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Stable individual differences in number discrimination in infancy

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Abstract

Previous studies have shown that as a group 6-month-old infants successfully discriminate numerical changes when the values differ by at least a 1:2 ratio but fail at a 2:3 ratio (e.g., 8 vs. 16 but not 8 vs. 12). However, no studies have yet examined individual differences in number discrimination in infancy. Using a novel numerical change detection paradigm, we present more direct evidence that infants' numerical perception is ratio-dependent even within the range of discriminable ratios and thus adheres to Weber's Law. Furthermore, we show that infants' numerical discrimination at six months reliably predicts their numerical discrimination abilities but not visual short-term memory at nine months. Thus, individual differences in numerical discrimination acuity may be stable within the first year of life and provide important avenues for future longitudinal research exploring the relationship between infant numerical discrimination and later developing math achievement.

Keywords

Numerical cognition; infant development; individual differences; cognitive development

A characteristic feature of adult approximate numerical discrimination is that it adheres to Weber's Law, i.e. the ratio rather than the absolute difference between numerosities determines discriminability (Dehaene, 1997). This ubiquitous finding suggests that adults represent discrete quantities approximately as continuous mental magnitudes, also referred to as analog magnitudes, that are proportional to the numerosity being represented (Dehaene & Changeux, 1993). Psychophysical studies in children and animals have found comparable results (e.g. Cantlon & Brannon, 2006; Huntley-Fenner & Cannon, 2000; Temple & Posner, 1998) suggesting developmental and evolutionary continuity in the nonverbal analog magnitude system.

Nevertheless, few studies have looked at individual differences in the analog magnitude system, especially across development. To our knowledge, all such previous studies have focused on older children and the relationship between approximate and exact number systems. Halberda et al. (2008) recently showed that individual differences in the acuity of the approximate number system at 14 years of age correlate with standardized math achievement scores as far back as kindergarten. Children with math disabilities also show marked difficulties on number comparisons with non-symbolic and symbolic stimuli suggesting a deficit in the approximate number system or the link between the exact, symbolic and approximate, non-symbolic numerical representations (Landerl et al., 2004; Price et al., 2007; Rousselle & Noel, 2007). However, there are no studies that have looked

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at individual differences in infants' numerical discrimination abilities and their stability across the first year of life.

Previous behavioral studies have shown that on average 6-month-old infants successfully discriminate visual arrays or auditory sequences that differ by a 1:2 ratio in numerosity irrespective of absolute value (e.g. 8 vs 16 or 16 vs 32); however, they fail to discriminate numerical differences with a 2:3 ratio (e.g., 8 vs 12 or 16 vs 24; Xu & Spelke, 2000; Xu et al., 2005). This pattern of success versus failure suggests that infants' ability to discriminate large numerosities is determined by Weber's Law. However, such evidence is indirect because it is inferred by the pattern of successes and failures at a group level rather than by psychometric functions characteristic of adult and non-human animal data.

The goals of the present study were four-fold. First, we test whether infants' numerical discriminations are ratio-dependent using a novel experimental paradigm. Second, we test whether numerical acuity increases over development in infancy as suggested by traditional looking-time methods (Lipton & Spelke, 2003). Third, we investigate whether individual differences in numerical acuity are stable over development. Fourth, we examine whether individual variability in numerical discrimination reflects general information processing or short-term memory abilities on the one hand, or instead more specific quantitative capacities on the other hand.

To assess numerical discrimination, we used a numerical change detection paradigm that provides a dependent measure that can be parametrically related to the amount of change in the stimuli. Our method is based on a paradigm initially developed by Ross-Sheehy, Oakes, and Luck (2003) to test infants' visual short-term memory. In their study, infants were presented with two different image streams on peripheral monitors. One of the streams contained one or more squares, heterogeneous in color, one of which randomly changed its color between consecutive images, while the other stream contained the same number of heterogeneously colored squares that did not change in color from image to image. Infants looked longer at the changing stream compared to the constant stream but were only successful when the number of squares was within their short-term memory capacity. For example, 6-month-old infants only showed a preference for the changing over the constant stream when a single square was presented in each stream, whereas by 10 months, infants showed a preference for the changing stream when two or three squares were presented in each image.

Here, we modified the color change detection paradigm to test the ability of infants to detect *numerical* changes. Infants were shown two streams of rapidly changing images, one of which remained constant in numerosity and the other of which alternated between two different numerosities (see figure 1). The numerical value in the non-changing image stream was either the smaller or the larger of the two values in the changing image stream, counterbalanced between participants. The side (left or right) of the non-changing image stream switched between trials for each infant. We predicted that if infants were able to discriminate between the two numerosities, they would look longer at the numerically changing stream compared to the numerically constant stream. By using different numerosity pairs (6 & 24 vs 6 or 24, 6 & 18 vs 6 or 18, 10 & 20 vs 10 or 20, 8 & 16 vs 8 or 16, and 12 & 18 vs 12 or 18[1]) in the changing image stream in a between-subject design in Exp.1, we were able to assess whether the magnitude of 6-month-old infants' preference for the numerically changing stream varied as a function of the numerical distance between the values in the changing stream. A second prediction of Weber's Law is that there should be no difference in the magnitude of infant's preference for the changing stream over the non-

[1]Hereafter, we will refer to these conditions as 6vs24, 6vs18, 10vs20, 8vs16, and 12vs18.

changing stream when the absolute differences between the two values in the changing stream varied but their ratio was constant. Thus, we tested infants on two number pairs that differed in absolute but not relative distance (10vs20 and 8vs16).

In Exp.2 and 3, we re-tested a subset of the 6-month-old infants tested in Exp.1 three months later when they were 9 months of age on the same numerical change detection task albeit with different numerosities (Exp. 2) or a color change detection task (Exp. 3) originally used by Ross-Sheehy, Oakes, and Luck (Ross-Sheehy et al., 2003). We predicted that as a group infants' numerical discrimination would increase from 6 to 9 months of age, but more importantly we were interested in whether infants' individual numerical discrimination scores at 6 months of age would predict their numerical discrimination scores at 9 months of age. We used the color change detection task to assess whether we were tapping general short-term memory abilities with the number change detection task or instead a more specific quantitative acuity. In the color change detection task, infants were presented with two peripheral image streams where one stream contained two heterogeneously colored squares that remained the same color and the other stream contained two heterogeneously colored squares one of which randomly changed between eight different colors. A positive correlation between performance in the numerical and the color change detection task would suggest that we were measuring a general information processing or short-term memory capacity. Alternatively, if numerical change detection scores were correlated between 6 and 9 months of age but numerical and color change detection scores were not, this would be more consistent with the idea that the numerical change detection task taps infants' quantitative capacities.

Materials and methods

Ratio-modulation of number discrimination at 6 months (Exp.1)

Participants—Eighty infants with a mean age of 6 months (m) and 1 day (d) (range = 5 m 13 d to 6 m 17 d; 38 females) participated, 16 in each of five conditions. Data from 22 additional infants were discarded due to fussiness (n=9), parental interference (n=6), equipment failure (n=5), or not looking to both screens during at least one of the trials (n=2). Four additional infants were excluded because their preference scores (see below) were more than two standard deviations above or below the mean of their respective conditions. Parents gave written informed consent to a protocol approved by the local Institutional Review Board.

Design—Infants were presented with two image streams simultaneously on two peripheral screens (see figure 1). In one of the image streams, images alternated between two different numbers of dots (changing image stream), while the other image stream only contained images with the same number of dots (non-changing image stream). Infants were randomly assigned to one of five conditions: 6vs24 (1:4 ratio), 6vs18 (1:3 ratio), 10vs20 (1:2 ratio), 8vs16 (1:2 ratio), and 12vs18 (2:3 ratio).

Stimuli—Every image was presented for 500 ms followed by 300 ms of blank screen. Every other image was the same between the two image streams and the identical images were interspersed by images that differed in numerosity. One third of the images that differed between the two streams were matched on total surface area, one third was matched on individual element size, and one third was matched on total perimeter. In an orthogonal manipulation, one half of the images that differed in numerosity were matched on density. Thus, the two image streams could not be differentiated based on element size, cumulative surface area, cumulative perimeter, or density.

Apparatus and procedure—Infants sat in a high chair or on a parent's lap approximately 105 cm away from the middle of three 17-inch computer screens. The distance between the center of the middle screen and the center of the peripheral monitors was 55 cm.

At the beginning of each trial, participants were presented with a colorful attractor on the middle screen. The experimenter manually started each trial when the infant looked at the attractor. Each trial lasted 60 seconds and there were a total of four trials for each infant. The side of the changing image stream alternated between trials and the order was counterbalanced between infants. Half of the infants in each condition saw a non-changing image stream that contained the larger numerosity, the other half saw the smaller numerosity. For example, in the 10vs20 condition, half the infants saw image streams containing 20 dots in each image in the non-changing stream and the other half of the infants saw image streams containing 10 dots in each image in the non-changing stream.

Infants' looking behavior was digitally recorded for later off-line coding. An experienced observer coded infants' looking behavior to the screens using a custom-made coding program written in RealBasic (Libertus, 2008). A second observer coded more than 25% of all participants and reliability between the two observers was extremely high (r=0.99).

Data analysis—We analyzed the proportion of time each infant spent looking at the changing and non-changing image streams as a function of each infant's total looking behavior to both screens. Thus, individual differences in overall attention to the stimuli were eliminated. We then calculated preference scores for each infant by subtracting the average percent looking time to the non-changing image stream from the percent looking time to the changing image stream across the four trials. Thus, a positive score indicates a preference for the changing over the non-changing image stream.

Reliability of individual number discrimination abilities (Exp.2)

Participants—Thirty of the infants tested in the 6vs24 (n=10), 6vs18 (n=5), or 10vs20 (n=15) conditions in Exp. 1 were re-tested at a mean age of 9 m and 6 d (range = 8 m 16 d to 10 m 17 d; 14 females). Data from three additional infants were discarded due to fussiness (n=2), and parental interference (n=1). Data from one additional infant was excluded because his change detection preference scores were more than two standard deviations above or below the mean distance to the least squares line of all other data points. We attempted to re-test all infants who participated in Exp. 1 with the exception of infants who had participated in the 2:3 ratio condition since they did not show positive preference scores at the group level for this condition. The obtained sample size was based on parents' ability to return for a follow-up visit at the appropriate age.

Design and data analysis—The numerical change detection task of Exp.2 was identical to the 12vs18 condition in Exp.1. Data was analyzed in the same way as in Exp.1. Again, a second observer coded more than 25% of all videos and reliability between the two observers was extremely high (r=0.99).

Relationship between number discrimination and visual short-term memory (Exp.3)

Participants—Sixteen infants who were tested at 6 months of age in Exp. 1 were tested in a color change detection task at a mean age of 9 m and 2 d (range = 8 m 13 d to 9 m 29 d; 8 females). Data from one additional infant was discarded due to equipment failure. Again, infants who had participated in the 2:3 ratio condition at 6 months were not re-recruited at 9 months of age since they did not show positive numerical change-detection at the group level. Exp. 3 was conducted after Exp. 2.

Design—The experimental design, apparatus, and procedure was identical to the numerical change detection task except that the non-changing image stream contained two heterogeneously colored squares never changing color from image to image, whereas the changing image stream contained two heterogeneously colored squares one of which randomly changed between eight colors (yellow, orange, red, green, cyan, blue, violet, black) from image to image. Note that the particular square that changed in color varied randomly from image to image.

Data analysis—We again calculated preference scores for each infant by subtracting the average percent looking time to the non-changing image stream from the percent looking time to the changing image stream across the four trials. A second observer coded 25% of all videos and reliability between the two observers was high (r=0.85).

Results – Ratio-modulation of number discrimination at 6 months (Exp.1)

A preliminary analysis showed that - as predicted by Weber's Law - there was no significant difference in preference scores (% looking to changing image stream *minus* % looking to non-changing image stream) between the two different 1:2 ratio conditions with distinct absolute values (i.e. 10vs20 and 8vs16; $t(30)=1.13$, $p=0.27$). Consequently, we collapsed the data from these two conditions for all further analyses. As can be seen in figure 2, one-sample t-tests comparing preference scores for each ratio to zero revealed that there was a significant preference for the changing stream for the 1:4 ($t(15)=4.3$, $p<0.001$), 1:3 ($t(15)=3.1$, $p<0.01$), and 1:2 ratio conditions ($t(31)=3.3$, $p<0.01$), but not for the 2:3 ratio condition ($t(15)=0.7$, $p=0.47$). Moreover, 14 out of 16 infants in the 1:4 ratio condition looked longer to the changing stream, 12 out of 16 infants in the 1:3 ratio condition, and 23 out of 32 infants in the 1:2 ratio condition. However, only 7 out of 16 infants in the 2:3 ratio condition preferred the changing over the non-changing stream.

A three-way ANOVA with ratio (2:3, 1:2, 1:3, and 1:4), non-changing numerosity (small or large), and first side of changing image stream (left or right) as factors with preference scores as the dependent measure showed a significant main effect of ratio ($F(3,79)=7.2$, $p<0.001$). No other main effects or interactions reached significance. Posthoc Tukey comparisons indicated significantly higher preference scores for the 1:4 ratio as compared to the 1:2 and 2:3 ratios (both *p*s<0.02), and for the 1:3 ratio as compared to the 2:3 ratio ($p<0.04$).

Finally, a linear regression across all four ratios yielded a significant linear increase in preference scores for the changing over the non-changing image stream as the ratio increased from 2:3 to 1:4 ($r=0.5$, $p<0.001$).

Results – Reliability of individual number discrimination abilities (Exp.2)

Thirty infants tested in the 6vs24, 6vs18, and 10vs20 conditions in Experiment 1 were retested in a 2:3 ratio (12vs18) contrast at 9 months of age. Unlike in Exp.1, 9-month-old infants looked significantly longer to the numerically changing image stream as compared to the numerically non-changing image stream in the 2:3 ratio condition (mean=4.4%, standard error=2.2; $t(29)=2.03$, $p=0.05$) indicating that as a group numerical discrimination ability improved with age[2]. Nineteen out of thirty infants looked longer to the changing as compared to the non-changing image stream. A two-way ANOVA with non-changing numerosity (small or large), and first side of changing image stream (left or right) as factors

[2]Preliminary analysis revealed no significant effects of the ratio condition in which infants were tested at 6 months of age on infants' preference scores at 9 months ($F(2,27)=0.39$, $p=0.96$). Thus, we collapsed data from all infants tested at 9 months of age.

and preference scores as dependent measure showed neither significant main effects of non-changing numerosity or side nor significant interactions.

We used linear regression to assess the relationship between infants' numerical change detection preference scores at 6 and 9 months of age. To account for the fact that infants were tested in different conditions at 6 months of age, we first normalized the 6-month preference scores to the maximum preference score of all infants in their respective condition and used these normalized 6-month preference scores as a possible predictor for infants' numerical change detection scores at 9 months. Our analysis revealed that numerical change detection preference scores at 6 months were a significant positive predictor of numerical change detection preference scores at 9 months (standardized beta=0.39, $p<0.04$; see figure 3).

Results – Relationship between number discrimination and visual short-term memory (Exp.3)

Sixteen infants tested in the 1:3 ratio condition in the numerical change detection task at 6 months were re-tested in a color change detection task at 9 months of age. Replicating previous findings (Ross-Sheehy et al., 2003), infants looked significantly longer to the changing color image stream as compared to the non-changing color image stream (mean=8.87%, standard error=3.35; $t(15)=2.65$, $p<0.02$). Thirteen out of sixteen infants looked longer to the changing as compared to the non-changing image stream. A two-sample t-test with first side of changing image stream (left or right) as a factor and color preference score as the dependent measure showed no significant effect. A linear regression analysis between the normalized numerical preference score at 6 months and the color preference score at 9 months showed no significant relationship (standardized beta=−0.15, $p=0.57$, see figure 4)[3].

Discussion

Our results allow four conclusions. First, we found that 6-month-old infants' preference to look at a numerically changing compared to a non-changing image stream varied as a function of numerical ratio. Secondly, in Exp. 2 we replicated previous findings that numerical acuity increases from 6 to 9 months such that at 9 months of age, infants succeed at discriminating a 2:3 ratio (Lipton & Spelke, 2003). The finding that infants' numerical discrimination abilities is ratio dependent confirms a large body of data from habituation paradigms, which indicate that 6-month-olds are able to discriminate numerosities that differ by a 1:2 ratio but not a 2:3 ratio (Brannon et al., 2004; Lipton & Spelke, 2003, 2004; Xu & Spelke, 2000; Xu et al., 2005) suggesting that 6-month-olds' discrimination threshold lies between a 1:2 and a 2:3 ratio. However, our paradigm allows us to extend this conclusion by demonstrating that infants' preference for a numerically changing image stream is parametrically related to the ratio between the two values in the changing stream. Specifically, the magnitude of the preference score increased with the ratio between the numerical values on the changing side. These findings provide quantitative evidence for the hypothesis that infants' number discrimination abilities are subject to Weber's Law and thus suggest that infants employ the same analog magnitude system to represent number as adults, children and nonhuman animals.

[3]A regression analysis using only the first 16 infants tested at 9 months of age also showed a significant positive relationship between 6 and 9 months (standardized beta=0.61, $p<0.02$). Thus, the positive results in Exp.2 and negative results in Exp. 3 do not appear to be due to a difference in statistical power. A two-sample t-test also showed no significant differences between the preference scores in the two tasks at 9 months ($t(44)=1.14$, $p=0.26$).

This finding is also consistent with a recent electroencephalography (EEG) experiment (Libertus et al., in press) which found parametric variations in neural oscillations as a function of numerical ratio in 7-month-old infants. In that study, infants were familiarized to a given numerosity and then subsequently presented with novel images of the familiar numerosity and one or two novel numerosities while their brain activity was recorded using EEG. Alpha-band (6–8 Hz) and theta-band (4–6 Hz) oscillations differed for novel and familiar numerical values. Most importantly, spectral power in the alpha band over midline and right posterior scalp sites was modulated by the ratio between the familiar and novel numerosities suggesting that infants' numerical discrimination abilities as measured by neural oscillations are governed by Weber's Law.

Our third and most important finding was that individual differences in infants' preferences for a numerically changing over a numerically constant image stream remained stable between 6 and 9 months of age providing the first evidence for stability of individual differences in number discrimination in the first year of life. Infants who showed a large preference for the numerically changing image stream at 6 months were more likely to prefer the numerically changing image stream again at 9 months. These results suggest that the change detection task is a reliable dependent measure for assessing early number sense acuity in infancy and may be a useful tool to investigate the relationship between infants' early number sense and later developing numerical abilities.

Our fourth finding was that individual differences in infants' numerical discrimination abilities are not related to their individual visual short-term memory abilities. Although numerical change detection scores at 6 months successfully predicted numerical change detection scores at 9 months, they were not correlated with color change detection scores at 9 months. This pattern of results suggests that the numerical change detection paradigm may capture individual differences in infants' quantitative abilities above and beyond infants' short-term memory abilities. Importantly, the experimental designs of the number and the color change detection tasks were very similar ruling out the possibility that the lack of a relationship may be due to differences in task affordances. However, future studies must address whether the individual differences captured here are specific to numerical abilities or reflect more general quantitative abilities (e.g., area, time, and density discriminations). To explore these important questions, it will be necessary to test infants in the change detection paradigm with a variety of quantitative and non-quantitative stimulus classes.

A fundamental question for developmental psychologists is what looking-time measures can tell us about underlying cognitive processes in infancy (Aslin, 2007). Conclusions about the infant mind stand on more solid ground when multiple different paradigms provide convergent evidence. Results from our numerical change detection paradigm support previous findings from the visual habituation and auditory head-orienting paradigms, which indicate that infants' numerical acuity is ratio-dependent and increases with age (Lipton & Spelke, 2003; Xu & Spelke, 2000). Although there have been some attempts to measure individual differences and individual reliability in general information-processing ability with the habituation method, this widespread technique is used to assess capacities at the group level (e.g. Arterberry & Bornstein, 2002; Bornstein & Benasich, 1986; Courage & Howe, 2001; Malcuit et al., 1991; Rose & Feldman, 1987). The numerical change detection paradigm may allow more systematic study of individual differences in cognition and reliability of measures over development given that the dependent measure appears to provide a parametric assessment of infant's perception and stability at the level of the individual infant.

In conclusion, the numerical change detection procedure provides a dependent measure that shows systematic modulation as a function of numerical ratio and captures individual differences in numerical abilities at a very young age. Our findings confirm that the approximate number system held by 6-month-old infants shares the same signature of ratio-dependent discrimination as seen in adult humans, older children, and non-human animals. Moreover, while numerical acuity increases from 6 to 9 months of age at the group level, individual differences in numerical acuity are stable over this period. Future work must pinpoint whether the task taps more general quantitative sensitivity, or more specific numerical abilities. Our next step will be to use the numerical change detection task to track individual differences in numerical sensitivity in infancy into early and later childhood and attempt to shed light on the controversial question of the relationship between infants' numerical abilities and later emerging symbolic math abilities (Carey, 2009).

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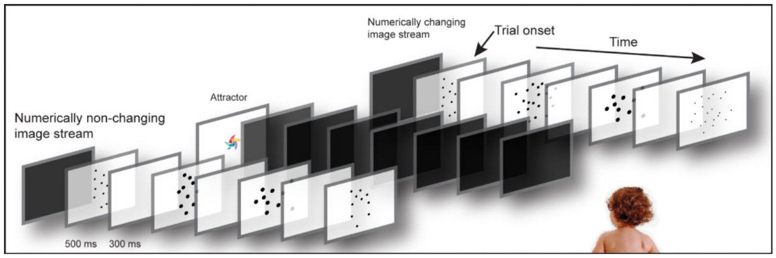

Figure 1.

Experimental design of numerical change detection task. Each trial started after the presentation of a central fixation stimulus. During each trial, infants were presented with two image streams simultaneously on two peripheral screens. In the numerically changing image stream, images contained two different numerosities in alternation (here: 10 and 20), while the numerically non-changing image stream contained only images with the same numerosity (here: 10). Infants' looking time to each of the image streams was measured.

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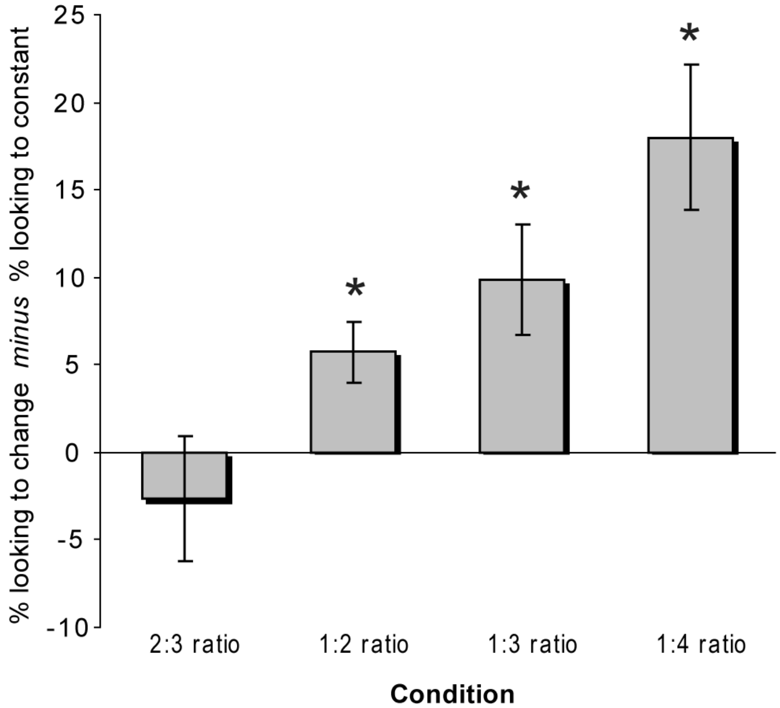

Figure 2.
6-month-old infants' preference scores for numerically changing image streams in four different ratio conditions. A positive preference score indicates longer looking times to the numerically changing image stream as compared to the non-changing stream. Significantly positive preference scores were found for the 1:2, 1:3, and 1:4 ratio conditions (* = $p<0.05$). Furthermore, preference scores increased with increasing relative numerical disparity. Error bars reflect standard errors.

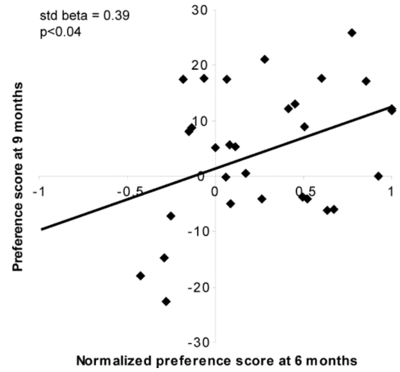

Figure 3.
Infants' numerical discrimination abilities at 6 months reliably predicted their numerical discrimination abilities at 9 months. 6-month preference scores were normalized to account for absolute differences in scores based on the ratio condition in which the infant was initially tested.

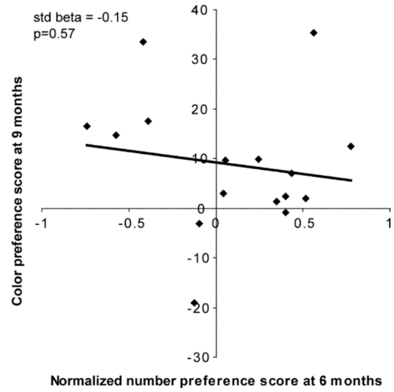

Figure 4.

Infants' numerical discrimination abilities at 6 months do not predicted their color discrimination abilities at 9 months.