# Temporal discrimination increases in precision over development and parallels the development of numerosity discrimination

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## Abstract

Time perception is important for many aspects of human behavior, and a large literature documents that adults represent intervals and that their ability to discriminate temporal intervals is ratio dependent. Here we replicate a recent study by vanMarle and Wynn (2006) that used the visual habituation paradigm and demonstrated that temporal discrimination in 6-month-old infants is also ratio dependent. We further demonstrate that between 6 and 10 months of age temporal discrimination increases in precision such that by 10 months of age infants succeed at discriminating a 2:3 ratio, a ratio that 6-month-old infants were unable to discriminate. We discuss the potential implications of the fact that temporal discrimination follows the same developmental progression that has been previously observed for number discrimination in infancy (Lipton & Spelke, 2003).

## Introduction

A large literature documents that nonhuman animals and adults represent time similarly (for reviews see Gibbon & Allan, 1984; Gibbon, Malapani, Dale & Gallistel, 1997; Meck, 2003). Species such as rats, mice, or pigeons can be trained to discriminate or reproduce temporal intervals and the signatures of their performance are common to adults tested in the same procedures. A ubiquitous finding across species is that timing behavior shows scalar variability. The scalar property has been interpreted as evidence that the variability (standard deviation) in temporal representations increases linearly with the mean of the interval being represented.

Very little research has addressed the development of timing abilities in humans. A handful of studies examined temporal discrimination in school-aged children (e.g. Droit-Volet, 2002; Droit-Volet, Clement & Wearden, 2001; Droit-Volet & Wearden, 2001) and revealed similarities in temporal discrimination between children, adults and nonhuman animals. In contrast, research with infants has often focused on showing conditioned responses to arbitrary periodicities (e.g. Clifton, 1974; Colombo & Richman, 2002; Demany, McKenzie & Vurpillot, 1977; Fitzgerald & Brackbill, 1968; Rivière, Darcheville & Clément, 2000; Trehub & Thorpe, 1989). Other studies indicate that infants are sensitive to temporal structure in both the auditory and visual modalities (e.g. Lewkowicz, 1989, 2000). Furthermore, a recent study by Lewkowicz (2003) demonstrated that between 4 and 10 months of age infants discriminate between audiovisual rhythms and that by 10 months of

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age infants notice when the intersensory temporal synchrony of a rhythmically uttered syllable is disrupted (see also Friedman, 2002).

Recently, vanMarle and Wynn (2006) used a visual habituation procedure to study temporal discrimination in 6-month-old infants. Their results show that temporal discriminations in infancy are ratio dependent which is consistent with the idea that temporal intervals may be remembered with scalar variability (i.e. the standard deviation in the remembered durations may increase linearly with the intervals represented). In their study infants were habituated to a puppet of 'Sylvester the Cat' that danced and emitted a tone for a given duration and were then tested with the same puppet dancing and sounding for the habituated duration or a novel duration. They found that infants looked longer at the static puppet that had danced/ sounded for the novel duration when the values differed by a 1:2 ratio. When the novel and familiar values differed by a 2:3 ratio infants showed no novelty effect. Successful discrimination of the 1:2 ratio and failure at the 2:3 ratio was found at two different sets of absolute values, strongly supporting the claim that temporal discrimination is dependent on the ratio and not the linear distance between intervals.

Interestingly, 6-month-old infants also require a 1:2 ratio to make numerical discriminations in both the auditory and visual modalities (Xu & Spelke, 2000; Lipton & Spelke, 2003). This parallel is particularly relevant because the *mode-control model* (Meck & Church, 1983), developed to explain counting and timing in rats, proposes a single representational system for number and time. In their landmark study, Meck and Church (1983) provided four sources of evidence that number and time are represented via a single mechanism and using a single interchangeable currency. First, rats spontaneously encoded both time and number when the two variables covaried. Second, the psychological midpoint between two anchor values (e.g. 2 s vs. 8 s and a count of 2 vs. 8) was at the geometric mean for both time and number. Third, when rats were administered methamphetamine (a dopamine agonist), they behaved as if the pacemaker increased in speed and thus required fewer counts and shorter durations to classify a stimulus as many or long as opposed to fewer or short. Finally, rats trained to classify a single tone as short or long transferred the discrimination to number (few vs. many) as if a count were equivalent to 200 ms. Collectively, these findings were interpreted as evidence that number and time are represented with a common currency.

More recent work, however, has suggested that there may be important asymmetries between counting and timing in rats and pigeons (e.g. Breukelaar & Dalrymple-Alford, 1998; Roberts, Roberts & Kit, 2002). The basic idea that animals may use a common mechanism to count and time is still largely supported; however, there is some suggestion that timing may occur more automatically than counting in some circumstances (e.g. Breukelaar & Dalrymple-Alford, 1998; Roberts *et al.*, 2002). In addition, the argument that rats transfer discriminations from the temporal to the numerical domain has been challenged (Balci & Gallistel, in press).

Similar studies to address whether human infants use a common mechanism to time and count have yet to be conducted. However, recent findings by vanMarle and Wynn (2006) demonstrating that 6-month-old infants require a 1:2 ratio to discriminate temporal intervals are consistent with this idea because infants require the same 1:2 ratio to discriminate numerical differences (Lipton & Spelke, 2003; Xu & Spelke, 2000). Similar levels of discrimination for time and number may imply similar levels of precision in the underlying representations of time and number and thus implicate a common currency.

In the case of number, Lipton and Spelke (2003) found that between 6 and 9 months of age infants' discrimination abilities increased in precision so that by 9 months of age infants were able to discriminate large numerical values that differed by a 2:3 ratio. If infants use a

common mechanism or representational currency for time and number then we should expect to see the same developmental changes in timing precision as has been observed in numerical representation.

## Experiment 1

The goal of the first study was to replicate the finding by vanMarle and Wynn (2006) that 6-month-old infants succeed at discriminating a 1:2 ratio in temporal intervals. We replicated their procedure except that stimuli were digital movies displayed on a computer monitor and a distinct set of absolute values were used.

### Method

**Participants**—Participants were 16 healthy full-term 6-month-old infants (mean age = 5 months 28 days, range: 5 months 11 days–6 months 11 days). Data from an additional three infants were discarded because of fussiness resulting in failure to complete at least four test trials. Five of the participants were female.

**Apparatus**—Infants were seated in a high-chair (or on a parent's lap) 60 cm from a computer monitor resting on a stage surrounded by blue fabric. Parents were seated next to their infants and instructed to keep their eyes closed and to refrain from talking to, touching, or otherwise interacting with their infant for the duration of the experiment. If an infant became fussy, the experimenter initiated a short break and then resumed the experiment. For an infant to remain in the final sample the break must have been less than 1 minute in duration and could not occur during the test phase.

A microcamera monitoring the infant's face and a feed directly from the stimulus presentation computer were multiplexed onto a TV monitor and VCR. An experienced experimenter blind to the experimental condition recorded the infants' looking behavior while viewing the live video with the display occluded. The experimenter listened to music through active noise-canceling headphones and was therefore unaware of the trial type being presented to the infant. A second observer blind to the condition scored 50% of the data via videotape, and reliability was 93%.

**Stimuli**—A digital video was created showing a puppet of a cow opening and closing its mouth (see Figure 1). The video consisted of three parts; the puppet motionless with mouth closed for 500 ms, the cow opening its mouth (330 ms), and finally the static image of the cow with the mouth open, which had a variable duration dependent on condition. The video was then altered so that the opening of the mouth was played in reverse direction to establish a mouth-closing event that was the exact reverse of the mouth-opening event. The duration of the static mouth open event was altered to be 840 ms and 2340 ms, using Adobe Premiere (Adobe Systems Incorporated, San Jose, CA). The auditory component of the stimulus consisted of three parts: an on-set and an off-set of the moo which lasted 350 ms each and a middle portion that was 800 or 2300 ms. This produced two videos with a total duration of 1.5 s or 3 s intervals.

Half the infants were habituated to the short duration and half to the long duration video. All infants were tested with six test trials that alternated between familiar and novel duration videos. The order of novel and familiar test trials was counterbalanced across infants.

**Procedure**—Informed consent was obtained from a parent of each participant before testing. The experimenter initiated trials when the infant looked in the direction of the computer monitor. The animated video of the cow opening its mouth, emitting a sound and then closing its mouth was played at the beginning of each trial. The static image of the last

frame of the video showing the cow puppet with its mouth closed then remained on the screen for the remainder of the trial. Recording of looking time began when the video sequence was completed. Thus looking time measures reflect infants' looks to the static cow puppet after it completed the open mouthed vocalization. Each trial continued until the infant looked at the static cow image for a minimum of 1 s and ended after the infant looked for a total of 60 s or looked away for a continuous 2 s. The habituation stimuli were presented until the infant met the habituation criterion (a 50% reduction in looking time over three consecutive trials, relative to the first three trials that summed to at least 12 s) or until 20 trials were completed.

## Results and discussion

Figure 2 shows mean looking time for the first three habituation trials, the last three habituation trials, the novel and the familiar test trials. Fifteen of the 16 infants met the habituation criterion and on average infants required 10.1 trials to habituate.

Infants successfully discriminated durations that differed by a 1:2 ratio. A $2 \times 2 \times 2$ mixed-factor ANOVA testing the between-subjects factors of habituation condition (short vs. long) and gender and the within-subjects factor of test trial type (novel or familiar duration) on infants' looking time yielded a significant main effect of trial type, $F(1, 12) = 6.22$, $p < .05$, and a significant interaction between gender and trial type, $F(1, 12) = 4.83$, $p = .05$. The interaction between trial type and gender was a result of males looking longer at the novel test trials compared to females.[1]

Further, a paired $t$-test revealed that infants looked significantly longer at the novel (8.6 s) compared to the familiar test trials (5.8 s), $t(15) = 3.48$, $p < .01$. This finding remained true when the infant who failed to meet the habituation criterion was excluded from analysis, $t(14) = 3.11$, $p < .01$. Twelve of the 16 infants preferred the novel test trials (Binomial, $p < .05$). Finally, infants showed a dishabituation effect to the novel test trials, looking longer at the novel test trials compared to the last three habituation trials (4.5 s), $t(15) = 3.59$, $p < .01$, but did not recover looking time to the familiar test trials, $t(15) = 1.76$, $p = .01$.[2]

These findings are consistent with results reported by vanMarle and Wynn (2006), which showed that 6-month-old infants succeeded at discriminating both .5 vs. 1 and 2 vs. 4 s.

## Experiment 2

Experiment 1 replicated results from vanMarle and Wynn (2006) and found that 6-month-old infants successfully differentiate temporal intervals that have a 1:2 ratio. Our main question was whether temporal discriminations would improve over development. Thus in the next experiment we tested 6- and 10-month-old infants in the same task using values that differ by a 2:3 ratio. Based on vanMarle and Wynn's finding, we predicted that 6-month-old infants would be unable to discriminate a 2:3 ratio in temporal intervals. However, if temporal discrimination follows the same developmental trajectory as number discrimination, then we should find that by 10 months of age infants can discriminate durations that differ by a 2:3 ratio.

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[1]Although there was an interaction between gender and trial type in this sample, it is important to note that no such effect was found in Experiments 2 and 3. In addition we conducted a $3 \times 2 \times 2$ ANOVA on the between-subjects factor of Experiment (1, 2, or 3) and gender and the within-subject factor of test trial type and found a main effect of gender, $F(1, 58) = 6.19$, $p < .05$, due to longer looking overall by males than females and no other significant interactions with gender ($ps > .1$).
[2]There were 8 data points out of a total of 384 data points that exceeded 3 standard deviations above the mean looking time for the sample. We did not exclude outliers for any experiment reported in this paper because the main results did not differ when outliers were excluded.

## Method

**Participants**—Participants were 16 healthy full-term 6-month-old infants (mean age = 6 months 3 days, range: 5 months 21 days–6 months 16 days) and 16 healthy full-term 10-month-old infants (mean age = 9 months 27 days, range: 9 months 14 days–10 months 15 days). Six of the 6-month-old infants and eight of the 10-month-old infants were female. Data from an additional six infants were discarded because of fussiness resulting in failure to complete at least four test trials. A second observer blind to the condition scored 50% of the data via videotape, and reliability was 96%.

**Procedure, apparatus and stimuli**—All aspects of the procedure, apparatus, and stimuli were identical to that used in Experiment 1 with the following exceptions. Half the infants in each age group were tested with 1 vs. 1.5 s and half the infants were tested with 2 vs. 3 s. Half the infants in each absolute value condition in each age group were habituated to the short duration and half to the long duration video. The maximum number of habituation trials was 20 for 6-month-old and 16 for 10-month-old infants. Two additional videos were constructed with an identical format to those used in Experiment 1 except the middle video (1 sec: 340 ms, 2 sec: 1340 ms) and audio portion (1 sec: 300 ms, 2 sec: 1300 ms), resulting in videos with durations of 1 s and 2 s.

## Results and discussion

Fifteen out of 16 6-month-old and all 16 10-month-old infants met the habituation criterion. On average, 6-month-old infants required 10.2 trials and 10-month-old infants 8.6 trials to habituate. Figure 3 shows the mean looking time for the first three habituation trials, the last three habituation trials, the novel and the familiar test trials for each age group.

The main purpose of Experiment 2 was to compare 6- and 10-month-old infants' ability to discriminate durations that differ by a 2:3 ratio. However, we first compared 6-month-old infants' performance in Experiments 1 and 2 by conducting a $2 \times 2$ ANOVA testing the between-subjects effects of experiment (ratio = 1:2, or 2:3) and the within-subjects factor of novelty on infants' looking times. The test revealed a marginally significant effect of novelty, $F(1, 30) = 4.14$, $p = .051$, and a significant interaction between novelty and experiment, $F(1, 30) = 5.45$, $p < .05$. The interaction reflects the fact that 6-month-old infants looked longer at novel trials when duration differed by a 1:2 ratio and not when it differed by a 2:3 ratio.

Our main result was that 10-month-old infants discriminated the 2:3 ratio in duration regardless of the absolute values of the durations and 6-month-old infants did not. This conclusion is supported by five different analyses. First, a $2 \times 2 \times 2$ mixed-factor ANOVA testing the between-subjects factors of age (6 vs. 10 months), absolute value (1 vs. 1.5 or 2 vs. 3 s), and the within-subjects factor of test trial type (novel or familiar duration) on infants' looking time yielded a significant main effect of test trial type, $F(1, 28) = 4.82$, $p < .05$, and a significant interaction between test trial type and age, $F(1, 28) = 5.24$, $p < .05$. No other effects were significant.

Second, for 10-month-old infants a $2 \times 2 \times 2$ mixed-factor ANOVA testing the between-subjects factors of habituation type (short vs. long duration) and gender; and the within-subject factor test trial type (novel or familiar duration) revealed a significant main effect of test trial type, $F(1, 12) = 12.24$, $p < .01$, and no other main effects or interactions. Third, paired $t$-tests revealed that 10-month-old infants looked significantly longer at the novel (8.7 s) compared to the familiar test trials (5.7 s), $t(15) = 3.7$, $p < .01$. Fourth, 14 of the 16 10-month-old infants looked longer at the novel compared to the familiar test trials (Binomial $p < .05$). Finally, 10-month-old infants showed a dishabituation effect to the novel test trials,

looking longer at the novel test trials compared to the last three habituation trials (5.8 s), $t(15) = 2.94$, $p < .05$, but did not recover looking time to the familiar test trials, $t(15) = 0.1$, $p = .92$.

In contrast, the same $2 \times 2 \times 2$ mixed-factor ANOVA for 6-month-old infants revealed no significant main effects or interactions, all $ps > .10$. Additionally, paired $t$-tests revealed that 6-month-old infants did not look differentially to the novel (7.1 s) and the familiar test trials (7.2 s), $t(15) = .06$, $p = .95$. This finding remained when the single infant who failed to meet the habituation criterion was excluded from analysis, $t(14) = .25$, $p = .80$. Only seven out of the 16 6-month-old infants looked longer at the novel compared to the familiar test trials (Binomial $p > .10$). Finally, 6-month-old infants did not dishabituate to the novel, $t(15) = 0.04$, $p = .96$, or familiar test trials, $t(15) = 0.19$, $p = .85$.

Results suggest that temporal discrimination increases in precision between 6 and 10 months. Ten-month-old infants but not 6-month-old infants are able to differentiate intervals that differ by a 2:3 ratio. In addition, the lack of a main effect of absolute value indicates that discrimination depends only on the ratio of the tested durations.

## Experiment 3

The goal of Experiment 3 was to identify the ratio for which 10-month-old infants can no longer make a temporal discrimination. We thus tested 10-month-old infants with values that differed by a 3:4 ratio.

### Method

The method was identical to that used in Experiments 1 and 2 except as follows. Participants were 16 healthy full-term 10-month-old infants (mean age = 10 months 2 days, range: 9 months 11 days–10 months 20 days). Eleven of the infants were female. Data from an additional seven infants were discarded because of fussiness resulting in failure to complete at least four test trials. All infants were tested with 3 vs. 4 s intervals. The 3 s video was identical to the ones used in Experiments 1 and 2; the 4 s video was identical in structure to the 3 s video except that the middle video and audio portion were lengthened to 3340 and 3300 ms, respectively. A second observer blind to the condition scored 50% of the data via videotape and reliability was 93%.

### Results and discussion

Thirteen of the 16 infants met the habituation criterion and took on average 9.8 trials to habituate. Figure 4 shows the mean looking time for the first three habituation trials, the last three habituation trials, the novel and the familiar test trials.

The main finding was that 10-month-old infants failed to discriminate durations that differed by a 3:4 ratio. A $2 \times 2 \times 2$ mixed-factor ANOVA testing the between-subjects factors of habituation condition (short vs. long) and gender and the within-subjects factor of test trial type (novel or familiar duration) on infants' looking time yielded no significant main effect of novelty, $F(1, 12) = 1.49$, $p = .25$, and no other significant effects or interactions, all $ps > .10$.

Similarly, a paired $t$-test revealed that infants did not look significantly longer at the novel (6.97 s) compared to the familiar test trials (6.03 s), $t(15) = .96$, $p = .35$. This finding remained when the three infants who failed to meet the habituation criterion were excluded from analysis, $t(12) = 0.83$, $p = .42$. Only nine out of the 16 infants looked longer at the novel compared to the familiar test trials (Binomial $p > .10$). Finally, infants failed to dishabituate to the novel, $t(15) = 1.57$, $p = .13$, or the familiar test trials, $t(15) = .77$, $p = .45$.

To compare 10-month-old infants' performance in Experiments 2 and 3 we conducted a 2 × 2 ANOVA with a between-subjects factor of ratio (2:3 vs. 3:4) and a within-subjects factor of novelty. Results reveal a significant main effect of novelty, $F(1, 39) = 10.1$, $p < .01$, and no other effects or interactions ($ps > .10$). The fact that there was no significant interaction between novelty and ratio is consistent with the trend to look longer at the novel duration in the 3:4 ratio condition and may suggest that some infants discriminated the 3:4 ratio. Lipton and Spelke (2003) obtained statistically similar patterns with 9-month-old infants tested with a 2:3 and 4:5 ratio between numerosities.

Finally, it is important to note that 10-month-old infants successfully discriminated durations that differed by only 1 second (2 vs. 3 seconds) and even by .5 second (1 vs. 1.5 seconds) in Experiment 1, thus the linear difference of 1 second used in Experiment 3 (3 vs. 4 seconds) was not the root of the difficulty.

## General discussion

The main finding of the present report is that between 6 and 10 months of age infants become better at discriminating temporal intervals. At 6 months, as reported by vanMarle and Wynn (2006), infants require a 1:2 ratio in duration for successful discrimination; however, by 10 months of age infants are capable of discriminating intervals that differ by a 2:3 ratio. Ten-month-old infants did not show statistically significant discrimination when durations differed by a 3:4 ratio, suggesting that this ratio is at least approaching the upper limit of their capacity.

Table 1 summarizes the results of our study along with those of vanMarle and Wynn (2006). The method used here was almost identical to that used by vanMarle and Wynn with the exception that the stimuli in our study were videotaped and displayed on a computer monitor whereas the stimuli in the vanMarle and Wynn study were live puppet events.

The finding that number and time discrimination follow the same developmental trajectory is consistent with the accumulator model proposed by Meck and Church (1983), which posits that a single mechanism is used for counting and timing. This parallel in increasing precision for time and number discriminations over development may be indicative of a common currency for time and number representations. However, it is also possible that similarities between number and time discrimination reflect a more general aspect of infants' discrimination processes. For example, general aspects of infant memory or attention processes may result in similar levels of discrimination for multiple stimulus dimensions. It is also possible that similarities in discrimination between number and time reflect a common code for magnitude representations more generally. For example, any stimulus dimension for which discrimination follows Weber's Law might show similar developmental trends in levels of discrimination.

vanMarle and Wynn (2006) argued that that the 1:2 ratio required for both time and number discrimination implicates a unique common code for these dimensions. They suggest that since previous studies indicate that area discrimination requires a different ratio for successful discrimination, then the common ratio between number and time is unlikely to reflect a general aspect of infant memory or attention. Specifically, vanMarle and Wynn pointed out that Brannon, Abbott and Lutz (2004) found that 6-month-old infants could not discriminate a 1:2 ratio in the cumulative surface area of a large array of dots. However, a more recent study demonstrated that 6-month-old infants do successfully discriminate a 1:2 ratio change in the size of a single element and fail to discriminate a 2:3 ratio change (Brannon, Lutz & Cordes, 2006). Thus it appears that the same ratio change is needed at 6 months of age for number, time and area discriminations, and the previous failure to

discriminate a 1:2 ratio in area was likely due to the fact that area discrimination required summing across arrays of dots rather than discriminating the area of single elements. An important remaining question that we are currently investigating is whether area discrimination follows the same developmental trajectory of increased precision over the second half of the first year of life.

The parallels in number, area, and time discrimination in infancy raise many questions and directions for future research. Since ratio dependence is a ubiquitous feature of magnitude discrimination in nonhuman animals, adults and human infants, more sensitive methods will be needed to identify whether a single mechanism is used to represent number and time in infancy. One possibility is that source analysis with event-related-potentials in infants could be used to examine whether the neural generators involved in forming number and time representations overlap and whether they differ from other dimensions such as area or weight.

In conclusion, we have demonstrated that temporal discrimination increases in precision between 6 and 10 months of age and follows a similar developmental trajectory to that of number. Although the common developmental trajectory may reflect a common currency for time and number, we suggest caution in such an interpretation given that 6-month-old infants also require a 1:2 ratio to discriminate area changes (Brannon *et al.*, 2006).

## Acknowledgments

## References

Balci F, Gallistel CR. Cross-domain transfer of quantitative discriminations: is it all a matter of proportion? Psychonomic Bulletin and Review 13(4):636–642. in press.

Brannon EM, Abbott S, Lutz DJ. Number bias for the discrimination of large visual sets in infancy. Cognition 2004;93 (2):B59–B68. [PubMed: 15147939]

Brannon EM, Lutz DJ, Cordes S. The development of area discrimination and its implications for number representation in infancy. Developmental Science 2006;9 (6):F59–F64. [PubMed: 17059447]

Breukelaar J, Dalrymple-Alford J. Timing ability and numerical competence in rats. Journal of Experimental Psychology: Animal Behavior Processes 1998;24 (1):84–97. [PubMed: 9438968]

Clifton RK. Heart rate conditioning in the newborn infant. Journal of Experimental Child Psychology 1974;18 (1):9–21. [PubMed: 4459438]

Colombo J, Richman WA. Infant timekeeping: attention and temporal estimation in 4-month-olds. Psychological Science 2002;13 (5):475–479. [PubMed: 12219817]

Demany L, McKenzie B, Vurpillot E. Rhythm perception in early infancy. Nature 1977;266 (5604): 718–719. [PubMed: 876350]

Droit-Volet S. Scalar timing in temporal generalization in children with short and long stimulus durations. Quarterly Journal of Experimental Psychology 2002;55 (4):1193–1209. [PubMed: 12420992]

Droit-Volet S, Clement A, Wearden J. Temporal generalization in 3- to 8-year-old children. Journal of Experimental Child Psychology 2001;80 (3):271–288. [PubMed: 11583526]

Droit-Volet S, Wearden JH. Temporal bisection in children. Journal of Experimental Child Psychology 2001;80 (2):142–159. [PubMed: 11529672]

Fitzgerald HE, Brackbill Y. Interstimulus interval in classical pupillary conditioning. Psychological Reports 1968;23 (2):369–370. [PubMed: 5698784]

Friedman WJ. Arrows of time in infancy: the representation of temporal-causal invariances. Cognitive Psychology 2002;44:252–296. [PubMed: 11971633]

Gibbon, J.; Allan, L. Timing and time perception. Vol. 423. New York: Annals of the New York Academy of Sciences; 1984.

Gibbon J, Malapani C, Dale CL, Gallistel C. Toward a neurobiology of temporal cognition: advances and challenges. Current Opinion in Neurobiology 1997;7 (2):170–184. [PubMed: 9142762]

Lewkowicz, DJ. The role of temporal factors in infant behavior and development. In: Levin, I.; Zakay, D., editors. Time and human cognition: A life-span perspective. Amsterdam: North-Holland; 1989. p. 9-62.

Lewkowicz DJ. The development of intersensory temporal perception: an epigenetic systems/ limitations view. Psychological Bulletin 2000;126:281–308. [PubMed: 10748644]

Lewkowicz DJ. Learning and discrimination of audiovisual events in human infants: the hierarchical relation between intersensory temporal synchrony and rhythmic pattern cues. Developmental Psychology 2003;39 (5):795–804. [PubMed: 12952394]

Lipton J, Spelke E. Origins of number sense: large-number discrimination in human infants. Psychological Science 2003;14 (5):396–401. [PubMed: 12930467]

Meck, WH., editor. Functional and neural mechanisms of interval timing. Boca Raton, FL: CRC Press; 2003.

Meck WH, Church RM. A mode control model of counting and timing processes. Journal of Experimental Psychology: Animal Behavior Processes 1983;9 (3):320–334. [PubMed: 6886634]

Rivière V, Darcheville JC, Clément C. Rapid timing of transitions in inter-reinforcement interval duration in infants. Behavioural Processes 2000;52:109–115. [PubMed: 11164679]

Roberts WA, Roberts S, Kit KA. Pigeons presented with sequences of light flashes use behavior to count but not to time. Journal of Experimental Psychology: Animal Behavior Processes 2002;28 (2):137–150. [PubMed: 11987871]

Trehub SE, Thorpe LA. Infants' perception of rhythm: categorization of auditory sequences by temporal structure. Canadian Journal of Psychology 1989;43 (2):217–229. [PubMed: 2486496]

vanMarle K, Wynn K. Six-month-old infants use analog magnitudes to represent duration. Developmental Science 2006;9 (5):F41–F49. [PubMed: 16911436]

Xu F, Spelke ES. Large number discrimination in 6-month-old infants. Cognition 2000;74 (1):B1–B11. [PubMed: 10594312]
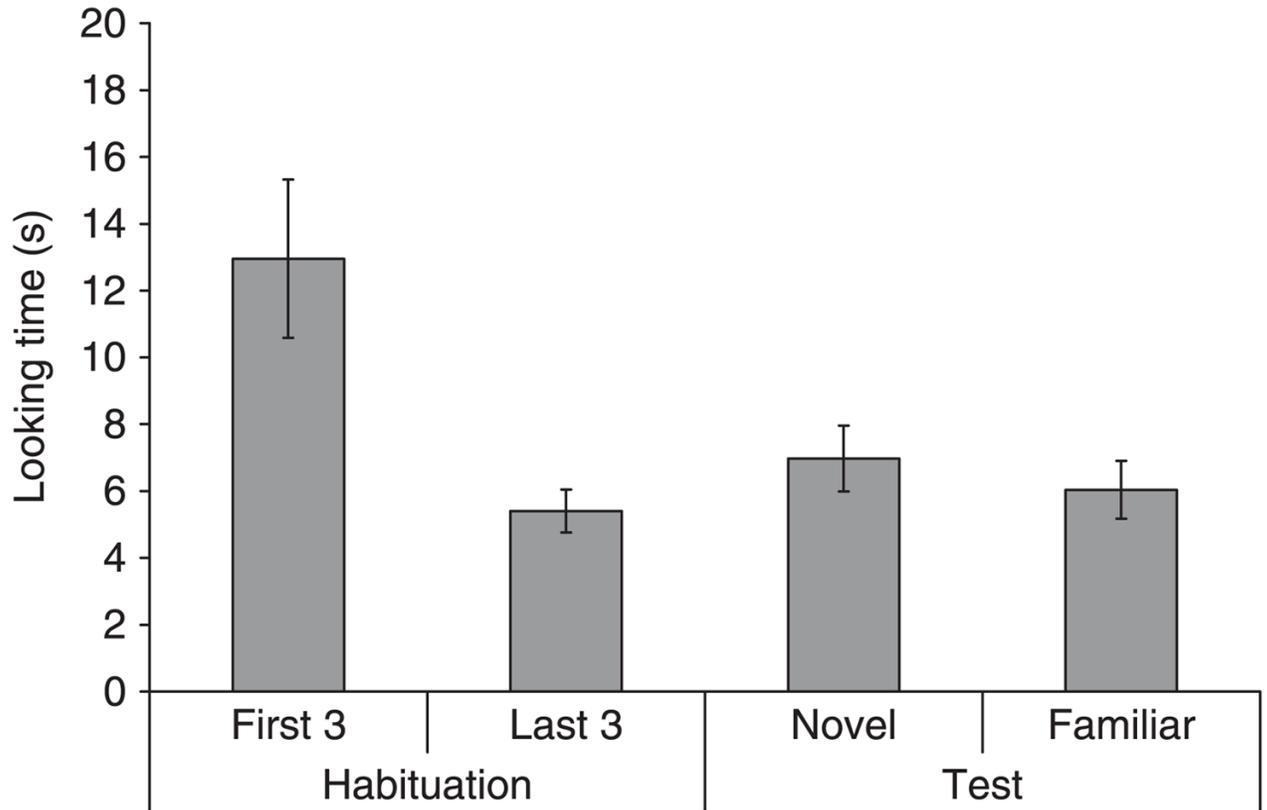
**Figure 1.**
Still images from the videos used in Experiments 1–3.
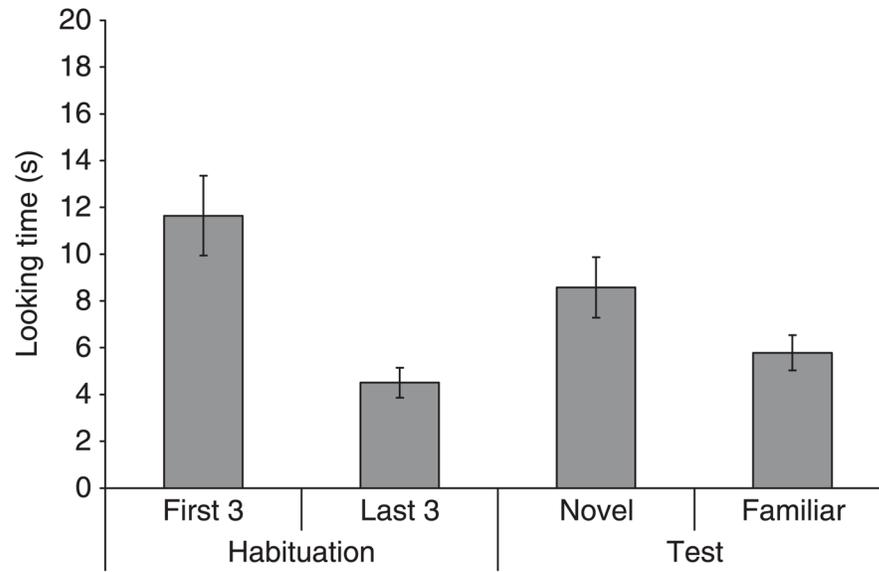
**Figure 2.**
Mean looking time to the first three and last three habituation trials and the novel and familiar test trials for 6-month-old infants tested with a 1:2 ratio temporal discrimination in Experiment 1. Error bars indicate standard errors.
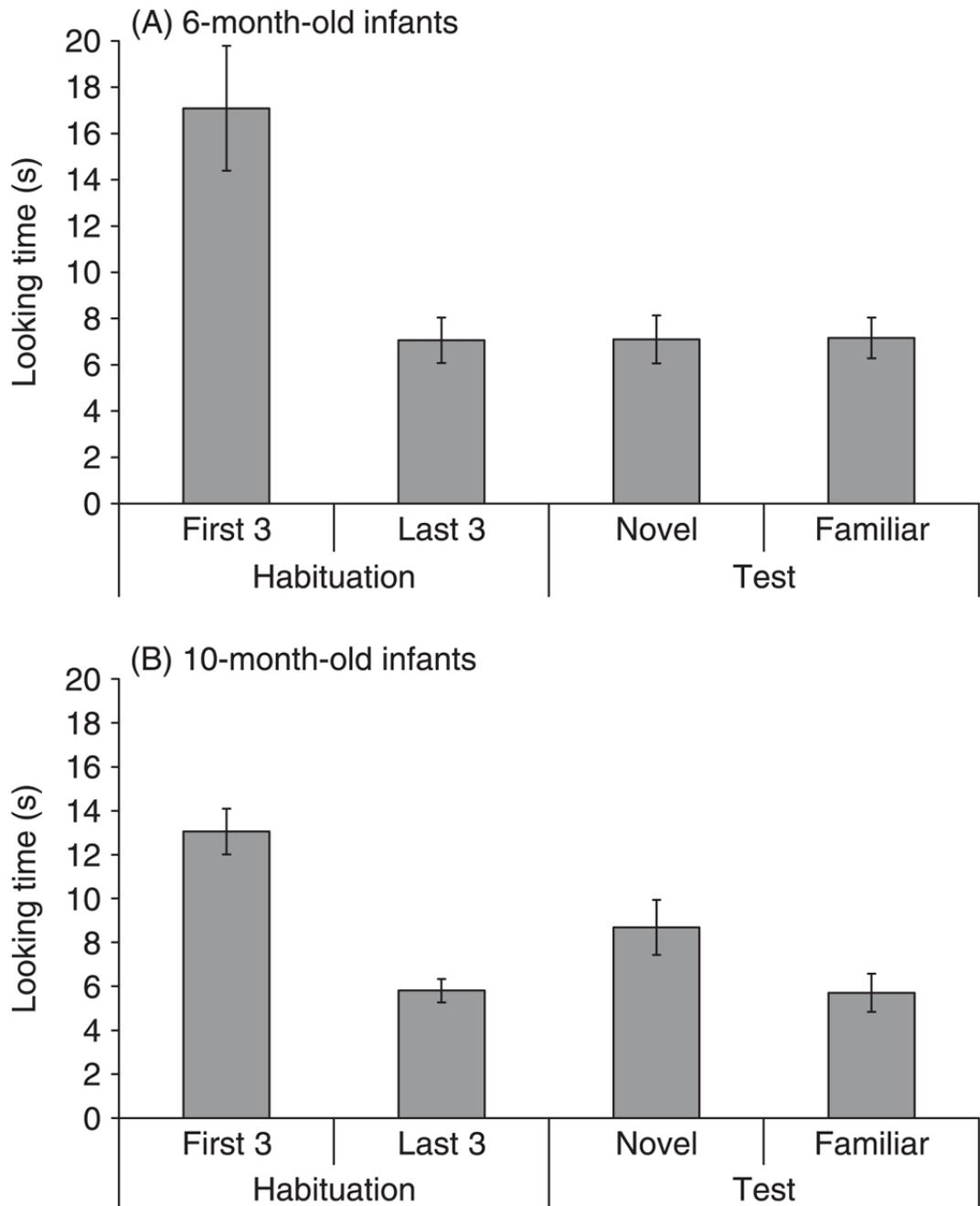
**Figure 3.**
Mean looking time to the first three and last three habituation trials and the novel and familiar test trials for 6-month-old infants (A) and 10-month-old infants (B) tested with a 2:3 ratio temporal discrimination in Experiment 2. Error bars indicate standard errors.

**Figure 4.**
Mean looking time to the first three and last three habituation trials and the novel and familiar test trials for 10-month-old infants tested with a 3:4 ratio temporal discrimination in Experiment 3. Error bars indicate standard errors.

**Table 1**

Infant time discrimination as a function of ratio and age

| Ratio | 6-month-olds | 10-month-olds |
|-------|--------------|---------------|
| 1:2 | .5 s vs. 1 s [*] | |
| | 2 s vs. 4 s [*] | |
| 2:3 | 1.5 s vs. 3 s [*] | |
| | 3 s vs. 4.5 s *ns* | |
| | .67 s vs. 1 s *ns* | |
| | 1 s vs. 1.5 s *ns* | 1 s vs. 1.5 s [*] |
| | 2 s vs. 3 s *ns* | 2 s vs. 3 s [*] |
| 3:4 | | 3 s vs. 4 s *ns* |

*Note*: Shaded cells are data from vanMarle and Wynn (2006), while unshaded cells refer to data from the present report.

[*] indicates successful discrimination whereas *ns* indicates non-significant differences.