

Response to Leibovich, Katzin, Harel, & Henik (in press)

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What is the precise role of cognitive control in the development of a sense of number?

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### Abstract

The theory put forward by Leibovich and colleagues of how children acquire a sense of number does not specify the mechanisms through which cognitive control plays a role in this process. We argue that visual attention and number word knowledge influence each other over development and contribute to the development of the concept of number.

We concur with Leibovich and colleagues' central claim that a 'sense of number' is acquired, rather than innate. An important question for future research is therefore *how* this sense of number is acquired over development. In their theoretical model of the development of the number concept, the authors proposed that domain-general cognitive abilities, such as language (specifically the acquisition of number words) and cognitive control (particularly inhibitory processes) are important for learning about number. However, they did not specify the mechanisms through which this learning occurs. We argue that considering cognitive control to be domain-general is problematic, as control does not operate in isolation, but instead acts in conjunction with relevant domain-specific knowledge that is in and of itself accruing over time (e.g., Amso & Scerif, 2015; Johnson, 2011). We agree with Leibovich et al. that determining the role of cognitive control in the development of the number concept is complicated by the fact that cognitive control is multi-componential. Here, we focus on two aspects of cognitive control: 1) top-down executive control of attention, and 2) bottom-up saliency driven attention orienting. The two interact with each other, as well as with perception and memory, over development (Amso & Scerif, 2015). In this commentary, we propose that the interaction between the development of selective attention to nonsymbolic numerosity and the acquisition of the meaning of number words in early childhood contribute to the development of the concept of number.

The theory that nonsymbolic representations of numerosity precede, and thus may scaffold the acquisition of, symbolic representations of number has been biased by the assumption that number sense is innate (Feigenson, Dehaene, and Spelke 2004). Leibovich et al.'s rejection of this assumption allows us to consider that the causal mechanism underlying this relationship could go in the opposite direction. Acquiring number knowledge may exert a top-down influence on perception of nonsymbolic numerosity. Leibovich et al. mentioned the possibility that learning number words may help children separate discrete numerosity from continuous quantity (Mix, Levine, & Newcombe, 2016). Specifically, "because count words name the property of number, they could be potent attention-directing cues" (Mix et al., 2016, p. 20). Children are typically thought to understand the meaning of number words once they have learned the cardinality principle, which is that the last number word used when counting a set indicates the number of objects in the set. There is evidence that perception of nonsymbolic numerosity differs between young children who have acquired the cardinality principle and children who have not (Negen & Sarnecka 2014; Slusser & Sarnecka, 2011). Specifically, 2-6-year-old children who had not yet acquired the cardinality principle failed to choose the more numerous of two nonsymbolic arrays when discrete number conflicted with continuous quantity, whereas children who had acquired the cardinality principle succeeded (Negen & Sarnecka, 2014). Furthermore, in another study, 2-4-year olds were asked to sort cards depicting arrays of objects that varied along the dimensions of colour, shape, and numerosity, and all children successfully sorted by colour and shape. However, only children who knew the cardinality principle accurately sorted cards based on the number of objects in the arrays (Slusser & Sarnecka, 2011). This suggests that once children learn the meaning of number words, as evidenced by their grasp of cardinality, they develop a better attentional template for discrete numerosity. However, as the existing evidence is correlational, the direction of the

relationship between learning the cardinality of numerical symbols and processing the numerosity of nonsymbolic arrays remains unclear.

An alternative to the suggestion that a nonsymbolic number sense per se fosters symbolic understanding is that certain properties of nonsymbolic arrays increase the bottom-up saliency of discrete numerosity, and that this could in turn influence the development of understanding the cardinality of number symbols. For example, young children are more likely to use discrete number to make magnitude judgments for sets smaller than four than for larger sets (Cantrell, Kuwabara, & Smith, 2015). Constraints of visual attention could explain this discrepancy in magnitude judgments across set sizes: four is the maximum number of objects that can be attended to in parallel (Trick & Pylyshyn, 1994). Thus, arrays of up to four objects can be enumerated quickly and accurately, known as subitizing (Kaufman & Lord, 1949). Leibovich et al., argued that subitizing was not relevant to their theoretical proposal as most studies discussed focused on nonsymbolic magnitudes outside of the subitizing range. However, they ignored the possibility that the ability to attend to individual items in parallel may play a role in learning to select discrete numerosity separately from non-numerical magnitude. Indeed, Carey (2001) proposed that children map number words up to four onto representations of nonsymbolic quantity of small sets. Therefore, bottom-up attention to numerosity could enable learning the initial meaning of number words.

A third, and we believe more likely, possibility is that that an interaction between bottom-up and top-down attention (guided by relevant number knowledge) scaffolds children's acquisition of the number concept. Such a perspective could resolve the debate on whether efficient processing of approximate nonsymbolic number is a cause or a consequence of the understanding of cardinality. Slusser and Sarnecka suggested, "children's understanding of the cardinality principle (...) *is the same thing as* their understanding that number words pick out numerosities" (2011, p. 9). Therefore, once children understand that the word five refers specifically to five objects, rather than the overall area they subtend, they have learned to select numerosity as a relevant stimulus dimension and come to understand that two sets of five objects are related based on their numerosity. This suggests that the salience of numerosity does not precede the ability to voluntarily select it, but rather that they influence each other bi-directionally.

In conclusion, future research should investigate learning mechanisms underlying the acquisition of a sense of number. Rather than studying cognitive processes in isolation, interactions between perception, attention, and number knowledge should be investigated. Furthermore, gaining a better understanding of developmental learning mechanisms necessitates testing bi-directional hypotheses and moving beyond correlational, cross-sectional approaches.

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