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Origins of Spatial-Numerical Bias

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Abstract. Spatial-numerical associations are prevalent in numerical cognition yet their origin is poorly understood. We discuss several candidates accounts and conclude that reading is a secondary factor while finger counting, natural number statistics, and embodied magnitude processing are likely to be of primary importance for the origin SNARC.

1 INTRODUCTION

Healthy Western adults tend to associate small numbers with left space and larger numbers with right space. This association affects their entire behavioral repertoire, from response choices to key pressing, arm and eye movements, hand apertures, and attention allocation. Over 100 experiments have now studied this spatial-numerical association of response codes or SNARC [1]. Yet there is no consensus as to how SNARC originates. This omission delays the understanding of SNARC in real-life numerical cognition, such as arithmetic [2, 3]. We first reject the frequently proposed dominant notion of SNARC as emerging from reading habits and then discuss alternative candidates.

2 THE ROLE OF READING

Early studies [4, 5] proposed that a left-to-right directional scanning habit is initially acquired with reading and might "spill over" into the numerical domain, thus causing the SNARC: But three arguments suggest that left-right reading habits alone cannot account for the entire SNARC.

First, some cultures have multiple reading habits that all contribute to SNARC: In Chinese-English readers the presentation format of a number (Chinese or Arabic symbol) determines whether it is mapped vertically or horizontally [6]. Hebrew readers have no SNARC - presumably because word and number reading habits cancel each other [7].

Second, effects of reading habits are much more short-lived than originally thought. The original idea that it requires years of exposure to a different reading culture to change a person's SNARC [4] runs against the observation that Russian-Hebrew bilinguals modify their SNARC after reading only a few minutes of Cyrillic or Hebrew text [8]. Even reading a single word changes the SNARC from one second to the next [9]. And even <u>during</u> reading, SNARC reflects the positioning of small digits on the left or right side of a text [10]. Thus, directional reading habits provide only a small contribution to the overall SNARC.

Developmental data also argue against a strong contribution from reading to SNARC. 4.5-year-old children already explore objects more efficiently when they are numbered in left-to-right ascending order [11, 12], establishes the small-left association as a default SNARC in Western cultures that needs to be explained.

3 OTHER CULTURAL CONTRIBUTIONS

First, SNARC might reflect culturally acquired finger counting habits. Most children acquire number concepts through finger counting when observing their parents. A cross-cultural comparison showed that adults in English-speaking countries prefer to start counting on the fingers of their left hand [13]. Thus, they associate small numbers with left space, and might have done so as children. Left-starters as a group have a stronger and more consistent SNARC [14] but studies of finger counting preferences in pre-school children are, surprisingly, still missing.

Second, language use offers an explanation for the default SNARC. The adjectives "left" and "small" are both linguistically marked (as are "odd" and "bad"). These concepts are more complex and less frequently used than their opposites ("right", "large", "even", "good"). Linguistic markedness can account for the odd-left association (the MARC effect; [15]) and this might extend to small-left associations. Limited familiarity [16] or complete lack of larger number words [17] is associated with logarithmically compressed spatial-numerical mappings but nothing is known about SNARC in animals although they show size and distance effects [18].

Comparing SNARC across cultures and species can inform this debate. Finger counting habits are clearly culture-dependent [13] and different languages vary in how they mark spatial and numerical concepts.

4 EMBODIED MAGNITUDE PROCESSING

Our brains have developed to control our bodies, which in turn constrain our cognition and action. This elementary truth has recently regained attention as "embodied cognition", often also as "grounded" or "situated cognition". We propose a hierarchical relationship between these terms before discussing implications of this view for the origin of SNARC.

The most fundamental aspect of cognitive representations is their *grounding* which reflects properties of the world. One example is the large numbers-up and small numbers-down association from accumulating objects [19]. Interestingly, small digits occur more frequently on the left side of multi-digit numbers. According to the Newcomb-Benford Law, the probability of the digit "1" occurring in the first, second, third or fourth position of multi-digit numbers drawn randomly from real life, is usually .37, .19, .12, and .09, respectively [20]. SNARC might be grounded in our internalization of this statistic [10].

On top of conceptual grounding, *embodied* representations are shaped by sensori-motor constraints of the body, as in finger counting [14] and grasp aperture modulation [21]. Finally, range and context dependence of SNARC [4,22] reflect *situated*

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number concepts. The embodiment stance makes three predictions about mathematical practice that can inform our search for the origins of SNARC.

First, different body postures, and their effects on spatial reference frames, should influence SNARC. Supporting this prediction, healthy adults generate smaller random numbers while turning their head left and larger random numbers while turning their head right [23]. Crossing hands over lateralized response keys can eliminate SNARC [24]. For right-hand responses, there is an index over ring finger advantage for small numbers, which reverses when the hand is held palm up [25]. Also, small digits facilitate left-hand recognition from an egocentric perspective (fingers pointing up), but right-hand recognition in an allocentric view (fingers pointing down) [26]. However, when situated in conflict, visual space dominates over hand space [27].

Secondly, embodiment predicts that special bodies should impact on our spatial minds and thus affect SNARC. There is clinical evidence that this is in fact the case. Patients with right hemisphere lesions, who fail to attend to the left side of their body and who neglect left hemispace, err towards large numbers when asked to bisect number intervals [28].The error in explicit number interval bisection is not correlated, however, to right-ward displacements in the bisection of real lines [29], nor does left-sided neglect manifest itself as small-number bias in random generation [30]. This indicates that, while hemispatial neglect affects orientation along a number line, the laws that govern attention in physical and number space are not identical.

A third prediction from the view of embodied magnitude processing is that functional hemispheric asymmetries should interact with the magnitude of SNARC in a given situation. Evidence for this comes from dual task paradigms, where left-hemisphere verbal memory load abolished SNARC in parity decisions but not in magnitude comparisons, whereas the opposite interference pattern occurred for right-hemisphere visual-spatial load [31]. These findings point to opposite hemispheric contributions to SNARC in different situations. Hemispheric activation paradigms can also bias healthy subjects' preference for small or large numbers during digit randomization [32]. Handedness, one of the most conspicuous signs of hemispheric specialization, does not influence SNARC per se [4] but could well do when space-number interactions are further modulated by finger use [14] or emotional valence [33].

5 OUTLOOK

Our brief review illustrates the bewildering number of potential sources of the association between number and space. We believe that this reflects the human capacity to quickly learn to associate any symbol or abstract relation with a spatial position or relationship [34, 35]. Thus, SNARC is the expression of some general cognitive rule that reflects the "placement" of an image in space (the spatialisation of ideas) and the relative (in)compatibility that emerges from using lateral effectors to respond to these ideas. Studies with children and amputees are likely to further advance our understanding of this intriguing phenomenon. The embodied cognition approach is a most suitable framework for further progress along this path.

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