

Multiple visual cues enhance quantitative perception in infancy

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Abstract

Infants possess basic capabilities to assess various quantitative properties such as number, size, and time. Preverbal discriminations are approximate, however, and similarly limited by ratio across these dimensions. Here, we present the first evidence that redundant quantitative unisensory information—namely, simultaneous visual cues to both number and size—accelerates six-month-olds' quantitative competence. Using a habituation-dishabituation paradigm, results demonstrate that, when provided with synchronous visual cues to different quantitative properties, infants make more precise discriminations than when they receive information about a single cue alone. Such redundant conceptual information may be more salient than non-redundant information, which could better recruit attention and result in more precise learning and remembering than when such information is presented through only one cue.

Introduction

Even before they acquire language, infants are capable of perceiving various quantitative dimensions such as time, size, and number (e.g., Brannon, Lutz, and Cordes, 2006; Jordan, Suanda, and Brannon, 2008; Lipton and Spelke, 2003; Wood and Spelke, 2005; Xu and Spelke, 2000; Xu, 2003; Xu et al., 2005). This ability is approximate in that it follows predictions made by Weber's Law: infants' ability to distinguish between two magnitudes is a function of the ratio between the competing magnitudes (e.g., Xu, & Spelke, 2000; Bijeljac-Babic, Bertoni, & Mehler, 1993; Brannon, Abbot, & Lutz, 2004; Gao, Levine, & Huttenlocher, 2000; Izard, Sann, Spelke, & Streri, 2009). For example, six month-olds successfully distinguish a 1:2 size change of a visual object, but fail to notice a 2:3 size change (Brannon, Lutz, & Cordes, 2006). Similarly, when tested with visual stimuli, six-month-old infants require a 1:2 ratio for successful discrimination of large numerical sets, failing to discriminate a 2:3 ratio change (e.g., Wood and Spelke, 2005; Xu and Spelke, 2000; Xu, 2003; Xu et al., 2005). By 9 months of age, however, infants successfully discriminate a 2:3 change in number (Lipton, & Spelke,

2003). This pattern suggests that discrimination abilities of infants show similar perceptual and cognitive limits across various dimensions of visual quantity.

When provided with redundant information about quantity through multiple sensory modalities, however, infants' discrimination abilities improve to a level previously thought attainable only after additional months of development. For example, although six-month-old infants fail to distinguish a 2:3 ratio change in number when provided with a single visual cue to number, they succeed when given cues simultaneously in both the visual and auditory modalities (Jordan, Suanda, & Brannon, 2008). Five-month-olds discriminate differing rhythmic patterns when presented audiovisually, but fail when presented only with a cue from the auditory or visual modality alone (Bahrick and Lickliter, 2000). Similarly, 3-month-olds are capable of discriminating differing tempos only when they are presented redundantly across multiple modalities (Bahrick, Flom, and Lickliter, 2002).

This tendency for infants' perceptual abilities to improve when provided with multiple synchronous sensory cues has been explained by the Intersensory Redundancy Hypothesis (see Bahrick and Lickliter, 2000 for review). The hypothesis states that redundant stimulation from multiple sensory modalities efficiently recruits infants' attention by providing overlapping sensory information, thereby causing the redundantly specified property to become perceptual "foreground", while other sensory stimulation remains "background". This, in turn, fosters perceptual differentiation, learning, and memory for redundant, amodal properties before other unisensory, modality-specific stimulus properties.

The effect of *intratensory* redundancy on infants' cognitive abilities, however, remains to be empirically tested. Multisensory stimulation in the form of intersensory redundancy may not be the only way to boost infant quantitative competency; the multiple numerical cues provided by intersensory redundancy may be more important than the multisensory nature of the stimulation itself. Redundant conceptual information, regardless of

sensory modality, may be more salient than non-redundant information, which could better recruit attention and result in more precise learning and remembering than when such information is presented through only one cue. Here, we test the hypothesis that redundant *visual* stimuli will improve infants' quantitative discrimination abilities.

Methods

Participants

Twenty eight full-term six-month-old infants were tested (female= 14, mean age = 6 months 2 days; range: 5 months 15 days to 6 months 14 days). Participants were recruited from birth records obtained from the Utah Department of Health.

Design

Infants were randomly assigned to one of two conditions. Thirteen infants were habituated to a silent movie in which a ball bounced 8 times, while the remaining 15 infants were habituated to a silent movie in which a ball bounced 12 times. The size of the ball which bounced 8 times was exactly two-thirds the surface area of the ball that bounced 12 times. Following habituation, infants were tested with novel silent movies in which the ball bounced 8 or 12 times in alternation for six trials (order counterbalanced). The relative size difference of the balls bouncing 8 versus 12 times remained during test. Importantly, these stimuli closely mirror previous studies (see Jordan, Suanda, and Brannon, 2008 for test of 6-month-olds with these exact stimuli on number discriminations; see Brannon, Lutz, and Cordes, 2006 for test of 6-month-olds on discriminating this ratio of surface area), which demonstrated that 6-month-old infants fail to discriminate this ratio when either number or surface area are tested in isolation.

Stimuli

Infants were habituated to silent movie events of a ball that appeared to drop and then bounce up after making contact with a surface (see Jordan, Suanda, and Brannon, 2008). The size of the ball differed depending on its number of bounces: A ball which bounced 8 times (14.07 cm) covered exactly two-thirds of the total surface area as a ball which bounced 12 times (21.11 cm). The size of the individual ball was fixed and did not vary during the movie. Movies were constructed using Macromedia Flash and displayed on a computer within a 19 x 23 cm area.

Temporal parameters (Table 1) were controlled following Wood and Spelke (2005). 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. Therefore, on average during habituation 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. During the habituation phase, the six movies in each condition repeated in random order for 16 trials, or until the 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.

Table 1. Habituation and test trial parameters

	Bounce Duration (ms)	Interbounce Interval	Total Bounce Duration	Total Interbounce Interval	Total Duration of Sequence	Bounce Height (cm)	Total Bounce Height
<i>Test Trials</i>							
8	471	367	3768	2569	6337	10	80
12	315	233	3780	2563	6343	6.67	80
<i>Habituation Trials</i>							
8	67	333	536	2664	3200	1	8
8	200	300	1300	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
<i>Mean</i>	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	10008	14	168
<i>Mean</i>	367	250	4400	3000	7400	7.5	90

Surface area, circumference, and diameter remained constant within each trial type for 8 and 12 bounce videos respectively.

Surface Area (8 = 14.07cm, 12 = 21.11cm); Circumference (8 = 13.30cm, 12 = 16.28cm); Diameter (8 = 4.23cm, 12 = 5.18cm).

Apparatus and Procedure

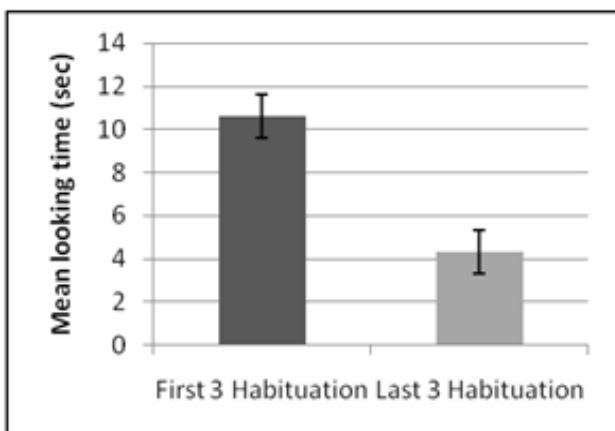
Infants sat on their guardian's lap approximately 60 cm away from a large monitor. Each test trial was initiated by the experimenter when the infant was looking in the direction of the monitor. Following the movie sequence, the last frame of the video was held fixed and remained on the screen for the remainder of the trial. Looking time to the fixed frame was recorded until the infant looked away for a continuous 2 seconds after looking at the fixed 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 silent 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. Inter-rater reliability averaged 93.63% for all infants. Twenty-five percent of infants were coded by a single trained coder.

Results

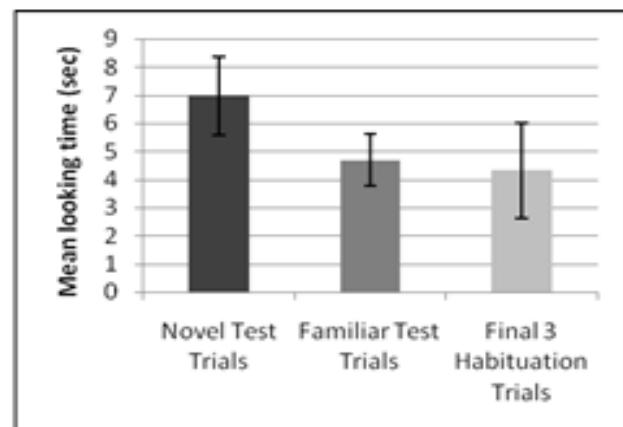
An alpha of .05 was used for all comparisons. Infants required an average of 9.68 trials to reach habituation. Twenty five of the 28 infants reached habituation before all 16 habituation trials were complete. A paired-sample *t* test indicated that infants viewed the first 3 habituation trials significantly longer than the final 3 habituation trials, $t(27) = 9.46, p < .001$, Cohen's $d = 3.71$.



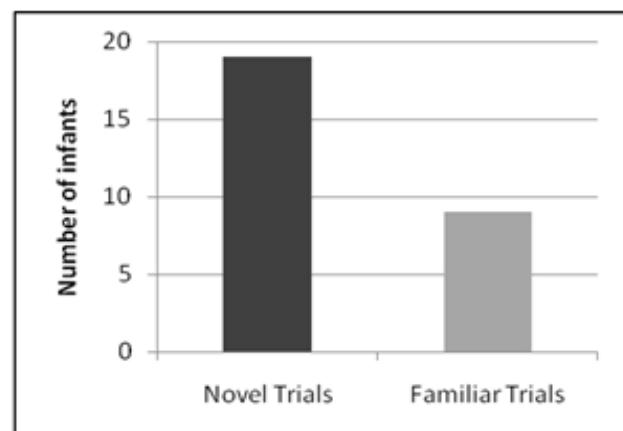
A $2 \times 2 \times 2$ repeated measures ANOVA was used to examine the relationship between the between-subject factors, gender and habituation condition (eight vs. twelve), and the within-subject factor, test trial type (novel vs. familiar). This analysis identified a significant main effect of test trial type, indicating that looking time within novel test trial types ($\mu = 6.92$ seconds) were significantly longer than looking times within familiar test trial types ($\mu = 4.62$ seconds; $F(1, 24) = 6.459, MSE = 12.02, p = .018$, Cohen's $d = .689$). No other main effects or interactions were significant.

A priori paired samples *t* test comparisons between pairs of novel and familiar test trials identified significant looking time differences between the first pair of novel and familiar test trials ($t(27) = 2.474, p = .02$, Cohen's $d = .970$), and the second pair of novel and familiar test trials ($t(27) = 2.196, p = .037$, Cohen's $d = .861$). However, looking time between novel and familiar test trials within the third pair of test trials were not significantly different ($t(27) = -.858, p = .399$, Cohen's $d = .336$). Infants looked significantly longer at novel test trials than the final three habituation trials ($t(27) = 3.26, p = .003$, Cohen's $d = 1.28$). However, looking times for familiar test trials did not differ from the

final three habituation trials ($t(27) = .641, p = .527$, Cohen's $d = .251$).



Binomial sign tests indicate that the number of infants who looked longer at novel test trial types ($n = 19$) was significantly larger than the number of infants who looked longer at familiar test trial types ($n = 9$) (sign-test, $p = .043$).



Discussion

These results demonstrate that infants' quantitative visual discriminations do not adhere to one strict ratio limit. With visual stimuli providing two simultaneous quantitative cues, six-month-old infants make more precise discriminations than previously reported in other studies when they received information about either number or surface area alone (Jordan, Suanda, and Brannon, 2008; Brannon, Lutz, and Cordes, 2006). Our experiment is therefore the first to demonstrate an increase in quantitative precision resulting from redundant information provided by synchronous visual cues.

Past research has demonstrated that multiple sources of information presented across sensory modalities must be synchronous in order to be beneficial to infant learning in various domains (Bahrick, & Lickliter, 2000). In the current experiment, the change in number and surface area occurred in synchrony; however, the change did not occur across sensory modalities. Thus, multisensory stimulation in the

form of intersensory redundancy is not the only way to boost infant quantitative competence (Jordan et al., 2008). Instead, the multiple numerical cues provided by intersensory redundancy may be more important than the multisensory nature of the stimulation itself. Redundant conceptual information, regardless of sensory modality, may be more salient than non-redundant information, which could better recruit attention and result in more precise learning and remembering than when such information is presented through only one cue.

The exact mechanism through which infants accomplish this feat remains unknown. Recent epigenetic theories suggest that infants are endowed with basic capabilities to detect and process intersensory stimuli at birth, but that experiences throughout development are necessary to enhance these abilities (Lewkowicz, 2000). These experiences may begin in utero (Kisilevsky, 1995; Schaal, Orgeur, & Rognon, 1995; Bekoff, 1995), and continue throughout infancy and into childhood (Milner, & Bryant, 1968). However, as suggested by Lewkowicz (2000) only relatively recently have studies begun acknowledging and investigating the pervasive effects of multimodal stimulation on infants' perceptual abilities.

One area that has until recently been largely overlooked are infants' abilities to learn from synchronous stimulation within a single sensory modality. In their everyday environments, it is possible that infants experience synchronous unisensory stimulation no less often than they experience synchronous multisensory stimulation. Therefore, given the proposed importance of experience on the development of perceptual capabilities, the capacity of infants to perceive synchronous unisensory cues may be similar to their capacity to perceive synchronous multisensory cues in many domains. The current results mark an initial step in better understanding how infants utilize multiple temporally and spatially synchronous cues from the same sensory modality.

Our results are the first to indicate that infants' abilities to discriminate between quantities are improved by the presentation of redundant *intratemporal* cues. Redundant visual stimulation may cause more effective encoding of quantity by selectively recruiting infants' attention to visual properties of magnitude, thereby resulting in increased neural responsiveness to synchronous, redundant quantitative information. Therefore, when given multiple synchronous intratemporal cues, infants may have experienced greater signal strength and decreased variance for their ratio-dependent quantitative representations in memory.

It is necessary, however, to investigate the physiological bases of this enhanced quantitative ability in order to clarify potential causes and correlates. Recent findings have shown promise in identifying patterns of brain activation specifically involved in numerical understanding, even in infancy (Libertus, Pruitt, Woldorff, & Brannon, 2009). It has been hypothesized that there may be similar mental algorithms and neural areas devoted to common magnitude

processing, as opposed to completely discrete, compartmentalized areas responsible for processing specific quantitative properties individually (e.g., Cantlon et al., 2009).

Much work is still needed now to determine the extent of these findings. For instance, what other synchronous visual stimulation is capable of improving infants' quantitative abilities? Do these findings generalize outside of the domain of quantity, across other amodal properties? Does discrimination of properties in other sensory modalities such as audition benefit from synchronous intratemporal presentation? To better understand the role of synchrony in producing such effects, it would also be informative in the future to provide infants with the same overall amount of information about size and number changes, but to present these changes asynchronously. These questions should be addressed before we can begin to understand the limits of infant intratemporal processing capabilities.

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