space and number: participants were faster to produce "high" pitches in response to "high" numbers. Moreover, the strength of this effect was unrelated to the strength of the traditional SNARC. We argue that these results undermine the privileged status of space as a representational substrate for number.

Keywords: number; pitch; SNARC; spatial representation.

Introduction

Number and space are intimately connected. For instance, Dehaene and colleagues (1993) found that participants are faster to classify smaller numbers when responding in left space, but faster to classify larger numbers when responding in right space—the so-called *Spatial-Numerical Association of Response Codes*, or SNARC. Research over the past two decades has confirmed automatic, unconscious interactions between number and space (see Hubbard, Piazza, Pinel, & Dehaene, 2005 for a review). In order to account for this effect, some researchers have posited the existence of a mental number line (e.g., Dehaene, Piazza, Pinel, & Cohen, 2003), a directed spatial representation of number with smaller numbers associated with left space, and larger numbers with right space. On this account, the SNARC effect falls out of this spatial representation of number.

Space has been argued to play a similar representational role for other conceptual domains. For example, Rusconi and colleagues (2006) demonstrated an automatic association between *pitch* and space, such that participants were faster to respond to lower *pitches* when responding in lower *space*, and vice versa—the Spatial-*Musical* Association of Response Codes, or SMARC. On the basis of this pitch-space correspondence, the authors concluded that the mental representation of pitch, like number, is spatial.

Note, however, that for both the SNARC and the SMARC tasks, the very nature of the task forces participants to respond spatially. It is not surprising that experimentalists have often looked to space as a response medium, especially when one considers how space is ready-to-hand as a tool more generally (Kirsh, 1995), well-suited to lending structure to more abstract domains (Lakoff & Johnson, 1980). As a result, space has become the default medium for investigating number representation, while other possible response modalities have been ignored (Núñez, in press; Núñez, Doan, & Nikoulina, under review). For example, Treccani and Umilta (2010), responding to claims that number may not be inherently spatial, suggested that, "in order to clarify this issue, it would be necessary to evaluate whether other symbols and/or stimuli conveying ordinal meaning are equally readily associated with space" (2010, p. 5). But associations between space and other conceptual domains—time, pitch, etc.—say nothing about the mental representation of number representation, *per se*. Inquiring into the role of space for the representation of number requires investigating situations where space is not forced upon the participant as a representational tool.

Alternate explanations of the SNARC

A few researchers have begun to question whether the SNARC is best explained by invoking an inherently spatial representation of number, let alone a directed, uni-dimensional mental number line (Proctor & Cho, 2006; Landy, Jones, & Hummel, 2008; Fischer, 2006; Santens & Gevers, 2006). One alternative proposal, the polarity-correspondence hypothesis (Proctor & Cho, 2006), argues that, when performing binary categorization tasks, both stimuli and the response categories will naturally have a "polarity," and response times will be faster when there is a match between stimuli polarity and response polarity (Proctor & Cho, 2006). According to this hypothesis, the SNARC is the result of privileging both larger numbers and rightward space, and thus assigning these the same "polarity"—and not to any spatial representation of number. It's unclear, however, exactly how this polarity is ascribed.

Another explanation is due to Walsh (2003), whose *A Theory of Magnitude* (ATOM) posits a single shared magnitude system for space, time, and number. Cohen Kadosh, and colleagues (2008) suggest that the common cortical mechanism proposed by Walsh could support "any comparison that can be classified as "more" or "less"" (2008, p. 475). Indeed, Núñez et al. (under review) found that participants readily map number onto non-spatial responses, including representations in terms of force and intensity of vocalizations.

Fischer (2006) notes that the SNARC is likely be related to one's embodied experience of associating number and space—whether in writing, grouping objects, or counting on one's fingers—and not necessarily due to an innate spatial encoding. He also notes individual differences in and flexibility of space-number associations. Fischer's proposal has much in common with claims in Conceptual Metaphor Theory (Lakoff & Johnson, 1980), which claims abstract concepts are structured by cross-domain inference-preserving mappings, often from a more concrete domain (e.g. space) to a more abstract domain (e.g. number). The SNARC effect may reflect a metaphorical mapping between number and space that emerges through experience and is shaped by culture (Núñez, 2009). Crucially, a single domain often has more than one metaphorical conceptualization, which suggests that the association between number and space may be one of many possible cross-domain mappings.

Interestingly, even critical work on the spatial representation of number continues to use experimental designs in which space holds a place of prominence. For example, Santens and Gevers (2006) found that participants responded faster to small numbers when their response was close to a central reference, and faster to large numbers when far away. They argued that these results point to a more general response discrimination effect, rather than a stable mental number line. While this addresses important questions about the specificity of the spatial encoding of number, it does not tease apart the spatial from the non-spatial.

The question remains: Is the connection between number and space exceptional, or is it one among many cross-domain mappings? In this vein, Landy, Jones, and Hummel (2008) had participants use non-spatial responses to number stimuli. Participants made both parity and magnitude judgments, responding with either a verbal "yes" or "no". Participants were quicker to say "yes" to large numbers and "no" to small numbers. The authors concluded that the results suggest that *polarity correspondence* (Proctor & Cho, 2006) may account for the kinds of interactions that are observed in the SNARC effect, even when space is not implicated.

Space, number, and pitch

These results highlight the fact that the pattern of results found in the SNARC effect is not restricted to spatial responses. Nevertheless, in many ways space is particularly well suited to represent other conceptual domains: it's multidimensional, continuous, even metrically structured. Other conceptual and perceptual domains are similarly rich in structure—such as pitch. The structure of pitch perception is highly complex (Cohen Kadosh et al, 2008), and like space, seems rich in representational affordances. And yet nobody seems to argue for, or even expect, a *pitched*-representation of number. The present study takes this as its starting point, and investigates the similarities between space and pitch as response media during numerical tasks.

In two experiments, participants were presented with a single-digit number and had to make a magnitude judgment, indicating whether the number was greater or less than five. Unlike previous studies in which spatial representation was confounded with spatial reporting (almost always in the form of manual response), the present study required participants to respond via *pitch,* by producing un-sustained high or low-pitched "ahs." If the pattern of results exhibited by the SNARC is the result an exceptional spatial representation of number, then either: (i) we should not expect a selective interaction between response pitch and number magnitude, analogous to the interaction seen in the SNARC, or (ii) if we do find such an interaction, we should be prepared to argue that number is inherently *tonal*.

However, if the SNARC is but one manifestation of a more general cognitive phenomenon, then one might even expect selective interactions between pitch and number. High and low pitches are often associated with small and large objects, respectively (imagine a squeaking mouse, a roaring dinosaur). Alternatively, we use "high" and "low" for both numbers and pitches, and this learned association may manifest itself in automatic cognitive processing. In either case, the observation of a selective interaction between pitch and number would suggest that participants are "Seeing Number as Pitch" —the *SNAP* effect.

Methods

Participants

51 undergraduates at the University of California, San Diego, received partial course credit for participating in the experiment.

Procedure

Participants completed two experiments: a *Pitch Response* task, and a *Spatial Response* task. The experiments were programmed using E-Prime (Psychology Software Tools, Pittsburgh, PA, USA). Each experiment consisted of two blocks of 80 randomly presented stimuli, for a total of 160 trials. Both involved a number magnitude judgment, but differed in the response modality. The mapping between number magnitude and required response was changed between blocks. Blocks began with written instructions, followed by practice trials, and then 80 experimental trials. The stimuli consisted of the Arabic numerals 1 through 9, excluding the number 5, presented visually in the middle of the screen. Each digit was presented 10 times in each block.

Trials began with a fixation cross in the center of a computer monitor, presented for 1000ms. Then the number stimulus was presented in the center of the computer monitor for a maximum of 3000 ms. Participants had to judge where the number was greater or less than 5, and respond by either vocalizing (Experiment 1) or pressing a button (Experiment 2). Participants were told to respond as quickly and accurately as possible.

Since we were interested in whether number and pitch would interact spontaneously, the Pitch Response experiment was always completed before the Spatial Response experiment.

Pitch-Response Task: Participants were asked to produce either "high-pitched" or "low-pitched" un-sustained "ahs" as vocal responses, spoken aloud into a microphone, for numbers greater than 5 or less than 5, depending on the mapping. The ordering of blocks and mappings were counterbalanced. Before the beginning of each block, participants were presented with 16 practice trials in order to ensure they understood the task. Each trial began by playing a short reference tone. Responses were coded online by an experimenter blind to the stimuli. During the experiment, the experimenter sat facing away from the computer and recorded whether each response was high- or low-pitched.

Spatial-Response Task: Participants also completed the classic, explicit SNARC task (Dehaene et al., 1993), in which they had to respond spatially by pressing buttons on a serial response box: either the leftmost button with their left hand, or the rightmost button with their right hand. Buttons were identified by their color (green or red). Participants were presented with 8 practice trials before each block, and responses were automatically collected by the computer, and thus were not coded by an experimenter as above.

Results

Seven subjects were removed from analysis due to low accuracy (< 70%), leaving 44 participants for analysis. For these remaining subjects, accuracy was quite high for both tasks: 97% for the spatial response task, and 96% for the pitch-response task. Incorrect trials were removed for subsequent analysis.

Pitch-Response

Median RTs for correct responses were calculated for each subject, number, and pitch response, following Dehaene (1993). Next, number magnitude was collapsed across number pairs, so that 1 was combined with 2, 3 with 4, 6 with 7, and 8 with 9. We conducted a 3x4x2 mixed design ANOVA, with pitch response (high, low) and number magnitude (1-2, 3-4, 6-7, 8-9) as within-subjects factors, and block order as between subjects. Analyses used R statistical software (R Development Core Team, 2008).

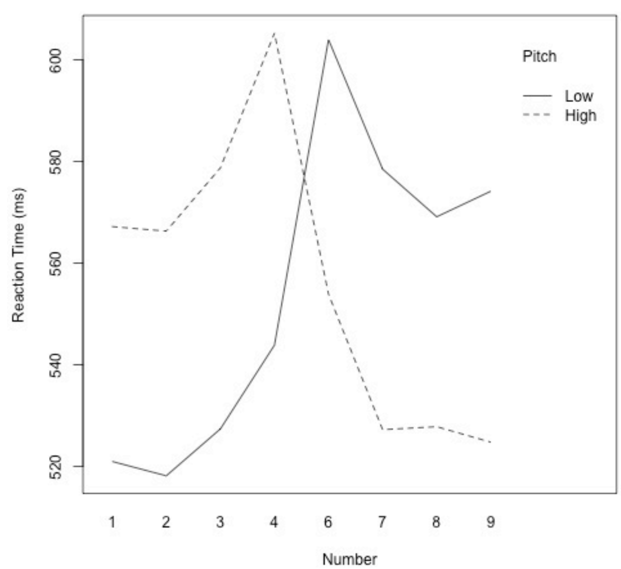

Figure 1: Median RTs in the pitch-response task.The interaction between Pitch and Number is significant.

There was no main effect of block order or pitch. An interaction between block order and number approached significance ($F(1,126)=2.56$, $p=0.058$), but is difficult to interpret. There was a main effect of number, ($F(3,126)=27.49$, $p<0.01$, $\eta_p^2 = 0.40$), probably driven by the known Distance Effect, where number comparison is faster for more distant number pairs.

The only other effect approaching significance was a the interaction between pitch and number ($F(3,126) = 18.67$, $p<0.01$, $\eta_p^2 = 0.31$)—the SNAP effect. For numbers less than 5, participants were faster to respond with a low-pitched response than a high-pitched response (median RTs of 514ms and 585ms, respectively), while for larger numbers, participants were faster to respond with a high-pitched response than a low pitched response (median RTs of 581ms and 515.5ms, respectively). See Figure 1.

These effects were also significant in an analysis of accuracy. We conducted a 2 (pitch) x 4 (number magnitude) x 2 (block order) mixed design ANOVA with mean accuracy as the dependent measure. The interaction between block order and number was again approaching significance (F(1,42)=3.18, p=0.08), and the main effect of number was highly significant (F(3,126)=10.19, p<0.01, $\eta_p^2 = 0.20$). The SNAP was again significant (F(3,126)=2.7544, p < 0.05, η_p^2 = 0.06).

Spatial-Response

Analysis for the Spatial Response task was similar. Median RTs for correct responses were calculated for each subject, number, and left-right response, and analyzed using a 2 x 4 x 2 mixed design ANOVA, with response location (Left, Right) and number magnitude (1-2, 3-4, 6-7, 8-9) as within-subjects factors, and block order as between-subjects.

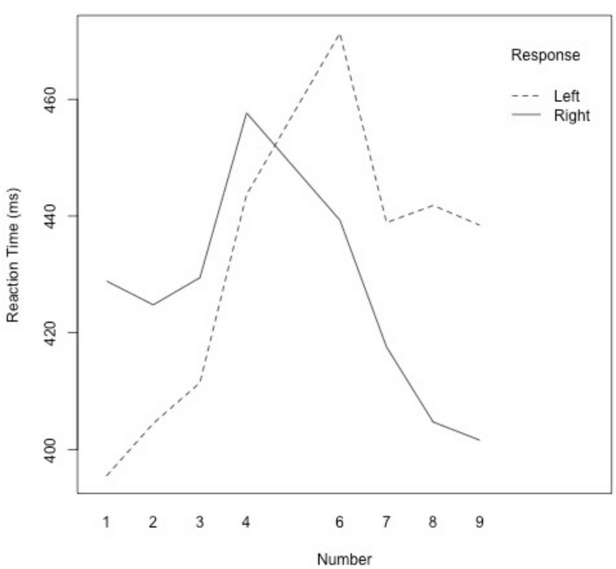

Figure 2: Median RTs for left and right responses for each digit in the spatial-response task.

There were no effects of block order. There was a main effect of number (F(3,126)=26.10, F<0.001, η_p^2 = 0.38), again probably driven by the Distance Effect. The only other effect was a significant interaction between response location and number magnitude (F(3,126)=8.4667, p<0.01, η_p^2 = 1.8)—the SNARC effect. All other effects were p>0.1.

We also did an analysis on accuracy, using a 2 (response) x 4 (number magnitude) x 2 (block order) mixed design ANOVA. The main effect of number magnitude was again highly significant (F(3,126)=16.33, p<0.01, η_p^2 = 0.28). There was also a three-way interaction between response, number magnitude, and block order (F(3,126)=4.6628, p=0.004, η_p^2 = 0.10), although this is difficult to interpret. The SNARC effect was again significant (F(3,126), p=0.001, η_p^2 = 0.12).

Comparing Pitch and Spatial Responses

To compare subjects' performance on the Pitch- and Spatial-Response tasks, the effects were analyzed using the regression approach introduced in Fias et al (1996). Linear regressions were performed for each subject's performance in both the Pitch- and Spatial-Response tasks. The difference in median reaction time (dRT) between response category (high vs. low; or left vs. right) was calculated for each subject and number. For instance, the dRT in the Pitch task was the difference between high-pitched and low-pitched responses for each number. Next, for each subject, dRT was regressed onto number magnitude. The weight of the number magnitude predictor can then be used as a measure of the size of the SNAP or SNARC effect.

Over the 44 participants, the size of the SNAP and the SNARC effects were significantly different (paired two-tailed t-test, t(43)=-3.05, p<0.01). To see if the size of the SNARC effect was predictive of the strength of the SNAP effect, they were put into a linear regression analysis with SNARC size as a predictor. The weight of the SNARC size predictor did not approach significance (β=-0.015, t(42) = -0.464, p > 0.6, r^2 = 0.005). Thus, there was no evidence of a relation between the sizes of the SNARC and SNAP.

Discussion

We investigated the mental processing of number by extending the SNARC paradigm to a novel response modality: pitch. Participants had to judge the relative magnitude of a single digit number, but instead of responding spatially—as has traditionally been done—participants responded using modulations in pitch, with either a high or a low pitched vocalization. If the interaction between number and space exhibited in the SNARC effect is truly indicative of an inherently spatial representation of number, then we should not expect to find analogous interaction effects for other response modalities. However, when given the opportunity to respond non-spatially, participants exhibited exactly such an interaction between number and pitch—the SNAP (Seeing Numbers as Pitch) effect. Furthermore, for each subject, the strength of the SNAP effect seemed independent of the strength of the SNARC effect.

These results add to a growing body of research that questions the primacy and stability of an underlying spatial encoding of number. On the basis of results like the SNARC effect, researchers have concluded that the mental representation of number is fundamentally spatial (e.g., Dehaene, Piazza, Pinel, & Cohen, 2003), with some going so far as to posit an innate, directed "mental number line." If the SNARC is only one manifestation of a more general cognitive capacity to think about or represent one domain in terms of another—as the present results suggest—then this undercuts any conclusions one might draw about the primacy of space as a representational medium.

This is not to deny that space is often used to represent number. Cultural artifacts that map number to space are ubiquitous in Western culture, and artifacts such as number lines—of the material, not mental, sort—are particularly useful as representational aids during numerical cognition. But these spatial representations are neither universal nor eternal, and care must be taken when drawing conclusions about the underlying cognition that led to their development (Núñez, 2009). Space, as a ready-to-hand representational medium, is highly privileged in the creation of concrete artifactual representations of abstract concepts, number included. The ease and ubiquity of spatial representation does not, in itself, entail the fundamentality of space in the mental representation of number. Recent experimental evidence has shown that, when given the opportunity, participants can systematically map number to various modalities—including intensity of squeezing and amplitude of vocalization—in ways which show many of the hallmark features found in spatial representations (e.g., logarithmic compression), but which also differ in precise ways related to enculturation (Núñez et al., under review). The ability to map numbers to a concrete line, therefore, is less exceptional than it might appear.

Claims about mental representation of number, of course, are not based on the mere observation of concrete, artifactual space-number mappings. The discovery of the SNARC effect suggested a much more fundamental connection between number and space: fast, automatic, and unconscious. If number interacts with space even when relations between number and space are irrelevant to the task, then this seems to point to some privileged and fundamental role for space in the representation of number. However, the reasoning applied to arrive at this conclusion also applies to the pitch data we have reported here: Namely, if one takes SNARC data and from it posits that number is represented spatially, perhaps in the form of a mental number line, then one must also claim, given the present results, that number is represented in terms of *pitch*. Indeed, the same would hold for any experiment that shows, like this one, that number interacts with some other response medium. This seems untenable. Few would accept, without serious reservations, the claim that the mental representation of number is, in some fundamental sense, *musical.* And yet number interacts with both space and pitch in the same selective and automatic way.

If the pattern of interaction between number and space is not exclusive to these domains, but also shows up when pitch is mapped to space (Rusconi et al, 2006) or when number is mapped to pitch (the SNAP effect found in this study), then this points to a much more general phenomenon. This may be an instance of a general polarity-correspondence effect (Proctor & Cho, 2006). Or, it may emerge from strategic problem solving, whereby the participants opportunistically recruit whatever resources are at hand, even when those resources are not necessarily germane to the task (Santens & Gevers, 2006). It could also be the result of more general magnitude extraction (e.g., Walsh, 2003) or of a domain-general capacity to map between conceptual domains (Lakoff & Johnson 1980). Regardless of the ultimate explanation, the present demonstration, that number interacts with non-spatial domains in systematic and selective ways, adds to the growing body of research that, at the very least, space is but one of the resources that contribute to the rich conceptual structure of number, and that the particular combination of these resources can vary across cultures and individuals (e.g., Núñez, in press).

While previous research has looked at how other non-spatial responses interact with performance on numeric tasks, these have all involved binary responses—such as "yes" and "no" (e.g., Landy et al., 2008)—which readily lend themselves to polarity-correspondence (Proctor & Cho, 2006). Pitch, on the other hand, provides participants with a continuous, graded, directed and experientially-rich response domain, and thus is more analogous with spatial representation than with a simple binary choice. That is, pitch is a rich continuum that may allow people to map finer distinctions than with "yes" and "no" responses. Such gradation is unavailable when the available responses are *a priori* restricted to two strict alternatives by the very structure of the response modality, and so could not be captured in the non-spatial stimuli used in previous experiments (e.g., Landy et al., 2008). While the present study also had participants perform a binary categorization, the possibility exists that participants modulated their pitch in a manner that corresponds to the increases or decreases in numerical distance from a central pitch. Though we did not fully exploit the continuous nature of pitch in the present study, we are currently investigating whether such nuanced modulations in pitch occur during the task.

One deflationary account of these results is that the SNAP effect is the result of the composition of a number-space mapping (SNARC) and a space-pitch mapping (SMARC), and therefore is ultimately spatial. Recall that the SMARC is an association between "higher" pitches and higher space, and between "lower" pitches and lower space (Rusconi et al., 2006; Cohen Kadosh et al, 2008). This is unsurprising given the way we talk about pitch (high versus low) in English, particularly in the light of research showing that metaphorical language (e.g., "high pitch") is often the surface manifestation of underlying conceptual mappings—for instance, between pitch and space (Lakoff & Johnson, 1980). Furthermore, the instructions of the present study included the terms "high pitch" and "low pitch," and such spatial terms may have primed a spatial construal of pitch.

Such a "spatial-mediation" account is interesting and provocative, in that it suggests that cross-domain mappings of the sort that underlie the SNARC and SMARC effects are compositional during online, low-level cognition. However, it is unlikely, for a number of reasons. For one, the SNARC is notoriously fragile, and can disappear in the face of very slight priming (Fischer et al, 2010). Even more problematic are the results of Beecham et al. (2009), who found that, for each individual, performance on a SNARC task was independent of performance on a SMARC task. These findings are problematic for a spatial-mediation account, which requires reliable and coordinated mappings between both number and space, and space and pitch. Moreover, we found that the strength of an individual's SNARC effect did not predict the strength of their SNAP, a surprising finding if the latter is parasitic on the former.

Conclusion

The present investigation suggests that conclusions drawn on the basis of observed space-number interactions may be premature, particularly if those effects are not viewed in the context of cross-domain mappings more generally. The current results in no way undermine the robust evidence for automatic activations of parietal regions involved in spatial cognition during numerical cognition (Hubbard et al, 2005). However, they *do* highlight the ways in which the pragmatics of experimental design can influence theory-building. Experimental designs in which participants respond spatially are easy to set up and conduct; indeed, space is particularly salient and ready-to-hand tool for thinking and acting (Kirsh, 1995). But the jump from the availability and accessibility of space, to its importance as a basic domain for the mental encoding of abstract concepts, is premature until we have documented the ways in which spatial responses differ from the myriad other ways in which we can respond. Pitch is but one example—and we've seen here that already, when compared to pitch, space loses its singular luster. Rather than speaking directly to the mental representation of number, results like the SNAP effect—and the SNARC effect before it—highlight the ways in which cognition depends on the recycling of diverse resources (Anderson, 2010). Such assemblages may be more or less stable, and may increase in stability over time – whether as a result of enculturation or mere co-activation (Núñez, 2009). While number and space are certainly related in interesting and complex ways, the nature of this relationship may be best investigated by studying the relationships between number and other conceptual domains or response modalities—and avoiding snap judgments about the nature of mental representation.

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