Symbolic, numeric, and magnitude representations in the parietal cortex

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Abstract: We concur with Cohen Kadosh & Walsh (CK&W) that representation of numbers in the parietal cortex is format dependent. In addition, we suggest that all formats do not automatically, and equally, access analog magnitude representation in the intraparietal sulcus (IPS). Understanding how development, learning, and context lead to differential access of analog magnitude representation is a key question for future research.

We agree with Cohen Kadosh & Walsh's (CK&W's) central contention that representation of number in the parietal lobes is format dependent. The authors should be commended for presenting the clearest discussion yet of this topic, and for revisiting and reinterpreting findings from older studies. It is indeed surprising how many investigators have abandoned their own results only to reiterate staid theories. In this context, one is reminded of Ioannidis (2005): "[F]or many current scientific fields, claimed research findings may often be simply accurate measures of the prevailing bias" (p. 0696). By explicitly pointing out research biases extant in the literature, CK&W present the field with an opportunity to consider new interpretations and formulate more targeted research questions.

CK&W frame their review in terms of abstract number representations in the parietal cortex, as is the norm in the field. However, a more appropriate question is: How do various symbolic systems exploit magnitude-processing capacities of the intraparietal sulcus (IPS) and under what conditions?

CK&W do not address exactly why, or how, numerical formats differ in the degree to which they evoke effects consistent with an analog magnitude representation. By focusing on the absence of transfer of magnitude information across formats, the authors appear to have overlooked more fundamental differences between formats that have roots in experience and development.

Given that numerical symbols are cultural artifacts that are learned over time, we believe that not all formats will necessarily access analog-magnitude representations equally, and, in general, the degree to which a format has access to this representation depends on past exposure and current task context.

The findings reported by Cohen Kadosh et al. (2007b) in a twotrial adaptation paradigm are consistent with our view. This study found that presenting the same digit twice produced less activity in the right IPS compared to sequential presentation of two different digits. When the two numbers were presented in different formats (digit and number word), there were no differences in activity for same or different quantities, consistent with a format-dependent view. However, there was also no difference between same and different quantities when both numbers were presented as number words. This result is inconsistent with the view that number words are automatically represented as magnitudes in the IPS, a central assumption of both the abstract and non-abstract views.

One intriguing result from Cohen Kadosh and colleagues' (2007b) study is that although number words did not show numerosity-related adaptation, they did produce robust activity in the IPS, comparable to the level observed for digits. This suggests that the IPS can encode number words in a nonmagnitude-dependent manner. Strong evidence for notationdependent activity in the IPS also comes from neurophysiological studies: Diester and Nieder (2007) found that monkeys who had learned to pair digits with dots activated distinct neuronal populations for each format. However, some of the digit-selective neurons did not demonstrate graded tuning curves; instead they fired only for a specific digit (Diester, personal communication). These non-magnitude representations are potential precursors to the development of automatic analog magnitude representations. Consistent with this proposal were results from a training study by Lyons and Ansari (2009) in which participants learned a pairing of arbitrary symbols with approximate magnitudes. Although the IPS was active both early and late in training, and distance effects grew more pronounced with experience, only late in training did activity in the IPS correlate with individual differences in the size of the distance effect.

Our view is also consistent with existing behavioral data, including those cited by CK&W. For example, among Japanese participants, digits and Kanji numbers, but not Kana scripts, showed interference from numerical magnitude on a font size discrimination task (Ito & Hatta 2004). Like number words, Kana scripts may not evoke an automatic analog magnitude representation. This is possibly because Kanji numbers elicit magnitude representations in their visual form more so than Kana scripts (Kanji number symbols begin with one, two, and three (horizontal) lines and have closer ideographic connection to numerosities than do Kana script). In this case, differential degrees of magnitude representation could be due to limited experience with Kana scripts in the context of number processing.

Context can influence magnitude representations, even within formats. For example, adults in the Mundurucu tribe produce behavior consistent with a compressed analog magnitude (i.e., logarithmic) for dot displays. Within verbal number words, Mundurucu words evoked logarithmic representations, whereas Portuguese words evoked linear representations (Dehaene et al. 2008). Grade-school-aged children have both linear and logarithmic representations on the same stimuli depending on whether they were in a 0–100 range or a 0–1000 range (Siegler & Opfer 2003). How these behaviors are represented in the brain is currently unknown, but we suggest that this involves more than the IPS – they are likely to depend on the context-dependent interaction of the IPS with the ventral visual stream and the prefrontal cortex (Wu et al. in press).

How can we disambiguate the view that different neuronal populations encode different formats with the same magnitudebased organization, from the idea that different populations have dissimilar analog-magnitude representations that are contextand experience-dependent? Longitudinal developmental research and learning paradigms, such as Lyons and Ansari (2009), could go a long way towards clarifying such questions. CK&Wnote that null effects have been over-interpreted as evidence of notation dependence – many studies may, in fact, have been grossly underpowered to detect notation-specific effects. Increasing sample sizes, particularly in imaging studies, would be a simple way to increase detection and improve interpretability and generalizability of research findings. Finally, feature selection and classification algorithms, which search for consistent patterns of activation between conditions, could potentially uncover differences between formats that would not be manifest in differences in overall levels of activation (Ryali & Menon 2009).

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