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Brief article

Intersensory redundancy accelerates preverbal numerical competence

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Abstract

Intersensory redundancy can facilitate animal and human behavior in areas as diverse as rhythm discrimination, signal detection, orienting responses, maternal call learning, and associative learning. In the realm of numerical development, infants show similar sensitivity to numerical differences in both the visual and auditory modalities. Using a habituation–dishabituation paradigm, we ask here, whether providing redundant, multisensory numerical information allows six-month-old infants to make more precise numerical discriminations. Results indicate that perceptually redundant information improved preverbal numerical precision to a level of discrimination previously thought attainable only after additional months of development. Multimodal stimuli may thus boost abstract cognitive abilities such as numerical competence.

Keywords: Numerical cognition; Multisensory processes; Cognitive development; Intersensory redundancy; Infancy

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1. Introduction

Much evidence supports the claim that preverbal infants have rudimentary numerical competence (e.g., Brannon, 2002; Brannon, Abbott, & Lutz, 2004; Jordan & Brannon, 2006; Lipton & Spelke, 2003, 2004; Xu & Arriaga, 2007; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005). For instance, seven-month-old infants can match the number of faces they see to the number of voices they hear, thus equating numerical value across sensory modalities, and six-month-old infants can discriminate between large numerical values (e.g., Jordan & Brannon, 2006; Xu & Spelke, 2000). The ability to discriminate large numerical values in infancy, however, is dependent on the ratio between the values. When six-month-old infants are habituated to visual arrays that contain 8 or 16 dots and then tested with new, alternating dot arrays of both numerosities, they look longer at the test displays with the novel numerosity (Xu & Spelke, 2000). In contrast, infants of this same age fail to discriminate 8 vs. 12 dots, suggesting that at six months, infants require a 1:2 ratio to make numerical discriminations between visual arrays (see also Xu, 2003; Xu et al., 2005).

Lipton and Spelke (2003) showed the same ratio dependence for numerical discrimination of auditory stimuli in infancy. Specifically, in a preferential head-orienting paradigm, six-month-old infants discriminated 8 vs. 16 tones but failed to discriminate 8 vs. 12 tones, suggesting that a 1:2 ratio is also necessary for auditory number discrimination at six months of age. Finally, six-month-old infants likewise require a 1:2 ratio to successfully discriminate the number of visual events (in the form of puppet jumps; Wood & Spelke, 2005). This precision with which infants make numerical discriminations increases with age such that by nine months, infants can discriminate 8 dots from 12 dots, 4 puppet jumps from 6 puppet jumps, and 8 tones from 12 tones (Lipton & Spelke, 2003; Wood & Spelke, 2005; Xu & Spelke, 2000). Collectively, such data suggest that (1) Regardless of the sensory modality in which stimuli are experienced, at six months of age infants require a 1:2 ratio for successful numerical discrimination; and (2) Between six and nine months of age, the threshold of discrimination increases from a 1:2 ratio to a 2:3 ratio.

Here, we challenge this accepted view in the infant numerical literature by asking whether the precision with which infants make numerical discriminations is enhanced if they are provided with synchronous, redundant information about number through multiple sensory modalities. When given information that is redundant across multiple senses, non-human animals and humans tested on a wide variety of non-numerical dimensions have been shown to improve in accuracy and/or reaction time, relative to performance with unisensory stimuli (e.g., Bahrick & Lickliter, 2000; Gogate & Bahrick, 1998; Lewkowicz & Kraebel, 2004; Lickliter, Bahrick, & Honeycutt, 2002; Lovelace, Stein, & Wallace, 2003; Mellon, Kraemer, & Spear, 1991; Meredith & Stein, 1983). For example, multimodal cues occurring together in time and space enhance responses of multisensory neurons in the superior colliculus of cats to a level above the responses evoked by unisensory cues; multisensory cues also produce behaviorally evident increases in cats' effectiveness at detecting, orienting towards, and approaching the cue as compared with responses to unimodal sensory cues (e.g., Meredith & Stein, 1983; Stein, Huneycutt, & Meredith, 1988). Intersensory redundancy also facilitates prenatal perceptual learning in bobwhite quail (Lickliter et al., 2002). Birds who received prenatal exposure to a patterned light paired synchronously with maternal calls better learn these calls than birds that received asynchronous, multisensory information prenatally and birds that received only auditory information prenatally. Further evidence that multisensory signals enhance learning in young animals derives from a study by Mellon and colleagues (1991) in which preweanling rats demonstrated greater behavioral suppression to a light if that light had previously been paired with a tone than if it had been presented alone.

In humans, intersensory redundancy has been shown to facilitate stimulus discrimination across the lifespan. For young human adults, presenting a light in conjunction with a sound enhances the ability to detect low-intensity sounds (Lovelace et al., 2003). Although in elderly adults sensory processes often deteriorate (e.g., Corso, 1971; Lichtenstein, 1992), multisensory presentation of stimuli has been shown to enhance discriminations. For example, in one study response times of 65 to 90-year-old adults to multisensory stimuli in a two-alternative forced-choice discrimination task were as fast as reaction times of 18 to 38-year-old adults to unisensory stimuli (Laurienti, Burdette, Maldjian, & Wallace, 2006).

Multimodal stimuli can also enhance discrimination in human infants. Five-month-old infants habituated to a multisensory rhythm were shown to discriminate a novel rhythm, while infants habituated to a unisensory rhythm were unable to do so (Bahrick & Lickliter, 2000). Similarly, three-month-old infants can differentiate between variants of tempo following bimodal but not unimodal habituation (Bahrick, Flom, & Lickliter, 2002). Intersensory redundancy in the form of synchronized vocalizations and object motion facilitated learning of arbitrary speech–object relations in seven-month-old infants (Gogate & Bahrick, 1998). These varied examples illustrate that multimodal stimuli can enhance discrimination throughout development. However, researchers have yet to investigate the effects of intersensory redundancy on the development of an abstract ability such as numerical cognition.

Here, we address this issue by asking a novel question: Does synchronous, redundant sensory information about number increase the precision with which infants make numerical discriminations? As reviewed above, previous studies have repeatedly found that six-month-old infants fail in discriminating visual arrays and auditory tone sequences of 8 vs. 12 (a 2:3 ratio). In contrast to the accepted view, we predict that this may not indicate global, steadfast signature limits of numerical precision only improved by additional neurological maturation, but rather that given synchronous, redundant information about number through multiple sensory modalities, six-month-old infants may successfully perform this 2:3 ratio discrimination. We additionally predicted that *redundant numerical* information would be necessary for this discrimination; simply giving infants numerical information through one modality paired with non-numerical stimulation through another modality would be insufficient.

2. Experiment 1: Synchronous visual and auditory numerical information

Experiment 1 tested infants' numerical discrimination of 8 vs. 12 ball bounces when each visual ball impact was synchronized with a tone.

2.1. Methods

2.1.1. Participants

Sixteen full-term six-month-old infants were tested (9 males, mean age 6 months 6 days, range: 5 months 12 days to 6 months 22 days). Four additional infants were excluded from analyses due to fussiness or parental interference.

2.1.2. Design

Infants were randomly assigned to one of two conditions. Half of the infants were habituated to audiovisual movies in which a ball dropped and bounced 8 times, while the other half were habituated to audiovisual movies in which a ball dropped and bounced 12 times. Infants were then tested with novel audiovisual movies in which a ball bounced 8 or 12 times in alternation for six trials (order counterbalanced).

2.1.3. Stimuli

Infants were habituated to audiovisual movie events of a ball that appeared to drop and then bounce up after making contact with a surface. The ball bounced 8 or 12 times in each movie, and a tone occurred with the ball impact in all habituation and test movies. Movies were constructed using Macromedia Flash and displayed on a computer within a 19×23 cm area; tones were constructed using Adobe Audition. Tones were variable in length across trials and were always half the duration of the bounce event listed in Table 1. Composite auditory and visual stimuli were then constructed using Adobe Premiere. Sound was played from a central speaker.

Temporal parameters (Table 1) were controlled following Wood and Spelke (2005). Specifically, during habituation, rate, duration, inter-event interval, and height of individual ball bounces were approximately equal for the 8- and 12-bounce sequences and were constant within trial but varied across trial. Thus, on average 12-bounce sequences lasted longer and contained more motion than 8-bounce sequences. In contrast, during test sequences, total sequence duration, cumulative height of ball bouncing, and total inter-event interval were approximately equal for the 8-bounce and 12-bounce sequence.

There were six distinct habituation sequences for 8- and 12-bounce events. The six habituation movies in each condition repeated in a random order for 16 trials or until an infant met the habituation criterion. The six test trials consisted of novel 8- and 12-bounce movies shown in alternation, and occurred randomly without replacement for the first six habituation trials.

2.1.4. Apparatus and procedure

Infants sat in a high chair 60 cm from a large monitor. The experimenter initiated each trial when the infant looked in the direction of the computer monitor. Follow-

Table 1
Parameters of habituation and test trials

	Bounce duration (ms)	Interbounce interval	Total bounce duration	Total interbounce interval	Total duration of sequence	Bounce height (cm)	Total bounce height
Test trials							
8	471	367	3768	2569	6337	10	80
12	315	233	3780	2563	6343	6.67	80
Habituation trials							
8	67	333	536	2664	3200	1	8
8	200	300	1600	2400	4000	4	32
8	333	233	2664	1864	4528	8	64
8	400	267	3200	2136	5336	7	56
8	533	200	4264	1600	5864	11	88
8	667	167	5336	1336	6672	14	112
Mean	367	250	2933	2000	4933	7.5	60
12	67	333	804	3996	4800	1	12
12	200	300	2400	3600	6000	4	48
12	333	233	3996	2796	6792	8	96
12	400	267	4800	3204	8004	7	84
12	533	200	6396	2400	8796	11	132
12	667	167	8004	2004	10,008	14	168
Mean	367	250	4400	3000	7400	7.5	90

ing the movie sequence, a static image of the last frame of the video remained on the screen for the rest of the trial. Looking time to the static frame was recorded until the infant looked away for a continuous 2 s after looking at the static image for a minimum of 1 s, or after a maximum of 60 s. The habituation phase continued until the infant met the habituation criterion, defined as a 50% reduction in looking time over 3 consecutive trials relative to the first 3 trials that summed to at least 12 s, or until 16 trials were completed. The test phase consisted of six audiovisual movies, three of which consisted of 8-bounce and three of which consisted of 12-bounce events.

A micro-camera monitoring the infant's face and a feed from the stimulus presentation computer were multiplexed onto a TV monitor and VCR. Each session was recorded for later reliability coding. An experienced experimenter blind to the experimental condition and wearing active noise-cancelling headphones playing music recorded infants' looking behavior while viewing the live video with stimulus display occluded. A second blind observer scored 75% of data via videotape without sound, and reliability was 92.7%.

2.2. Results

Fig. 1 shows the average looking time to the first and last three habituation trials and the novel and familiar test trials. On average, infants required 11.3 trials to habituate. Fourteen out of 16 infants habituated. A $2 \times 2 \times 2$ ANOVA examining

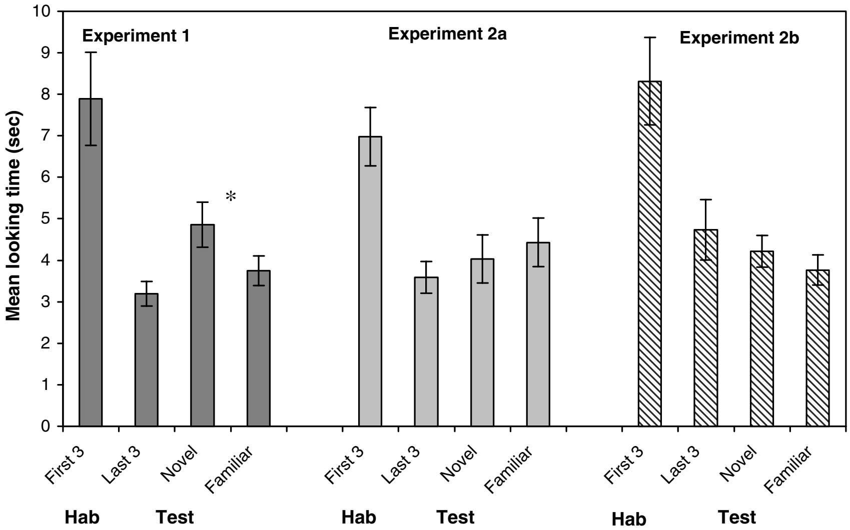

Fig. 1. Mean looking times for the first three habituation trials, last three habituation trials, test trials with novel numerosity, and test trials with familiar numerosity for Experiment 1, 2a, and 2b. Error bars represent standard error.

the effects of between-subject factors of gender and habituation condition (eight vs. twelve) and within-subject factor of test trial type (novel vs. familiar number) on infants' looking time revealed a significant main effect of test trial type, $F(1,12) = 5.69$, $p = .034$, and no other main effects or interactions (all p's $> .05$). Thus, the main finding was that infants looked significantly longer to the novel compared to the familiar test trials ($t(15) = 2.64$, $p = .0185$, Cohen's $d = .61$)[1]. Infants also looked significantly longer at the novel test trials compared to the last three habituation trials ($t(15) = 2.45$, $p = .0158$, Cohen's $d = .96$). In contrast, there was no significant difference between the last three habituation trials and the familiar test trials ($t(15) = 1.00$, $p = .331$, Cohen's $d = .20$). Fourteen out of 16 infants looked longer at the novel than the familiar number (binomial, $p < .0021$).

3. Experiment 2a: Visual numerical information only

Experiment 2a tested infants' numerical discrimination of 8 vs. 12 ball bounces that were purely visual.

[1] Results were similar when we analyzed data only from the 14 infants who habituated; in this case, $t(13) = 2.21$, $p = .0454$.

3.1. Methods

3.1.1. Participants

Sixteen full-term six-month-old infants were run in this study (7 males, mean age 6 months 5 days, range: 5 months 15 days to 6 months 14 days). Five additional infants were excluded from the analyses due to fussiness or parental interference.

3.1.2. Design

Infants were randomly assigned to one of two conditions. Half of the infants were habituated to silent movies in which a ball dropped and bounced 8 times, while the other half were habituated to silent movies in which a ball dropped and bounced 12 times. Infants were then tested with novel silent movies in which a ball bounced 8 or 12 times in alternation for six trials (order counterbalanced).

3.1.3. Stimuli

The movies used in Experiment 2a were played silently in all habituation and test movies.

3.1.4. Apparatus and procedure

All aspects of the apparatus and procedure were identical to Experiment 1. The second observer scored 75% of data via videotape, and reliability was 94.6%.

3.2. Results

Fig. 1 shows the average looking time to the first and last three habituation trials and the novel and familiar test trials. On average, infants required 10.5 trials to habituate. Eleven out of 16 infants met the habituation criterion. A $2 \times 2 \times 2$ ANOVA examining the effects of between-subject factors of gender and habituation condition (eight vs. twelve) and within-subject factor of test trial type (novel vs. familiar number) on infants' looking time revealed no main effect of novelty ($F(1,12) = .168$, $p = .68$). There were no other main effects or interactions (all p's $> .05$). Thus, our main finding was that infants did not look longer to movies that depicted the novel number of bounces compared to the familiar number of bounces ($t(15) = .15$, $p = .87$, Cohen's $d = .21$; Fig. 1)[2]. There was also no significant difference between looking time from the last three habituation trials to the novel test trials ($t(15) = 22$, $p = .83$, Cohen's $d = .13$) or the familiar test trials ($t(15) = .50$, $p = .62$, Cohen's $d = .37$). Only 8 out of 16 infants looked longer at the novel than the familiar number (binomial test, $p = .598$). These results replicate all previous studies testing the precision of infants' numerical discriminations at six months of age with unimodal stimuli.

[2] The same null effect held for the 11 infants who met the habituation criterion, $t(10) = -.219$, $p = .831$. A similar proportion of infants habituated in Wood and Spelke (2005) and Xu (2003).

4. Experiment 2b: Visual numerical information with auditory non-numerical information

Experiment 2b replicated Experiment 2a, except that classical music was played while each visual event occurred. This music did not contain synchronous numerical information; it merely started when a visual sequence started, and stopped when a visual sequence ended. Thus, infants received multisensory information, but it was not redundant *numerical* information.

4.1. Methods

4.1.1. Participants

Sixteen full-term six-month-old infants were tested (11 males, mean age 6.14 months 4.34 days, range: 5 months 17 days to 6 months 24 days). Two additional infants were excluded from analyses due to fussiness or parental interference.

4.1.2. Stimuli

The movies used in Experiment 1 were modified so that classical music instead of tones occurred with the visual stimuli in all habituation and test movies.

4.1.3. Apparatus and procedure

All aspects of the apparatus and procedure were identical to Experiment 2a. The second observer scored 69% of data via videotape, and reliability was 95.8%.

4.2. Results

Fig. 1 shows the average looking time to the first and last three habituation trials and the novel and familiar test trials. On average, infants required 11.3 trials to habituate. Thirteen out of 16 infants habituated. A $2 \times 2 \times 2$ ANOVA examining the effects of between-subject factors of gender and habituation condition (eight vs. twelve) and within-subject factor of test trial type (novel vs. familiar number) on infants' looking time revealed no main effect of novelty ($F(1,12) = .188, p = .673$). There were no other main effects or interactions (all p's $> .05$). Thus, the main finding was that infants did not look longer to movies depicting the novel number of bounces compared to the familiar number of bounces ($t(15) = .97$, $p = .34$, Cohen's $d = .13$; Fig. 1)[3]. There was also no significant difference between looking time from the last three habituation trials to the novel test trials ($t(15) = .646, p = .52$, Cohen's $d = .07$) or the familiar test trials ($t(15) = 1.31, p = .209$, Cohen's $d = .20$). Ten of the 16 infants looked longer at the novel than the familiar number (binomial test, $p = .227$). A 2×2 ANOVA with variables novel vs. familiar and no auditory vs. music stimulation revealed no effect of novelty ($F(1,30) = .102$, $p = .752$) and no condition interaction ($F(1,30) = .500$, $p = .485$). These results show that, even when given visual numerical information

[3] The same null effect held for the 13 infants who met the habituation criterion, $t(12) = .1.27$, $p = .227$.

accompanied by non-numerical auditory stimulation, infants cannot discriminate numerical stimuli occurring in a 2:3 ratio.

5. Discussion

We later replicated Experiment 1 with 16 additional infants to ensure our main results still held. After adding this second group of 16 infants to the original infants from Experiment 1, we found that infants receiving multisensory information about number still looked longer at the novel rather than the familiar number during test (($t(31) = 2.425$, $p = .021$)). A 2×2 ANOVA comparing novelty (novel vs. familiar) and experimental condition (Experiment 1 vs. 2) revealed no main effect of novelty ($F(1,62) = .407$, $p = .526$) and no interaction ($F(1,62) = 1.806$, $p = .184$). Given both of our control studies in Experiment 2 and the number of other studies that have failed to find that six-month-old infants discriminate large numbers occurring in a 2:3 ratio (Lipton & Spelke, 2003, 2004; Wood & Spelke, 2005; Xu & Spelke, 2000; Xu., 2003; Xu et al., 2005), our replication of Experiment 1 is critical.

Thus, infants successfully discriminated numerical values with a 2:3 ratio when exposed to multimodal audiovisual numerical events but not unimodal visual numerical events or multimodal events in which one modality provided non-numerical information. Our data replicate the many previous studies demonstrating that across a wide variety of unimodal stimuli, six-month-old infants fail to discriminate numerosities such as 8 vs. 12 that differ by a 2:3 ratio (Lipton & Spelke, 2003, 2004; Wood & Spelke, 2005; Xu & Spelke, 2000; Xu., 2003; Xu et al., 2005). The current results further indicate that multimodal numerical stimuli increase infants' sensitivity to numerical differences, allowing them to construct more precise representations of number.

Increased numerical precision due to the multisensory stimulation in Experiment 1 could plausibly be attributed to a variety of explanations. For example, the greater amount of information provided through multisensory stimulation could increase infants' general arousal and provide them with more information through which to compare numerical values. To discount this hypothesis, prior studies asking whether intersensory redundancy enhances cognitive, perceptual and even social development have run control conditions in which asynchronous or non-redundant multisensory information is presented to the infant (i.e., Bahrick & Lickliter, 2000; Flom & Bahrick, 2007; Lickliter et al., 2002; Lickliter, Bahrick, & Huneycutt, 2004). In all such situations, infants fail to discriminate the property being tested unless it is synchronously and redundantly specified across multiple modalities. We address this hypothesis in our current study by including our own control condition in Experiment 2b. Experiment 2b eliminates increased arousal from increased amounts of information as a possible alternative, since infants in this condition received multisensory input—including a numerical visual component and an auditory component that was not providing synchronous numerical information—and did not show facilitated numerical processing.

We argue that a more compelling explanation is that the synchronous, redundant information about *number* in Experiment 1 may have actually improved the signal strength of numerical magnitude representations, perhaps decreasing the variance of these representations in memory. In other words, the numerical intersensory redundancy could have selectively recruited infants' attention to the amodal, redundant property of number and caused more effective encoding of this property. A possible underlying mechanism for this selective attentional recruitment is an increase in neural responsiveness to redundant stimulation (e.g., Meredith & Stein, 1983; Stein et al., 1988). Previous work on the effects of intersensory redundancy in infancy in non-numerical domains suggests that this selective attentional recruitment may even occur at the expense of accurate encoding of other non-redundantly specified and modality-specific properties, such as color and pitch. It remains to be tested whether infants in Experiment 1 showed a decrement in encoding any information about modality-specific properties such as bounce height while showing increased encoding of the redundantly specified numerical property.

Another important future direction will be to determine whether the *synchrony* between the numerical information presented in these two modalities is essential for infants to make this discrimination. Currently, it is unknown whether six-month-old infants who are given visual and auditory numerical information played asynchronously would be able to discriminate 8 from 12 ball bounces. Infants in such a condition would receive the same *total amount* of multisensory numerical stimulation as they did in Experiment 1. The intersensory redundancy hypothesis, however, predicts they would fail to discriminate 8 from 12 in such a condition, due to the lack of *temporal synchrony* between numerical information from different modalities.

Finally, a caveat to our conclusions must be acknowledged. In the current report, we compare audiovisual events with visual events. It is conceivable that infants presented with audiovisual events in Experiment 1 relied solely on auditory information. We deem this unlikely, given Lipton and Spelke's (2003) prior demonstration that six-month-old infants failed to orient longer to an auditory sequence that differed in number from the familiarization sequence by a 2:3 ratio, using the numerosities 8 vs. 12. We did not attempt to replicate their experiment here. Lipton and Spelke (2003) used sounds that differed in frequency within both familiarization and test, whereas tone frequency was constant throughout our experiment. It is possible, although we believe unlikely, that infants make more precise numerical discriminations in the auditory domain when sound frequency is homogeneous. A recent study with 3 to 6-year-old children, however, showed no advantage for homogeneous over heterogenous arrays in a numerical ordering task with visual stimuli (Cantlon, Fink, Safford, & Brannon, 2007). While our current results would still demonstrate increased precision in numerical discrimination at six months of age, the explanation could no longer be attributed to intersensory redundancy. We also note that our design of controlling for continuous variables by varying some properties in habituation while holding them constant in the test phase and vice versa does not completely rule out a subject's using one such variable for discrimination. However, given the ratios of these continuous variables employed, infants would have to possess a much finer temporal discrimination ability than has previously been shown at this age with either unimodal or multimodal stimuli to do so.

It is also interesting to note that infants additionally show increased precision in *temporal* discrimination with multisensory stimulation. For example, five-month-old infants habituated to a multisensory rhythm can discriminate a novel rhythm, while infants habituated to a unisensory rhythm fail (Bahrick & Lickliter, 2000). Similarly, three-month-old infants can differentiate between variants of tempo following bimodal but not unimodal habituation (Bahrick et al., 2002). This precision also increases with age: Infants at six months successfully discriminate a 1:2 ratio but not a 2:3 ratio change in the duration of a multisensory audiovisual event, whereas by ten months infants successfully discriminate a 2:3 ratio (vanMarle & Wynn, 2006; Brannon, Suanda & Libertus, 2007). Although at first glance this developmental pathway seems markedly similar to the trend observed within the visual and auditory modalities for number, it is important to recall that all of these temporal discrimination studies used events providing redundant audiovisual information. Future studies should thus continue to explore infants' discrimination capacities for time with unimodal vs. multimodal stimuli to identify factors determining whether intersensory redundancy facilitates temporal discriminations; there may be parallel psychophysical limitations among these different types of temporal (rhythm, duration, tempo) discriminations depending on whether stimulation is unimodal or bimodal.

In sum, infants' discriminations of multimodal and unimodal numerical displays clearly do not adhere to the same ratio limit. With multisensory numerical stimuli, infants are able to make a highly precise numerical discrimination at an earlier age than previously reported. The current findings underscore the importance of using multisensory stimuli when probing the developmental trajectory of multiple cognitive domains. Attempts to identify critical thresholds of discrimination at different ages are unlikely to yield global, steadfast signature limits of competence. A crucial question for future research is whether multisensory facilitation in the field of numerical understanding can be harnessed for educational benefit across the human lifespan.

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