

Development of Multimodal Processing in Infancy

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A number of studies have investigated infants' abilities to extract and discriminate number from multimodal events. These results have been mixed for several possible reasons, including aspects of the experimental design that provide perceptual cues that are unrelated to number, and are known to influence looking preferences. This experiment used a preferential looking paradigm to investigate whether 6- to 9-month-old infants can extract the amodal property of number from an arbitrarily related multimodal event sequence when nonnumerical confounds are removed. Results demonstrate that female infants discriminate number from a multimodal presentation by 6 months, whereas males do so by 8 months. Further, the study underscores the importance of controlling for low-level perceptual cues in looking time experiments aimed at examining infants' cognitive abilities.

An ongoing question among developmental researchers concerns the nature and development of the ability of young infants to represent the numerosity of a set of objects or series of events. Many studies have examined infants' sensitivity to discrete numbers in purely visual displays. In those studies, infants often successfully discriminate between displays with different numbers of objects (Antell & Keating, 1983; Cordes & Brannon, 2008; Starkey & Cooper, 1980; Strauss & Curtis, 1981). However, there is evidence that this discrimination might not be based on numerosity per se, but instead is due to infants' sensitivity to stimulus attributes such as visual area of objects, magnitude of visual contrast, and so on, which are typically confounded with number (Clearfield & Mix, 1999, 2001; Feigenson, Carey, & Spelke, 2002; Newcombe, 2002). Other research has investigated infants'

ability to make numerical discriminations using multimodal events; that is, simultaneous auditory and visual presentation (Jordan & Brannon, 2006; Jordan, Suanda, & Brannon, 2008; Kobayashi, Hiraki, & Hasegawa, 2005; Mix, Huttenlocher, & Levine, 1996; Mix, Levine, & Huttenlocher, 1997; Moore, Benenson, Reznick, & Kagan, 1987; Starkey, Spelke, & Gelman, 1990). However, some of those studies also confound numerosity with other amodal (nonmodality specific), nonnumerical perceptual variables, such as rate, rhythm, tempo, or duration (Kobayashi et al., 2005; Moore et al., 1987; Starkey et al., 1990).

PREFERENTIAL LOOKING TASKS

Typically, forced-choice preferential looking tasks attempt to probe infants' discrimination abilities by simultaneously showing participants two displays differing with respect to a single critical variable, and using differences in looking time as the primary measure of interest. Starkey, Spelke, and Gelman (1983, 1990) were the first to use this method to test infants' multimodal sensitivity to number. They presented 6- to 8-month-old infants with two photographs, one with two objects and the other with three objects, and as the pictures were visible, infants heard drumbeats from a central location. Either two or three drumbeats were presented, and rate of the beats or overall sound duration were controlled for separately. Infants looked significantly longer at the display that numerically matched the auditory presentation in both constant-rate and constant-duration conditions. Starkey et al. concluded that infants represent small numerical sets in a manner not limited to a single sensory domain.

Some research, however, contradicts Starkey et al.'s results. For example, Moore et al. (1987) and Mix et al. (1997), using similar methods and same-aged infants, found that infants looked longer at the numerically unmatched visual display. Mix et al. (1997) also added conditions in which drumbeat sequences varied in rate and duration on a trial-by-trial basis, and failed to find a significant difference between looking time toward the two displays. Furthermore, Mix et al. (1996) used a matching task to examine whether 3- and 4-year-olds can judge numerical equivalence across modalities, and found that 3-year-olds performed at chance levels whereas 4-year-olds correctly identified the numerically matched display. From this, Mix et al. (1996) concluded that the ability to numerically match multimodal auditory and visual stimuli might not develop until early childhood.

Another line of preferential looking experiments, using socially relevant stimuli, supports the hypothesis that infants can match visual and auditory stimuli solely on the basis of number (Jordan & Brannon, 2006). For example, Jordan and Brannon (2006) showed infants a display of two movies; on one side was a movie of two women and on the other side a movie of three women. Simultaneously, infants heard only a single audio stream of either two or three women saying the

word "Look" repeatedly (between-subject design). This study simultaneously controlled for rate and duration of the auditory and video sequences. The results revealed that 7-month-old human infants looked longer at the display with the number of faces that numerically matched the number of voices they heard speaking. Jordan and Brannon suggested that infants' success might have hinged on the ecological relevance of the stimuli used (voices and faces), which leaves open the important question of whether infants can detect the numerical correspondence between multimodal, arbitrarily related stimuli.

VIOLETION OF EXPECTATION TASKS

Typically, violation of expectation tasks attempt to probe infants' cognition by serially showing participants a test event that is either consistent or inconsistent with an expectation formed during habituation or familiarization trials, and measuring whether infants look longer at the unexpected compared to the expected event. Wynn (1996) used this method to test infants' ability to extract number from a series of purely visual puppet jumps presented in a habituation paradigm. First, she habituated infants to a puppet jumping either two or three times, with a variable gap between jumps that resulted in different overall durations for each jump sequence. On alternate test trials, infants saw sequences with either the same or a different number of puppet jumps. Same-number sequences differed from the habituation sequence in both jump rate and duration of movement. Different-number sequences varied from the habituation sequence in either jump rate or duration of movement. Across conditions, 6-month-old infants looked significantly longer at the display with a novel number of jumps, leading Wynn to conclude that infants enumerated the events and successfully discriminated two-jump from three-jump sequences.

Recently, results from extensions of Wynn's experiment have drawn her conclusions into question. Clearfield (2004) replicated Wynn's finding and went on to test whether those results could be accounted for by discrimination of non-numerical perceptual variables, such as rate of jumping or time of motion during the jump sequence. To examine this, Clearfield's Experiment 2 habituated 5- to 7-month-old infants to either two- or three-jump events, with a variable jump rate on each trial. Test trials alternated between the familiar number and a novel number of jumps, both with a different jump rate from those presented during the habituation trials, but the same rate as each other. Infants did not look at one display significantly longer than the other, suggesting that the results of the first experiment might have been due to the change in jump rate rather than the change in number of jumps. Experiment 3 habituated 6- to 8-month-old infants to two- or three-jump events, followed by test trials that alternated between the same or a different number of jumps. In same-number test trials, the duration of puppet motion differed

from habituation, whereas in different-number test trials, the total duration of puppet movement matched habituation. Infants looked significantly longer at event sequences with a new duration of motion but the same numbers of jumps, demonstrating that under these conditions infants were more sensitive to change in amount of motion than change in number. These findings indicate that infants' looking behavior is highly sensitive to differences in perceptual attributes of the display, and suggest that infants' previous successes on numerical tasks might have been driven by nonnumerical factors.

More recently, violation of expectation experiments have been used to investigate infants' sensitivity to numerosity presented through multimodal displays. The purpose was to create displays in which matching occurred in a natural and synchronous manner, generating greater ecological validity. Kobayashi and colleagues (2005) designed a multimodal experiment similar to the purely visual paradigms of Wynn, Clearfield, and others. They used two familiarization situations: In the first, 6-month-old infants were familiarized to two or three dolls impacting the surface of a stage, each emitting a single tone at the moment of impact. The second situation was identical, except that an opaque screen was placed on the stage to completely conceal the dolls at the moment of impact. Test trials immediately followed, in which infants saw a static display containing only the screen, and heard either two or three tones at either a constant rate or constant duration. After the tones, the screen dropped to reveal either two or three dolls. In both conditions infants looked significantly longer at the nonmatching number of dolls. The researchers concluded that infants expected to see the same number of dolls as they heard tones. As in other studies, because rate and duration were not simultaneously varied, it is possible that infants' looking patterns were biased by nonnumerical factors. In this case, if during familiarization infants learned to associate the visual stimulus of greater surface area with the auditory stimulus of longer duration, they might have looked longer during test because the outcome violated this expected match, rather than an expected number.

RATIONALE FOR THIS EXPERIMENT

Researchers have demonstrated conclusively that infants' looking patterns are sensitive to both single-modality perceptual variables and amodal nonnumerical information that often covary with number. Prior studies of infants' numerical abilities have varied in the degree to which they controlled for these different confounds. We believe these discrepancies are responsible for the inconsistent results in the current literature. In this experiment, we used a preferential looking paradigm that simultaneously controlled for many of the confounding variables demonstrated to be important to test whether infants can discriminate small numerosities from multimodal, arbitrarily related stimuli. First, infants were familiarized to an audi-

tory-visual display in which anthropomorphic animals jumped twice in one location and three times in another for equal overall durations. Infants were then tested by keeping the two animals static while playing two or three tones at a novel rate and overall duration from familiarization. Because visual displays were static during test trials, there could be no confounding effect of jump rate, trial duration, or amount of motion. Therefore, infants could only have responded differentially to the sides of the display by correctly extracting the numerosity presented at each location, not by relying on low-level amodal perceptual cues.

METHOD

Participants

Sixty-eight healthy, full-term infants completed the study. They included twenty-two 6-month-olds (*M* age = 6 months, 15 days; 11 boys and 11 girls), twenty-six 7-month-olds (*M* age = 7 months, 16 days; 13 boys and 13 girls), and twenty 8-month-olds (*M* age = 8 months, 20 days; 10 boys and 10 girls). An additional 11 infants were tested but excluded from the final analysis because of failure to complete at least half of the test trials ($n = 5$), fussiness ($n = 3$), or apparatus malfunction ($n = 3$). Infants were recruited through fliers, letters to parents, and word of mouth. The Institutional Review Board approved the experimental protocol, and informed consent was obtained from a parent of each infant. Infants received a small gift (t-shirt with lab logo or a toy) for their participation.

Apparatus and Stimuli

Testing was done in a small, dimly lit testing room. Infants sat approximately 70 cm away from a dual-monitor display, either in a table-mounted infant seat (SassySeat) or in their parent's lap. Monitors were covered by a single piece of black cardboard with cutouts that allowed viewing of only the regions where the stimuli were presented. Stimuli were presented in two 11.4-cm wide and 19.0-cm high viewing areas ($9.27^\circ \times 15.18^\circ$) spaced 41 cm apart horizontally. The attention-getter stimulus was presented in a 7.6-cm square area in the center of the display. A video camera located approximately 4 cm below the center of the display was used for live observation and to record the infant's face for offline coding.

Familiarization stimuli consisted of movies of anthropomorphic cartoon animals jumping up and down in place, with a synchronized chord that played from the start of each jump until the animal landed back down on the surface. Test stimuli were a single frame of each animal standing stationary on the surface accompanied by the test tones. A set of six anthropomorphic characters (pig, panda, koala, brown bear, Pooh bear, and fox) were created and animated in Poser 5 (Curious

Labs) and three unique computer-generated chords were added using Adobe Premiere Pro 2.0. Animals were 6.4 cm wide by 8.9 cm high, and were paired with another animal in such a way to ensure that the two were distinguishable from each other yet matched on nonnumerical perceptual variables that might influence looking behavior, such as shape, surface area, and overall mean luminance (koala with panda, Pooh bear with pig, and fox with brown bear). Participants heard the audio sequence through two standard computer speakers concealed behind the monitors. Between trials the experimenter played the attention-getter video, which consisted of a colorful spinning ring paired with a cowbell tone, until the infant redirected his or her attention toward the center of the display. Programming and presentation of the task were accomplished using the software package Presentation 9 (Neuro-behavioral Systems).

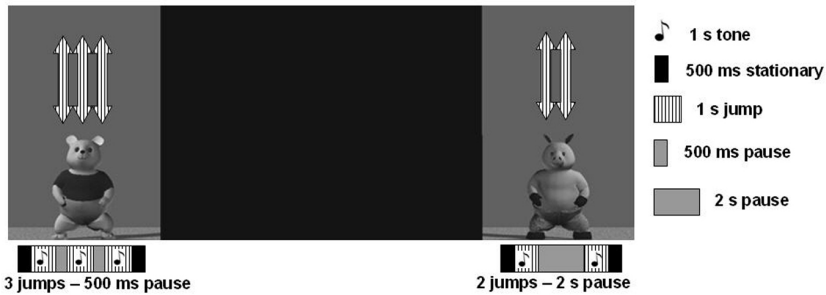
Design

The following experimental procedure was repeated three times per infant. Each repetition is referred to as a trial set, and involved a different pair of animals and a different auditory chord. Each trial set consisted of six familiarization trials and two test trials. In this manner, every infant saw a total of 18 familiarization trials and six test trials.

Familiarization trials. Each trial set began with six familiarization trials, three on each side in alternating sequence. This began with either a two-jump sequence on the right monitor or a three-jump sequence on the left monitor, initial side randomly determined. At the start of each trial, the animal stood stationary for half a second, after which it began a sequence of 1-sec jumps (.5 sec up, .5 sec down), with a tone lasting for the entire 1-sec jump duration. After the last jump of the sequence, the character remained on the screen for half a second before disappearing. Two-jump familiarization sequences involved a 2-sec silent gap between each jump (long pause), and three-jump sequences involved a silent gap of 500 msec between jumps (short pause). Both two- and three-jump sequences lasted a total of 5 sec, providing infants with equal durations to visually examine each stimulus (see Figure 1).

Test trials. Following familiarization trials, infants were presented with two identical test trials representing a single numerosity, separated by the attention-getter video to direct infants' attention to the center of the screen. During the entire duration of the test trials the two familiarization animals stood stationary on their respective sides of the screen. After a half-second delay, infants heard a two-tone or three-tone audio sequence played at a novel rate and novel overall duration. Test sounds consisted of a two-tone short-pause sequence (lasting 3.5 sec) or a three-tone long-pause sequence (lasting 8 sec). Following the tone, the animals remained sta-

A.



B.

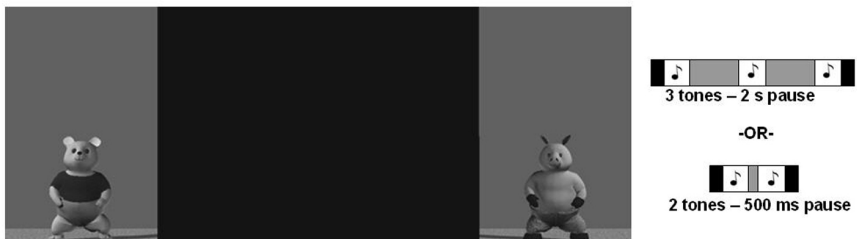


FIGURE 1 Schematic of experimental procedure using Pooh-bear and pig pairing. Familiarization jump sequence (a) and test trial display with auditory sequence only (b). Actual visual stimuli were in color and did not include arrows.

tionary on the screen for 6 additional sec, during which infants' looking time was measured. Pairs of identical test trials were counterbalanced such that numerosity (2 or 3) and therefore side of numerical match (right or left) appeared in alternating order (see Table 1 for possible order combinations). Figure 1 illustrates one example of familiarization and test trials presented in the experiment.

Coding

Test sessions were captured and digitized from videotape using Adobe Premiere Pro 2.0, and coded offline using Noldus Observer 5.0 software. Infants' looking during the 6 sec of silence following each auditory sequence was coded as either toward the left side, right side, center of the display, or away from the display. Because the positions of the left and right stimuli were separated by a large distance, distinguishing the side of fixation was fairly unambiguous. The coder was blind to familiarization and test trial order, and to numerosity of the test sequences. A second blind observer coded 25% of the test sessions, and mean interobserver reliability was .92.

TABLE 1
Familiarization and Test Trial Orders

	<i>First Trial Set</i>	<i>Second Trial Set</i>	<i>Third Trial Set</i>
Order 1			
Familiarization start side	Right	Right	Right
Test trial match side	Right	Left	Right
Order 2			
Familiarization start side	Right	Right	Right
Test trial match side	Left	Right	Left
Order 3			
Familiarization start side	Left	Left	Left
Test trial match side	Right	Left	Right
Order 4			
Familiarization start side	Left	Left	Left
Test trial match side	Left	Right	Left

Note. Each infant was assigned to one of the four orders shown.

RESULTS

Looking time differences between the numerically matched and unmatched sides were analyzed using a series of repeated measures analyses of variance (ANOVAs). Because of our limited sample size, it was not feasible to include all variables in an omnibus test. For that reason we first examined whether there was an effect of familiarization start side and test match side on infants' looking behavior. In this $2 \times 2 \times 2$ analysis, numerical match (matched or unmatched) was a within-subjects variable, whereas familiarization start side (left or right) and test match start side (left or right) were between-subject variables. A significant main effect of numerical match emerged, $F(1, 64) = 3.858, p < .05, \eta^2 = 0.057$, in which infants looked longer at the numerically matched side of the display ($M = 2.162, SD = 0.703$) than the numerically unmatched test side ($M = 1.921, SD = 0.691$); however, as expected, no effect of familiarization start side or test match side was found. These results show that infants were able to discriminate the numerically matched and unmatched locations, regardless of familiarization and test trial orders. Consequently, those factors were excluded from subsequent analyses, allowing sufficient power for further analyses of our variables of interest.

To explore the variables of interest, we ran a separate $2 \times 3 \times 2 \times 3$ ANOVA using numerical match (matched or unmatched), trial set (1, 2, or 3), sex (male or female), and age group (6-, 7-, or 8-month). This yielded two significant main effects, two significant two-way interactions, and one significant three-way interaction. The main effect of numerical match was again significant, $F(1, 60) = 5.599, p < .05, \eta^2 = 0.085$, as was the main effect of trial set, $F(2, 59) = 3.311, p < .05, \eta^2 =$

0.101. Post-hoc comparisons (simple effects *t* tests) indicated infants looked longer in the first ($M = 2.21$, $SD = 0.934$, $p < .05$) and second trial set ($M = 2.12$, $SD = 1.200$, $p < .05$) compared to the third ($M = 1.85$, $SD = 1.350$), most likely an effect of boredom or fatigue near the end of the task. Because there was no significant interaction between numerical match and trial set, we are able to rule out the presence of a learning effect wherein infants showed increased ability to numerically match across test trials. A strong two-way interaction between numerical match and sex emerged, $F(1, 60) = 12.520$, $p < .001$, $\eta^2 = .173$, revealing that female infants looked longer at the matched ($M = 2.34$, $SD = 0.771$) than unmatched ($M = 1.73$, $SD = 0.585$) side of the display, whereas male infants looked slightly longer at the unmatched side of the display ($M = 2.11$, $SD = 0.744$) than at the matched ($M = 1.98$, $SD = 0.586$). Another two-way interaction was found between numerical match and age, $F(2, 60) = 3.263$, $p < .05$, $\eta^2 = 0.098$, indicating that across both sexes, 6-month-olds exhibited approximately equal looking to the matched ($M = 2.19$, $SD = 0.756$) and the unmatched ($M = 2.27$, $SD = 0.805$) sides of the display, whereas both 7- and 8-month-old infants looked longer at the matched side than the unmatched side (7-month: matched $M = 2.06$, $SD = 0.723$; unmatched $M = 1.85$, $SD = 0.631$; 8-month: matched $M = 2.26$, $SD = 0.631$; unmatched $M = 1.68$, $SD = 0.526$). Finally, a significant three-way interaction between numerical match, sex, and age emerged, $F(2, 60) = 3.047$, $p < .05$, $\eta^2 = 0.10$, in which girls looked significantly longer at the numerically matched side at all ages, but boys did so only at 8 months of age. This three-way interaction is shown in Table 2 and represented graphically in Figure 2.

To further explore this numerical match, sex, and age interaction, we conducted a series of follow-up one-sample *t* tests to compare infants' relative pref-

TABLE 2
Mean Looking Time (Standard Deviation) to the Numerically Matched
and Unmatched Display, Number of Subjects who Matched, and Matched
Preference Score (Standard Deviation) by Age Group and Sex.

Age	Sex	Looking Time		Number who Matched	Matched Preference Score
		Matched	Unmatched		
6-month	Female	2.57 (0.77)*	1.87 (0.54)	7/11	.57 (.101)*
	Male	1.81 (0.54)	2.56 (0.89)	3/11	.41 (.155)
7-month	Female	2.25 (0.91)*	1.69 (0.57)	10/13*	.58 (.106)*
	Male	1.88 (0.44)	2.01 (0.66)	5/13	.49 (.113)
8-month	Female	2.21 (0.57)*	1.63 (0.67)	10/10**	.56 (.098)*
	Male	2.31 (0.71)*	1.74 (0.35)	8/10**	.57 (.061)**

Note. Looking times are given in seconds. Matched preference scores were calculated by dividing infants' looking time to the matched display by their overall looking time.

* $p < .05$. ** $p < .01$.

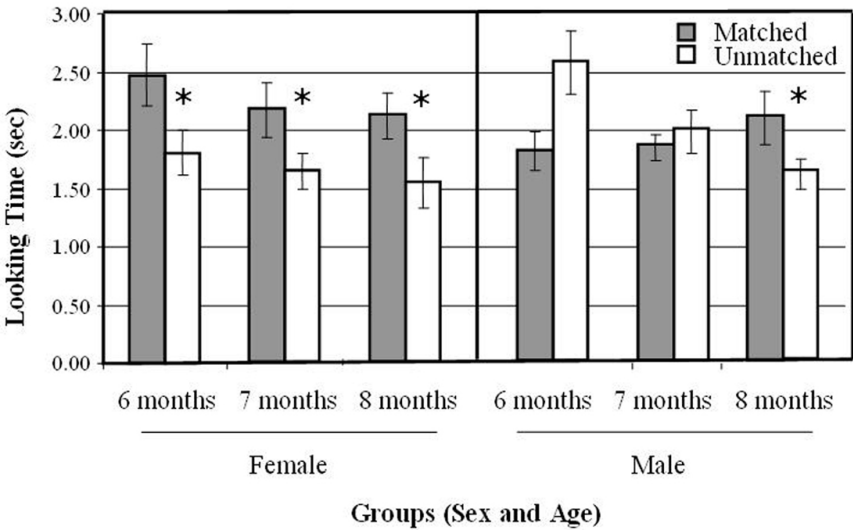


FIGURE 2 Mean looking time and standard errors to the numerically matched and unmatched sides of the display across all test trials, grouped by sex and age. * denotes $p < .05$.

erence for the matched versus unmatched location. A match preference score was calculated for each infant by dividing the time spent looking at the matched location by the time spent looking at the matched and unmatched location. Consistent with the preceding analyses, 6-, 7-, and 8-month-old female and 8-month-old male infants had significantly greater match preference scores compared to chance (0.5). The number of infants with a match preference score greater than chance and the mean preference scores by age group and sex are presented in Table 2

DISCUSSION

This study used a preferential looking paradigm to investigate whether 6- to 9-month-old infants can succeed at representing small numerosities presented through auditory and visual sensory modalities when amodal nonnumerical cues are removed. The results demonstrate that 6-, 7-, and 8-month-old female infants looked longer at the numerically matched side of the display during the test trials, whereas only 8-month-old boys looked longer at the numerically matched side. Because the task was carefully designed to control for nonnumerical variables, we are confident in concluding that infants' looking behavior was guided by the numerical information within the auditory-visual sequences of the familiarization tri-

als. This demonstrates that female infants are capable of discriminating between small, multimodally presented numerosities by 6 months and that male infants can do so by 8 months.

The task was designed to eliminate confounding perceptual cues known to influence looking time, making it unlikely that infant discrimination was based on nonnumerical attributes. First, two- and three-jump sequences varied within each modality in both rate and overall duration between familiarization and test trials, to ensure that infants' preference for the matched side could not have been based on these factors. Second, the static display shown during the test trials removed any chance that infants could visually discriminate the sides of the display based on the differences in physical features or amount of motion of the stimuli. Rather, a visual preference for the numerically matched side must have been guided by the numerical information extracted from the preceding familiarization trials.

Researchers have previously argued that infant behavioral responses to auditory-visual events might be sensitive to quantitative differences in stimulation within and between modalities, so another important aspect of this experimental design was that cues related to level of stimulation were eliminated. For example, it has been suggested that infants seek the most moderate level of stimulation across modalities, considered to be a product of the infants' internal state of arousal and properties of the stimulus. This view originates from the observation that young infants exhibit a differential response to auditory (or visual) stimuli varying in level of stimulation following exposure to visual (or auditory) stimuli of a fixed level of stimulation (Lawson & Turkewitz, 1981; Lewkowicz & Turkewitz, 1980, 1981; Moore, 1995). Accordingly, this interpretation has been offered to explain results from previous studies of multimodal numerical processing demonstrating that infants prefer the numerically unmatched display (Mix et al., 1997; Moore et al., 1987) by reasoning that infants who heard three tones were more likely to prefer the visual stimulus containing two objects. Another viewpoint states that in certain multimodal experimental conditions, infants preferentially match stimuli across modalities that are of equivalent levels of stimulation (Rose & Ruff, 1987; Turkewitz, Gardner, & Lewkowicz, 1984). In experiments specifically testing numerical processing, numerosity was often confounded with level of stimulation such that infants might have matched the more stimulating of two sounds with the more stimulating of two sights (Kobayashi et al., 2005; Starkey et al., 1983, 1990).

Although differences in level of stimulation most likely served as a confounding amodal nonnumerical cue in some previous experiments of multimodal numerical processing, we reason that they cannot account for the data obtained from our experiment, from the perspective of either the optimal or equivalent stimulation hypothesis. Given that our experiment involved test trials in which static visual stimuli were matched on nonnumerical attributes, infants were not given the

opportunity to perform a relative judgment of which visual stimulus would elicit a more moderate level of stimulation across modalities. Therefore, there is reason to believe that across test trial sets, and counterbalanced for numerically matched side, infants did not find one animal character more or less stimulating than the other. Moreover, if infants had used memory to rely on the representations formed during familiarization to subsequently seek the ideal level of stimulation during test, the data should have revealed that infants looked longer at the unmatched location. The results obtained across age groups and both sexes, however, do not support this argument as an explanation for the data. Thus, we are confident in concluding that infants' visual preference for the matched side was not contingent with the optimal stimulation hypothesis. Likewise, the findings cannot be explained on the basis of matching levels of stimulation between the visual and auditory modalities. The task was designed such that the ratio of stimulus time in each modality relative to the overall duration of the trial (or any other such derived variable) was different for the two numbers and changed from familiarization to test trials. For instance, during familiarization trials, infants were exposed to both 2 and 3 sec of jump and tone time over an equal duration of 5 sec, corresponding to 0.4 and 0.6 relative amounts of stimulation, respectively. Based on this, the three-jump sequence provided a greater extent of stimulation compared to the two-jump sequence. The opposite was true during the test trials, where the two-jump sequence provided a greater extent of stimulation (0.57) than the three-jump sequence (0.375), per unit time. The hypothesis that infants match multimodal stimuli based on equivalent levels of stimulation would predict that infants' visual preference should have been to the numerically unmatched location. Thus, it is unlikely that infants based their looking behavior on equal levels of stimulation, rather than on number.

The process by which infants are able to extract number from multimodal tasks is not entirely understood. Some have argued that infants make one-to-one correspondences between auditory and visual stimuli, suggesting that number is extracted separately from each modality and only afterward compared for equivalence (Starkey et al., 1990). An alternative explanation is that multimodal numerical matching is one of many skills that relies on shared spatial location (Lawson, 1980; Neil, Chee-Ruiter, Scheier, Lewkowicz, & Shimojo, 2003; Richardson & Kirkham, 2004) and temporal synchrony (Bahrick, 1983, 1994; Bahrick & Lickliter, 2002; Bahrick, Lickliter, & Flom, 2004; Flom & Bahrick, 2007; Gibson & Pick, 2000; Jordan et al., 2008; Lewkowicz, 1996, 2000; Lickliter & Bahrick, 2001) to bind auditory and visual events; that is, intersensory redundancy between modalities facilitates the extraction of an integrated multimodal representation, in this case, of number. One important way in which these two explanations differ is that the one-to-one correspondence hypothesis predicts that unimodal matching tasks would be easier than multimodal matching tasks, whereas the intersensory redundancy hypothesis predicts multimodal tasks should be easier. Intersensory

redundancy has been supported by evidence showing that infants succeed in perceptual, cognitive, and social tasks when information is presented multimodally, but not when it is limited to a single sensory domain. For example, in a perceptual task, 3-month-old infants successfully detect differences in the tempo of an object's impact on a surface in multimodal presentations, but not unimodal ones (Bahrick, Flom, & Lickliter, 2002); in a cognitive task, 10-month-old infants successfully individuate objects when those shown were associated with a known verbal label, but not when the objects shown had no label associated with them (Rivera & Zawaydeh, 2006); and within the social domain, the ability to discriminate emotional expressions from multimodally presented information emerges before the ability to discriminate emotion from unimodal auditory or visual information (Walker-Andrews, 1997). Further, there is good evidence that intersensory redundancy supports infants' ability to predict the temporal sequences of presented objects (Kirkham, Slemmer, & Johnson, 2002) and identify word boundaries (Christiansen, Allen, & Seidenberg, 1998).

Together with the recent findings of Jordan et al. (2008), this study provides evidence that intersensory redundancy may facilitate multimodal processing of number. Whereas Jordan et al. (2008) showed that infants are aided by intersensory redundancy when discriminating large numbers (8 vs. 12), this study extends their finding by demonstrating that when provided with multimodal, temporally synchronous numerical information, the same is true for the discrimination of small numbers (2 vs. 3). Although our study does not directly test the intersensory redundancy prediction that a task providing multimodal information should be easier than one presented unimodally, we have reason to believe it unlikely that infants relied on purely auditory (number of tones) or visual (number of jumps) information to succeed in this task. First, because the auditory stimuli always came from a centralized speaker location, infants must, at minimum, have associated the number within the auditory sequence with a visual stimulus at a given location, indicative of an intermodal association. Hence, successful behavior during the test trials could not have been accomplished without matching numerosity within the auditory stimulus with a specific visual location. This design allows us to rule out the possibility that infants simply associated a tone with a number, independent of visual information. Furthermore, previous research has established that for purely visual presentations, infants fail to discriminate two from three when confounding stimulus attributes such as visual area of objects, magnitude of visual contrast, and amount of motion are removed (Clearfield & Mix, 1999, 2001; Feigenson et al., 2002; Newcombe, 2002). Similarly, there is evidence that 9-month-old infants cannot discriminate between purely auditory sequences of two versus three (Lipton & Spelke, 2004). We believe infants may have succeeded in our task, although they failed at these other tasks, in part because our perceptual controls eliminated factors that could obscure the numerical intersensory redundancy. An interesting question for future research is whether infants are also able to make numerical dis-

criminations using asynchronous multimodal information or whether, as proposed by Lewkowicz and others, infants first develop the ability to unify multimodal information through temporal synchrony, and it is not until later that the ability to detect asynchronous relations emerges.

The interaction between sex and age reveals that female infants looked longer toward the numerical match at a younger age than did male infants. This result is consistent with similar sex differences found in other studies. Although the majority of infant studies do not find a sex difference, those that do, often find an advantage for female infants. For example, female infants' looking behavior seems sensitive to violations in the physical properties of objects, including object permanence and collision, earlier than male infants (Baillargeon, 1995; Baillargeon & DeVos, 1991; Kotovsky & Baillargeon, 1994). Additionally, Moore and Cacas (2006) tested a version of Wynn's (1992) addition and subtraction experiment and found longer looking at the incorrect results only for the female infants in their sample, whereas the male infants tended to be influenced by their familiarity with the test displays. This study provides further evidence that female infants might be precocious in their acquisition of some early cognitive abilities.

CONCLUSIONS

Consistent with previous studies, our results support the conclusion that by 8 months of age infants are able to extract and represent small numerosities from a multimodal event (Jordan & Brannon, 2006; Kobayashi et al., 2005; Starkey et al., 1983, 1990), and further demonstrate that female infants can do so as early as 6 months. By designing a paradigm in which the influence of single-modality and amodal nonnumerical perceptual variables known to affect infants' looking behavior was removed, we demonstrate that infants' preference for the matched displays was driven by differences in numerosity alone. This study underscores the importance of implementing careful experimental controls when examining perceptual or cognitive abilities in infants.

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