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Hysteresis-induced changes in preverbal infants' approximate number precision

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ABSTRACT

Infants represent the approximate number of items in visual and auditory arrays. These number representations are noisy: for example, whereas 6-month-olds discriminate numerosities that differ by a 1:2 ratio (e.g., 8 vs. 16 dots), they fail to discriminate a 2:3 ratio (e.g., 8 vs. 12 dots) until 9 months old. How should we understand the nature of the representations underlying this performance? One possibility is that the precision of approximate number representations is fixed at a given age; alternatively, precision may be dynamic and context dependent. Here we asked whether one aspect of context—prior numerical experience—influences preverbal approximate number precision. We familiarized 6-month-old infants with pairs of images containing different numerosities. Critically, as trials progressed, the ratio of the two numerosities within each pair also gradually progressed– either from highly discriminable ratios to ratios that became harder to discriminate, or vice versa. After this ordered numerical training, we tested infants' ability to discriminate numerosities differing by a challenging 2:3 ratio, with which infants of this age typically fail. In three experiments, we found that 6-month-old infants successfully discriminated the 2:3 ratio after starting with easy ratios and progressing to hard ones, but not after starting with hard ratios and progressing to easy ones, despite experiencing identical numerosities across these two conditions. This "numerical hysteresis" effect was feedback-dependent: infants only succeeded with the scaffolded training when they received trial-by-trial feedback. Together, these results provide evidence for a temporary modulation of infants' number sense.

1. Introduction

Preverbal infants have an intuitive sense of number. For example, 6-month-old infants who are habituated to arrays of eight dots (or sounds) dishabituate when later shown 16, and vice versa (Lipton & Spelke, 2003; Xu & Spelke, 2000). When presented with two streams of images, one repeatedly showing images of 8 dots, the other alternating between 8 and 16 dots, 6-month-old infants look longer at the numerically changing stream than the numerically constant stream (Libertus & Brannon, 2010). These findings and others, which obtain when controlling for non-numerical stimulus dimensions such as cumulative surface area, individual dot size, and array density, show that 6-month-olds represent the numerical difference between, for example, 8 and 16.

This ability to discriminate numerosities without verbally counting is underwritten by the Approximate Number System, or ANS (Dehaene, 1997; Feigenson, Dehaene, & Spelke, 2004), a hallmark feature of which is ratio-dependence. That is, the discriminability of two numerosities represented by the ANS depends on the numerosities' ratio. Six-month-old infants exhibit this classic

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performance signature—they reliably discriminate 8 dots from 16, and 16 from 32 (a 1:2 ratio), but under the same testing conditions they fail to discriminate 8 from 12 or 16 from 24 (a 2:3 ratio) (Feigenson, 2011; Libertus & Brannon, 2010; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). This ratio-dependence does not reflect visual limitations, as 6-month-olds show the same precision when presented with auditory sequences (Lipton & Spelke, 2003). Notably, ANS precision improves over development. Whereas 6-month-old infants fail to discriminate numerosities that differ by a 2:3 ratio, at 9 months of age they succeed in both the visual and auditory modalities (Libertus & Brannon, 2010; Lipton & Spelke, 2003; Xu & Arriaga, 2007). This improvement in ANS precision continues throughout childhood, with precision eventually peaking in early adulthood (Halberda & Feigenson, 2008; Halberda, Ly, Wilmer, Naiman, & Germine, 2012; Odic, Libertus, Feigenson, & Halberda, 2013), although individual differences in precision are observed across development (Halberda, Mazzocco, & Feigenson, 2008; Libertus & Brannon, 2010; Starr, Libertus, & Brannon, 2013).

How should we understand the nature of approximate number precision? Current views of the ANS suggest that a stimulus (e.g., 16 dots) will, if presented repeatedly, trigger a range of mental activations that form a distribution with some mean (e.g., at approximately 16) and standard deviation. It is this standard deviation (i.e., representational noisiness) of the distribution of activations that is thought to change with development, and that varies between individuals. This conceptualization often assumes ANS precision to be relatively fixed for a given person, or for a given age group. Yet some evidence suggests that ANS precision is more dynamic than this.

One piece of support for dynamic ANS precision comes from the enhancing effects of redundant information. In one study, researchers compared infants' ability to discriminate the numerosities of stimuli that were synchronously presented in two sensory modalities (a ball seen to bounce varying numbers of times, and that made a sound each time it bounced) with their ability when the same stimulus was presented only visually. Whereas 6-month-old infants failed to discriminate numerosities differing by a 2:3 ratio when stimuli contained only visual numerical information (as in previous work that also used a single modality), infants succeeded when presented with synchronous visual and auditory input (Jordan, Suanda, & Brannon, 2008). Further work found that even multiple sources of information from a single sensory modality can benefit numerical performance. Baker, Mahamane, & Jordan, 2014 observed that after habituating to a ball of a constant size bouncing a constant number of times, 6-month old infants dishabituated to a ball of a novel size, bouncing a novel number of times (i.e., infants detected a change in numerosity that was confounded with a change in object area), even with a challenging 2:3 ratio, despite failing to detect a 2:3 change in numerosity or surface area alone.

A second line of evidence for the dynamic nature of ANS precision comes from studies that borrowed an approach from dynamical psychophysics to ask whether trial order affects numerical discrimination (Odic, Hock, & Halberda, 2014; Wang, Odic, Halberda, & Feigenson, 2016). Five-year-old children saw two arrays of dots and had to decide which array had more without counting. Some of the trials contained ratios that were easily discriminable (e.g., 5 blue dots versus 10 yellow); others contained ratios that were much more difficult (e.g., 9 blue dots versus 10 yellow). Instead of ratio difficulty varying randomly across trials, as in previous studies using this method, difficulty changed systematically as the task unfolded. Some children started with the easiest ratios (e.g., 1:2) and gradually moved to the hardest ones (e.g., 9:10), whereas others started with the hardest ratios and gradually moved to the easiest ones. All children received trial-by-trial feedback telling them whether their choices were correct. In this task, children who started with the easier ratios performed significantly better than children who started with the harder ratios, despite all children ultimately completing the same number of trials at each ratio, and all other aspects of the presentation being identical (Odic et al., 2014; Wang et al., 2016). Notably, even when the feedback was reversed (i.e., when correct responses triggered negative auditory feedback, and incorrect responses triggered positive feedback), children who first experienced the easier ratios exhibited improved ANS precision. However, when feedback was removed altogether, the effect disappeared (Odic et al., 2014). These findings suggest that the recent history of one's ANS discriminations affects representational precision—a phenomenon termed "ANS hysteresis," following the dynamical psychophysics literature.

Can recent ANS experience also produce precision shifts in infants? One reason to be doubtful is that ANS hysteresis might rely on conscious, top down cognition. For example, a possible interpretation of the findings of Odic et al. (2014) and Wang et al. (2016) is that receiving feedback changed the way children felt about their own ability to perform the task. Children who began with easier discriminations (and who therefore started the task with more positive feedback) might have felt more confident and positive ("I'm pretty good at this game!"), and hence could have been more motivated or attentive than children who began with harder discriminations. The disappearance of ANS hysteresis without feedback is consistent with this view. Although Odic et al. (2014) found that "reversed feedback" still increased ANS performance in children who started with easier numerical ratios, it is conceivable that children recognized the feedback as reversed and discounted or mentally un-reversed it. One way to test whether self-perception caused the ANS hysteresis effect is to test preverbal babies, who have a less developed sense of their own task competence. If a conscious sense of self-efficacy underlies ANS hysteresis, then the effect should not obtain with infants.

A second reason to ask whether ANS hysteresis is observed in infants is to better understand the conditions under which ANS precision is malleable. Jordan and colleagues found that 6-month-olds showed enhanced precision when multiple sources of quantity information were available (e.g., when habituation and test stimuli differed in both visual and auditory numerosity, or in both visual numerosity and surface area) (Baker et al., 2014; Jordan et al., 2008). But numerical information often is only available from a single sensory modality—for example, a distant flock of birds can be visually enumerated, but is likely to be silent. And approximate number can be represented in the absence of any correlated visual features like area (e.g., estimating the number of ideas proposed in a meeting). These issues led us to ask whether, early in life, ANS precision still can be changed when intersensory information is unavailable, and when numerosity changes are unconfounded from changes in continuous dimensions.

In the present study we asked whether numerical precision is modulated by infants' prior history of numerical discrimination. Infants saw two screens on which dot arrays were continuously flashed. On one screen, the numerosity of the arrays remained