



Published in final edited form as:

Dev Neuropsychol. 2011 ; 36(6): 651–667. doi:10.1080/87565641.2010.549883.

Parallels in Stimulus-Driven Oscillatory Brain Responses to Numerosity Changes in Adults and Seven-Month-Old Infants

Melissa E. Libertus,

Department of Psychological and Brain Sciences, Johns Hopkins University, Baltimore, Maryland, and Psychology and Neuroscience, Center for Cognitive Neuroscience, Duke University, Durham, North Carolina

Elizabeth M. Brannon, and

Psychology and Neuroscience, Center for Cognitive Neuroscience, Duke University, Durham, North Carolina

Marty G. Woldorff

Psychology and Neuroscience, Center for Cognitive Neuroscience, Duke University, Durham, North Carolina

Abstract

Previous studies provide *indirect* evidence for an ontogenetically continuous Approximate-Number System. We employed a rapid steady-state visual-presentation paradigm combined with electroencephalography to measure stimulus-driven neural oscillatory responses to numerosities in infants and adults. Steady-state repetition of the same numerosity across a 2.4-sec time block yielded an increase in the stimulus-locked neural entrainment in both groups. Entrainment changes following a numerosity switch varied by the ratio of the numerosities, consistent with Weber's Law. These similarities thus provide *direct* evidence for an ontogenetically continuous Approximate-Number System. Moreover, the degree of neural entrainment significantly predicted infants' number discrimination measured behaviorally two months later.

As human adults we confront numerical information on a daily basis when paying our bills, calculating the costs of a purchase, or keeping track of scores at a sports event. Even though we have the means to represent numerical information exactly under these circumstances by using numerical symbols such as number words or Arabic numerals, we also can—and often do—estimate numerical outcomes without relying on exact representations.

Direct comparisons between non-human animals and human adults have revealed qualitative and quantitative similarities in numerical processing, suggesting that the nonverbal, Approximate Number System may be evolutionarily continuous. A variety of tasks that have tested non-human animals and adult humans have shown that nonverbal numerical discrimination conforms generally to Weber's Law (i.e., the ratio between the numerical values to be compared, rather their absolute difference, determines their discriminability). For example, when asked to choose the numerically smaller of two simultaneously presented visual arrays of objects, both monkeys' and human adults' accuracy and response time varied as a function of the ratio between the two numerical values (Cantlon & Brannon, 2006). Likewise, monkeys' and human adults' performance in an approximate addition task was similarly modulated by the ratio between the correct and incorrect choice (Cantlon &

Brannon, 2007). When adults and rats are tested in parallel designs that require numerical estimation, the variability of their estimates increases proportionally to the increase in numerical value (Cordes, Gelman, Gallistel, & Whalen, 2001; Platt & Johnson, 1971; Whalen, Gallistel, & Gelman, 1999). Thus, it appears that the ability to represent numerical information approximately is independent of language and relies on an onto-and phylogenetically continuous system.

In addition to behavioral parallels between non-human animals and humans, there is also growing evidence that homologous regions of the brain support number representation. Nieder and colleagues have found that single neurons in parietal and prefrontal cortex in monkeys are selective for the number of elements in a visual array (Nieder, 2005; Nieder, Freedman, & Miller, 2002; Nieder & Miller, 2004; see also Roitman, Brannon, & Platt, 2007). Such data support a large body of research by Dehaene and colleagues and others that indicate that the intraparietal sulci support the representation of numerical meaning in humans (e.g., Dehaene, Molko, Cohen, & Wilson, 2004).

While there is ample evidence for phylogenetic continuity in the Approximate Number System, evidence for an ontogenetic continuity is sparse. Several studies have directly compared children's and adults' performance in the same tasks and found parallels in behavioral markers (e.g., Barth et al., 2006) and brain activation (Cantlon, Brannon, Carter, & Pelphrey, 2006; Temple & Posner, 1998), but comparable evidence between infants and adults is rare. The primary support for an ontogenetic continuity in infancy is drawn from the fact that infants' number discrimination abilities appear to be guided by Weber's Law as observed in adulthood. Previous behavioral studies using variants of the standard visual habituation paradigm widely employed in infant research have shown that 6-month-old infants are able to discriminate numbers larger than 3 that differ by a 1:2 ratio (e.g. 8 and 16) but fail with a 2:3 ratio (e.g., 8 and 12; Lipton & Spelke, 2003, 2004; Xu & Spelke, 2000). Thus, infants' success and failure to discriminate numerosities seems to be determined by the ratio between the numerical values and not their absolute difference.

Two recent studies provide additional behavioral and neural evidence for ratio-dependent number discrimination in infancy across a wide range of ratios. In the first set of behavioral studies, 6-month-old infants were tested in a numerical change-detection paradigm, a variant of a preferential looking paradigm in which infants were presented with two image streams side-by-side (Libertus & Brannon, 2010). One image stream contained different images that all had the same number of elements (numerically constant image stream), while the other image stream alternated between images of two different numerosities (numerically changing image stream). In such a design, infants are expected to look longer to the changing image stream as compared to the constant image stream, presumably due to the former being more novel or interesting, if they are able to detect the numerical change. Using this paradigm, 6-month-old infants' preference for the changing image stream increased as the numerical ratio became more discriminable, that is, the proportion of time spent looking at the changing side increased linearly from a 1:2 to a 1:3 to a 1:4 ratio.

In the second set of studies, Libertus and colleagues (2009) recorded electroencephalography (EEG) from 7-month-old infants while they were first familiarized to a given number of objects and subsequently presented with novel images of either one or two novel numerosities or the familiar numerosity. Induced EEG power in the 6–8 Hz range elicited by the familiar numerosity was largest and decreased as a function of numerical ratio between the familiar and novel numerosity. These data were interpreted as reflecting variations in attention to numerosity as a function of novelty. Together, these two studies suggest that infants' number discrimination abilities are governed by Weber's Law, similar to the functional relationships seen in adult numerical perception.

Parallels between infants' and adults' Approximate Number Systems were also found in another electrophysiological study with infants that compared the neural locus of number and object discrimination. Izard, Dehaene-Lambertz, and Dehaene (2008) recorded EEG from 3-month-old infants in a numerical adaptation paradigm in which they were repeatedly presented with the same number of one type of cartoon animal. On rare occasions, the number of animals or the type of animal changed, and brain responses to the number or object deviants was compared to the standards. Changes in number but not in object type elicited differences in brain response over parietal regions typically implicated in numerical processing in adults. In contrast, object changes elicited differences in brain response over temporal regions typically associated with object categorization in adults. Thus, these parallels suggest that infants already employ similar brain regions as adults to process the approximate numerical information of observed environmental stimuli.

While these studies provide indirect evidence for an ontogenetically continuous Approximate Number System, direct comparisons of infants and adults in the same task are lacking, mostly due to the constraints imposed by testing infants and the inapplicability of infant paradigms to adult testing. Here, we sought to overcome these issues by employing a rapid steady-state visual-presentation (RSVP) paradigm in conjunction with EEG recordings of brain activity to measure stimulus-driven neural oscillatory stabilization and destabilization patterns in response to repeated presentation of the same numerosity relative to changes in numerosity. This novel design allowed us to test infants and adults in the same paradigm and collect relatively large amounts of data from infants in a short period of time.

Furthermore, few studies have looked at individual differences in the Approximate Number System, especially across development. Most previous studies have focused on children's basic numerical processing and their relationship to math abilities. For example, Halberda, Mazocco, and Feigenson (2008) showed that acuity of the Approximate Number System at 14 years of age correlated with standardized math achievement scores as far back as kindergarten. Similarly, three recent studies have provided evidence that children's performance on a symbolic number comparison task and non-symbolic arithmetic is predictive and correlates with their math achievement scores (De Smedt, Verschaffel, & Ghesquière, 2009; Gilmore, McCarthy, & Spelke, 2010; Holloway & Ansari, 2009). Lastly, Libertus and Brannon (2010) found that individual differences in infants' number discrimination at six months were predictive of their number discrimination but not their color-discrimination abilities at 9 months.

Thus, we also assessed the relationship between the neural markers measured in the EEG experiment reported here and an established behavioral marker of infant number discrimination measured two months later. These additional analyses allowed us to validate that our novel rapid steady-state visual-presentation paradigm taps into the same Approximate Number System in infancy as other behavioral paradigms and is capable of predicting the development of numerical abilities later in infancy.

METHODS

Participants

Fourteen adults with a mean age of 26 years ($SD = 5.8$ yrs, 10 females) and 28 infants with a mean age of 7 months and 5 days ($SD = 17$ days, 15 females) participated in this study. Data from an additional seven infants and one adult were excluded due to fussiness (four infants), insufficient looking to the screen, that is, less than three artifact-free trials of each trial type (three infants), or fatigue (one adult). We attempted to re-test all infants two months after their initial visit for an additional behavioral study comprised of a numerical change-detection task and an object-categorization task. We were successful in re-recruiting 19 of

the 28 infants (9 females) (mean age = 8 months 30 d, $SD = 13$ days). Parents of infant participants and adult participants gave written informed consent to a protocol approved by the local Institutional Review Board. Parents of infant participants received \$10 for travel compensation and a gift for their infant, and adult participants were reimbursed with \$10/hr for the participation in this study.

Stimuli and Procedure

EEG stimuli and procedure—Participants passively viewed rapid streams of multiple-element images (Figure 1) that flickered at a frequency of 12.5 Hz (40 msec on, 40 msec off).¹ Every 400 msec across a period of 2,400 msec, a new flickering image of a given number of elements was presented. Counterbalanced as a between-subject factor for infants and within-subject factor for adults, the numerosity of the arrays was drawn from two different sets of numerical values: 8, 12, and 24, or 6, 9, and 18. After 2,400 msec, the number of elements changed by a 1:3, 1:2, or 2:3 ratio (e.g., from 8 to 24 elements).

Each image was composed of a given number of black dots on a gray background. Dot size and location were varied between images, in order to control for other possible sources of effects besides numerosity. One fourth of the switches between two numerosities were equated on cumulative surface area between the image immediately preceding the number switch and the one following it, one fourth were equated on cumulative perimeter, one fourth were equated on individual element size, and one fourth were random switches. Figure 1 illustrates a possible stimulus sequence.

Each run started out with a short movie clip to direct the participant's attention to the screen. The experimenter manually started the experiment once the participant was quietly attending to the screen and, in the case of the infants, initiated additional movie clips throughout the run if the infant lost interest in the screen. Each run was composed of 120 2,400-msec blocks and lasted about 5 min without interruption. Infants typically completed one or in exceptional cases two runs. All adults completed six runs, three runs for each set of numerosities, and six runs in an additional task not reported here.²

Adults sat in a comfortable chair, and infants sat in a high chair or on a parent's lap, in both cases approximately 90 cm away from a computer screen. Soft music whose timing was random to the stimulus presentation was played in the background for both adults and infants, but the main purpose was to help infants remain calm. A microcamera monitored the participants' face and eye movements. For infants only, an online observer coded the infants' looking behavior to the screen during the entire run. In addition, the signal from the camera was multiplexed with the signal from the stimulus presentation computer onto a videotape.

EEG acquisition—Brain electrical activity was recorded using 19 tin electrodes for infants and 64 tin electrodes for adults placed in a custom-made elastic cap (Electrocap, Inc., Eaton, Ohio). The 64 channels for adults included four eye electrodes in order to help detect eye blinks and thereby aid in artifact rejection. For adults, impedances were maintained under 2 k Ω for the mastoid and ground electrodes, under 10 k Ω for the eye-channels, and

¹Rapidly flickering visual stimuli have been found to drive the neural response and provide an improvement in signal-to-noise ratio (Meigen & Bach, 2000). Traditional EEG studies with infants often struggle with low signal-to-noise ratio; thus, we sought to overcome this issue by employing a rapid steady-state visual-presentation. The 12.5-Hz flicker frequency was chosen as one that produces a robust driven steady-state response but still fits well within the constraints of the 60-Hz screen refresh rate.

²Adults completed another version of the identical rapid steady-state visual-presentation paradigm with the same numerical stimuli albeit with a different flicker frequency (25 Hz). Order of flicker frequencies was counterbalanced between participants in an ABBA-design. The results of this experiment were excluded from the present paper because brain responses showed the same pattern as with the 12.5-Hz flicker frequency but were weaker. For this reason, infants were only tested with the 12.5-Hz flicker frequency.

under 5 k Ω for all the other electrodes. For infants, impedances were maintained as low as possible, aiming for under 5 k Ω for mastoids and under 10 k Ω for all other electrodes. For infants, due to the relative softness of their skin, simply filling the electrodes with gel and eliminating air bubbles was sufficient, but some very light abrading was used if necessary. For the adults, light abrading was used to achieve low impedances. Recordings were referenced to the right mastoid during acquisition. The EEG was amplified with a gain of 150 in infants and 1,000 in adults, with a recording bandpass of 0.01–100 Hz, and the amplified EEG was digitized continuously at a rate of 500 Hz/channel onto disk. The recorded EEG was examined off-line (both visually and with computer algorithms) to reject those epochs with eye movements or other electrical artifacts in any of the channels. Trials in which the maximum or minimum amplitude exceeded $\pm 250 \mu\text{V}$ for adults and $\pm 500 \mu\text{V}$ for infants in any channel were marked as artifacts, most likely reflecting slow drift, and trials in which the peak-to-peak amplitude exceeded $150 \mu\text{V}$ for adults and infants were excluded as most likely reflecting eye or other movement-related activity. Only trials in which the participant was looking to the screen were included in the analysis. On average, each infant that was included in the analysis contributed data from 34 2,400-msec blocks (~25% of all presented trials), and each adult contributed data from an average of 550 2,400-msec blocks (~77% of all presented trials).

EEG data analysis—The recorded EEG data was segmented, time-locked to the onset of each 2,400-msec block. Next, each 2,400-msec block was segmented into six 400-msec segments, that is, segments for each individual repeating numerosity image. A Fast Fourier transform (FFT) was then applied to the data, using a Hanning window with 10% tapering on each end and a resolution of 1.953 Hz. The magnitudes of FFT-transformed data were subsequently averaged separately in 800-msec segments (i.e., averaged for the first and second, third and fourth, and fifth and sixth repeating numerosity image following the six different possible numerosity switches, for example, an 8-to-12 switch, 12-to-8 switch, 8-to-24 switch, 24-to-8 switch, 12-to-24 switch, and 24-to-12 switch).

To determine the changes in the driven oscillatory response of the brain to the repeated presentation of the same numerosity irrespective of the magnitude of the preceding number switch, we also averaged the magnitudes of the FFT-transformed data for adults across all number switches, that is, we calculated the average response to the first, second, and third 800-msec segment irrespective of numerosity. We then calculated the slope of the line through the three data points for each adult participant at each channel and compared these slopes to zero using two-tailed one-sample *t*-tests. A cluster of spatially contiguous midline and right posterior scalp sites showed significant ($p < .01$) increases in power at the flicker frequency with repeated presentation of the same numerosity, thereby providing a region of interest for subsequent analyses of number-selective responses. Note that the region of interest could only be determined in this way for the adults, in light of the fact that it was relatively unlikely that the infants were able to detect all numerical switches, especially for those with a 2:3 ratio.

To assess number-selective responses, we tested whether the repetition effect over our region of interest was modulated by the ratio of the numerosity switches. To this end, we estimated the slope of the line through the three data points separately for each participant and each switch type. After removing outliers in which the slope exceeded two standard deviations above or below the mean separately for each age group, we averaged power across midline scalp sites and across right scalp sites, respectively, to have one measure for each of these locations. This procedure thus allowed us to directly compare infants and adults in the subsequent analyses. More specifically, we then submitted the slope values to a four-way mixed-design ANOVA with age (infants or adults), location (midline or right), ratio (2:3, 1:2, or 1:3 ratio), and direction (small-to-large number switch or large-to-small

number switch) as factors. Preliminary analyses showed no effects of absolute numerical value, so we collapsed across this factor here. We hypothesized that the steepness of the slope of the driven-oscillation amplitude of a new numerosity should vary as a function of the ratio of the preceding switch, independent of age and switch direction.

Behavioral experiment stimuli and procedure—In the numerical change detection task, run two months following the EEG experiment, infants were presented with two image streams simultaneously on two peripheral screens. Each image was presented for 500 msec followed by a 300-msec blank screen. In one of the image streams, images alternated between two different numbers of dots (12 and 18) while the other image stream contained images of a single numerosity (12 or 18). As in the EEG experiment, continuous variables that covary with numerosity (e.g., cumulative area of the elements) were equated between the two image streams. At the beginning of each trial, a colorful attractor was presented on a center screen until the infant attended to the center location. The experimenter then manually started each trial. There was a total of four trials, each lasting 60 sec, counterbalanced for the side of the changing image stream. In addition, half of the infants saw a non-changing image stream that contained the smaller of the two numerosities in the changing image stream (i.e., 12 dots); the other half saw a non-changing image stream that contained the larger of the two numerosities (i.e., 18 dots). If infants were able to discriminate the alternating numerosities, they should spend more time looking at the changing image stream as compared to the numerically non-changing image stream.

In addition to the numerical change-detection task, infants were tested on an object categorization task with vehicles and animals similar to a paradigm employed by Mandler and McDonough (1993). Infants were first familiarized to different exemplars of one category (e.g., different types of toy vehicles) and then presented with a novel exemplar of the familiar category followed by a novel exemplar of the novel category (e.g., a toy animal). The toys were presented to each infant for 20 sec and during that time infants were allowed to explore the object as they pleased. If infants are able to categorize these toys correctly (vehicles vs. animals), they should spend more time exploring the novel exemplar of the novel category as compared to the novel exemplar of the familiar category.

Behavioral experiment data analysis—For the numerical change-detection task, we analyzed the proportion of time each infant spent looking at the numerically changing versus the non-changing image streams as a function of the total time infants spent looking 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. A positive score thus indicated a preference for the numerically changing over the non-changing image stream. Previous results suggested that, at 9 months of age, infants' preference score for the 2:3 ratio tested in this experiment would be significantly greater than zero (Libertus & Brannon, 2010).

For the object-categorization task, we analyzed the proportion of time each infant spent looking or looking at and touching each object as a function of the total trial time for this object to account for slight variations in trial duration. We then calculated the object categorization score for each infant by subtracting the percent exploration time for the novel exemplar in the familiar category from the percent exploration time for the novel exemplar in the novel category. Thus, a positive score indicates longer exploration of the novel category. Based on previous findings (e.g., Mandler & McDonough, 1993), we predicted that infants would have a significant positive exploration score.

EEG-behavior analysis—We performed two different analyses to assess the relationship between our EEG and behavioral measures for infants. For both analyses, we only used EEG data from the location with a significant effect of ratio. First, we performed a median split for each behavioral preference score. We then compared the EEG slopes for the three different ratio switches between infants with high and low scores in the behavioral measures using independent sample *t*-tests. Second, for each behavioral preference score we entered the slope of the repetition effect for each of the six different number switches as predictors in a linear regression model to test whether brain activity was a significant predictor for the respective behavioral performances.

RESULTS

EEG Experiment

Determination of region of interest—One-sample *t*-tests comparing the slopes (i.e., the change in stimulus-driven EEG power in the time period following the numerosity switch) averaged across all number switches for each adult participant to zero revealed significant ($p < .01$) increases in power at the flicker frequency with repeated presentation of the same numerosity over a cluster of occipital and parietal channels (see Figure 2; midline: occipital channel 35 (~Oz), occipito-parietal channel 36 (~POz); right: occipital channel 44 (~O2), occipito-parietal channel 46 (~PO2), inferior parietal channel 56 (~P4)). Thus, for the remainder of the analyses we focused on these sets of channels as an orthogonally established region of interest for the adults and on corresponding midline and right occipital and parietal channels for the infants (midline parietal channel Pz, right occipital channel O2, right parietal channel P4). As described in the data analysis section, we averaged the slopes of the repetition effect over midline and right scalp sites, respectively, to better enable direct comparisons of infant and adult responses. Thus, in the following we will only refer to these as the averaged midline and averaged right scalp locations.

Number-selective repetition effect—A four-way mixed-design ANOVA with factors of age (infants or adults), location (midline or right), ratio (2:3, 1:2, or 1:3 ratio), and direction (small-to-large number switch or large-to-small number switch), and with the slope of the repetition effect as the dependent variable, showed a significant main effect of ratio ($F(2,52) = 4.10, p < .03$). The data pattern underlying this main effect was an increasing slope value with increasing ratio. Pair-wise comparisons between the slopes following the three different ratio switches demonstrated a significantly greater positive slope for the 1:3 ratio as compared to the 2:3 ratio ($p < .04$; uncorrected for multiple comparisons). The other two comparisons did not reach statistical significance (both $ps > .08$).

In addition to the main effect of ratio, we found significant interactions between location and direction ($F(1,26) = 11.13, p < .01$) and between group, location, and direction ($F(1,26) = 9.48, p < .01$). These interactions were due to a stronger repetition effect following a switch from large to small numerosities over the midline region in infants whereas right scalp locations showed a stronger repetition effect following a switch from small to large numerosities. Furthermore, we found a significant interaction between location, ratio, direction, and group ($F(2,52) = 3.19, p < .05$). Separate three-way mixed-design ANOVAs for each location revealed a significant main effect of ratio over the midline location ($F(2,52) = 5.30, p < .01$) but not over the right hemisphere ($F(2,52) = 1.85, p = .17$). Pair-wise comparisons between the slopes following the three different ratio switches at the midline location demonstrated a significantly greater positive slope for the 1:3 ratio as compared to the 1:2 ($p < .04$; uncorrected) and 2:3 ratios ($p = .01$; uncorrected), but the comparison between the 1:2 and 2:3 ratio did not reach significance ($p = 0.26$). No other main effects or interactions reached significance.

Behavioral Experiment

As predicted, 9-month-old infants showed a positive numerical change detection preference score that was significantly greater than zero (mean = 5.96, $t(18) = 3.21$, $p < .01$), as well as a significant positive object categorization score that was significantly greater than zero (mean = 12.72, $t(13) = 2.35$, $p < .04^3$).

Based on a median split of the numerical preference scores, we compared the slopes of the previously recorded EEG repetition effect for the three different ratios at the midline location between the infants who were classified as having a high preference for the numerically changing image stream and those who had a low preference. An independent sample t -test revealed a significant difference in the EEG entrainment slopes between these two groups following a 2:3 ratio switch ($t(16) = 2.76$, $p = .014$), but not following a 1:2 or 1:3 ratio switch (both $ps > 0.15$). Figure 3 shows the distribution of the difference in slopes for the high versus low performing infants and illustrates that the largest difference was found over midline parietal scalp sites, the same location that was found to be the most sensitive to numerical ratio in infants and adults.

An analogous analysis using the object categorization scores to split the 9-month-old infants into high and low performing “object categorizers” did *not* yield any significant differences in their previously recorded ratio-related EEG measures.

In an alternative analysis, a stepwise linear regression model was applied, with the slope of the repetition effect for the six different number switches at the midline location used as possible predictors. This analysis yielded a significant model predicting numerical discrimination based on the two slopes following a 2:3-ratio switch in numerosity ($R^2 = 0.77$, $F(2,9) = 15.17$, $p = .001$; std beta_{8-12 switch} = 0.88, std beta_{12-8 switch} = 0.5). Thus, the more positive the slope following a 2:3-ratio switch in the EEG experiment at 7 months, the larger the infant’s preference score in a 2:3-ratio change-detection task at 9 months. No other EEG slope values yielded significant predictions of the numerical change detection score measured 2 months later. In addition, none of the slopes of the EEG repetition effect were a significant predictor for the object categorization scores at 9 months.

DISCUSSION

Using a novel, rapid, steady-state visual-presentation paradigm, we observed an increase in the oscillatory neural activity at the stimulation frequency with repeated presentation of the same numerosity in both adults and infants over midline posterior scalp sites across 2400-ms time periods, which was reflected by a positive slope in the stimulus-driven EEG power over that time. This increase appears to reflect an entrainment of stimulus-driven neural activity, at least over the 2,400-msec blocks used in this study. The increase in neural synchrony was found to be larger following a relatively large numerical switch as compared to a relatively small numerical switch (e.g., a 1:3 ratio switch as compared to a 2:3 ratio switch). Importantly, this synchronization pattern was not affected by the direction of the numerical switch (i.e., from a small to a larger numerosity versus the opposite direction) or by the absolute values presented. Thus, the increased neural entrainment seems to be solely determined by the ratio between the numerosities in two adjacent 2,400-msec blocks.

The qualitative and quantitative similarities in the infants and adults between the neural synchronization to numerical repetition suggest that our task taps a shared Approximate

³There was no data for the object categorization task available from two infants due to fussiness during the procedure. In addition, the data from one infant for this task was classified as an outlier (more than two standard deviations above or below the mean) and was thus removed from further analyses.

Number System. Previous studies have explored the neural bases of numerical cognition in human infants (Berger, Tzur, & Posner, 2006; Izard et al., 2008; Libertus et al., 2009). However, none of these studies directly compared infants and adults in the same task. Thus, these results provide the first direct, neural evidence for continuity in the Approximate Number System from preverbal infants to educated human adults.

Prior studies have suggested that synchronized neural activity may be an important mechanism by which information is encoded in the brain (Buzsaki & Draguhn, 2004; Engel & Singer, 2001; Varela, Lachaux, Rodriguez, & Martinerie, 2001). Higher frequency oscillations are assumed to reflect neural activity in a confined, localized region of the brain whereas lower frequency oscillations may reflect communication between distant brain regions. Increased induced gamma-synchronization in infants and adults appears to be an index of feature binding, a process that is necessary for object perception (Csibra, Davis, Spratling, & Johnson, 2000; Tallon-Baudry, Bertrand, Delpuech, & Pernier, 1996). It has also been suggested that increased induced gamma-activity reflects conscious perception of visual stimuli (Rodriguez et al., 1999) as well as of auditory stimuli (Joliot, Ribary, & Llinas, 1994). Furthermore, if attended stimuli are presented in a rhythmic fashion, as was done in the present study, oscillations in sensory cortices tend to entrain to the rhythm and show an increased response at this frequency (Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008; Schroeder & Lakatos, 2009). Hence the increasing stimulus-driven oscillatory EEG power observed in our study may reflect the build-up of an entrainment of this sort, in turn perhaps reflecting strengthened communication between neural networks that respond to numerical information and a more robust mental representation of a given numerosity. We infer that this entrainment response is largest following a relatively large number switch because the degree to which the entrained neural activity is perturbed following such a switch is greater than in the case of a small number switch.

The observed neural synchronization pattern as a result of repeated presentation of a given numerosity may be due to two possible underlying mechanisms. On the one hand, it is possible that the neural networks representing the numerical stimuli initially respond asynchronously to a given numerosity and become more synchronized with repeated presentation. Metaphorically speaking, activity in these neural networks resembles an audience wave that can be observed during a large sports event. Initially, a cheerleader might encourage people to start the wave. During this stage, or in our case, in the first 800 msec of the 2,400-msec block, the wave is not clearly visible and synchronized yet, as it may take a bit of time for everyone to get the timing coordinated. However, as the wave travels around the stadium, people get into the rhythm and the wave becomes more clearly defined and synchronized. This may correspond to the observation that spectral power in the EEG at the stimulation frequency increases with repeated presentation of the same numerosity.

Alternatively, the audience wave may be initiated but only few people respond initially, whereas the others remain seated unsure as to what to do or whether it is worth getting up. Similarly, only few neurons may initially respond to the presentation of a new numerosity. However, as the wave travels the stadium, more and more people get involved and the wave increases in strength. Correspondingly, the increase in spectral power with repeated presentation of the same numerosity may be due to an increase in the number of neurons firing or interacting in response. Given the methods used in this study, it is not possible to dissociate these two possible mechanisms; however, it also would seem that they are not necessarily mutually exclusive and it is possible that a combination of the two underlies the observed increase in spectral power.

Irrespective of the underlying mechanism, it may seem surprising that spectral power *increased* with repeated presentation of the same numerosity. For example, numerous studies using rapidly flickering visual stimuli found increases in the stimulus-driven spectral power with increased attention, and thus decreases in power with decreased attention (see Womelsdorf & Fries, 2007, for a review). Given that attention, and for that matter sensory-evoked responses, typically decrease with adaptation to a stimulus, it seemed reasonable to expect to observe a *decrease* in spectral power with repeated presentation of the same numerosity. However, since we observed effects in the opposite direction, it is possible that our effects do not reflect changes in attention. Instead, they might reflect a specific synchronizing, or entrainment, response to the repeating numerical aspect of the stimuli. Future studies in which varying task instructions may require different levels of attention to the numerical stimuli, as well as studies that invoke responses to non-numerical switches, are needed to fully address this question.

Another point to consider is that our design only employed 2,400-msec blocks of a given numerosity. Thus, it is possible that 2,400 msec was not sufficient to capture the full temporal course of the stimulus-driven response following a given numerosity switch. It is conceivable that there are two distinct processes at play when participants view such steady-state stimuli: one being an entrainment process and the other being an adaptation process. During the first few seconds of repeated presentation of the same numerosity, the entrainment process may trump the adaptation process. That is, there may be a net initial stabilizing increase in synchrony in the first few seconds. However, over time the adaptation process might start to dominate leading to an adaptation-related decrease in synchronization. In fact, our infant results of a negative slope following the 2:3-ratio numerosity switch may suggest such an effect. More specifically, we know that, at least behaviorally, most infants at this age cannot discriminate numerosity changes of a 2:3 ratio very well (e.g., Libertus & Brannon, 2010; Xu & Spelke, 2000). Thus, it is highly likely that most of the infants in our study perceived the 2:3-ratio switch as a continuation of the previous numerosity block, thereby yielding a perception of the same repeated numerosity for 4,800 msec instead of 2,400 msec. The fact that we observed a negative slope following a 2:3-ratio switch (see Figure 4B) may thus suggest that the initial increase in stimulus-driven EEG power over the first few seconds of a repeated numerosity resulting from some sort of entrainment process may have been followed by a decrease in power due to eventual stimulus adaptation or dwindling of attention. Future studies that employ longer block lengths are needed to fully answer this question.

Lastly, at least for the adults, the changes in numerosity were within the typical range of discrimination. Hence, it is important to consider whether the adult participants may have been able to anticipate the numerical switches at the end of each 2,400-msec block. If so, it could be argued that the increase in spectral power at the flicker frequency could therefore reflect an increase in anticipation of the switch. However, if the neural response were merely a reflection of tracking the elapsed time since the last switch, we would not expect to observe ratio-dependent differences in the response. Furthermore, participants were unable to anticipate the magnitude of the numerical switch as the switches were randomly intermixed and each numerical value was included in relatively large and relatively small numerical switches. Thus, it seems impossible that our observed increases in power merely reflect differences in anticipation of a switch without encoding of the numerical information.

It is interesting to note that we found qualitatively similar neural response patterns in infants and adults for our 12.5-Hz flicker frequency even though this frequency is typically associated with different cognitive functions. In adults, the 12.5-Hz flicker frequency falls within the upper alpha band, which for *ongoing* EEG activity is frequently associated with decreases in attentional processes and cognitive performance in general (Klimesch, 1999;

Thut, Nietzel, Brandt, & Pascual-Leone, 2006; Worden, Foxe, Wang, & Simpson, 2000). In contrast, in infants the 12.5-Hz flicker frequency lies outside their functional equivalent for the adult alpha-band (Marshall, Bar-Haim, & Fox, 2002; Stroganova, Orekhova, & Posikera, 1999). Thus, future studies will need to disentangle the relationships between the stimulus-driven oscillatory activity at different flicker frequencies and the traditional cognitive roles associated with ongoing or induced EEG activity at nearby frequency bands. It might also be useful to assess which stimulation frequency provides the strongest response for this or other cognitive functions. This information may provide insights into the nature of the underlying neural networks (e.g., Buzsaki & Chrobak, 1995).

To our knowledge, this is the first study to directly compare infants' and adults' neural responses in the same numerical task. Our results show qualitatively similar ratio-dependent increases in spectral power at the flicker frequency with repeated presentation of the same numerosity for both infants and adults. These findings thus provide direct evidence for an ontogenetically continuous Approximate Number System that is already functional in preverbal infants.

Furthermore, infants' EEG synchronization pattern to numerical stimuli at seven months of age was a significant predictor of their numerical discrimination abilities but not their object-categorization abilities two months later, suggesting that both paradigms provide useful measures of number-specific discrimination abilities in infancy (see also Libertus & Brannon, 2010). Both the neural entrainment and the change-detection measures seem to be sensitive to individual differences in number-discrimination abilities at a very young age and thus hold promise for longitudinal studies that track individual infants' developmental progression in numerical cognition and achievement.

CONCLUSIONS

Our study shows that a neural synchronization or entrainment response is elicited in response to rapid flickering images of a repeated numerosity in both seven-month-old infants and adults. In both groups, the degree of synchronization following a numerical switch was determined by the ratio between adjacent numerosity blocks, as predicted by Weber's Law. Thus, these similarities in brain response provide direct evidence for an ontogenetically continuous Approximate Number System that is shared between infants and adults. Moreover, EEG entrainment to repeated numerical stimulation was a significant predictor of infants' number discrimination measured behaviorally two months later, validating this novel EEG paradigm as a reliable measure for individual differences in infants' number discrimination.

Acknowledgments

We thank Stacey Blase, Caitlin Gillard, Emily Hopkins, Tina Liang, and Melissa Mang for helping with data collection and Tineke Grent-'t Jong for aid in data analysis.

The work with adults in this study was supported by NIMH grant R01-MH60415 to MGW, and the work with infants by a James McDonnell Scholar Award and R01-MH066154 to EMB.

References

- Barth H, La Mont K, Lipton J, Dehaene S, Kanwisher N, Spelke E. Non-symbolic arithmetic in adults and young children. *Cognition*. 2006; 98(3):199–222. [PubMed: 15876429]
- Berger A, Tzur G, Posner MI. Infant brains detect arithmetic errors. *Proceedings of the National Academy of Sciences*. 2006; 103(33):12649–12653.

- Buzsaki G, Chrobak JJ. Temporal structure in spatially organized neuronal ensembles: A role for interneuronal networks. *Current Opinion in Neurobiology*. 1995; 5(4):504–510. [PubMed: 7488853]
- Buzsaki G, Draguhn A. Neuronal oscillations in cortical networks. *Science*. 2004; 304(5679):1926–1929. [PubMed: 15218136]
- Cantlon JF, Brannon EM. Shared system for ordering small and large numbers in monkeys and humans. *Psychological Science*. 2006; 17(5):401–406. [PubMed: 16683927]
- Cantlon JF, Brannon EM. Basic math in monkeys and college students. *Public Library of Science Biology*. 2007; 5(12):e328.
- Cantlon JF, Brannon EM, Carter EJ, Pelphrey KA. Functional imaging of numerical processing in adults and 4-y-old children. *Public Library of Science Biology*. 2006; 4(5):e125.
- Cordes S, Gelman R, Gallistel CR, Whalen J. Variability signatures distinguish verbal from nonverbal counting for both large and small numbers. *Psychonomic Bulletin & Review*. 2001; 8(4):698–707. [PubMed: 11848588]
- Csibra G, Davis G, Spratling MW, Johnson MH. Gamma oscillations and object processing in the infant brain. *Science*. 2000; 290(5496):1582–1585. [PubMed: 11090357]
- Dehaene S, Molko N, Cohen L, Wilson AJ. Arithmetic and the brain. *Current Opinion in Neurobiology*. 2004; 14(2):218–224.
- De Smedt B, Verschaffel L, Ghesquière P. The predictive value of numerical magnitude comparison for individual differences in mathematics achievement. *Journal of Experimental Child Psychology*. 2009; 103(4):469–479. [PubMed: 19285682]
- Engel AK, Singer W. Temporal binding and the neural correlates of sensory awareness. *Trends in Cognitive Sciences*. 2001; 5(1):16–25. [PubMed: 11164732]
- Gilmore CK, McCarthy SE, Spelke E. Non-symbolic arithmetic abilities and mathematics achievement in the first year of formal schooling. *Cognition*. 2010
- Halberda J, Mazocco MM, Feigenson L. Individual differences in non-verbal number acuity correlate with maths achievement. *Nature*. 2008; 455(7213):665–668. [PubMed: 18776888]
- Holloway ID, Ansari D. Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children's mathematics achievement. *Journal of Experimental Child Psychology*. 2009; 103(1):17–29. [PubMed: 18513738]
- Izard V, Dehaene-Lambertz G, Dehaene S. Distinct cerebral pathways for object identity and number in human infants. *Public Library of Science Biology*. 2008; 6(2):e11.
- Joliot M, Ribary U, Llinas R. Human oscillatory brain activity near 40 Hz coexists with cognitive temporal binding. *Proceedings of the National Academy of Sciences*. 1994; 91(24):11748–11751.
- Klimesch W. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Research: Brain Research Reviews*. 1999; 29(2–3):169–195. [PubMed: 10209231]
- Lakatos P, Karmos G, Mehta AD, Ulbert I, Schroeder CE. Entrainment of neuronal oscillations as a mechanism of attentional selection. *Science*. 2008; 320(5872):110–113. [PubMed: 18388295]
- Libertus ME, Brannon EM. Stable individual differences in number discrimination in infancy. *Developmental Science*. 2010; 13(6):900–906. [PubMed: 20977560]
- Libertus ME, Pruitt LB, Woldorff MG, Brannon EM. Induced alpha-band oscillations reflect ratio-dependent number discrimination in the infant brain. *Journal of Cognitive Neuroscience*. 2009; 21(12):2398–2406. [PubMed: 19016603]
- Lipton JS, Spelke ES. Origins of number sense. Large-number discrimination in human infants. *Psychological Science*. 2003; 14(5):396–401. [PubMed: 12930467]
- Lipton JS, Spelke ES. Discrimination of large and small numerosities by human infants. *Infancy*. 2004; 5(3):271–290.
- Mandler JM, McDonough L. Concept formation in infancy. *Cognitive Development*. 1993; 8(3):291–318.
- Marshall PJ, Bar-Haim Y, Fox NA. Development of the EEG from 5 months to 4 years of age. *Clinical Neurophysiology*. 2002; 113(8):1199–1208. [PubMed: 12139998]
- Meigen T, Bach M. On the statistical significance of electrophysiological steady-state responses. *Documenta Ophthalmologica*. 2000; 98:207–232. [PubMed: 10945442]

- Nieder A. Counting on neurons: The neurobiology of numerical competence. *Nature Reviews Neuroscience*. 2005; 6(3):177–190.
- Nieder A, Freedman DJ, Miller EK. Representation of the quantity of visual items in the primate prefrontal cortex. *Science*. 2002; 297(5587):1708–1711. [PubMed: 12215649]
- Nieder A, Miller EK. A parieto-frontal network for visual numerical information in the monkey. *Proceedings of the National Academy of Sciences*. 2004; 101(19):7457–7462.
- Platt JR, Johnson DM. Localization of position within a homogeneous behavior chain: Effects of error contingencies. *Learning and Motivation*. 1971; 2:386–414.
- Rodriguez E, George N, Lachaux JP, Martinerie J, Renault B, Varela FJ. Perception's shadow: Long-distance synchronization of human brain activity. *Nature*. 1999; 397(6718):430–433. [PubMed: 9989408]
- Roitman JD, Brannon EM, Platt ML. Monotonic coding of numerosity in macaque lateral intraparietal area. *Public Library of Science Biology*. 2007; 5(8):e208.
- Schroeder CE, Lakatos P. Low-frequency neuronal oscillations as instruments of sensory selection. *Trends in Neurosciences*. 2009; 32(1):9–18. [PubMed: 19012975]
- Stroganova TA, Orekhova EV, Posikera IN. EEG alpha rhythm in infants. *Clinical Neurophysiology*. 1999; 110(6):997–1012. [PubMed: 10402087]
- Tallon-Baudry C, Bertrand O, Delpuech C, Pernier J. Stimulus specificity of phase-locked and non-phase-locked 40 Hz visual responses in human. *Journal of Neuroscience*. 1996; 16(13):4240–4249. [PubMed: 8753885]
- Temple E, Posner MI. Brain mechanisms of quantity are similar in 5-year-old children and adults. *Proceedings of the National Academy of Sciences*. 1998; 95(13):7836–7841.
- Thut G, Nietzel A, Brandt SA, Pascual-Leone A. Alpha-band electroencephalographic activity over occipital cortex indexes visuospatial attention bias and predicts visual target detection. *Journal of Neuroscience*. 2006; 26(37):9494–9502. [PubMed: 16971533]
- Varela F, Lachaux JP, Rodriguez E, Martinerie J. The brainweb: phase synchronization and large-scale integration. *Nature Reviews Neuroscience*. 2001; 2(4):229–239.
- Whalen J, Gallistel CR, Gelman R. Nonverbal counting in humans: The psychophysics of number representation. *Psychological Science*. 1999; 10(2):130–137.
- Womelsdorf T, Fries P. The role of neuronal synchronization in selective attention. *Current Opinion in Neurobiology*. 2007; 17(2):154–160. [PubMed: 17306527]
- Worden MS, Foxe JJ, Wang N, Simpson GV. Anticipatory biasing of visuospatial attention indexed by retinotopically specific alpha-band electroencephalography increases over occipital cortex. *Journal of Neuroscience*. 2000; 20(6):RC63. [PubMed: 10704517]
- Xu F, Spelke ES. Large number discrimination in 6-month-old infants. *Cognition*. 2000; 74(1):B1–B11. [PubMed: 10594312]

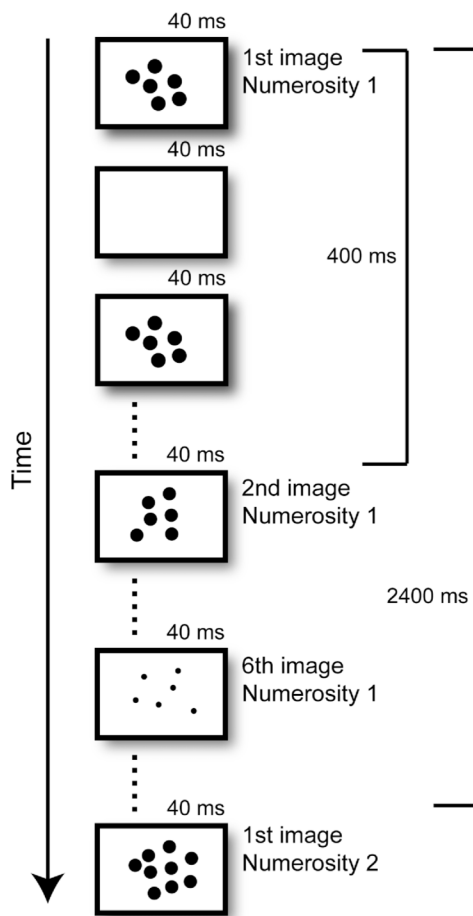
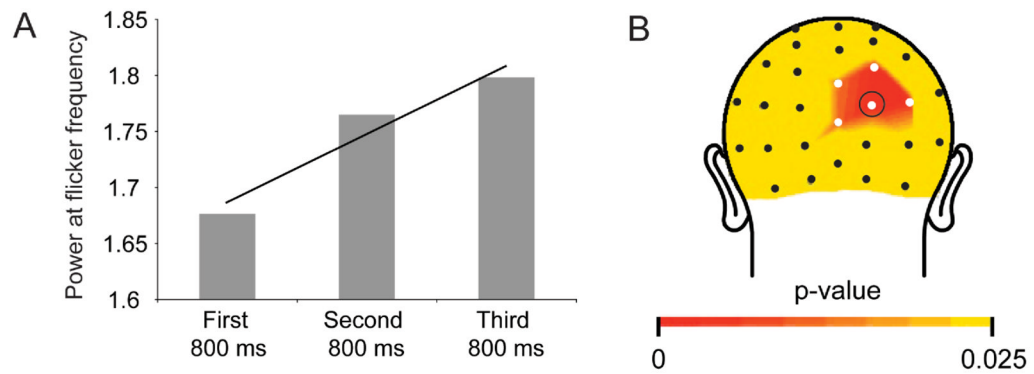


FIGURE 1. Experimental design. Participants passively viewed rapid streams of images flickering at a stimulation frequency of 12.5 Hz (i.e., 40 msec on/40 msec off). Every 400 msec, a new image was presented. After 2,400 msec (i.e., six images of the same numerosity), the number of elements changed by a 1:3, 1:2, or 2:3 ratio (e.g., from 8 to 24 elements).

**FIGURE 2.**

A Power at the flicker frequency across all number switches for each 800-msec segment over a sample occipito-parietal channel (circled in B) for adults. B: Topographical distribution of the p -values for the statistics testing for a repetition effect in adults averaged across all changes in numerosity. Scalp sites highlighted in white showed significant repetition effects across all ratio switches ($p < .01$) and were thus used to define the region of interest. (color figure available online)

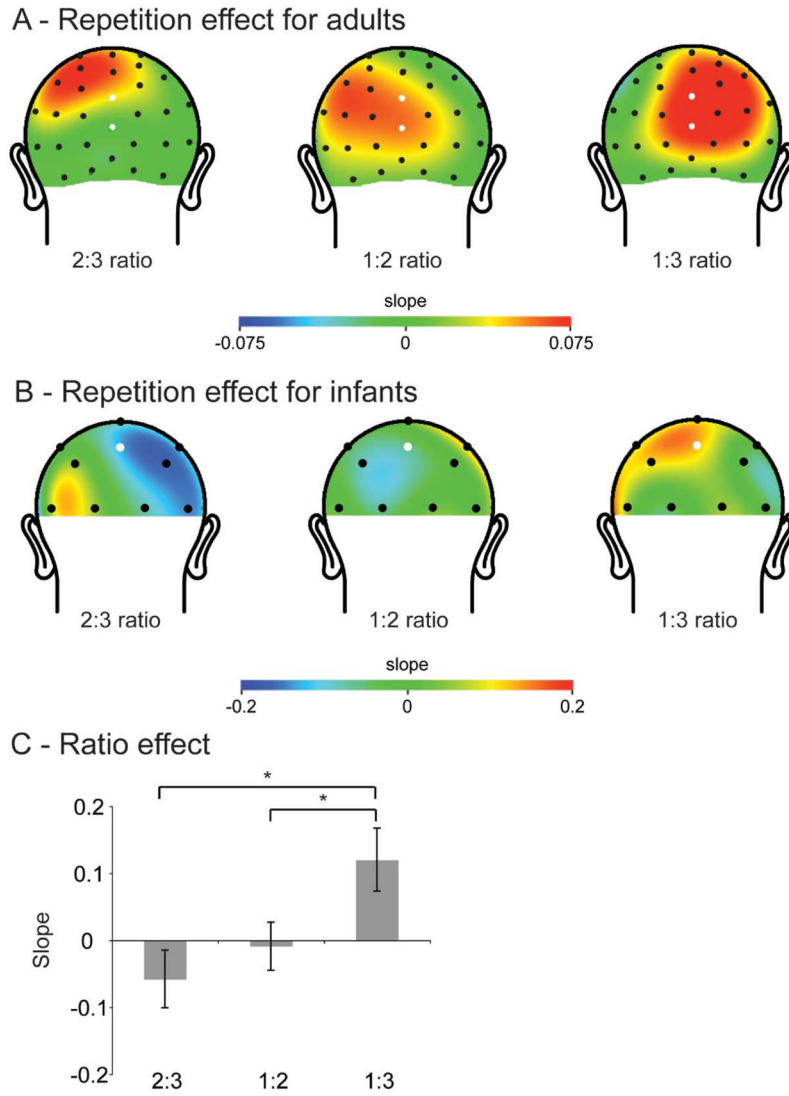


FIGURE 3. A: Topographical distribution of the slopes of the repetition effect for adults, shown separately for the time periods following the different ratio switches. Channels showing significant effects of ratio, which were over midline occipito-parietal scalp sites, are highlighted in white. B: Topographical distribution of the slopes of the repetition effect for infants separated by ratio. Channels showing significant effects of ratio are highlighted in white. C: Slopes for each ratio over midline scalp sites averaged across both age groups. Significant ($p < .05$) pair-wise comparisons are indicated by *. Error bars reflect standard errors. (color figure available online)

2:3 ratio:
Avg. slope high minus low performing infants

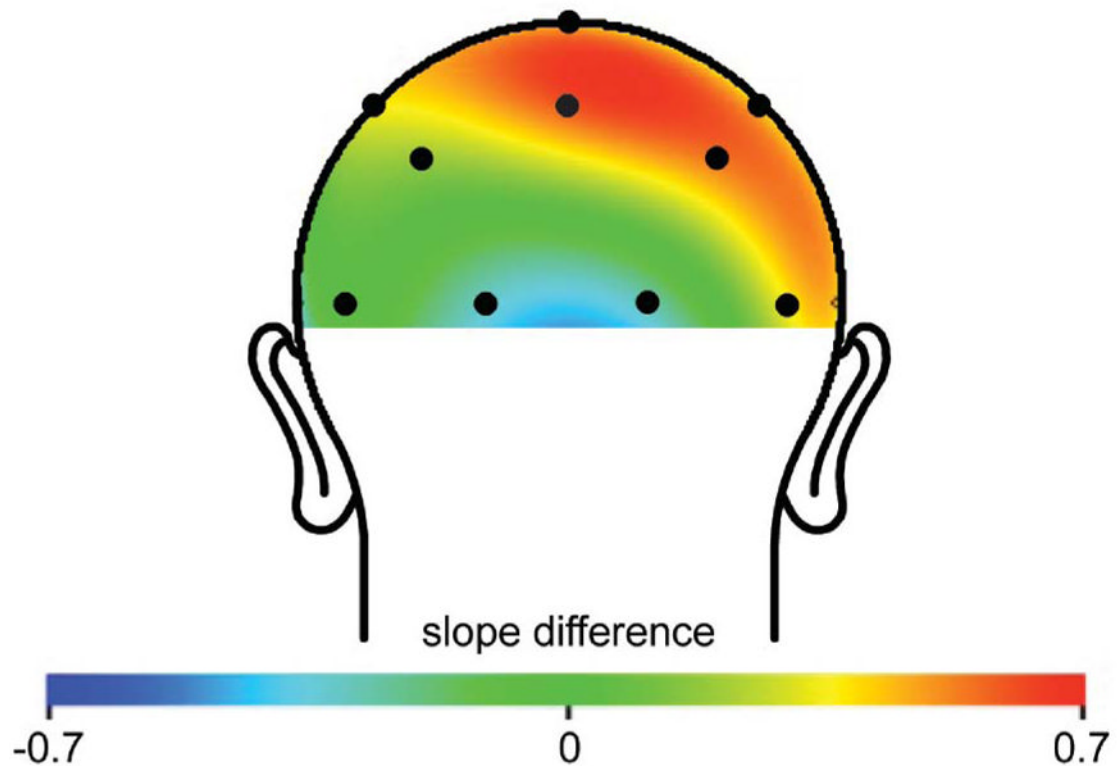


FIGURE 4.

The distribution of the differences in slopes (i.e., the changes in the electroencephalogram (EEG) power in the 2,400-msec time period following the 2:3-ratio switch) for the high versus low performing infants in the later numerical change detection task. The largest difference was found over midline parietal scalp sites, the same location that was found to be sensitive to numerical ratio. (color figure available online)