Received: 8 May 2020 | Accepted: 29 September 2020

DOI: 10.1111/infa.12373

INFANCY THE OFFICIAL JOURNAL OF THE INTERNATIONAL CONGRESS OF INFANT STUDIES WILEY

RESEARCH ARTICLE

Dynamic changes in numerical acuity in 4-month-old infants

Jinjing (Jenny) Wang[1,2] | **Lisa Feigenson**[1]

[1]Department of Psychological and Brain Sciences, Johns Hopkins University, Baltimore, MD, USA

[2]Department of Psychology, Rutgers University, New Brunswick, NJ, USA

Correspondence
Jinjing (Jenny) Wang, Department of Psychology, Rutgers University, 152 Frelinghuysen Road, Piscataway, NJ 08854-8020.
Email: jinjing.jenny.wang@rutgers.edu

Funding information
NIH, Grant/Award Number: R01 HD057258

Abstract

Preverbal infants represent the approximate numerosity of visual and auditory arrays: By 6 months old, they reliably discriminate eight dots or tones from 16 (a 1:2 ratio), but not eight from 12 (a 2:3 ratio). The precision of this approximate number sense improves gradually over childhood and into adulthood. However, less is known about numerical abilities in younger infants, and in particular, whether there is developmental change in the number sense in the first half year of life. Here, in four experiments, we measured numerical precision in 4-month-old infants ($N = 128$) using a visual habituation task comparable to that in studies of older infants. We found that 4-month-olds exhibited poorer numerical discrimination than the 6-month-olds tested in previous studies, dishabituating to a 1:4 change in numerical ratio, but not a 1:3 change. Like older infants, 4-month-olds' numerical precision improved when they were provided with redundant visual and auditory input; when both visual and auditory information were present, 4-month-olds discriminated a 1:3 but not a 1:2 ratio. These results suggest that Approximate Number System precision develops in early infancy and may be sensitive to intersensory redundancy as early as four months of age.

KEYWORDS

Approximate Number System, cognitive development, infants, intersensory redundancy, numerical cognition

1 | INTRODUCTION

Long before learning to count, children have an intuitive sense of quantity that allows them to estimate numerosities. The Approximate Number System that supports these "gut-sense" intuitions represents numbers as noisy analog magnitudes whose standard deviations increase with the size of the quantity being represented (Dehaene, 1997; Feigenson et al., 2004; Piazza et al., 2004; Whalen et al., 1999). This results in ratio-dependent performance in numerical tasks, such as deciding which of two arrays is more numerous without counting; for example, both adults and children make more errors when quickly comparing 18 versus 20 dots than 10 versus 20 dots (e.g., Halberda & Feigenson, 2008; Moyer & Laudauer, 1967). And although numerate humans who learn counting and basic mathematics also come to represent number precisely (Feigenson et al., 2004), people retain the use of the ANS throughout life (e.g., Cantlon & Brannon, 2006), even in cultures that lack formal mathematics education or an elaborated verbal counting routine (Gordon, 2004; Pica et al., 2004).

One notable feature of the ANS is that although in humans it is present at birth (Izard et al., 2009), it also exhibits marked developmental change. ANS precision increases between the ages of 3 and 6 years (Halberda & Feigenson, 2008; Odic et al., 2013) and peaks in adulthood, after which it gradually declines (Halberda et al., 2012). Some of this sharpening of ANS representations appears to be driven by experience with counting and formal mathematics. Adults with more math education outperform those with less on simple non-verbal numerical approximation tasks in both western and indigenous cultures (Lindskog et al., 2014; Piazza et al., 2013). Among children, early symbolic number understanding predicts later numerical approximation performance (Elliott et al., 2019; Lyons et al., 2018; Mussolin et al., 2014), and children exhibit gains in ANS precision when they master the meanings of the number words (Shusterman et al., 2016). Such findings suggest that experience thinking about number—especially with the use of external symbol systems to represent precise quantities—may fine-tune the developmentally primitive representations of the ANS.

However, the ANS also exhibits change that appears to be independent of exposure to counting or mathematics training, in that precision increases well before such experience begins. Whereas 6-month-old infants discriminate 1:2 numerical ratios (e.g., arrays of 8 vs. 16 dots), and fail, under the same conditions, to discriminate 2:3 ratios (Xu & Spelke, 2000), by 9 to 10 months of age, infants can discriminate 2:3 ratios but fail with 4:5 (Lipton & Spelke, 2003; Xu & Arriaga, 2007; Xu & Spelke, 2000).

Thus, developmental change in ANS representations begins early—but how early? Although few published studies have examined the characteristics of the ANS prior to 6 months of age,[1] two seminal reports found that newborn infants looked longer at visual arrays that matched the approximate number of syllables in an auditory sequence (Coubart et al., 2014; Izard et al., 2009). In those studies, infants significantly preferred numerically matching arrays over arrays that mismatched by a 1:3 ratio (e.g., they looked longer at four shapes when hearing four syllables compared to 12 syllables and looked longer at six shapes when hearing six compared to 18) and showed a marginally significant preference for matching arrays over arrays that mismatched by a 1:2 ratio (e.g., looking longer at four when hearing four compared to eight). Similarly, newborn infants detected a 1:3 ratio auditory numerical change when accompanied with a 1:3 ratio visual length change (de Hevia et al., 2014). These findings show, critically, that the ANS is functional in newborn humans. With respect to the question of early developmental change, one might be tempted to conclude that ANS precision remains fairly constant between zero and 6 months—integrating the results from newborns with those from older

[1]Here, we focus on work that investigates infants' representations of approximate number, as opposed to work on infants' ability to precisely represent one, two, or three individual objects, as this latter ability appears to rely on a separate representational system (e.g., Feigenson et al., 2004; Hyde & Spelke, 2011; Xu, 2003).

infants, it would appear that newborns can discriminate arrays differing by a 1:3 numerical ratio and potentially even a 1:2 ratio (Coubart et al., 2014; Izard et al., 2009), just shy of the precision shown at 6 months across a range of paradigms (including violation of expectation, visual change detection, and visual habituation: Feigenson, 2011; Libertus & Brannon, 2010; Wood & Spelke, 2005; Xu & Spelke, 2000).

However, this interpolation does not offer a fair comparison, due to methodological differences between the studies with newborns and those with older infants. Whereas 6- to 10-month-olds have mostly been tested with unimodal arrays presenting either visual or auditory information (Libertus & Brannon, 2010; Lipton & Spelke, 2003; Xu & Arriaga, 2007; Xu & Spelke, 2000) or were induced to establish a visual expectation from separately presented auditory information (Feigenson, 2011), the studies with newborns involved intersensory redundancy (or cross-magnitude redundancy, in the case of de Hevia et al., 2014). Newborns saw visual arrays (with all items presented simultaneously) while they heard auditory sequences of varying numerosity, or, in other work, experienced simultaneous congruent changes in numerosity and length. Such redundancies across modalities or magnitude dimensions have been shown to enhance the precision of ANS representations: For example, 6-month-olds who failed to discriminate visual arrays differing by a 2:3 numerical ratio succeeded when presented with synchronous visual and auditory input (Jordan et al., 2008). And Baker et al. (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 (see also de Hevia et al., 2014). Therefore, it remains unclear whether newborns' approximate number performance was accelerated by the redundancies they experienced—in which case ANS precision may indeed undergo significant developmental improvement prior to 6 months—or whether newborns were too young to experience this type of ANS sharpening, in which case ANS precision may be more stable early in life.

One other series of studies examined approximate number abilities in children younger than 6 months. de Hevia et al. (2017) asked whether 4-month-old infants can encode the ordinal information in sequences of numerosities. They found that after being habituated to numerically ascending arrays (e.g., seeing 4, then 12, then 36 shapes), infants successfully dishabituated to numerically descending arrays, but only when the numerosities within the sequences differed by a 1:3 ratio. With a 1:2 ratio (e.g., 6, then 12, then 24 shapes), infants failed (and interestingly, infants who were habituated to descending sequences failed to respond to a change in ordinal direction, even with the easier 1:3 ratio; de Hevia et al., 2017). Again, though, methodological differences between this study and work with older infants make it difficult to draw conclusions regarding developmental change. The 4-month-olds in de Hevia et al.'s study had to detect a reversal of ordinal direction, rather than represent any particular approximate cardinality—potentially making their task easier than the habituation tasks used with older infants. On the other hand, these 4-month-olds saw sequences of briefly flashed arrays, rather than receiving much longer viewings of static arrays—potentially making de Hevia's task harder than the habituation tasks. Because of these task differences, no existing data enable a fair comparison between the numerical precision of 6-month-olds and that of younger infants.

In the current study, we addressed the question of early developmental change in the Approximate Number System by examining numerical performance in infants younger than 6 months. We had two aims. The first was to determine the numerical ratio with which 4-month-old infants can perform successful numerical discriminations with unimodal stimuli. The second was to ask whether numerical precision responds dynamically to changes in input prior to 6 months—that is, whether the nature of the stimuli can sharpen young infants' numerical precision. Because to our knowledge 4-month-old infants have not been tested using numerical habituation, we began with what we anticipated would be an easy-to-discriminate numerical ratio of 1:4. In Experiment 1, we habituated 4-month-old infants to a constant number of visual items (either 6 or 24) and then compared their looking at arrays containing the habituated number versus a novel number (6 vs. 24). We found that infants successfully discriminated this 1:4 numerical ratio with unimodal visual stimuli, so in Experiment 2 we tested another group of infants with a harder 1:3 ratio (6 vs. 18 items), again using unimodal stimuli. We found that infants failed to respond to this less discriminable numerical change. To ask whether infants as young as 4-months experience increases in ANS precision as a result of input change, in Experiment 3 we asked whether 4-month-old infants can successfully discriminate a 1:3 ratio when provided with synchronous visual and auditory numerical input. These infants succeeded, so in our last experiment we probed the limits of 4-month-olds' dynamic numerical improvement, testing infants with a harder 1:2 ratio.

2 | EXPERIMENT 1: VISUAL DISCRIMINATION OF A 1:4 NUMERICAL RATIO BY 4-MONTH-OLD INFANTS

2.1 | Method

2.1.1 | Participants

Thirty-two full-term 4-month-old infants (mean age 4 months 2 days, *SD* = 9 days; 18 girls) participated. Since no previous published studies have examined 4-month-old infants' visual discrimination using a habituation paradigm, we conducted a power analysis assuming a medium effect size (0.25), with an alpha level of 0.05. This showed that a sample of 32 provided 80% power to detect a difference in responses to novel versus familiar numerosity stimuli. Six additional infants were tested but excluded from the sample because of fussiness (4) or experimenter error (2). Infants in this and all of the other experiments in this series were reported to be healthy by their parents or caregivers. Infants received a small gift (e.g., book, toy, t-shirt) to thank them for their participation.

The study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from a parent or legal guardian for each child before any assessment or data collection. All procedures were approved by the Institutional Review Board at the Johns Hopkins University.

2.1.2 | Design and stimuli

Infants were habituated to displays of either six or 24 yellow cartoon smiley faces that varied in spatial position across trials (Figure 1). We used schematic face stimuli based on previous studies of infants' numerical processing (e.g., Cordes & Brannon, 2009; Feigenson, 2011; Izard et al., 2009). Across habituation trials, the overall envelope of the stimuli (15.5 cm × 17 cm) and individual item size remained constant, such that total cumulative stimulus area, density, and luminance were constant throughout habituation. Each item in the six-item arrays measured 2.7 cm in diameter, and in the 24-item arrays measured 1.35 cm in diameter. Following habituation, infants were presented with six test trials that alternated between six and 24 items. All of the test stimuli were 1.9 cm in diameter. The overall envelope of the stimuli was 7 cm × 9.5 cm for the six-item array and 14 cm × 19 cm for the 24-item array. As such, density was identical across test trials and was equidistant from that seen during

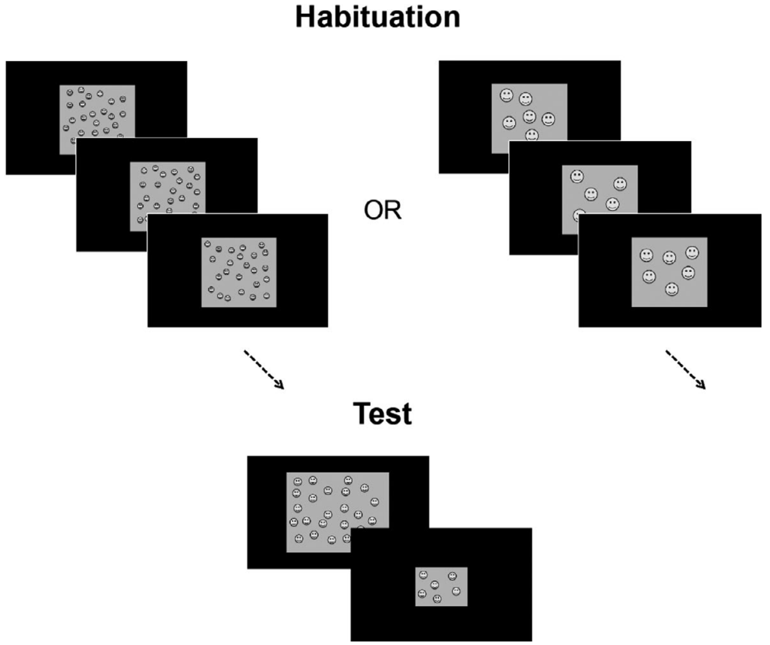

FIGURE 1 Example habituation and test displays in Experiment 1, in which arrays differed by a 1:4 numerical ratio

habituation, and the cumulative area in the six and 24 item test arrays (17 vs. 68 cm^2) was equidistant from that seen during habituation (34 cm^2). Whether infants were habituated to six or 24 items and whether six or 24 was shown first during test were counterbalanced across participants.

2.1.3 | Apparatus and procedure

Infants sat on a caregiver's lap approximately 100 cm from a 17-inch computer monitor. Caregivers were instructed to look at the back of infants' heads or to close their eyes. An experimenter stood behind the monitor, concealed by a curtain, where she could see infants' faces on a separate hidden screen but could not see the stimuli.

Each trial began with the onset of the stimulus array, accompanied by a ringing sound to attract infants' attention. A minimum look of 0.5 s was required to start each trial, which continued until infants looked away for consecutive 2 s or had looked for a maximum of 60 s. The standard criterion was used to determine when infants had habituated (e.g., Xu & Spelke, 2000). Habituation was reached when infants' average looking time over three consecutive habituation trials was less than half of their average looking during the first three habituation trials. If this criterion was not met, a maximum of 14 habituation trials were presented. Immediately following habituation, infants were presented with six test trials that alternated between six and 24 items.

Infants' looking was coded live by an experienced observer in another room who was watching on a monitor; the observer remotely signaled the experimenter when the looking criteria had been met (i.e., when each trial ended, and when habituation had been reached). Looking was later coded off-line by a separate observer, blind to experimental condition, to ensure accuracy. Inter-coder reliability was over 95%.

2.2 | Results

Twenty out of 32 infants reached the habituation criterion, showing a significant decline in visual interest over the course of habituation. A repeated-measures ANOVA with Test Trial Type (novel or familiar numerosity) and Test Pair (1st, 2nd, 3rd) as within-subject factors and Habituation Number (larger or smaller numerosity) and First Test Trial (novel or familiar numerosity) as between-subject factors revealed a significant effect of Trial Type, $F(1, 28) = 9.55$, $p = .004$, $\eta_p^2 = .25$, a significant Trial Type × Test Pair interaction, $F(2, 56) = 6.09$, $p = .004$, $\eta_p^2 = .18$, and no other significant effects, Fs < 1.6, ps $> .23$. At test, infants looked longer at the novel numerosity arrays ($M = 7.00$ s, $SD = 4.52$ s) than familiar numerosity arrays ($M = 5.05$ s, $SD = 2.60$ s), $t(31) = 3.18$, $p = .003$, *Cohen's* $d = .56$. Post hoc pairwise comparisons revealed significant difference between the novel and familiar numerosities in the first test pair, $p < .001$, and no difference in looking during the second or third test pairs (ps $> .88$). All post hoc analyses were conducted with Bonferroni correction. Collapsing across all trial pairs, 23 out of 32 infants looked longer at the novel than the familiar numerosity arrays (exact binomial test, $p = .02$).

This pattern also obtained when analyzing only the data from the 20 infants who reached the habituation criterion. A repeated-measures ANOVA with Test Trial Type (novel or familiar numerosity) and Test Pair (1st, 2nd, 3rd) as within-subject factors and Habituation Number (larger or smaller numerosity) and First Test Trial (novel or familiar numerosity) as between-subject factors revealed a significant effect of Trial Type, $F(1, 16) = 7.64$, $p = .01$, $\eta_p^2 = .32$, a significant Trial Type × Test Pair interaction, $F(2, 32)=3.95$, $p = .03$, $\eta_p^2 = .20$, and no other significant effects, Fs < 2.9, ps $> .15$. Post hoc pairwise comparisons revealed a significant difference in the first test pair, $p = .01$, and no other significant effects (ps $> .51$). Fifteen out of these 20 infants looked longer at the novel numerosity than the familiar numerosity arrays (exact binomial test, $p = .04$; Figure 2).

3 | EXPERIMENT 2: VISUAL DISCRIMINATION OF A 1:3 NUMERICAL RATIO BY 4-MONTH-OLD INFANTS

3.1 | Method

3.1.1 | Participants

A new group of 32 full-term 4-month-old infants (mean age 4 months 5 days, $SD = 10$ days; 13 girls) participated. Five additional infants were tested but excluded from the sample because of fussiness.

3.1.2 | Design, stimuli, and procedure

All aspects were as in Experiment 1, except for the stimuli. Infants were habituated to arrays containing either six or 18 cartoon smiley faces, and then, all infants were tested with arrays of six and 18 faces in alternation. The habituation stimuli measured 2.7 cm in diameter (six-item arrays) or 1.55 cm in diameter (18-item arrays), and the test stimuli measured 2 cm in diameter. The envelope of the array was 13.5 cm × 4.7 cm in habituation, and 9.5 cm × 12.6 cm for the six-item test arrays and 16 cm × 21.7 cm for the 18-item test arrays.

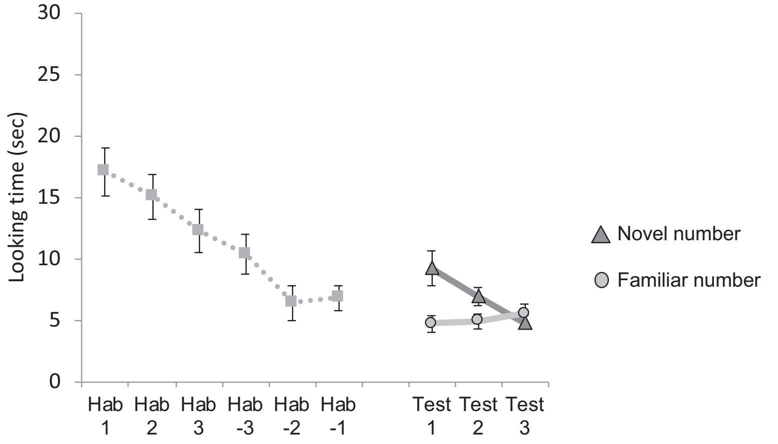

FIGURE 2 Mean looking times on the first and last three habituation trials and test trials in Experiment 1 (1:4 ratio; ±SEM)

3.2 | Results

Nineteen out of 32 infants reached the habituation criterion, showing a significant decline in visual interest over the course of habituation. A repeated-measures ANOVA with Test Trial Type (novel or familiar numerosity) and Test Pair (1st, 2nd, 3rd) as within-subject factors and Habituation Number (larger or smaller numerosity) and First Test Trial (novel or familiar numerosity) as between-subject factors revealed no significant effects, Fs < 2.5, ps $> .13$. At test, infants did not look longer at the novel numerosity arrays ($M = 4.81$ s, $SD = 3.62$ s) than familiar numerosity arrays ($M = 4.40$, $SD = 2.86$), $t(31) = 0.77$, $p = .45$, *Cohen's d* $= .14$. Only 18 out of 32 infants looked longer at the novel numerosity arrays (exact binomial test $p = .60$). Similarly, there were no significant effects when analyzing only the data from the 19 infants who reached the habituation criterion, all Fs < 1.6, ps $> .22$. Nine out of these 19 infants looked longer at the novel numerosity than the familiar numerosity arrays (exact binomial test, $p = 1$).

We compared infants' ability to discriminate 1:4 versus 1:3 numerical ratios using a repeated-measures ANOVA with Ratio Condition (1:4 in Experiment 1 or 1:3 in Experiment 2), Habituation Number (larger or smaller numerosity), and First Test Trial (novel or familiar numerosity) as between-subjects factors and Test Trial Type (novel or familiar numerosity) and Test Pair (1st, 2nd, 3rd) as within-subject factors. This revealed a marginally significant effect of Ratio Condition, $F(1,56) = 3.71$, $p = .06$, $\eta_p^2 = .06$, and a significant effect of Test Trial Type, $F(1,56) = 7.69$, $p = .008$, $\eta_p^2 = .12$. These effects were qualified by a significant Ratio × Test Trial Type × Test Pair interaction, $F(2,112) = 3.80$, $p = .03$, $\eta_p^2 = .06$. Consistent with previous analyses, infants in Experiment 1 who were tested with a 1:4 ratio discrimination showed a large preference for the novel numerosity on the first test trial pair (post hoc pairwise comparisons: $p < .001$ for the first test pair; $p > .88$ for the remaining test pairs), whereas infants in Experiment 2 who were tested with a 1:3 ratio discrimination showed no preferences (ps $= 1$). Taken together, these results suggest that 4-month-old infants show ratio-dependent performance when discriminating the numerosities in visual arrays, succeeding at detecting a 1:4 change but failing to detect a 1:3 change (Figure 3).

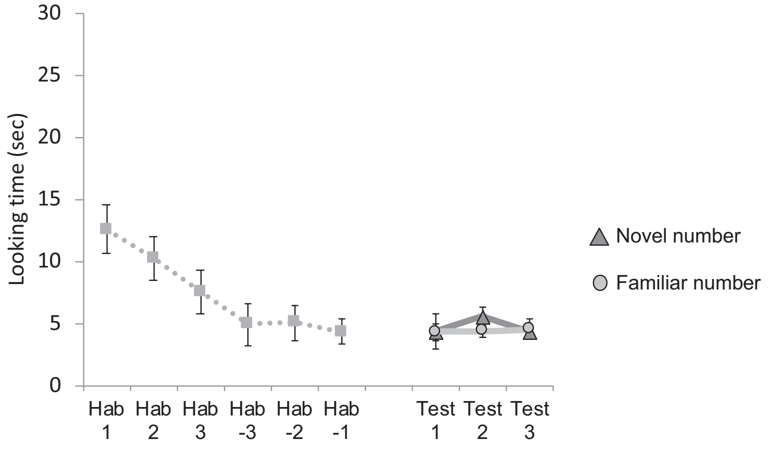

FIGURE 3 Mean looking times on the first and last three habituation trials and test trials in Experiment 2 (1:3 ratio; ±SEM)

3.3 | Discussion

The findings of Experiments 1 and 2, together with previous research, are consistent with the interpretation that ANS precision changes with development. When presented with visual arrays, 4-month-old infants successfully discriminate a 1:4 ratio (Experiment 1), but fail to discriminate a 1:3 ratio (Experiment 2), whereas 6-month-old infants successfully discriminate a harder, 1:2 ratio in the same habituation paradigm, when presented with unimodal visual stimuli (Xu & Spelke, 2000).

Why did the 4-month-old infants in Experiment 2 fail to discriminate a 1:3 numerical ratio, whereas the newborns tested by Coubart et al. (2014) and Izard et al. (2009) succeeded? One possibility, raised earlier, is that newborns in these previous studies experienced enhancement of ANS precision from the intersensory presentation of stimuli (i.e., accumulating an approximate representation of a given number of sounds, and simultaneously seeing that number of visual items), similar to the benefit observed in 6-month-olds in previous work (Jordan et al., 2008). To test the hypothesis that having redundant visual and auditory input affects the numerical precision of infants younger than 6 months, in Experiment 3 we asked whether 4-month-old infants can discriminate a 1:3 ratio when provided with synchronous visual and auditory numerical input.

4 | EXPERIMENT 3: VISUAL AND AUDITORY DISCRIMINATION OF A 1:3 NUMERICAL RATIO BY 4-MONTH-OLD INFANTS

4.1 | Method

4.1.1 | Participants

A new group of 32 full-term 4-month-old infants (mean age 4 months 4 days, *SD* = 7 days; 12 girls) participated. Nine additional infants were tested but excluded from the sample because of fussiness (8) or parental interference (1).

4.1.2 | Design, stimuli, and procedure

Infants were habituated to either six or 18 cartoon smiley faces, with visual controls for non-numerical continuous dimensions as in Experiment 2. However, unlike in Experiment 2, each stimulus item appeared sequentially, each accompanied by a chime sound. Non-numerical aspects of the auditory chime sequences were controlled for: individual chimes in the habituation sequences were identical in duration (250 ms) and density (two chimes per second); as such, numerosity and total sound duration (total length of the sound sequence) were confounded during habituation. In the test trials, the cumulative duration of the chimes (2,700 ms) and the total duration of the auditory sequence (5,400 ms) were each equated across the novel and familiar numerosity sequences. This ensured that infants could not rely on total sound duration or sound density (which were also equidistant from habituation) to discriminate the stimuli. Once each visual stimulus had appeared, it remained visible throughout the duration of the trial, and infants' looking was measured starting from the onset of the final stimulus. Whether the smaller or larger numerosity was presented during habituation and whether the familiar or the novel numerosity was presented first during the test trials were counterbalanced across participants.

4.2 | Results

Thirty-one out of 32 infants reached the habituation criterion, showing a significant decline in visual interest over the course of habituation. A repeated-measures ANOVA with Test Trial Type (novel or familiar numerosity) and Test Pair (1st, 2nd, 3rd) as within-subject factors and Habituation Number (larger or smaller numerosity) and First Test Trial (novel or familiar numerosity) as between-subject factors revealed a significant effect of Trial Type, $F(1, 28) = 17.39$, $p < .001$, $\eta_p^2 = .38$, and a significant Trial Type × Habituation Number × First Test Trial interaction, $F(1, 28) = 4.44$, $p = .04$, $\eta_p^2 = .14$. There were no other significant effects, Fs < 1.9, ps > .18. Post hoc pairwise comparisons revealed a significant difference between infants' looking at the novel versus the familiar numerosity among infants who had been habituated to the larger numerosity and were tested first on the familiar numerosity, $p = .046$. There were no other significant post hoc pairwise comparisons, ps > .15. At test, infants looked longer at the novel numerosity arrays ($M = 9.33$ s, $SD = 6.48$ s) than familiar numerosity arrays ($M = 5.10$ s, $SD = 4.31$ s), $t(31) = 4.17$, $p < .001$, Cohen's $d = .74$ (Figure 4). Twenty-seven out of 32 infants looked longer at the novel numerosity arrays (exact binomial test, $p < .001$). The same overall pattern was also obtained when analyzing only data from the 31 infants who reached the habituation criterion. The ANOVA yielded a significant effect of Trial Type, $F(1, 27) = 16.76$, $p < .001$, $\eta_p^2 = .38$, and a Trial Type × Habituation Number × First Test Trial interaction, $F(1, 27) = 4.38$, $p = .05$, $\eta_p^2 = .14$. Post hoc pairwise comparisons revealed a marginally significant difference between infants' looking at the novel versus the familiar numerosity among infants who had been habituated to the larger numerosity and were tested first on the familiar numerosity, $p = .07$. There were no other significant effects, ps > .17.

Next, we compared the results from the 1:3 ratio condition of Experiment 2 (visual information only) to those of Experiment 3 (synchronous visual and auditory information), to ask whether the presence of redundant sensory information significantly improved 4-month-old infants' ANS precision. A repeated-measures ANOVA with Experiment (2 or 3), Habituation Number (larger or smaller numerosity), and First Test Trial (novel or familiar numerosity) as between-subject factors and Test Trial Type (novel or familiar numerosity) as a within-subject factor revealed significant effects of Experiment, $F(1,56) = 7.05$, $p = .01$, $\eta_p^2 = .11$, and Test Trial Type, $F(1,56) = 15.56$, $p < .001$, $\eta_p^2 = .22$, qualified

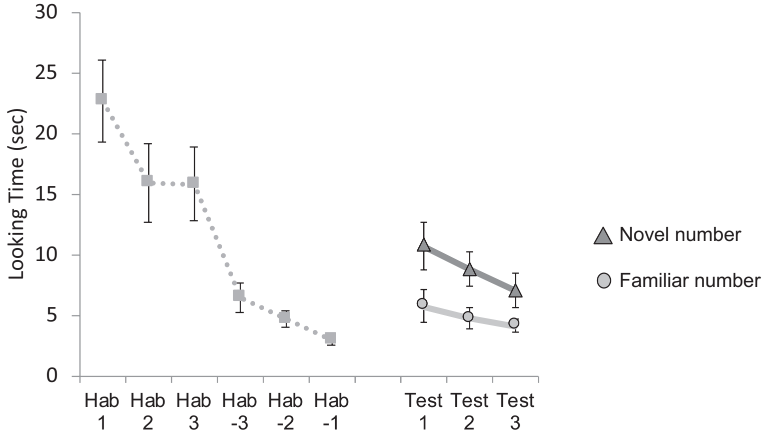

FIGURE 4 Mean looking times on the first and last three habituation trials and test trials in Experiment 3 (1:3 ratio with redundant sensory information; ±SEM)

by an Experiment × Test Trial Type interaction, $F(1,56) = 10.92$, $p = .002$, $\eta_p^2 = .16$. Consistent with previous analyses, infants looked longer at the novel numerosity arrays (which differed from the habituation arrays by a 1:3 numerical ratio), but only in Experiment 3, when presented with both visual and auditory numerical information (post hoc pairwise comparison between novel and familiar numerosities was $p = 1$ for Experiment 2, and $p < .001$ for Experiment 3).

5 | EXPERIMENT 4: VISUAL AND AUDITORY DISCRIMINATION OF A 1:2 NUMERICAL RATIO BY 4-MONTH-OLD INFANTS

How much does redundant sensory input improve ANS precision in 4-month-olds? To find out, we presented infants with a harder, 1:2 ratio discrimination using sequences containing both visual and auditory information.

5.1 | Method

5.1.1 | Participants

A new group of 32 full-term 4-month-old infants (mean age 4 months 2 days, *SD* = 10 days; 16 girls) participated. Seven additional infants were tested but excluded from the sample because of fussiness.

5.1.2 | Design, stimuli, and procedure

All aspects were as in Experiment 3, except for the stimuli. Infants were habituated to arrays containing either six or 12 cartoon smiley faces, and then, all infants were tested with arrays of six and 12 faces in alternation. The habituation stimuli measured 2.7 cm in diameter (six-item arrays) or 1.9 cm in diameter (12-item arrays), and the test stimuli were 2.3 cm in diameter. The envelope of the array was 15 cm × 14 cm in habituation, and 10.5 cm × 13.6 cm for the six-item test arrays and 15.7 cm × 19.1 cm for the 12-item test arrays. Individual chimes in the habituation sequences were identical in duration (320 ms) and density (two chimes per second). In the test trials, the cumulative duration of the chimes (2,700 ms) and the total duration of the auditory sequence (5,400 ms) were equated across the novel and familiar numerosity sequences.

5.2 | Results

Thirty out of 32 infants reached the habituation criterion, showing a significant decline in visual interest over the course of habituation. A repeated-measures ANOVA with Test Trial Type (novel or familiar numerosity) and Test Pair (1st, 2nd, 3rd) as within-subject factors and Habituation Number (larger or smaller numerosity) and First Test Trial (novel or familiar numerosity) as between-subject factors revealed a significant Trial Type × Test Pair × Habituation Number interaction, $F(2, 56) = 4.04$, $p = .03$, $\eta_p^2 = .13$, and no other significant effects, Fs < 2.8, ps $> .08$. Post hoc pairwise comparisons revealed a marginally significant difference in looking at the Novel numerosity on the first Test Pair versus the second Test Pair, $p = .08$, and no other significant effects, ps $= 1$. However, overall, infants did not look longer at the novel numerosity arrays ($M = 5.50$ s, $SD = 3.69$ s) than the familiar numerosity arrays (5.44 s, $SD = 7.39$ s), $t(31) = .04$, $p = .96$, *Cohen's* $d = .009$. Only 12 out of 32 infants looked longer at the novel numerosity arrays (exact binomial test $p = .22$). The same overall pattern obtained when analyzing only the data from the 30 infants who reached the habituation criterion. The ANOVA yielded a marginally significant Trial Type × Test Pair × Habituation Number interaction, $F(2, 52) = 3.35$, $p = .06$, $\eta_p^2 = .11$, and no other significant effects, Fs $< .1$, ps $> .07$.

We then compared infants' ability to discriminate 1:3 versus 1:2 numerical ratios when presented with intersensory arrays, using a repeated-measures ANOVA with Ratio Condition (1:3 in Experiment 3 or 1:2 in Experiment 4), Habituation Number (larger or smaller numerosity), and First Test Trial (novel or familiar numerosity) as between-subject factors and Test Trial Type (novel or familiar numerosity) and Test Pair (1st, 2nd, 3rd) as within-subject factors. This revealed a significant effect of Test Trial Type, $F(1,56) = 7.38$, $p = .009$, $\eta_p^2 = .12$, which was qualified by a significant Ratio × Test Trial Type interaction, $F(1,56) = 6.15$, $p = .02$, $\eta_p^2 = .10$. Consistent with previous analyses, infants looked longer at the novel numerosity in the 1:3 ratio condition ($p = .003$) but not the 1:2 ratio condition ($p = 1$), despite both containing redundant intersensory information (Figure 5).

6 | GENERAL DISCUSSION

In four experiments, we investigated numerical discrimination abilities in 4-month-old infants. We found that when presented with unimodal visual arrays, infants successfully discriminated six items from 24 (a 1:4 ratio) but failed to discriminate six items from 18 (a 1:3 ratio; Experiments 1 and 2). When presented with nearly identical displays accompanied by auditory sequences in which the onset of each visual item was synchronized with the onset of an auditory chime, 4-month-olds succeeded at discriminating the 1:3 ratio difference with which they had previously failed (Experiment 3). This addition of intersensory information appeared to improve infants' discrimination performance, up to a limit: 4-month-olds failed to discriminate a 1:2 ratio difference even with arrays containing visual and auditory information.

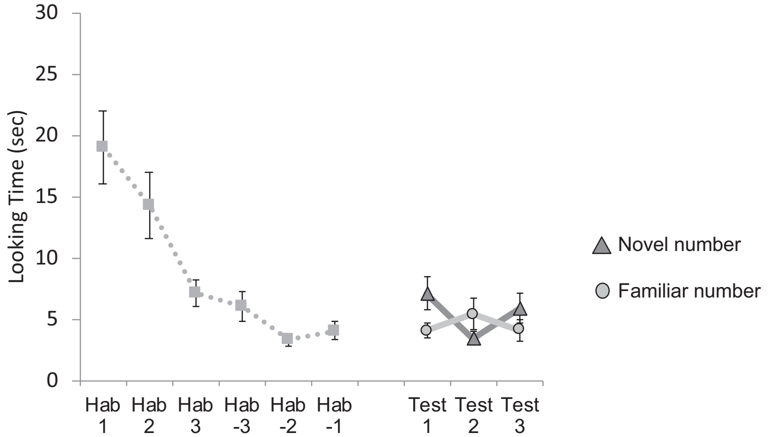

FIGURE 5 Mean looking times on the first and last three habituation trials and test trials in Experiment 4 (1:2 ratio with redundant sensory information; ±SEM)

Our results support the conclusion that ANS precision improves between 0 and 6 months of age. Whereas at 4-months infants appear to require a 1:4 numerical change to discriminate unimodal visual arrays, by 6 months they succeed with a 1:2 change (Feigenson, 2011; Libertus & Brannon, 2010; Wood & Spelke, 2005; Xu & Spelke, 2000). This suggests rapid tuning of numerical representations during infancy. However, it is less clear whether the ANS also sharpens between the ages of 0 and 4 months. When presented with visual and auditory input, both 4-month-olds and newborns can discriminate a 1:3 numerical ratio, but not a 1:2 ratio—suggesting that ANS precision might remain unchanged over this period.

Alternatively, it might be that we would observe developmental improvements in ANS precision between 0 and 4 months if other aspects of infants' tasks were equated. Even though both the current study and those by Coubart et al. (2014) and Izard et al. (2009) presented infants with intersensory visual and auditory stimuli, other aspects of testing were quite different. In particular, the crossmodal preference task used with newborns does not require building and maintaining a representation of numerosity across trials. Newborns must store in working memory a representation of the approximate number of sounds in an auditory sequence, but then can immediately compare that numerosity to each visual stimulus. In contrast, habituation studies like that used here (and in studies by Cordes & Brannon, 2009a, 2009b; Lipton & Spelke, 2003; Wood & Spelke, 2005; Xu, 2003; Xu & Arriaga, 2007; Xu & Spelke, 2000) exert greater demands on memory. Infants must maintain a representation of the habituation numerosity for the several minutes of the habituation phase, in order to mentally compare it to the test arrays. To compare ANS precision in newborns and older infants, future work either should test newborn infants in a habituation task (for a related method, see de Hevia et al., 2014), or should test older infants in a crossmodal visual preference task so that the results can be compared with those of Izard et al. (2009).

Importantly, combined with those of previous investigations, our results provide evidence that while individual differences in the precision of the Approximate Number System are stable over development (Elliott et al., 2019; Libertus & Brannon, 2010; Libertus et al., 2013; Starr et al., 2013), the ANS of a given individual at a given age is more dynamic than previously construed. Even for infants, whose number representations are relatively coarse, and for whom obtaining an exact measure of ANS precision is challenging, numerical performance depends on the nature of the experienced input. ANS discriminations are affected by intersensory redundancy (Jordan et al., 2008), the presence of congruent changes across disparate magnitude dimensions (Baker et al., 2014; de Hevia et al., 2014), recent history making numerical discriminations (Wang et al., 2018), and even experience with verbal counting routines (Wang & Feigenson, 2019). Thus, rather than having fixed precision, the ANS appears to output representations that fluctuate dynamically.

So which aspect of the stimuli improved infants' performance in the present studies? Based on previous findings that intersensory redundancy enhances numerical discrimination in 6-month-old infants (Jordan et al., 2008), we designed Experiments 3 and 4 to provide 4-month-old infants with synchronous auditory and visual numerical information and found that these infants successfully discriminated a 1:3 ratio with which they had failed when only visual information was available. As such, our results are consistent with previous work showing the effects of intersensory information on infants' processing, both in tasks involving numerosity (Jordan et al., 2008) and in other domains (e.g., Bahrick & Lickliter, 2000; Kirkham et al., 2012). However, our Experiments 2 and 3 also differed from each other in other respects. First, the stimuli in Experiment 2 were presented simultaneously, in that the entire array appeared at once. In contrast, the stimuli in Experiment 3 initially were presented sequentially (each item appeared on-screen in sequence) and then were available simultaneously (each item remained visible after it appeared, such that eventually the whole set was visible).[2] Therefore, infants might have performed better in Experiment 3 than Experiment 2 because they have better numerical precision for sequential arrays than simultaneous ones—or have better precision for auditory arrays than visual ones. Our study cannot rule out these interpretations, because we did not present infants with a silent version of the stimuli in Experiment 3. However, previous studies found that adults have similar numerical precision for simultaneous and sequential arrays (Barth et al., 2003) and that 6-month-old infants exhibit the same numerical precision for simultaneous visual arrays (e.g., Xu & Spelke, 2000) as for sequential visual (Wood & Spelke, 2005) and sequential auditory arrays (Lipton & Spelke, 2003). Other work finds slightly worse performance for sequential compared to simultaneous stimuli (Anobile et al., 2018; Libertus et al., 2020). These results suggest that it is unlikely that the enhancement in infants' performance was driven by an auditory > visual or a sequential > simultaneous advantage, although it remains possible that either of these affected 4-month-olds' performance differently than that of older participants (e.g., 6-month-olds or adults).

If intersensory redundancy was responsible for the change in infants' numerical precision, how might it be helping? One possibility is that perceiving converging information from distinct sensory modalities selectively directs infants' attention to the amodal numerical dimension of the stimulus arrays, thereby increasing the strength of the numerical signal infants receive (Bahrick & Lickliter, 2000). This account is supported by animal research which finds better responses to redundant visual and auditory cues compared to cues presented in a single modality (Stein et al., 1988)—even when cues are presented prenatally (Lickliter et al., 2002), along with changes in neural responses to redundant stimuli (Meredith & Stein, 1983). It is possible that redundant amodal information has top-down modulating effects on responses to sensory input, enhancing responses to the redundant information (e.g., numerical information for infants in the current experiments), and attenuating responses to other information (e.g., non-numerical information such as luminance and density). Such an explanation is also consistent with the Signal Clarity hypothesis proposed by Cantrell et al. (2015; Cantrell & Smith, 2013; see Dibavar, 2018, for further discussion).

In sum, the current study fills a gap in our understanding of infants' early numerical processing. Our findings highlight the presence of developmental change in infants' numerical precision during the first year of life and underscore that this precision is flexible rather than fixed. Understanding

[2]We thank an anonymous reviewer for raising this point.

the mechanism by which ANS precision changes over time, even in the absence of counting or other mathematical input, remains a key question for future research.

ACKNOWLEDGMENTS

This research was supported by NIH grant R01 HD057258 to LF.

CONFLICT OF INTEREST

The authors declare no conflicts of interest with regard to the funding source for this study.

ORCID

Jinjing (Jenny) Wang https://orcid.org/0000-0001-8350-7656

REFERENCES

Anobile, G., Arrighi, R., Castaldi, E., Grassi, E., Pedonese, L., Moscoso, P. A., & Burr, D. C. (2018). Spatial but not temporal numerosity thresholds correlate with formal math skills in children. *Developmental Psychology*, *54*(3), 458.

Bahrick, L. E., & Lickliter, R. (2000). Intersensory redundancy guides attentional selectivity and perceptual learning in infancy. *Developmental Psychology*, *36*(2), 190–201.

Baker, J. M., Mahamane, S. P., & Jordan, K. E. (2014). Multiple visual quantitative cues enhance discrimination of dynamic stimuli during infancy. *Journal of Experimental Child Psychology*, *122*, 21–32.

Barth, H., Kanwisher, N., & Spelke, E. (2003). The construction of large number representations in adults. *Cognition*, *86*(3), 201–221.

Cantlon, J. F., & Brannon, E. M. (2006). Shared system for ordering small and large numbers in monkeys and humans. *Psychological Science*, *17*(5), 401–406.

Cantrell, L., Boyer, T. W., Cordes, S., & Smith, L. B. (2015). Signal clarity: An account of the variability in infant quantity discrimination tasks. *Developmental Science*, *18*(6), 877–893.

Cantrell, L., & Smith, L. B. (2013). Open questions and a proposal: A critical review of the evidence on infant numerical abilities. *Cognition*, *128*(3), 331–352.

Cordes, S., & Brannon, E. M. (2009a). Crossing the divide: Infants discriminate small from large numerosities. *Developmental Psychology*, *45*(6), 1583–1594.

Cordes, S., & Brannon, E. M. (2009b). The relative salience of discrete and continuous quantity in young infants. *Developmental Science*, *12*(3), 453–463.

Coubart, A., Izard, V., Spelke, E. S., Marie, J., & Streri, A. (2014). Dissociation between small and large numerosities in newborn infants. *Developmental Science*, *17*(1), 11–22.

De Hevia, M. D., Addabbo, M., Nava, E., Croci, E., Girelli, L., & Cassia, V. M. (2017). Infants' detection of increasing numerical order comes before detection of decreasing number. *Cognition*, *158*, 177–188.

de Hevia, M. D., Izard, V., Coubart, A., Spelke, E. S., & Streri, A. (2014). Representations of space, time, and number in neonates. *Proceedings of the National Academy of Sciences*, *111*(13), 4809–4813.

Dehaene, S. (1997). *The number sense: How the mind creates mathematics*. Oxford University Press.

Dibavar, M. R. (2018). Infants' intermodal numerical knowledge. *Infant Behavior and Development*, *52*, 32–44.

Elliott, L., Feigenson, L., Halberda, J., & Libertus, M. E. (2019). Bidirectional, longitudinal associations between math ability and approximate number system precision in childhood. *Journal of Cognition and Development*, *20*(1), 56–74.

Feigenson, L. (2011). Predicting sights from sounds: 6-month-olds' intermodal numerical abilities. *Journal of Experimental Child Psychology*, *110*(3), 347–361.

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences*, *8*(7), 307–314.

Gordon, P. (2004). Numerical cognition without words: Evidence from Amazonia. *Science*, *306*(5695), 496–499.

Halberda, J., & Feigenson, L. (2008). Developmental change in the acuity of the" Number Sense": The Approximate Number System in 3-, 4-, 5-, and 6-year-olds and adults. *Developmental Psychology*, *44*(5), 1457–1465.

Halberda, J., Ly, R., Wilmer, J. B., Naiman, D. Q., & Germine, L. (2012). Number sense across the lifespan as revealed by a massive Internet-based sample. *Proceedings of the National Academy of Sciences*, *109*(28), 11116–11120.

Hyde, D. C., & Spelke, E. S. (2011). Two signatures of number processing in human infants: Evidence for two core systems underlying numerical cognition. *Developmental Science*, *14*(2), 360–371.

Izard, V., Sann, C., Spelke, E. S., & Streri, A. (2009). Newborn infants perceive abstract numbers. *Proceedings of the National Academy of Sciences*, *106*(25), 10382–10385.

Jordan, K. E., Suanda, S. H., & Brannon, E. M. (2008). Intersensory redundancy accelerates preverbal numerical competence. *Cognition*, *108*(1), 210–221.

Kirkham, N. Z., Wagner, J. B., Swan, K. A., & Johnson, S. P. (2012). Sound support: Intermodal information facilitates infants' perception of an occluded trajectory. *Infant Behavior and Development*, *35*(1), 174–178.

Libertus, M. E., & Brannon, E. M. (2010). Stable individual differences in number discrimination in infancy. *Developmental Science*, *13*(6), 900–906.

Libertus, M. E., Feigenson, L., & Halberda, J. (2013). Is approximate number precision a stable predictor of math ability? *Learning and Individual Differences*, *25*, 126–133.

Libertus, M. E., Odic, D., Feigenson, L., & Halberda, J. (2020). Effects of visual training of approximate number sense on auditory number sense and school math ability. *Frontiers in Psychology*, *11*, 2085.

Lickliter, R., Bahrick, L. E., & Honeycutt, H. (2002). Intersensory redundancy facilitates prenatal perceptual learning in bobwhite quail (*Colinus virginanus*) emryos. *Developmental Psychology*, *38*(1), 15.

Lindskog, M., Winman, A., & Juslin, P. (2014). The association between higher education and approximate number system acuity. *Frontiers in Psychology*, *5*, 462.

Lipton, J. S., & Spelke, E. S. (2003). Origins of number sense: Large-number discrimination in human infants. *Psychological Science*, *14*(5), 396–401.

Lyons, I. M., Bugden, S., Zheng, S., De Jesus, S., & Ansari, D. (2018). Symbolic number skills predict growth in nonsymbolic number skills in kindergarteners. *Developmental Psychology*, *54*(3), 440–457.

Meredith, M. A., & Stein, B. E. (1983). Interactions among converging sensory inputs in the superior colliculus. *Science*, *221*(4608), 389–391.

Moyer, R. S., & Laudauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature*, *215*(5109), 1519–1520.

Mussolin, C., Nys, J., Content, A., & Leybaert, J. (2014). Symbolic number abilities predict later approximate number system acuity in preschool children. *PLoS One*, *9*(3), e91839.

Odic, D., Libertus, M. E., Feigenson, L., & Halberda, J. (2013). Developmental change in the acuity of approximate number and area representations. *Developmental Psychology*, *49*(6), 1103–1112.

Piazza, M., Izard, V., Pinel, P., Le Bihan, D., & Dehaene, S. (2004). Tuning curves for approximate numerosity in the human intraparietal sulcus. *Neuron*, *44*(3), 547–555.

Piazza, M., Pica, P., Izard, V., Spelke, E. S., & Dehaene, S. (2013). Education enhances the acuity of the nonverbal approximate number system. *Psychological Science*, *24*(6), 1037–1043.

Pica, P., Lemer, C., Izard, V., & Dehaene, S. (2004). Exact and approximate arithmetic in an Amazonian indigene group. *Science*, *306*(5695), 499–503.

Shusterman, A., Slusser, E., Halberda, J., & Odic, D. (2016). Acquisition of the cardinal principle coincides with improvement in Approximate Number System acuity in preschoolers. *PLoS One*, *11*(4), e0153072.

Starr, A., Libertus, M. E., & Brannon, E. M. (2013). Number sense in infancy predicts mathematical abilities in childhood. *Proceedings of the National Academy of Sciences*, *110*(45), 18116–18120.

Stein, B. E., Huneycutt, W. S., & Meredith, M. A. (1988). Neurons and behavior: The same rules of multisensory integration apply. *Brain Research*, *448*(2), 355–358.

Wang, J. J., & Feigenson, L. (2019). Infants recognize counting as numerically relevant. *Developmental Science*, *22*(6), e12805.

Wang, J. J., Libertus, M. E., & Feigenson, L. (2018). Hysteresis-induced changes in preverbal infants' approximate number precision. *Cognitive Development*, *47*, 107–116.

Whalen, J., Gallistel, C. R., & Gelman, R. (1999). Nonverbal counting in humans: The psychophysics of number representation. *Psychological Science*, *10*(2), 130–137.

Wood, J. N., & Spelke, E. S. (2005). Infants' enumeration of actions: Numerical discrimination and its signature limits. *Developmental Science*, *8*(2), 173–181.

Xu, F. (2003). Numerosity discrimination in infants: Evidence for two systems of representation. *Cognition*, *89*(1), B15–B25.

Xu, F., & Arriaga, R. I. (2007). Number discrimination in 10-month-old infants. *British Journal of Developmental Psychology*, *25*(1), 103–108.

Xu, F., & Spelke, E. S. (2000). Large number discrimination in 6-month-old infants. *Cognition*, *74*(1), B1–B11.

How to cite this article: Wang J(, Feigenson L. Dynamic changes in numerical acuity in 4-month-old infants. *Infancy*. 2020;00:1–16. https://doi.org/10.1111/infa.12373