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Predicting sights from sounds: 6-month-olds' intermodal numerical abilities

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ABSTRACT

Although the psychophysics of infants' nonsymbolic number representations have been well studied, less is known about other characteristics of the approximate number system (ANS) in young children. Here three experiments explored the extent to which the ANS yields abstract representations by testing infants' ability to transfer approximate number representations across sensory modalities. These experiments showed that 6-month-olds matched the approximate number of sounds they heard to the approximate number of sights they saw, looking longer at visual arrays that numerically mismatched a previously heard auditory sequence. This looking preference was observed when sights and sounds mismatched by 1:3 and 1:2 ratios but not by a 2:3 ratio. These findings suggest that infants can compare numerical information obtained in different modalities using representations stored in memory. Furthermore, the acuity of 6-month-olds' comparisons of intermodal numerical sequences appears to parallel that of their comparisons of unimodal sequences.

Introduction

Why is thinking about the world as populated by quantities—from the number of people in a room to the number of dollars in a wallet—so easy and automatic? Although it was once thought that numerical abilities were not acquired until early childhood (Piaget, 1952), research of the past 30 years has shown that in fact numerical competence is present from the start of postnatal life (for reviews, see Dehaene, 2009; Feigenson, Dehaene, & Spelke, 2004; Libertus & Brannon, 2009).

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Recent work has revealed several key properties of the mental system supporting these basic numerical abilities. Infants' numerical representations, like those of adults and nonhuman animals (Cantlon, Platt, & Brannon, 2009; Feigenson et al., 2004), exhibit a signature pattern of ratio dependence. For example, 6-month-old infants can discriminate visual arrays differing by a numerical ratio of 1:2 across a range of absolute numerosities and with non-numerical dimensions carefully controlled. However, these 6-month-olds fail to discriminate similar arrays differing by a ratio of 2:3 (Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005), showing that their numerical representations are relatively coarse. By 9 to 10 months, infants succeed with a 2:3 ratio but fail with a 4:5 ratio (Xu & Arriaga, 2007). The acuity of numerical discriminations continues to sharpen throughout childhood (Halberda & Feigenson, 2008; Piazza et al., 2010), eventually reaching the adult level of approximately 9:10. This evidence suggests that throughout the lifespan and across species, numerical representation is subserved by an approximate number system (ANS) that produces noisy numerical estimates.

Besides its hallmark imprecision, a second important property of the ANS is its ability to receive input from multiple sensory modalities. For example, infants perform ratio-dependent numerical discriminations not only for visual items such as dots but also for auditory items such as sequentially presented tones. Moreover, the developmental change in acuity that is observed for auditory arrays parallels that observed for visual arrays; infants discriminate auditory sequences differing by a 1:2 numerical ratio at 6 months and a 2:3 ratio at 9 months (Lipton & Spelke, 2003, 2004). This parallel in the numerical abilities of infants presented with sights and sounds is consistent with two interpretations. First, the ANS might ignore the sensory properties of incoming stimuli and produce truly abstract numerical representations. Alternatively, the ANS might be better described as an operation available within each modality, producing numerical representations that remain modality specific.

One way to decide between these alternatives is to ask not just whether infants can represent number in multiple modalities but also whether they can transfer numerical information from one modality to another. Early efforts to do this achieved mixed results. When 6- to 9-month-olds were shown two visual arrays containing different numbers of objects and simultaneously heard 2 or 3 drumbeats, they sometimes showed a preference to look longer at the numerically matching array but other times showed no preference or even looked longer at the nonmatching array (Mix, Levine, & Huttenlocher, 1997; Moore, Benenson, Reznick, Peterson, & Kagan, 1987; Starkey, Spelke, & Gelman, 1983). However, subsequent studies using more naturalistic linkages between sights and sounds obtained more positive results. For example, 7-month-olds who saw videos of 2 and 3 human faces side by side and heard either 2 or 3 different voices played through a speaker looked longer at the video that numerically matched the audio (Jordan & Brannon, 2006b). In another study, 6-month-olds were familiarized to the experience of a visual object making a sound on impacting a surface. After this familiarization, infants were shown an occluded stage, heard either 2 or 3 sounds played, and then saw that the stage was revealed to contain either 2 or 3 objects. Infants looked longer at outcomes in which the number of objects mismatched the number of tones (Kobayashi, Hiraki, & Hasegawa, 2005; see also Kobayashi, Hiraki, Mugitani, & Hasegawa, 2004). Similar results have been obtained in other sensory modalities. For example, 5-month-olds who were familiarized to the experience of feeling either 2 or 3 objects placed in their hands sequentially looked longer when shown an image depicting a mismatching number of objects than a matching one (Féron, Gentaz, & Streri, 2006).

However, one problem with concluding from the above studies that infants possess abstract, amodal number representations is that these studies tested infants with only small numbers of items. Although the ANS is capable of representing very small numerosities such as 1, 2, and 3 (Cordes & Brannon, 2009a; Cordes, Gelman, Gallistel, & Whalen, 2001), much evidence suggests that infants often represent arrays containing 1, 2, or 3 items in terms of separate individuals rather than as an array with an approximate cardinal value (Feigenson & Carey, 2003; Feigenson, Carey, & Hauser, 2002; Feigenson et al., 2004; Xu, 2003). This would be akin to representing an array containing 3 dots as Object A, Object B, and Object C rather than as "exactly 3" or "approximately 3." For this reason, the above studies are consistent with infants having determined intermodal matches between individual objects and individual sounds or tactile experiences (Jordan, Clark, & Mitroff, 2010) without invoking any numerical representations at all.

One recent study does provide evidence of intermodal comparison using the ANS. Newborn infants were first familiarized to auditory sequences containing a fixed number of syllables. Following this familiarization, infants saw visual arrays depicting either of two numerosities and again heard the fixed number syllable sequence played repeatedly. Infants looked longer when the visual and auditory information matched than when it mismatched by a 1:3 ratio. For example, infants who heard 6 syllables looked longer at arrays containing 6 shapes than at those containing 18 shapes, and infants who heard 18 syllables looked longer at arrays containing 18 shapes than at those containing 6 shapes. When the ratio was decreased to 1:2 (4 vs. 8 sounds/shapes), infants showed only a marginally significant preference (Izard, Sann, Spelke, & Streri, 2009). Because this study tested infants with numbers known to be outside of the 1- to 3-item range of individual object representation, and because infants' intermodal matching was modulated by numerical ratio, these results offer evidence of genuinely abstract, amodal approximate number representations.

The work by Izard and colleagues (2009) raises several interesting questions. First is the question of whether the correspondence in number between visual information and auditory information was computed at the level of perception or in memory. Infants in that study saw visual items concurrently with hearing the fixed number syllable sequence. This design (similar to that of Jordan & Brannon, 2006b) meant that infants could match a currently experienced visual numerosity to a currently experienced auditory numerosity. Still unknown is whether infants can store in memory a specifically numerical representation formed in one modality and later compare it with a numerical representation formed in a different modality, similar to when hearing a number of pennies fall into an opaque jar and being able to anticipate how many pennies will be seen on peering inside. The question is whether infants can *predict* how many items will be seen after a given number of sounds have been heard. Given that the utility of numerical representations is their role in computation (as when comparing the approximate number of food items in two foraging patches or when adding or subtracting two quantities), and given that memory is required to perform such computations, it is important to determine whether infants can detect intermodal numerical correspondences not just across immediately perceived stimuli but also across remembered stimuli.

This ability to use memory to compare numerical representations formed across different modalities has been demonstrated in adults (Barth, Kanwisher, & Spelke, 2003) and 5-year-olds (Barth, La-Mont, Lipton, & Spelke, 2005), who can mentally add two sequentially presented arrays of dots and compare the resultant numerosity with the numerosity of a subsequent sequence of tones. However, participants in these tasks were old enough to have had experience with symbolic number, and having access to number symbols may have played an important role in coordinating the numerical representations across modalities. Infants who are several years short of acquiring such number symbols have been shown to use memory to compare representations across modalities, but only for small arrays of one to three objects, leaving open whether infants' success depended on numerical representations or on non-numerical representations of individual objects (Féron et al., 2006; Kobayashi et al., 2004, 2005). Therefore, it remains unknown whether children without access to number words can perform cross-modal numerical comparisons of large approximate numerosities using memory (i.e., without seeing and hearing stimuli at the same time).

Second, the psychophysical characteristics of infants' intermodal numerical representations remain to be described. In particular, it is unknown whether infants' numerical discriminations across modalities are worse than, better than, or the same as their discriminations within a single modality. Infants' intermodal discriminations might be worse than (i.e., less precise than) their unimodal discriminations because there may be a cost to translating information formed from input to one sensory modality into a format that can be compared with that in a different modality. Alternatively, infants' intermodal discriminations might be better than their unimodal discriminations because intersensory redundancy sometimes has been observed to sharpen numerical acuity (Jordan & Baker, 2011; Jordan, Suanda, & Brannon, 2008). Although previous studies documented this sharpening effect only when auditory information and visual information were available concurrently, it is possible that coordinating information from multiple modalities in memory also increases representational precision. A third possibility is that infants might have the same numerical acuity whether tested across or within modalities. To decide among these possibilities, infants' intermodal numerical performance should be compared with their unimodal performance (Barth et al., 2003). Izard and colleagues (2009) tested infants with two numerical ratios and found that infants robustly succeeded at matching the two numerosity pairs that differed by a 1:3 ratio (4 vs. 12 and 6 vs. 18) but only marginally succeeded at matching the pair that differed by a 1:2 ratio (4 vs. 8). It is unclear whether this performance is better or worse than would be expected under unimodal conditions because the acuity of neonates' unimodal numerical representations has yet to be described. Testing the intermodal numerical abilities of older infants, whose unimodal numerical abilities have been well characterized, will help to address this question.

The current series of experiments aimed to address these two challenges. The first aim was to determine whether infants can compare a memory representation of an approximate numerosity that was formed from information in one modality with a subsequent experience of an approximate numerosity in a different modality. Infants were tested in a violation-of-expectation paradigm in which they heard a given number of tones and then saw two visual outcomes: one that matched the number of tones and one that did not. Because sounds and sights were never experienced at the same time, to succeed at this task infants needed to form and maintain in memory abstract representations with approximate numerical content. Second, to compare infants' intermodal and unimodal numerical discrimination, infants were tested with a wider range of numerical ratios, including some known to be within and some known to be outside of 6-month-olds' discrimination ranges for unimodal stimuli.

In Experiments 1 to 3, infants were presented with numerosities that mismatched by ratios of 1:3, 1:2, and 2:3, respectively. If 6-month-olds (who have been shown by previous studies to successfully discriminate unimodal arrays differing by a 1:2 ratio [Brannon, Abbott, & Lutz, 2004; Lipton & Spelke, 2003, 2004; Xu, 2003; Xu and Spelke; 2000; Xu et al., 2005]) here fail to discriminate intermodal arrays differing by a 1:2 ratio (as did the neonates in Izard et al.'s (2009) study), then this would suggest that infants' intermodal numerical representations are less precise than their unimodal representations. If 6-month-olds (who have been shown by previous studies to fail to discriminate unimodal arrays differing by a 2:3 ratio [Lipton & Spelke, 2003, 2004; Xu & Spelke, 2000; Xu et al., 2005]) here succeed at discriminating intermodal arrays differing by a 2:3 ratio, then this would suggest that infants' intermodal numerical representations are more precise than their unimodal representations.

Experiment 1

In the first experiment, 6-month-old infants first were familiarized to a one-to-one pairing of objects and sounds on a computerized display. Infants saw a short movie in which two-dimensional objects appeared one by one at the top of the display. Each time an object appeared, a short "ding" played. Infants then saw the object drop to a resting position at the bottom of the screen. This familiarization gave infants the opportunity to learn that each object was paired with one sound. Importantly, the number of items shown and heard during familiarization was designed to be equidistant from the two numbers presented on the test trials (see Method below), thereby eliminating the possibility of creating familiarity or novelty biases for any particular numerosity. On the subsequent test trials, infants saw the entire display occluded, heard a given number of sounds, and then saw the occluder lifted to reveal a number of objects that either matched or did not match the number of sounds just heard.

It is important to note that extant studies involving cross-modal comparisons have found different indicators of success. In some cases infants looked significantly longer when the information across two modalities was congruent, but in other cases infants looked longer when it was incongruent. However, these results are not haphazard. Overall, studies that led infants to have an expectancy that later was violated (Kobayashi et al., 2004, 2005), or that relied on representations stored in memory (Féron et al., 2006), found longer looking at numerical mismatches. For example, in Kobayashi and colleagues' (2005) study, infants first heard a given number of sounds and then saw either a matched or mismatched number of objects revealed. Infants looked longer at the numerical mismatch, as though visually seeking more information about the outcome that was inconsistent with their expectations. In contrast, studies that measured infants' spontaneous preference to look at arrays while hearing a continually looping auditory sequence (without first showing infants an event that set up any particular expectation) found longer looking when information matched across modalities (Izard et al., 2009; Jordan & Brannon, 2006b). Because the current series of experiments used a violation-of-expectation procedure, the infants tested here were predicted to look longer at numerical mismatches than at numerical matches.

The finest ratio with which infants have shown robust intermodal representation of approximate numerosity is 1:3 (in the studies of neonates by Izard et al., 2009). In Izard and colleagues' (2009) study, infants were presented with concurrent auditory and visual numerical information. The current experiment, therefore, asked whether 6-month-olds can discriminate numerosities differing by a 1:3 ratio (4 vs. 12), this time using numerical representations stored in memory.

Method

Participants

The participants were 16 full-term infants (9 boys and 7 girls). Their mean age was 5 months 29 days (range = 5 months 15 days to 6 months 14 days). All infants who were tested were included in the final analysis. Infants were recruited through their parents by telephone and by mail, and they received a small gift (shirt, book, or stuffed toy) to thank them for their participation.

Design

The testing session began with 4 familiarization trials in which infants were given the experience of each auditory tone coinciding with a single object without any occlusion. To make the displays interesting to infants, the objects used were yellow smiley faces with simple black eyes and mouths, similar to the schematic faces that have been used in previous investigations of both intermodal and unimodal numerical abilities in infants (Cordes & Brannon, 2009a, 2009b; Izard, Dehaene-Lambertz, & Dehaene, 2008; Izard et al., 2009). Each familiarization trial contained 8 tones and 8 faces. Because 8 is the arithmetic midpoint between the test values 4 and 12, this design ensured that infants did not receive more exposure to a particular numerosity prior to the test phase.[1]

For the test phase, half of the infants were randomly assigned to the 4 Tones condition, in which 4 tones played sequentially while the screen was occluded. The other half of the infants were assigned to the 12 Tones condition, in which 12 tones played sequentially while the screen was occluded. During the playing of the tones, no objects were visible (because the occluder covered nearly all of the screen). After the tone sequence had finished, all infants saw the occluder lifted to reveal an array containing either 4 or 12 faces (with order counterbalanced across infants). There were 8 test trials, each of which contained a tone sequence (either 4 or 12 tones, with numerosity constant for each infant) followed by the revealing of an outcome array (4 or 12 faces, each seen four times in alternating order by each infant).

Stimuli

Throughout the experiment, the auditory stimuli were 500-ms-long tones. The 8 faces shown during the familiarization phase were 1.3 cm in diameter, and the faces shown during the test phase were 2.5 cm (4-face test outcome) and 0.92 cm (12-face test outcome) in diameter. In this way, the cumulative perimeter of the faces, a continuous dimension to which infants of this age have shown sensitivity (Clearfield & Mix, 1999), was controlled. The cumulative perimeter on the 8-face familiarization trials (32.67 cm) was the approximate geometric midpoint (Cordes & Brannon, 2008, 2009b) between the cumulative perimeter of the 4-face test trials (31.42 cm) and the 12-face test trials (34.68 cm). As

[1] Previous results differ on whether the arithmetic mean (Droit-Valet, Clement, & Fayol, 2003) or the geometric mean (Beran, Johnson-Pynn, & Ready, 2008; Jordan & Brannon, 2006a) is the point of subjective equality between two nonverbal number representations in children. Here the arithmetic mean was used to determine familiarization numerosities. In Experiments 2 and 3, the arithmetic mean was also the closest whole number to the geometric mean. This was not the case in Experiment 1, where the arithmetic mean was geometrically closer to 12 than to 4. However, if the familiarization numerosity (8) had affected infants' looking preferences during the test trials, then this would be revealed by a preference for one of the two test numerosities (e.g., a preference for 4) regardless of the number of sounds infants had just heard. That this was not the observed pattern suggests that the numerosity presented during familiarization did not determine infants' looking preferences. However, given the abundance of evidence for ratio-dependent numerical discrimination performance in infants (for a review, see Libertus & Brannon, 2009), it will be prudent to consider the geometric mean rather than the arithmetic mean to be the point of subjective equality in future investigations of infants' numerical competence.

such, the two numerosities presented during the test phase were equally novel in terms of their cumulative perimeter.

Procedure

Infants sat in a high chair approximately 60 cm from a computer screen that was surrounded by a curtain. Parents sat approximately 60 cm behind infants and were asked not to interact with infants throughout the experimental session. The experimenter controlled the study from behind the curtain and was not visible to infants during the experiment. A concealed video camera positioned below the computer screen recorded infants' looking behavior.

The experiment began with an attention-attracting sun image accompanied by a simple melody. As soon as infants looked at the screen, the experimenter pressed a key to begin the first familiarization trial. On each familiarization trial, the sun image disappeared and 8 smiley faces appeared one at a time from the top of the screen, with each dropping to a resting position at the bottom of the screen before the next face appeared (see Fig. 1). The faces dropped at a variable rate averaging 2 per second (4 ms elapsed from the start of the familiarization trial to the landing of the last smiley face). The appearance of each face was accompanied by a tone. On the familiarization trials only, all 8 faces remained visible and unmoving at the bottom of the screen (their landing positions varied slightly among the 4 familiarization trials) until infants either looked away from the screen for 2 s (continuous) or had looked at the screen for a total of 60 s. Either of these occurrences was signaled by an experienced observer who watched the live video of the testing session in an adjacent room. When a trial ended, the observer pressed a key to signal the experimenter in the testing room. In between each trial, the attention-attracting sun image appeared to refixate infants' gaze.

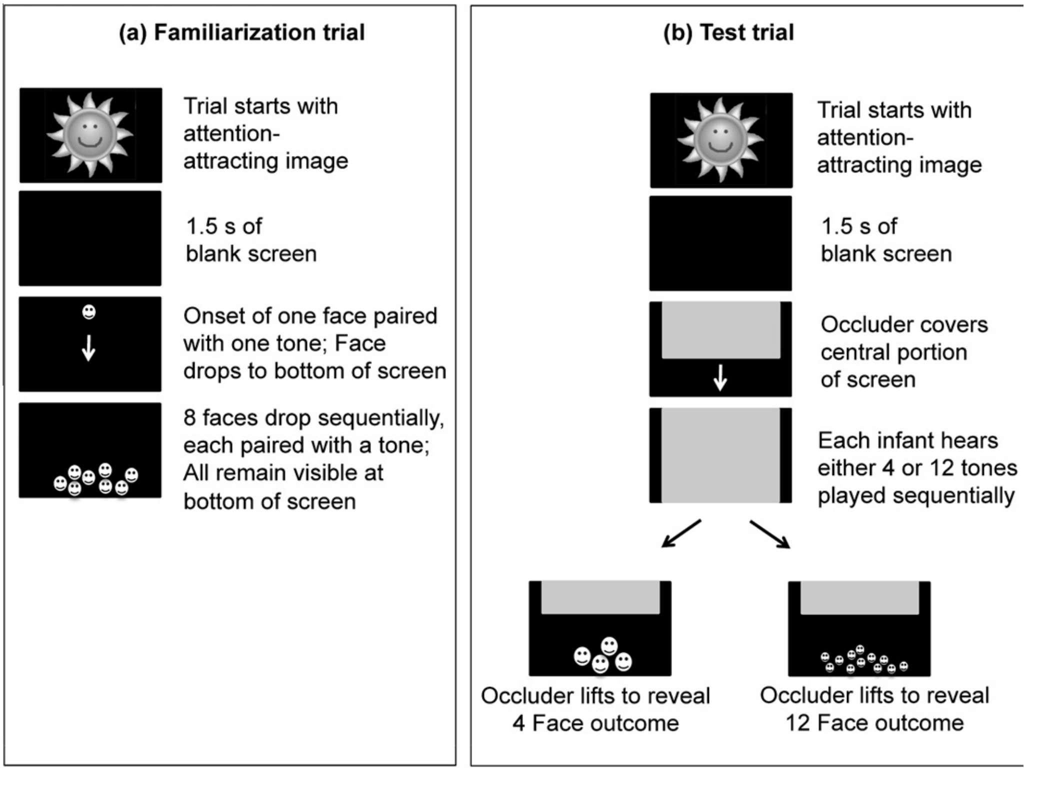

Fig. 1. (A) Sample familiarization trial from Experiment 1. (B) Sample test trial from Experiment 1.

The 4 familiarization trials were followed by 8 test trials (see Fig. 1). Each test trial began with a black screen. After 2 s, a 15.9 × 23.4-cm gray occluding rectangle entered from the top, covering the entire screen except for 8.2 cm on the right and left, such that infants could not see smiley faces appear at the top or land at the bottom. Immediately after the occluder was in place, a series of either 4 or 12 tones was played at a variable rate, averaging 2 per second. The total time elapsed on the 4-face test trial from the start of the first sound until the occluder was raised was 2.1 s, and the total time elapsed on the 12-face test trial was 6.7 s. The duration of the familiarization sequence was 4 s, the approximate midpoint between these two test durations. In this way, the durations of the two test events were equally novel relative to that seen during familiarization.

After the last tone had played, the occluder lifted to reveal the test outcome, which alternated between 4 and 12 faces. The faces were static at the bottom of the screen, arranged in a random-looking placement that differed from trial to trial. The faces remained visible until infants either looked away from the screen for 2 s (continuous) or had looked for a total of 60 s.

Infants' looking times were recorded live by the observer in the adjacent room, and all trials were later rescored for reliability. Both the original observer and the observer who rescored the testing session were blind to the experimental condition in which infants were tested. Their reliability averaged 95% across all trials. Any trial that was greater than 3 standard deviations from the group average was excluded from analysis, along with its yoked pair, and was replaced with the mean of all other infants' looking on that trial; for example, if an infant's looking on the first number mismatch test trial differed from the group average by more than 3 standard deviations, then both that trial and the same infant's first number match trial were replaced with the group average. Of 128 test trials, 2 were replaced in this way.

Results

Although infants' looking during the 4 familiarization trials was recorded, because these trials were designed only to familiarize infants with the pairing of a tone with each face, and because all 4 familiarization trials were identical, no specific predictions were made about looking on these trials (either in absolute terms or compared with looking during the test trials). For this reason, infants' familiarization looking times are not reported for any of the experiments in this series.

Infants' average looking during the test trials is illustrated in Fig. 2. A repeated-measures analysis of variance (ANOVA) with tone number (whether infants heard 4 or 12 tones) and test order (whether infants saw 4 or 12 faces revealed on the first test trial) as the between-participants factors and face number (whether infants saw 4 or 12 faces revealed) and test pair (whether it was the first, second, third, or fourth test pair) as the within-participants factors yielded an interaction between tone number and face number, $F(1, 12) = 7.19$, $p = .02$, $\eta_p^2 = .38$, revealing that infants' preference for outcomes containing 4 or 12 faces depended on whether they had just heard 4 or 12 tones. This effect was further explored with a planned paired *t* test comparing infants' average looking on trials on which the

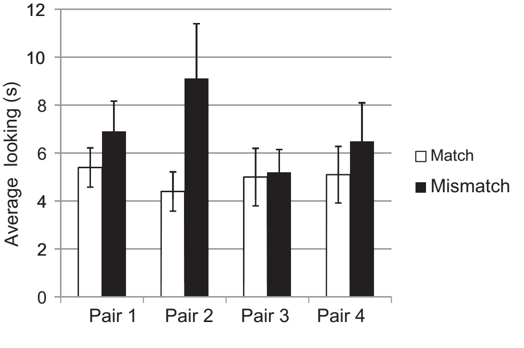

Fig. 2. Infants' looking times on numerical match and mismatch trials in Experiment 1.

number of tones mismatched the number of faces (number mismatch trials: 6.91 s) with their looking on trials on which the number of tones matched the number of faces (number match trials: 4.98 s). Infants looked significantly longer at the number mismatch trials, $t(15) = -2.707$, $p = .016$.

This preference to look longer when the number of tones mismatched the number of faces differed somewhat across the four test pairs, as revealed by a three-way interaction among tone number, face number, and test pair, $F(3, 36) = 2.90$, $p = .048$, $\eta_p^2 = .20$. This reflected the fact that although infants looked longer at the number mismatch trials than at the number match trials on all four test pairs, this effect was the weakest on the third test pair. No other main effects or interactions were observed.

The results of Experiment 1 suggest that 6-month-olds' numerical representations are sufficiently abstract to allow them to use information presented in one sensory modality to predict what would occur in a different modality. Specifically, infants used the number of sequentially presented tones they heard to predict the number of simultaneously presented faces they would see. This resulted in infants looking longer at visual arrays that differed by a 1:3 numerical ratio from a just-experienced auditory sequence. Hence, infants can match approximate numerosities across sensory modalities even when auditory information and visual information are not concurrently available.

Infants' success in Experiment 1 raises the question of how precise infants' intermodal approximate number representations are. In previous studies, 6-month-olds have been shown to discriminate 1:2 numerical ratios within a single sensory modality (Lipton & Spelke, 2003, 2004; Xu, 2003; Xu & Spelke, 2000; Xu et al., 2005), but the one study testing infants' intermodal representations of large numerosities found that neonates were only marginally successful at discriminating 1:2 ratios (Izard et al., 2009). It is unclear whether this marginal success was caused by the fact that these infants were considerably younger than the 6-month-olds whose 1:2 discrimination success has been well documented (e.g., Jordan et al., 2008; Libertus & Brannon, 2010; Lipton & Spelke, 2003, 2004; Xu, 2003; Xu & Spelke, 2000; Xu et al., 2005) or by the intermodal nature of the task. Therefore, Experiment 2 asked whether 6-month-olds also can succeed at discriminating 1:2 ratios when using memory to compare approximate numbers of sights and sounds.

Experiment 2

In the second experiment, 6-month-old infants were tested using methods identical to those of Experiment 1 except that numerical mismatches instantiated a 1:2 ratio.

Method

Participants

The participants were 16 full-term infants (10 boys and 6 girls). Their mean age was 5 months 26 days (range = 5 months 15 days to 6 months 10 days). One additional infant was excluded due to fussiness.

Design and stimuli

As in Experiment 1, infants first were presented with familiarization trials designed to provide exposure to one-to-one pairings of objects and sounds. All familiarization trials contained 6 sequentially presented smiley faces, each paired with an identical tone. As in Experiment 1, the number of familiarization faces was chosen to be midway between the numerosities shown during the test phase (4 and 8), thereby making the test outcomes equally numerically novel relative to the familiarization arrays. The faces dropped at the same rate as in Experiment 1, averaging 2 per second, and were 1.3 cm in diameter.

During the test phase, all infants saw the majority of the screen occluded. Half of the infants then heard a sequence of 4 tones, and the other half heard 8 tones, played at the same rate as during familiarization. All infants then saw the occluder lift to reveal 4 and 8 smiley faces presented on alternating test trials with order counterbalanced across infants. The faces were either 1.7 cm (4-face test outcome) or 1.1 cm (8-face test outcome) in diameter. Hence, the cumulative perimeter of the 6-face familiarization trials (24.5 cm) was the approximate geometric midpoint between the cumulative perimeter seen in the 4-face test trials (21.36 cm) and the 8-face test trials (27.66 cm). In this way, the cumulative perimeters contained in the 4-face and 8-face test outcomes were equally novel relative to the cumulative perimeter seen during familiarization. As in Experiment 1, there were 8 total test trials.

As in Experiment 1, any trial that was greater than 3 standard deviations from the group average was excluded from analysis, along with its yoked pair, and replaced with the mean of all the other infants' looking on that trial. Of 128 test trials, 2 were replaced in this way.

Procedure

The procedure was identical to that of Experiment 1. Reliability between the two observers, both blind to the experimental condition, averaged 95% across all trials.

Results

Infants' average looking during the test trials is illustrated in Fig. 3. A repeated-measures ANOVA with tone number (whether infants heard 4 or 8 tones) and test order (whether infants saw 4 or 8 faces revealed on the first test trial) as the between-participants factors and face number (whether infants saw 4 or 8 faces revealed) and test pair (whether it was the first, second, third, or fourth test pair) as the within-participants factors yielded a main effect of test pair, $F(3, 36) = 5.49$, $p = .003$, $\eta_p^2 = .31$. This resulted from infants looking longer overall at the first test pair than at the other three test pairs, independent of the number of faces shown. Critically, the ANOVA also revealed an interaction between tone number and face number, $F(1, 12) = 7.59$, $p = .017$, $\eta_p^2 = .39$, suggesting that, as in Experiment 1, infants' preference for outcomes containing 4 or 8 faces depended on whether they had just heard 4 or 8 tones. This effect was further explored with a planned paired *t* test comparing infants' average looking on trials on which the number of tones differed from the number of faces (number mismatch trials: 4.75 s) with their looking on trials on which the number of tones matched the number of faces (number match trials: 3.46 s). Infants looked significantly longer at the number mismatch trials, $t(15) = -2.29$, $p = .037$. No other main effects or interactions were observed.

The results of Experiment 2 replicate and extend those of Experiment 1. Here infants looked longer at visual arrays that differed by a 1:2 ratio from the number of tones heard moments earlier. This result is consistent with infants' previously demonstrated success at discriminating 1:2 numerical ratios within either the auditory or visual modality, and suggests that infants' acuity for detecting intermodal numerical correspondences is at least as good as their acuity for detecting within-modality correspondences even when required to use memory to evaluate the numerical correspondence.

This success raises the question of how infants would perform with an intermodal numerical discrimination with which they have been shown to fail when presented with stimuli from a single modality. On the one hand, infants' thresholds within a single sensory modality might limit their abilities when presented with cross-modal experiences such as those in Experiments 1 and 2. If so, then infants should fail to detect intermodal mismatches that instantiate anything finer than a 1:2 ratio.

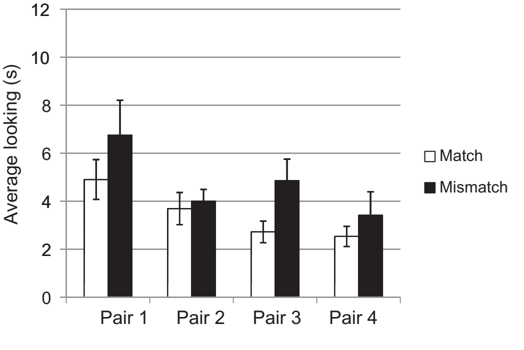

Fig. 3. Infants' looking times on numerical match and mismatch trials in Experiment 2.

Alternatively, infants might be able to perform finer numerical discriminations when comparing information across modalities. Jordan and colleagues (2008) found that 6-month-olds successfully discriminated arrays differing by a 2:3 ratio when presented with synchronous visual and auditory information (a ball that made a noise each time it bounced), but not when presented with visual information only (a ball bouncing silently) or with visual information and non-numerical auditory information (a ball bouncing while classical music played). This suggests that intermodal redundancy can sharpen numerical performance, perhaps because generating multiple noisy mental representations of a given numerosity decreases the overall variance associated with the representation of that numerosity (Jordan et al., 2008). However, it is unclear whether the same kind of sharpening should be observed in the current experimental design. Although both visual information and auditory information were presented to infants, they were not presented synchronously.

Experiment 3

In the third experiment, 6-month-old infants were tested using methods identical to those of Experiments 1 and 2 except that numerical mismatches instantiated a 2:3 ratio.

Method

Participants

The participants were 16 full-term infants (10 boys and 6 girls). Their mean age was 5 months 29 days (range = 5 months 15 days to 6 months 10 days). All infants tested were included in the final analysis.

Design and stimuli

All familiarization trials contained 5 faces (midway between the test outcomes of 4 and 6), each paired with an identical tone. The faces dropped at the same rate as in Experiments 1 and 2 and were 1.5 cm in diameter.

During the test phase, half of the infants heard a sequence of 4 tones and half heard 6 tones, played at the same rate as during familiarization. All infants then saw the occluder lift to reveal 4 and 6 smiley faces on alternating test trials with order counterbalanced across infants. The faces were either 1.73 cm (4-face test outcome) or 1.39 cm (6-face test outcome) in diameter. Hence, the cumulative perimeter of the 5-face familiarization trials was 23.56 cm, the approximate geometric midpoint between the cumulative perimeter seen in the 4-face test trials (21.74 cm) and the 6-face test trials (26.20 cm). As in Experiments 1 and 2, there were 8 total test trials.

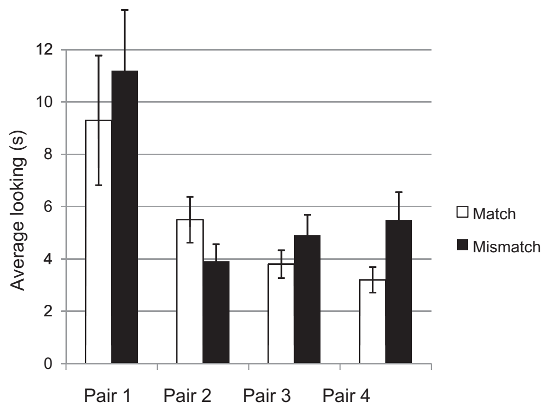

Fig. 4. Infants' looking times on numerical match and mismatch trials in Experiment 3.

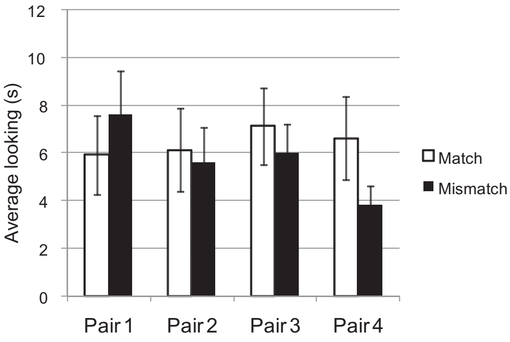

Fig. 5. Infants' looking times on numerical match and mismatch trials when tested with a 4:5 numerical ratio.

As in Experiments 1 and 2, any trial that was greater than 3 standard deviations from the group average was excluded from analysis, along with its yoked pair, and replaced with the mean of all the other infants' looking on that trial. Of 128 test trials, 2 were replaced in this way. An additional 2 test trials (a yoked pair) were replaced with the group mean due to a technical error during those trials.

Procedure

The procedure was identical to that of Experiments 1 and 2. Reliability between the two observers, both blind to the experimental condition, averaged 96% across all trials.

Results

Infants' average looking during the test trials is illustrated in Fig. 4. A repeated-measures ANOVA with tone number (whether infants heard 4 or 6 tones) and test order (whether infants saw 4 or 6 faces revealed on the first test trial) as the between-participants factors and face number (whether infants saw 4 or 6 faces revealed) and test pair (whether it was the first, second, third, or fourth test pair) as the within-participants factors first yielded a main effect of test pair, $F(3, 36) = 6.56$, $p = .001$, $\eta_p^2 = .35$. This resulted from infants looking longer overall at the first test pair than at the other three test pairs, independent of the number of faces shown. No other main effects or interactions were observed. Most importantly, there was no interaction between tone number and face number, $F(1, 12) = 2.03$, $p = .18$, revealing that, unlike in Experiments 1 and 2, infants' preference to look at test outcomes containing 4 or 6 faces was unrelated to whether they had just heard 4 or 6 tones.

This failure of 6-month-olds to discriminate between intermodal arrays that differed by a 2:3 ratio parallels performance of infants of the same age tested with unimodal stimuli (Lipton & Spelke, 2003; Lipton & Spelke, 2004; Xu & Spelke, 2000; Xu et al., 2005). This suggests that when auditory information and visual information are asynchronous, infants' intermodal numerical comparisons are no more accurate than their unimodal comparisons. However, to gain further confirmatory evidence that infants do not show success with intermodal arrays in the face of failure with unimodal arrays, a separate group of 16 infants was tested with an even more difficult 4:5 numerical ratio. Previous work has found that even older infants (9–10 months) fail to discriminate 4:5 ratios with unimodal arrays that are either auditory (Lipton & Spelke, 2003) or visual (Xu & Arriaga, 2007). A separate group of infants first heard either 4 or 5 tones played and then saw 4 and 5 faces revealed on alternating test trials. Analysis of infants' looking times again revealed no significant preference to look longer at either the numerically matching or mismatching test outcomes[2] (Fig. 5), further strengthening the conclusion that receiving numerical information from two modalities does not sharpen infants' discrimination abilities when auditory signals and visual signals are not presented concurrently.

[2] Interaction between tone number and face number, $F(1, 12) = 1.47$, $p = .25$.

General discussion

The current experiments aimed to address two outstanding questions regarding the abstractness of infants' numerical representations. The first question was whether infants can compare approximate numerical representations formed from auditory input with numerical representations formed from visual input when forced to rely on memory. Previous work investigating infants' intermodal representations either tested approximate number but did not require memory (Izard et al., 2009) or required memory but did not isolate approximate numerical representations (Féron et al., 2006; Jordan & Brannon, 2006b; Kobayashi et al., 2004; Kobayashi et al., 2005). Infants in the current experiments heard and saw stimuli at different times, thereby requiring the use of memory, and were presented with numerosities beyond the limits of individual object representation, thereby requiring approximate number representations. These infants were able to discriminate arrays in which the number of sounds just heard matched the number of sights currently seen from arrays in which auditory and visual numerosities mismatched. This suggests that numerical representations stored in working memory can support intermodal comparison, allowing infants to compare numerosities experienced in one sensory modality (e.g., audition) with numerosities experienced in another (e.g., vision).

The conclusion that infants were comparing auditory and visual arrays on the basis of numerosity, as opposed to some non-numerical attribute of the arrays, is supported by findings that even though infants are sensitive to various measures of continuous extent (Brannon, Lutz, & Cordes, 2006; Clearfield & Mix, 1999; Clearfield & Mix, 2001; Cordes & Brannon, 2008, 2009b; Feigenson, Carey, & Spelke, 2002), they not only succeed at representing numerosity when extent is tightly controlled (e.g., Brannon et al., 2004; Cordes & Brannon, 2009b; Lipton & Spelke, 2003, 2004; Xu & Spelke, 2000; Xu et al., 2005) but also seem to respond preferentially to number over extent, at least for large arrays (Brannon et al., 2004; Cordes & Brannon, 2008, 2009b). In the current experiments, infants saw test arrays that were controlled for cumulative perimeter, such that their looking patterns could not have reflected a preference to match larger numbers of tones with greater cumulative extent. However, this design meant that numerosity was negatively correlated with the perimeter of the individual faces. That is, the more faces revealed at test, the smaller each face. This leaves open the possibility that infants who heard greater numbers of tones did not expect greater numbers of objects to be revealed but rather expected *smaller* objects to be revealed.

Although the current data do not rule out this interpretation, it seems unlikely for several reasons. First, in the one previous study of cross-modal transfer of approximate number representations, infants looked longer at arrays with numerically matching than mismatching numbers of sounds even though both test arrays had equal individual item sizes (Izard et al., 2009). In Izard and colleagues' (2009) study, the length of individual tones in the auditory sequence correlated negatively with number (i.e., sequences containing more tones also contained shorter tones). It is possible that infants in Izard and colleagues' study matched larger numbers of visual objects to shorter tones and that infants in the current experiments matched larger numbers of tones to smaller objects. Such an interpretation would be reminiscent of the observation that very young infants sometimes appear to be motivated to maintain an optimal level of overall arousal across sensory modalities, preferring to look at a dimmer light when presented with auditory stimulation and at a brighter light in the absence of auditory stimulation (Lewkowicz & Turkewitz, 1980, 1981). However, this tendency to respond to cumulative stimulus intensity appears to diminish with age, such that by the time infants are 6 months old they respond to more specific aspects of the stimuli (Lewkowicz, 1994); for example, they match intermodal sequences on the basis of temporal properties independent of total intensity (Mendelson & Ferland, 1982). Furthermore, it is unclear why infants would attempt to sum stimulus intensity on the basis of a discrete aspect of the auditory stimulus (number of tones) and a continuous aspect of the visual stimulus (cumulative perimeter of the faces) rather than attending to either discrete or continuous aspects of both stimuli. For these reasons, intensity matching seems unlikely to explain infants' success in the current experiments and those of Izard and colleagues (2009). Second, infants have been shown to spontaneously transfer associations learned for area to number. In these previous experiments, infants spontaneously mapped larger object areas to larger numerosities (Lourenco & Longo, 2010). This makes it seem unlikely that infants in the current experiments would expect larger numbers of tones to pair with *smaller* individual objects (or smaller numbers of tones to pair with larger individual objects). For these reasons, the current data suggest that infants matched numerosities experienced through audition with numerosities experienced through vision.

The second question motivating the current research was whether the psychophysical function describing infants' intermodal numerical performance parallels that of their unimodal performance, as it did for the adults observed by Barth and colleagues (2003). Experiments 1 to 3 revealed that infants who were presented with intermodal events succeeded with the same ratios, and also failed with the same ratios, as infants presented with sights or sounds alone (Lipton & Spelke, 2003, 2004; Xu & Spelke, 2000; Xu et al., 2005). The conclusion that infants' intermodal numerical comparisons are no more or less precise than their unimodal comparisons should be tempered by the observation that the current experiments tested infants with stimuli that were somewhat different from those used in previous investigations. Although some other studies of infants' approximate number representations also used socially relevant stimuli such as faces (Cordes & Brannon, 2009a; Izard et al., 2008), many other experiments that focused on the psychophysics of infants' number representations presented simple nonsocial shapes (e.g., Xu, 2003; Xu & Arriaga, 2007; Xu and Spelke, 2000; Xu et al., 2005). Future research, therefore, should investigate whether infants' numerical representations are equally precise across a wider range of stimuli. However, at the present time, the results of the current experiments suggest that infants perform similarly with intermodal and unimodal numerical discriminations. Coupled with the previous finding that 6-month-olds who experience highly synchronized auditory and visual information experience a sharpening of their approximate number representations (Jordan et al., 2008), the current results suggest that a tight temporal link between events in two or more modalities may be required to increase numerical acuity beyond what is observed for unimodal stimuli. This conclusion is consistent with the recent observation of a benefit to early avian learning only when visual information and auditory information were temporally synchronous and not when they were presented in immediate alternation (Jaime, Bahrick, & Lickliter, 2010).

Taken together, these results add to the single existing published experiment demonstrating intermodal numerical comparison in the large number range by infants. In this way, the findings further highlight the abstract nature of preverbal representations of quantity. Rather than capturing modality-specific quantity information, representations formed by the ANS appear to signal information about items that can be seen, heard, or touched. This independence from any particular sensory modality may be instrumental in allowing children to later construct representations of symbolic numbers (Gilmore, McCarthy, & Spelke, 2007, 2010)—representations that allow us to think and communicate about quantities unbounded by the limits of immediate perception.

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