

Theoretical and methodological implications of variability in infant brain response during a recognition memory paradigm

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Abstract

Previously published reports have sought to elucidate the development of visual recognition memory in the human infant by investigating the modulation of infant ERPs by a familiar and novel face (e.g., de Haan & Nelson, 1997, 1999). Variability in infants' brain responses elicited under the same mnemonic condition, however, has not been previously examined. The present report undertook two separate analyses in order to examine two kinds of variability: variability in the brain's response to a stimulus over time as a function of stimulus repetition, and variability in the brain's response between subjects as a function of the total number of trials completed in an ERP session. There were three major findings: (a) the mid-latency negative component (Nc) and long-latency slow wave (SW) were found to dissociate cognitive processes associated with familiarity from processes associated with stimulus repetition, (b) individual differences in the number of trials an infant completes in an ERP session were observed to be associated with differences in the amplitude and latency of the Nc, and (c) individual differences in the number of trials an infant completes appear to reflect differences in the extent to which the familiar and novel faces are encoded. The implications of these results are discussed with respect to models of habituation and preferential looking, infant ERP methodology, and developmental processes.

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1. Introduction

Event-related potentials (ERPs) reflect the synchronous firing of neuronal populations in the cortex, and represent transient changes in the brain in response to a discrete event. These potentials propagate through extracellular space and are measured by electrodes placed on the scalp. ERPs have excellent temporal resolution, and thus can provide milliseconds by milliseconds information about ongoing cognitive processes. Due to the physical and physiological properties of the skull, scalp, and the brain, however, the signal-to-noise ratio during this type of recording can be quite low. In order to increase the signal relative to the noise, stimuli are presented such that the responses to a particular condition or category can be averaged across multiple trials. In order to create a stable average, psychophysicists who study adults often collect hundreds of trials from an individual participant. As would be expected, the requirements for developmental populations are reduced and the total number of trials for many infant-based experiments is between 40 and 100.

ERPs have been used to provide an important source of information about the development of visual recognition memory. The spatial and temporal information provided by ERPs permits the differentiation of cognitive processes that may not be directly reflected in behavior, as the recording method does not require a behavioral response by the subject. For example, [de Haan and Nelson \(1997\)](#) showed that the ERP to an a priori familiar stimulus depended on the context in which the stimulus was viewed (i.e., the perceptual properties of a novel stimulus with which it was paired). In this study, both the morphology and topography of infants' brain activity that differentiated the familiar and novel stimulus depended on the degree of perceptual similarity between the stimuli. Such differences suggest that different neural circuits, and hence, different cognitive processes may be invoked, depending on the context in which a stimulus is viewed.

Despite an increase in the use of ERPs with developmental populations, infant ERP studies have typically used one of two paradigms. The first is a standard oddball paradigm, in which two or more stimuli are presented repeatedly, with different frequencies of presentation, while ERPs are recorded. The second is a modified habituation paradigm in which the infant is first familiarized to a stimulus, and then presented with the familiar and a novel stimulus repeatedly while ERPs are recorded ([Nelson, 1994](#); [Nelson & Monk, 2001](#) for review). In addition, the majority of these studies have used faces as stimuli. To date, there are several major components that have been observed in the infant ERP. The two that are most relevant to this report include the middle-latency negative component (Nc) and the long-latency slow wave component (SW).

The Nc is a negative deflection in the ERP that peaks between 400 and 800 ms following stimulus onset. It is commonly observed to be maximal over fronto-central scalp regions, and is thought to reflect an obligatory attentional response. In general, the Nc is more negative to unexpected, unrecognizable events or to an infrequent stimulus ([Courchesne, Ganz, & Norcia, 1981](#); [Karrer & Ackles, 1987](#)), is sensitive to experience or familiarity ([Courchesne et al., 1981](#); [de Haan & Nelson, 1997, 1999](#); [Webb & Nelson, 2001a](#)), and can index habituation effects ([Nikkel & Karrer, 1994](#); [Snyder & Nelson, in preparation](#)). [Nelson \(1994\)](#) has suggested that the Nc may be an obligatory attentional response, since the component is present in the overall waveform to some degree regardless of the experimental manipulation.

The SW generally begins around 1,000 ms following stimulus onset and is commonly observed to be maximal over temporal scalp regions. [Courchesne and colleagues \(1981\)](#) have

proposed that this component might reflect categorization of events on the basis of their evident, concrete properties. In contrast, Nelson and Collins (1991) have demonstrated that the SW varies based on the degree to which a stimulus has been fully encoded. The SW has been observed to take one of three forms: (a) a positive-going slow wave (PSW) that is thought to reflect memory updating for a partially-encoded stimulus, (b) a negative-going slow wave that is thought to reflect the detection of a novel stimulus, and (c) a return to the baseline response (i.e., pre-stimulus response), which is thought to reflect the response to a fully encoded stimulus.

1.1. *The facial recognition paradigm*

In several previous ERP studies (de Haan & Nelson, 1997, 1999; Nelson et al., 2000) investigating visual recognition memory in infants, infants were shown an alternating sequence of two stimuli: an a priori familiar stimulus (the mother's face) and a novel stimulus (a novel female face). In the original report by de Haan and Nelson (1997), the researchers found that the ERP response to the familiar face differed from the ERP response to the novel face, while the ERPs for two novel faces did not differ. The authors concluded that the ERP differences reflected recognition of the familiar face.

In addition, the authors demonstrated that the ERP to the familiar stimulus depended on the context in which the stimulus was viewed. Specifically, the Nc was found to be larger (i.e., more negative) for the familiar face when the familiar and novel faces were dissimilar in appearance, but larger to the novel face when the two faces were similar in appearance. Likewise, the slow wave did not differentiate the familiar and novel faces when the faces were dissimilar in appearance, but was larger in amplitude to the novel face when the faces were similar in appearance.

In this paradigm, variability between conditions that may be due to extrinsic factors is controlled by presenting the familiar face and novel face with equal frequency and equating the signal-to-noise ratio of the ERP for each condition by requiring that the same number of trials go into the average for each. Thus, extrinsic variability between the *conditions* is controlled in order to allow appropriate inferences to be made regarding the experimental manipulation. Variability between *subjects*, however, has not been examined. This is mainly due to the large sample size that is required to examine individual differences versus normative cognitive processes. This variability takes at least two forms: (a) individual differences in encoding and recognition memory, and (b) individual differences in the number of trials completed (e.g., due to fussiness or inattention during the session which results in cessation of the testing procedure).

This previously unexamined variability in infant ERPs has important theoretical and methodological implications. First, variability in the brain's response to a stimulus over time has important theoretical significance with respect to behavioral measures of recognition memory, namely models of habituation and preferential looking. Habituation occurs through repeated presentation of a stimulus and, according to one well-accepted model, is thought to reflect stimulus encoding, thereby facilitating the infant's subsequent visual attention to a novel stimulus (see Bornstein, 1985; Sokolov, 1963). Although the visual habituation paradigm has been essential to the study of cognitive and perceptual development for over 40 years, little is known about the neurobiological mechanisms underlying habituation or preferential looking in the human infant.

Second, variability in the number of trials an infant completes may also have theoretical significance for models of habituation. Previous research indicates that there are individual differences in the rate at which infants habituate to visual stimuli (see Colombo & Mitchell, 1990 for review). These individual differences in rate of habituation have been inferred to reflect individual differences in the rate of stimulus encoding. That is, infants who habituate quickly are thought to encode stimuli faster than infants who habituate more slowly. Thus, individual differences in the number of trials an infant completes in a visual recognition ERP paradigm may reflect individual differences in speed of encoding; infants who complete fewer trials may habituate more quickly.

Finally, variability in the number of trials an infant completes also has important significance with respect to infant ERP methodology. Since the number of trials completed is largely infant controlled (i.e., testing is stopped if the infant becomes fussy or stops attending to the stimuli), there are typically large individual differences in the number of total trials completed, and hence, the total amount of exposure each infant has to the stimuli. In habituation research, the amount of exposure to a stimulus has been found to modulate memory for that stimulus: too little exposure during the habituation or familiarization phase may result in a preference for the familiar stimulus, or no preference at all. Likewise, prior exposure to the “novel” stimulus against which the “familiar” stimulus is compared at test may reduce or eliminate the “novelty preference” such that the infant’s visual fixations at test do not differentiate the familiar and novel stimuli. Thus, if some infants have had sufficient exposure to the novel stimulus to fully encode it, their ERPs may not differentiate between the novel and familiar stimuli or the degree to which the responses differ might vary across individuals.

1.2. *Variability in ERP response*

Due to the fact that multiple studies in our lab have used the same visual recognition paradigm, we now have a large enough sample size to examine variability in infant ERPs. In order to address the issues raised above, we examined two different kinds of variability in infant ERPs: (a) *intra*-subject variability, or variability in the brain’s response to a stimulus over time, as a function of stimulus repetition and (b) *inter*-subject variability, or variability in the brain’s response between subjects as a function of the total number of trials completed in an ERP session.

In the first analysis, the analysis of *intra*-subject variability, we examined variability in the brain’s response to a stimulus over time, as a function of stimulus repetition. Specifically, we compared infants’ brain responses elicited by the first 15 presentations of a stimulus to their brain responses elicited by the second 15 presentations of the same stimulus for both the novel and the familiar stimuli. This design allowed us to dissociate cognitive processes associated with familiarity per se from processes associated with stimulus repetition. Such a dissociation would also provide valuable information regarding the functional significance of specific infant ERP components.

Based on previous research with infants using this paradigm, we made several predictions. First, we expected to confirm previous findings that the Nc to the familiar face would be more negative than the Nc to the novel face, and that the SW would be larger to the novel face compared to the familiar face (de Haan & Nelson, 1999; Nelson et al., 2000) when the familiar

and novel face are dissimilar-looking in appearance. Second, since the infant is expected to already have some existing representation for the familiar face, we expected that the ERPs to the novel face would change more over time than the ERPs to the familiar face. Specifically, since the SW has been previously interpreted to reflect the process of memory updating for a partially encoded stimulus (Nelson, 1994, 1996), we expected that the SW to the novel face would become more positive over time as the novel face is encoded, and eventually return to baseline as the face became more familiar. With regard to the familiar stimulus, little is known about how many exposures an infant may need before being able to match a picture presented for a duration of only 500 ms to an internal representation of a familiar item. Thus, the response to the familiar face may take one of two forms, both of which would support our hypothesis: (a) the SW to the familiar face may not change by virtue of an instant match between the picture and a fully encoded representation, or (b) the SW may become less positive over time if a certain number of trials are needed to match the picture to the internal representation; once a match occurs, we presume no further updating of the representation. Thus, based on previous findings and the hypotheses stated above, we expected that the SW would reflect the electrophysiological equivalent of habituation.

In the second analysis, the analysis of inter-subject variability, we examined variability in the infant ERP as a function of total trials completed. Specifically, we compared the ERPs of three groups of infants: (a) infants who completed fewer than 60 trials, (b) infants who completed between 61 and 80 trials, and (c) infants who completed between 81 and 100 trials. Since there are individual differences in the amount of time it takes infants to habituate to a stimulus, it is hypothesized that differences between infants in the number of trials they complete may reflect, to some degree, individual differences in the rate of stimulus encoding. The fact that some infants become too fussy to continue testing earlier in the paradigm than others may reflect a disengagement of attention once the stimulus has been fully encoded. If this is the case, we would not expect to find differences in the ERPs between these groups of infants. Instead, we would expect the ERPs of each group of infants to differentiate the familiar from the novel stimulus, and that the total number of trials completed does not modulate this differentiation. Alternatively, the number of trials completed may not reflect individual differences in the *rate* of stimulus encoding, but the extent of stimulus encoding, resulting in a situation where some infants have encoded the stimuli more fully than others via more exposure. If this is the case, we would expect that the total number of trials completed modulates the differentiation of familiar from novel. Specifically, completing more trials should result in a greater degree of encoding such that infants who complete more trials should show less differentiation (or none at all) of the familiar and novel stimulus.

2. General method

2.1. Participants

Infant participants were recruited from an existing list of parents who had volunteered for research after being contacted by letter following the birth of their child. The infants were recruited to participate in one of three research projects at 6 months of age ($N = 94$; 50

female). The first group of infants was recruited as a normative, full-term comparison sample for a longitudinal study of infants of diabetic mothers (Study 1, $n = 44$; Nelson et al., 2000); the second group of infants was recruited as a cross-sectional comparison group for a longitudinal study of recognition memory (Study 2, $n = 25$; Webb & Nelson, submitted for publication); the third group of infants was recruited as a full-term comparison sample for a study of premature infants (Study 3, $n = 25$; Stolarova, Whitney, deReigner, Georgieff, & Nelson, in preparation). The majority of the infants were Caucasian. All infants were born at term (i.e., 38–42 weeks gestation) and were included in the final sample only if they had no history of visual or neurological abnormalities.

2.2. *Stimuli*

The stimuli were static color images of women's faces posing a neutral expression. Each woman was videotaped from the neck up while seated in front of a gray background and wearing a gray scarf to conceal her clothing. When shown to the subjects, each image averaged 14 cm at the widest point and 18 cm at the longest point. The familiar face was an image of the infant's mother; the novel face was an image of a dissimilar-looking female face (taken from the same database of faces); each infant tested saw a different novel face. For each familiar/novel pair, the faces differed on endogenous characteristics (face shape, hair color and style), but were matched based on exogenous characteristics (glasses and jewelry).

2.3. *Procedure*

Infants sat in a car seat or on a parent's lap 62.5 cm from the monitor. In the event the infant was seated in the parents lap, the parent was instructed to "act like a chair;" that is, to provide physical support but to not interact with her or his infant in any way. The visual angle subtended by the stimuli was approximately 8 degrees. An observer seated behind a screen surrounding the monitor watched the infant through a peephole and signaled the computer to repeat a trial if the infant was looking away from the screen. Brain activity was not recorded during trials in which the infant was not looking at the screen. If needed, a second experimenter tapped the monitor to attract the infant's attention to the images.

2.4. *Electroencephalogram (EEG) recording procedure*

The paradigm consisted of 100 trials of the familiar face and a novel face, presented in random order, with equal frequency (50/50% probability). Each trial consisted of a 100 ms pre-event baseline EEG recording, 500 ms presentation of the stimulus and EEG recording, 1,000 ms of post-stimulus EEG recording, and a variable inter-trial interval averaging 750 ms (range 500–1,000 ms). Each trial lasted between 2,100 to 2,600 ms.

The EEG was recorded using silver–silver–chlorided (Ag–Ag–Cl) electrodes referenced to vertex, and subsequently re-referenced to linked ears. The scalp electrodes were placed over midline (Oz, Pz, Cz, Fz) and lateral (T3, T4, T5, T6, C3, C4) scalp locations according to the 10–20 system (Jasper, 1958). A ground electrode was placed on the forehead. The electrodes were held in place with foam pads, Grass EC2 cream, and cloth headbands. Impedances were

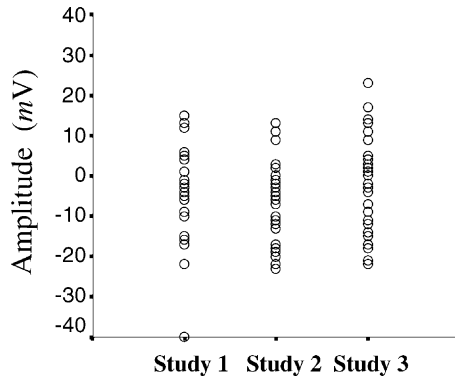


Fig. 1. Maximum negative amplitude of the Nc at the midline central lead (Cz) by original data source.

accepted if they were less than 10 k Ω . The electrooculogram (EOG) was recorded from bipolar miniature electrodes placed vertically below and above the right eye and held in place with small adhesive collars.

All bioelectrical signals were recorded using a Grass Neurodata Acquisition System with model 12 Grass amplifiers. In the original data recording for Study 1, the EEG gain was set to 10,000 and the EOG gain was set to 5,000. The recording headroom for Study 1 was $\pm 500 \mu\text{V}$. In the original data recording for Studies 2 and 3, the EEG gain was set to 20,000 and the EOG gain was set to 5,000. The recording headroom for Studies 2 and 3 was $\pm 250 \mu\text{V}$. Despite these differences in gain settings between the three studies, the precision with which the signal was digitized was similar. As can be seen in Fig. 1, the range in amplitude values across the three experiments is equivalent. The bandpass was 0.1–30 Hz, and a 60 Hz notch filter was engaged. The EEG was sampled every 10 ms (100 Hz).

2.5. ERP data reduction

ERP data were digitized on-line and then edited by computer algorithm. Data with excessive artifact were rejected. Excessive artifact was defined as (a) responses that exceeded $\pm 100 \mu\text{V}$; (b) any EOG artifact during stimulus presentation; (c) post-test impedances greater than 10 k Ω , and (d) systematic deflections (i.e., noise) at the reference electrodes. A standard blink correction algorithm (Gratton, Coles, & Donchin, 1983) was employed to correct for the influence of EOG on the EEG. The algorithm compares deflections in the EOG with deflections in the EEG, computes a model of the influence of eye movement on the EEG, and then subtracts activity from the EEG that is due to eye movement artifact.

3. Study 1: analysis of intra-subject variability

The goal of this analysis was to examine how the ERP response to a stimulus changes as the stimulus is repeated. First, only infants who had viewed more than 60 trials were selected for analysis ($N = 54$; 60% of original sample). Sixty trials was determined to be the minimum number of trials that could yield two good cross-averages for each of the novel and familiar

stimulus conditions for each infant, and simultaneously maximize retention of subjects from the original sample. Second, the data were re-averaged into separate blocks of 30 trials each (Block 1 = trials 1–30; Block 2 = trials 31–60). Within each block, 15 of the 30 trials consisted of presentations of the familiar stimulus and the remaining 15 trials consisted of presentations of the novel stimulus. Thus, Block 1 consists of two separate cross-averages: one average of the first 15 presentations of the familiar stimulus and one average of the first 15 presentations of the novel stimulus. The two cross-averages for Block 2 are comprised of the second 15 presentations of each of the stimuli. In order to be included in the final sample, each subject was required to have a sufficient number of artifact-free trials for both of the two blocks within each stimulus condition. Thus, each subject in the final sample was required to contribute four separate cross-averages: Familiar-Block 1, Familiar-Block 2, Novel-Block 1, and Novel-Block 2.

3.1. Methods

3.1.1. Participants

Of the 54 data sets selected for analysis, 19 infants (11 female) were included in the final data set; 35 infants were excluded due to poor data quality in at least one block for either stimulus condition. Problems with data quality included fewer than 10 trials in the cross-average ($n = 10$), and EEG or EOG artifact ($n = 25$). Given the requirement that infants must complete 60 trials, and the distribution of those trials across four conditions, the attrition rate in this analysis is comparable to other studies using infant ERPs (see de Haan & Nelson, 1997, 1999). See Table 1 for means and standard deviations of number of total trials and trials in the averages for included subjects.

3.1.2. ERP analysis

Based on inspection of the individual subject averages and the grandmeans, attention was focused on two major components at the anterior electrode sites: (a) the Nc, a mid-latency negative component occurring between 280 and 730 ms following stimulus onset, and (b) the SW, a long-latency slow wave component occurring between 900 and 1,500 ms following stimulus onset. At the occipital electrode (Oz) a separate analysis was conducted on a series of seven components: (a) the P135 from 100 to 170 ms after stimulus onset, (b) the N230 from 170 to 300 ms after stimulus onset, (c) the P400 from 300 to 585 ms after stimulus onset, (d) the P610 from 585 to 660 ms after stimulus onset, (e) the N700 from 660 to 820 ms after stimulus onset, (f) the P965 from 820 to 1,110 ms after stimulus onset, and (g) the slow wave from 1,110 to 1,500 ms after stimulus onset.

Table 1
Means (SD) for number of trials completed and trials in the averages for subjects included in Study 1: analysis of intra-subject variability

Block	N	Original data source (N)			Total trials completed	Trials in average	
		Study 1	Study 2	Study 3		Familiar	Novel
1 (Trials 1–30)	19	6	7	6	77.8 (13.8)	13.3 (1.5)	13.1 (1.6)
2 (Trials 31–60)	19	6	7	6	77.8 (13.8)	13.6 (1.7)	13.4 (2.0)

In general, the choice of windows is similar to that observed in previous visual ERP studies with infants (de Haan & Nelson, 1997, 1999; Nelson & Collins, 1991). For each component, we analyzed two variables: (a) average amplitude, defined as the average of the values across each sample in the window¹ and (b) latency to peak amplitude, defined as the time, relative to stimulus onset, at which the peak amplitude (maximum absolute value measured relative to baseline) occurs.

For anterior components, a repeated measures analysis of variance with Greenhouse–Geisser correction was conducted with condition (familiar, novel), block (Block 1, Block 2) and lead as within-subject factors. Lead effects were analyzed separately for midline leads (Pz, Cz, and Fz), central leads (C3, Cz, and C4) and temporal leads (T3, T4, T5, and T6). In order to clarify effects at temporal leads, a separate repeated measures analysis of variance with Greenhouse–Geisser correction was conducted with condition (familiar, novel), block (Block 1, Block 2), hemisphere (left, right) and region (anterior, posterior) as within-subject factors. Post hoc comparisons using Bonferroni correction were used to test for significance between cell means for main and interaction effects. For the occipital components, a repeated measures analysis of variance with Greenhouse–Geisser correction was conducted with condition (familiar, novel) and block (Block 1, Block 2) as within-subject factors. Post hoc comparisons using Bonferroni correction were used to test for significance between cell means for main and interaction effects (Figs. 2 and 3).

3.2. Results

3.2.1. Topography of the Nc

As has been previously reported, the Nc was observed to have an anterior-central distribution. It was maximal over fronto-central leads, as indicated by a main effect of lead at midline

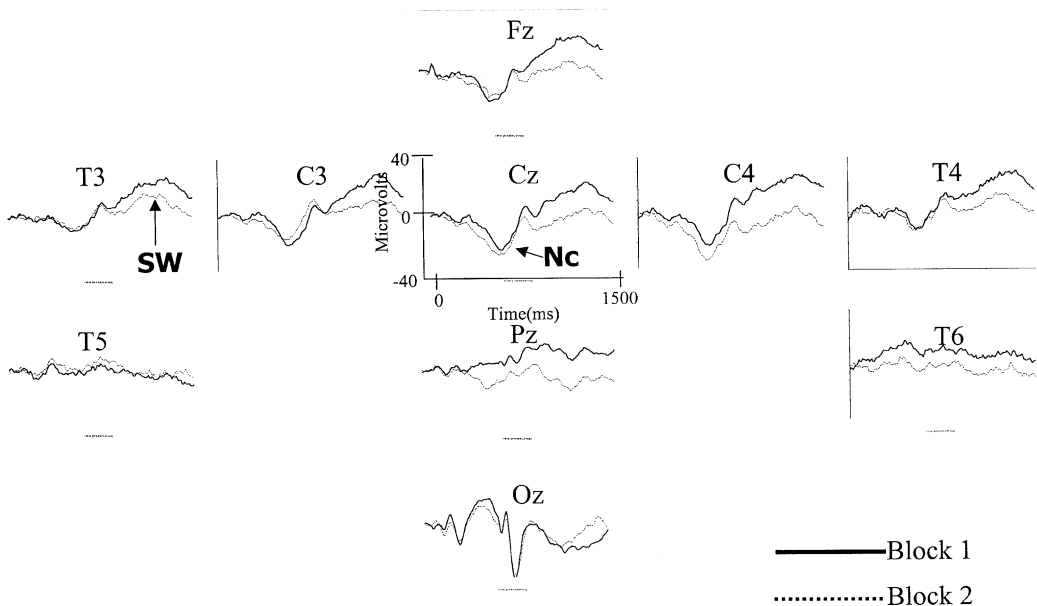


Fig. 2. ERP graphs of Blocks 1 and 2 for the familiar face.

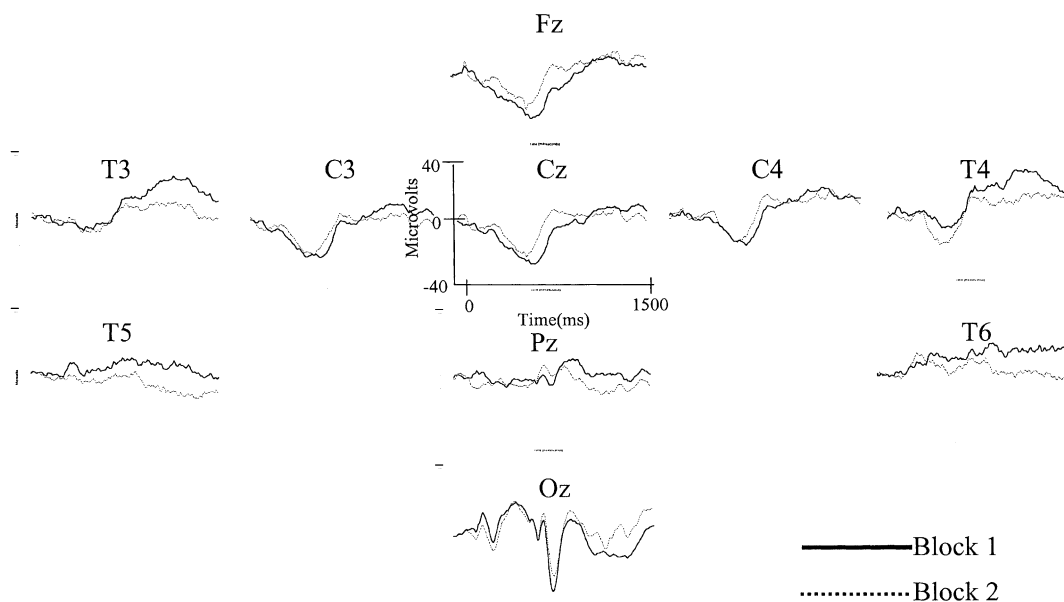


Fig. 3. ERP graphs of Blocks 1 and 2 for the novel face.

electrodes ($F(2, 36) = 13.7, p < .001$). Post hoc comparisons indicated that the amplitude of the Nc was more negative at Fz ($M = -8.3 \mu\text{V SE } 2$) and Cz ($M = -9.0 \mu\text{V SE } 2$) than at Pz ($M = -1.7 \mu\text{V SE } 2$).

At temporal leads, there was a main effect of lead ($F(3, 54) = 8.1, p < .001$); post hoc comparisons indicated that the Nc was more negative at the anterior-temporal electrodes T3 ($M = -2.5 \mu\text{V SE } 1$) and T4 ($M = -2.5 \mu\text{V SE } 2$) than at the posterior-temporal electrode T6 ($M = 4.8 \mu\text{V SE } 1$). This was confirmed by a main effect of region ($F(1, 18) = 12.6, p < .01$) in which the Nc reversed polarity between the anterior-temporal and posterior-temporal electrodes (anterior = $-2.5 \mu\text{V SE } 1$, posterior = $2.8 \mu\text{V SE } 1$). A significant hemisphere by region interaction ($F(1, 18) = 9.9, p < .01$), however, indicated that the main effect of region was due to the difference in amplitude over right-hemisphere electrodes only. Analysis of simple main effects indicated that the amplitude of the Nc was greater over posterior-temporal leads for the right-hemisphere but not for the left-hemisphere. Thus, the Nc appears widely distributed, is maximal over fronto-central leads, and reverses polarity over right-temporal leads, consistent with the literature pointing to a right temporal focus (e.g., fusiform gyrus) for face recognition.

3.2.2. Effects of condition and block on the amplitude of the Nc

The topography of the Nc was found to be modulated by the familiarity of the stimulus (significant condition by lead interaction at central leads, $F(2, 36) = 4.4, p < .05$). Although post hoc comparisons did not reach significance, the Nc appeared to be maximal over right-central leads for the familiar stimulus (C4 = $-8.7 \mu\text{V SE } 2$, Cz = $-8.5 \mu\text{V SE } 2$, C3 = $-5.7 \mu\text{V SE } 2$), and maximal over left-central leads for the novel stimulus (C4 = $-6.0 \mu\text{V SE } 2$, C3 = $-8.9 \mu\text{V SE } 2$, Cz = $-9.5 \mu\text{V SE } 2$). There were no other effects of condition or block on the amplitude of the Nc.

3.2.3. *Effects of condition and block on the latency to peak amplitude of the Nc*

There were no effects of condition or block on the latency of the Nc.

3.2.4. *Topography of the SW*

In general, the long-latency slow wave component appears largest over temporal scalp regions. There were main effects of lead ($F(3, 54) = 18.8, p < .001$), hemisphere ($F(1, 18) = 6.6, p < .05$), and region ($F(1, 18) = 29.8, p < .001$) at temporal leads. Post hoc comparisons indicated that the amplitude of the slow wave was larger over the right-hemisphere temporal leads ($M = 7.0 \mu\text{V SE } 1$) compared to the left-hemisphere temporal leads ($M = 3.6 \mu\text{V SE } 1$), and larger over anterior-temporal leads ($M = 9.5 \mu\text{V SE } 1$) compared to posterior-temporal leads ($M = 1.1 \mu\text{V SE } 1$). Simple main effects of the hemisphere by region interaction ($F(1, 18) = 9.5, p < .01$), indicated that the amplitude of the slow wave component was greater over the right-hemisphere for the posterior-temporal leads (left-posterior = $-1.8 \mu\text{V SE } 2$, right-posterior = $3.9 \mu\text{V SE } 2$), but not for the anterior-temporal leads (left-anterior = $8.9 \mu\text{V SE } 1$, right-posterior = $10.0 \mu\text{V SE } 1$). Thus, the slow wave component was maximal over anterior-temporal leads but showed a right-hemisphere bias at posterior-temporal leads.

3.2.5. *Effects of condition and block on the amplitude of the SW*

The amplitude of the slow wave component was modulated by block at both temporal leads ($F(1, 18) = 5.4, p < .05$) and central leads ($F(1, 18) = 4.3, p < .05$). Post hoc comparisons indicated that the amplitude of the slow wave component decreased from Block 1 ($M = 8.2 \mu\text{V SE } 2$ at temporal leads, $M = 9.2 \mu\text{V SE } 2$ at central leads) to Block 2 ($M = 2.3 \mu\text{V SE } 2$ at temporal leads, $M = 4.3 \mu\text{V SE } 2$ at central leads).

3.2.6. *Occipital components*

There were no effects of block or condition at the occipital lead.

3.3. *Discussion*

A major goal of the present analysis was to dissociate components of the infant ERP modulated by stimulus repetition from components of the infant ERP modulated by the a priori familiarity of the stimuli. We also made several predictions: (a) to confirm previous findings that the Nc to the familiar face would be more negative than the Nc to the novel face and that the SW would be larger to the novel face compared to the familiar face, and (b) that the SW to the novel face would change more than the SW to the familiar face (i.e., a condition by block interaction) by virtue of the assumption of an existing representation for the familiar face.

The hypothesized modulation of the Nc by memory condition was confirmed, but not by the same pattern of results reported in previous studies employing this paradigm. In contrast to previous findings, familiarity was observed to modulate the topography, but not the amplitude or latency of the Nc in the current analysis. Previous findings regarding the topography of amplitude effects, however, is very similar to the pattern of findings reported here. Specifically, when the familiar stimulus was observed to evoke a greater Nc, this effect was found at midline and right, anterior-temporal leads (e.g., de Haan & Nelson, 1997). When the novel stimulus was observed to evoke a greater Nc, the effect had a left, posterior-temporal topography. The

topography of the Nc in the current analysis was observed to be maximal over right-hemisphere leads for the familiar stimulus, but maximal over left-hemisphere leads for the novel stimulus.

The hypothesized modulation of the SW by memory condition was not confirmed. Instead, the amplitude of the SW was modulated by stimulus repetition and decreased in amplitude with greater exposure to the stimulus. Since the SW for both the novel and the familiar face appear to be modulated by repetition, it is not clear whether this modulation reflects encoding (i.e., familiarization), or simply repetition. That is, if the SW reflected encoding, we hypothesized that the ERPs to the novel face would change more than the ERPs to the familiar face, by virtue of the expectation that the infant already had some existing representation for the familiar face. This interaction between memory condition and repetition, however, was not observed in the present analysis.

It is difficult to explain why the current analysis does not replicate previous findings; this may be due to the fact that reports of the behavior of the SW have been inconsistent across investigations using this paradigm. The original study (de Haan & Nelson, 1997) reported no difference in the amplitude of the SW when the familiar face and novel face were dissimilar in appearance, but a larger SW to the novel face when the familiar face and novel face were similar in appearance. In contrast, subsequent work (de Haan & Nelson, 1999; Nelson et al., 2000) has reported a greater SW to the novel face when the familiar face and novel face were dissimilar in appearance. The observed behavior of the SW in this analysis, therefore, is consistent with the original report of the face recognition paradigm, but not with subsequent work. Resolution of this inconsistency is crucial to understanding the functional significance of this component.

Finally, previous studies (de Haan & Nelson 1997, 1999; Nelson et al., 2000) reported that the occipital components were not modulated by memory condition. The observed behavior of the occipital components in this report is consistent with those findings.

The results reported here suggest an interesting dissociation in the functional interpretation of the Nc and the SW. That is, the Nc was observed to be modulated by memory condition but not by repetition, whereas the SW was observed to be modulated by repetition but not by memory condition. Thus, this design allowed us to dissociate cognitive processes associated with familiarity (possibly reflecting recognition) from processes associated with stimulus repetition. This dissociation demonstrates the importance of ERPs to the study of cognitive development.

4. Study 2: analysis of inter-subject variability

The goal of this analysis was to examine individual differences in the brain's response to a familiar and a novel stimulus as a function of total trials completed (or number of exposures to a stimulus). To examine this, the data from the original sample was divided into three groups: (a) Group 1, infants who completed fewer than 60 trials, (b) Group 2, infants who completed between 61 and 80 trials, and (c) Group 3, infants who completed between 81 and 100 trials.

4.1. Methods

4.1.1. Participants

First, 94 data sets were subject to re-analysis. The data were divided into three groups and the same number of infants was included in each group. The first group contained infants who

Table 2

Means (SD) for number of trials completed and trials in the averages for subjects included in Study 2: analysis of inter-subject variability

Group	N	Original data source (N)			Total trials completed	Trials in average unequated S/N
		Study 1	Study 2	Study 3		
1 (<60)	17	6	5	6	50.2 (7.5)	17.9 (5.4)
2 (61–80)	17	3	7	7	69.8 (5.2)	25.2 (5.8)
3 (81–100)	17	13	3	1	94.7 (7.1)	37.1 (6)

had seen fewer than 60 total trials (Group 1, $N = 17$; 13 female); an additional 27 infants were excluded due to: (a) fewer than 10 trials per average ($n = 6$), (b) EOG or EEG artifact ($n = 12$), and (c) 9 infants were randomly excluded to reduce the sample to 17 infants. The second group contained infants who had seen between 61 and 80 total trials (Group 2, $n = 17$; 7 female); an additional 7 infants were excluded due to fewer than 10 trials per average ($n = 2$) and EOG or EEG artifact ($n = 5$). The third group contained infants who had seen between 81 and 100 total trials (Group 3, $N = 17$; 8 female); an additional 9 infants were excluded due to EOG or EEG artifact ($n = 4$) and 5 infants were randomly excluded to reduce the sample to 17 infants. See Table 2 for means and standard deviations of number of total trials and trials in the average for included subjects.

4.1.2. ERP data analysis

Two sets of analyses were performed on the same windows as used in the previous analysis. For the first analysis of inter-subject variability (i.e., unequated analysis), the data for each participant were averaged into two separate cross-averages, one for each stimulus condition. All available artifact-free trials for each stimulus condition were included in the cross-averages, with the constraint that the number of trials included in the cross-averages were matched across conditions for each participant. As seen in Table 2, due to the nature of individual differences in infant performance during the ERP experiments, there is a wide range in the total number of trials viewed, and thus a range in the number of trials in the cross-averages. Since the number of trials included in a cross-average strongly influence the signal-to-noise (S/N) ratio of the ERP, the group differences in mean number of trials included in the cross-averages result in group differences in S/N ratios in the ERPs. Thus, it is possible that group effects in the unequated analysis may reflect group differences in S/N ratios rather than individual differences in group performance. To investigate this possibility, a subset of 20 artifact-free trials was randomly selected from the total available trials of each cross-average in the unequated analysis and the data were re-averaged. Thus, the cross-averages in the second analysis of inter-subject variability (i.e., equated analysis) have equivalent S/N ratios across the three groups (Tables 3 and 4).

For both the unequated and equated analyses, a repeated measures analysis of variance was conducted using group (Group 1, Group 2, and Group 3) as a between-subject factor, and condition (familiar, novel) and lead as within-subject factors. Lead effects were analyzed separately for midline leads (Pz, Cz, and Fz), central leads (C3, Cz, and C4) and temporal leads (T3, T4, T5, and T6). In order to clarify effects at temporal leads, a separate repeated measures analysis of variance with group (Group 1, Group 2, and Group 3) as a between-subject

Table 3

Average amplitude (SE) for the Nc and SW by group after the S/N ratio was equated across groups

Trials	Midline leads (μV) ⁺	Central leads (μV)	Temporal leads (μV)
Nc			
<60	-4.0 (1.9)	-5.5* (1.8)	0.13 (1.7)
61–80	-10.4 (1.9)	-12.2* (1.8)	-4.1 (1.7)
81–100	-5.9 (1.9)	-7.1* (1.8)	0.6 (1.7)
SW			
<60	9.6 (2.3)	11.3 ⁺ (2.1)	6.0 (2.0)
61–80	4.2 (2.3)	6.0 ⁺ (2.1)	1.9 (2.0)
81–100	6.0 (2.3)	6.7 ⁺ (2.1)	1.2 (2.0)

* Significant at the $p < .05$ level.⁺ Marginal significance at the $p < .1$ level.

factor, and condition (familiar, novel), hemisphere (left, right) and region (anterior, posterior) as within-subject factors. An alpha level of 0.05 was used for all comparisons; in addition, the Greenhouse–Geisser p value was used to correct for the violation of the assumption of sphericity. Post hoc comparisons using Bonferroni correction were used to test for significance between cell means for main and interaction effects.

In general, whenever the results for the unequated and equated analysis matched, the results from the unequated analysis will be presented. When the results for the two analysis did not match, both sets of effects are presented (Fig. 4).

4.2. Results

4.2.1. Topography of the Nc

As in the previous analysis, the Nc was observed to be widely distributed, having an anterior-central peak, and showing an inversion in polarity over temporal leads. The average amplitude of the Nc was maximal over fronto-central leads, as illustrated by main effects of lead at midline ($F(2, 96) = 26, p < .001$) and central ($F(2, 96) = 3.7, p < .05$) electrodes, and a main effect of region ($F(1, 46) = 36, p < .001$) at temporal electrodes. For the midline leads, post hoc comparisons indicated that the amplitude of the Nc was more negative at Fz ($M = -7.8 \mu\text{V SE } 1$) and Cz ($M = -9.1 \mu\text{V SE } 1$) than at Pz ($M = -1.6 \mu\text{V SE } 1$). Similarly,

Table 4

Mean latency to peak amplitude (SE) for the Nc by group for both equal and unequal S/N ratios

Trials	Midline leads (ms)*	Central leads*	Temporal leads
Unequated S/N			
<60	536.1 (13)	518.0 (13)	490.7 (12)
61–80	485.7 (13)	471.0 (13)	458.6 (12)
81–100	521.8 (14)	487.8 (13)	481.5 (12)
Equated S/N			
<60	534.7 (13)	518.0 (16)	484.9 (12)
61–80	481.8 (13)	474.7 (16)	460.8 (12)
81–100	505.4 (13)	474.3 (16)	470.8 (12)

* Significant at the $p < .05$ level.

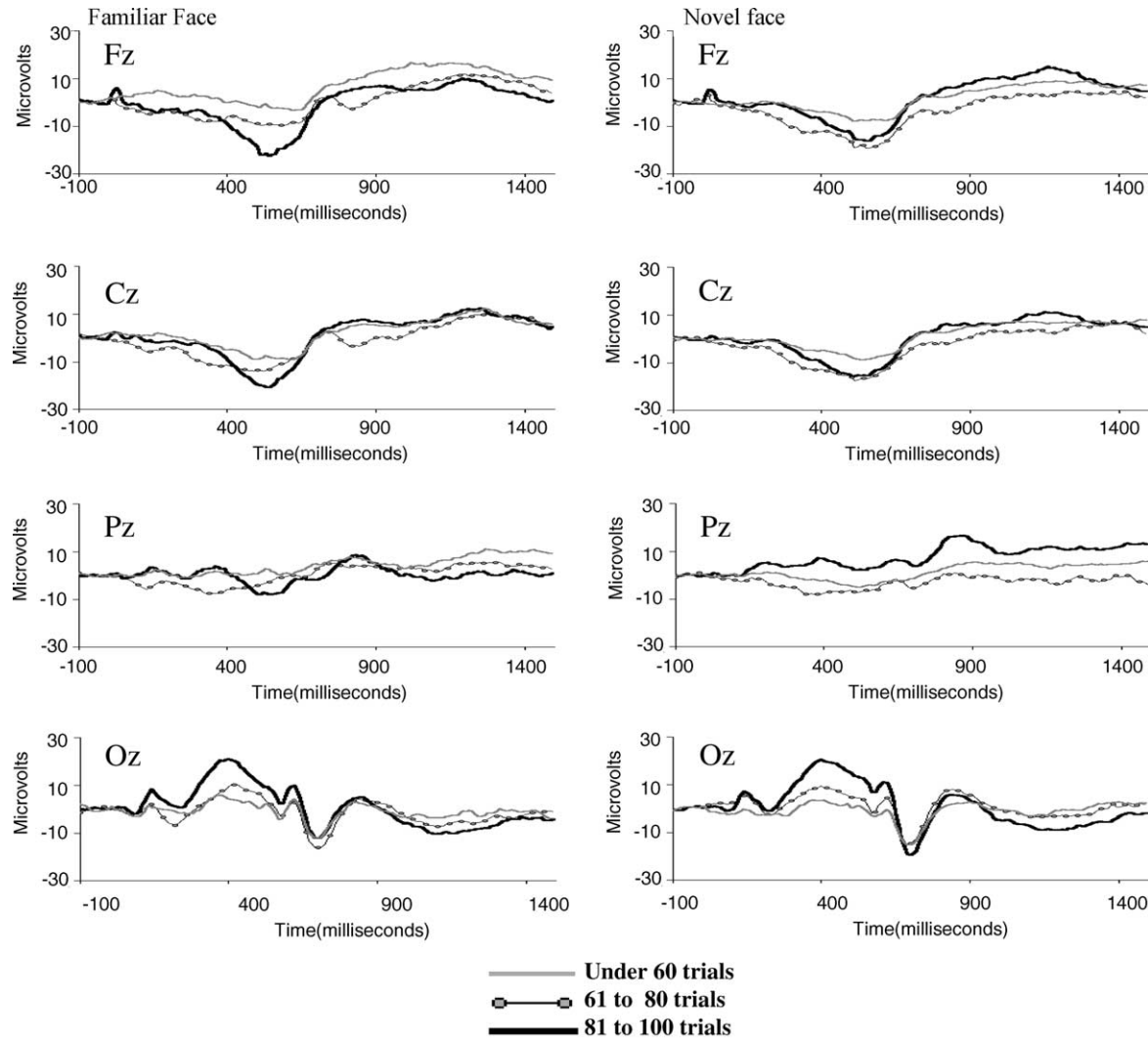


Fig. 4. ERP graphs of midline leads by group for both the familiar and novel faces.

the amplitude of the Nc was more negative at anterior-temporal leads ($M = -3.2 \mu\text{V SE } 1$) than at posterior-temporal leads ($M = 2.5 \mu\text{V SE } 2$), where there was a reversal in polarity.

A hemisphere by region interaction ($F(1, 18) = 9.9, p = .05$) in the equated analysis indicated that the difference in amplitude between anterior- and posterior-temporal electrodes was greater over the right-hemisphere compared to the left-hemisphere. Analysis of simple main effects indicated that the amplitude of the Nc was more negative at anterior-temporal leads than at posterior-temporal leads for both the right-hemisphere (right-anterior = $-4.6 \mu\text{V SE } 1$, right-posterior = $2.7 \mu\text{V SE } 1$) and the left-hemisphere (left-anterior = $-3.7 \mu\text{V SE } 1$, left-posterior = $1.1 \mu\text{V SE } 1$).

In parallel with the topography of the amplitude of the Nc, the latency to peak for the Nc showed main effects of lead at midline ($F(2, 92) = 3.6, p < .05$), and central ($F(2, 96) = 7.4, p < .001$) electrodes, and a main effect of region ($F(1, 48) = 11.1, p < .01$) at temporal electrodes. For the midline leads, post hoc comparisons indicated that the Nc peaked earlier at Cz ($M = 513 \text{ ms SE } 9$) than at Fz ($M = 532 \text{ ms SE } 10$). For the central leads, post hoc comparisons indicated that the Nc peaked later at Cz ($M = 513 \text{ ms SE } 9$) compared to both C3 ($M = 475.5 \text{ ms SE } 10$) and C4 ($M = 489.2 \text{ ms SE } 9$). In addition, the Nc peaked earlier at anterior-temporal leads ($M = 459.7 \text{ ms SE } 7$) than at posterior-temporal leads ($M = 494.2 \text{ ms SE } 10$), although a hemisphere by region interaction ($F(1, 46) = 8.5, p < .01$), indicated that the main effect of region was due to the difference in latency over right-hemisphere electrodes only. Thus, these latency effects are consistent with an anterior-central source, and a right-hemisphere bias, for the Nc.

4.2.2. *Effects of condition and group on the amplitude of the Nc*

There were no effects of group or condition on the amplitude of the Nc in the unequated analysis. As seen in Table 3, however, there was a main effect of group at central leads ($F(2, 48) = 3.6, p < .05$), and a condition by lead interaction at midline leads ($F(2, 96) = 3.6, p < .05$) for the equated analysis. With regard to the group effects, post hoc comparisons indicated that the average amplitude of the Nc for Group 2 ($M = -12.2 \mu\text{V SE } 2$) was more negative than that for Group 1 ($M = -5.5 \mu\text{V SE } 2$) at central electrodes. The average amplitude for Group 3 ($M = -7.2 \mu\text{V SE } 2$) was more negative than Group 1 but less negative than Group 2, although these comparisons did not reach significance. This same pattern of effects was seen at the midline leads, although this effect only approached significance ($p = .06$).

As seen in the analysis of intra-subject variability, the topography of the Nc was found to be modulated by the familiarity of the stimulus. In contrast to the specific pattern of results found in the previous analysis (Study 1), however, the interaction in the present analysis was found over midline rather than central leads. Analysis of simple main effects indicated that the amplitude of the Nc was maximal over central leads for the familiar stimulus (Fz = $-7.1 \mu\text{V SE } 1$, Cz = $-9.8 \mu\text{V SE } 1$, and Pz = $-2.6 \mu\text{V SE } 2$), but maximal over fronto-central leads for the novel stimulus (Fz = $-10.1 \mu\text{V SE } 2$, Cz = $-9.6 \mu\text{V SE } 2$, and Pz = $-1.3 \mu\text{V SE } 2$).

4.2.3. *Effects of condition and group on the latency to peak amplitude of the Nc*

Unlike the effects found for the amplitude of the Nc, both the main effects and the interaction effects for latency to peak amplitude of the Nc were the same for the unequated and equated analyses.

The latency to peak of the Nc was observed to be modulated by group. There were main effects of group for latency to peak of the Nc at both midline ($F(2, 48) > 3.9, p < .05$) and central ($F(2, 48) = 3.2, p < .05$) leads. Post hoc comparisons indicated that Group 2 displayed shorter latencies to peak amplitude than Group 1, at both midline and central leads. The other two comparisons did not reach significance. In addition, there was a group by condition interaction at temporal ($F(2, 48) = 5.0, p < .05$) leads, in which the response to the familiar face and novel face displayed different patterns across the groups. Analysis of simple main effects indicated that the response to the familiar face (Group 1 = 472.8 ms SE 17, Group 2 = 450.4 ms SE 17, and Group 3 = 497.6 ms SE 17) did not differ across the groups, whereas the response to the novel face (Group 1 = 497.1 ms SE 14, Group 2 = 471.2 ms SE 14, and Group 3 = 444.0 ms SE 14) did differ. Furthermore, the Nc peaked faster for the novel face ($M = 444.0$ ms SE 14) compared to the familiar face ($M = 497.6$ ms SE 17) for Group 3, whereas the difference in latency to peak for the familiar and novel faces did not reach significance for Groups 1 and 2.

Finally, there was a group by lead interaction at both midline (unequated analysis only, $F(4, 92) = 3.2, p < .01$) and central (both analyses, $F(4, 96) > 2.8, p < .05$) leads. Analysis of simple main effects indicated that the main effect of lead at central electrodes was due to differences in the latency to peak of the Nc for Group 1 only.

4.2.4. Topography of the SW

As seen in the analysis of intra-subject variability, the slow wave component was maximal over anterior-temporal leads. There was a main effect of lead at midline leads ($F(2, 92) = 3.6, p < .05$) in the unequated analysis, which did not reach significance in the equated analysis. There was also a main effect of region at temporal leads ($F(1, 46) = 57, p < .001$), which reached significance in both analyses: the amplitude of the slow wave was larger at anterior-temporal leads ($M = 8.4 \mu\text{V}$ SE 1) than at posterior-temporal leads ($M = 1.2 \mu\text{V}$ SE 1).

4.2.5. Effects of condition and group on the amplitude of the SW

There were no effects of condition or group on the amplitude of the slow wave in the unequated analysis. In contrast, there was a condition by hemisphere by group ($F(1, 48) = 4.0, p < .05$) interaction in the equated analysis. Post hoc comparisons, however, failed to reach significance.

4.2.6. Occipital components

There was a main effect of group for the amplitude of the P400 ($F(2, 46) = 3.8, p < .01$) in the unequated analysis. Post hoc comparisons indicated that the amplitude of the P400 increased from Group 1 ($M = 4.3 \mu\text{V}$ SE 3) to Group 2 ($M = 8.0 \mu\text{V}$ SE 3) to Group 3 ($M = 14.1 \mu\text{V}$ SE 3). This effect failed to reach significance in the equated analysis. There were no other effects of condition or group on the amplitude or latency of any of the remaining occipital components.

4.3. Discussion

The goal of this analysis was to examine individual differences in the brain's response to a familiar and a novel stimulus as a function of the total number of trials completed in an ERP

visual recognition paradigm. The rationale for this analysis was that the total number of trials an infant completes may reflect, to some degree, individual differences in habituation. Infants who habituate faster may complete fewer trials, etc. It should be noted, however, that the testing procedures used in these studies did not explicitly attempt to implement habituation. That is, no explicit criteria were applied to the decision to end the test session. Typically, the session was terminated when the infant became inattentive or too fussy to continue. The circumstances of each individual study, however, also influenced the decision about when to terminate testing.

A major goal of this analysis was to determine whether group differences in the number of trials completed reflect individual differences in the *rate* of stimulus encoding or the *extent* of stimulus encoding. If group differences reflect differences in the rate of stimulus encoding, we hypothesized that the ERPs of each group of infants would differentiate the familiar and novel stimulus (i.e., a main effect of condition), with a larger Nc to the familiar face and a larger SW to the novel face, but that the differentiation of familiar from novel would not be modulated by the total number of trials completed (i.e., no condition by group interaction). Alternatively, if group differences reflect differences in the extent of stimulus encoding, we predicted that the differentiation of familiar from novel would be modulated by the total number of trials completed (i.e., a condition by group interaction), and that more trials would result in a greater degree of encoding and, thus, less differentiation (or none at all) of the familiar and novel stimulus. Thus, obtaining a condition by group interaction would simultaneously support one hypothesis and refute the other.

The amplitude and latency of the Nc were found to be modulated by individual differences in the number of trials completed, whereas the topography of the Nc was found to be modulated by the familiarity of the stimulus. Specifically, the Nc of infants who completed between 61 and 80 trials was more negative and faster to peak than the Nc of infants who completed fewer than 60 trials. This effect was found at midline and central leads, where the Nc was observed to be maximal. At temporal leads, the latency of the Nc was found to be influenced by both individual differences in the number of trials completed as well as the familiarity of the stimulus (i.e., a condition by group interaction). Post hoc comparisons only reached significance, however, for infants who completed between 81 and 100 trials. Furthermore, since the Nc was observed to show a polarity inversion over temporal leads such that the posterior-temporal leads do not show a clear Nc, this effect is difficult to interpret and may actually reflect the interaction of the Nc with some other component. Thus, the interaction between number of trials completed and familiarity in the Nc is difficult to interpret, and likely reflects multiple factors.

Also, and consistent with the analysis of intra-subject variability, a priori familiarity was observed to modulate the topography, but not the amplitude or latency, of the Nc. As stated previously, the Nc is thought to reflect an obligatory attentional process that has been found to be greater in amplitude to a familiar stimulus, suggesting that a familiar stimulus evokes either more, or a different kind, of attention than a novel stimulus. Although the amplitude of the Nc did not differentiate the two stimuli in the present study, the topography of the Nc did differentiate the two stimuli. Furthermore, it did so across both the analyses of intra- and inter-subject variability. Since differences in the topography of ERP components suggest differences in the neural circuits and/or cognitive processes underlying them, this finding is consistent with the idea that the familiar and novel faces are being processed differently.

The slow wave component was observed to be maximal over anterior-temporal leads and was not modulated by either individual differences in the number of trials completed or familiarity alone. It was, however, found to be influenced by the interaction of the two (although post hoc tests failed to reach significance).

As can be seen from [Table 2](#), Group 3 (81–100 total trials) contains more subjects from Study 1 than from the other two studies. Thus, study of origin is confounded with group for Group 3. Given that this was a re-analysis of data, it is difficult to enumerate differences in testing experiences across infants on a post hoc basis. While it is possible that there were subtle differences in group demographics, all three studies recruited participants from the same theoretical population. Moreover, all three studies used similar data collection protocols, and the experimenter from Study 1 trained the experimenters from Studies 2 and 3. The data were also collected during the same time period, using the same data collection equipment and many of the same stimuli.

One possible explanation for the uneven distribution of study populations across Group 3 is experimenter bias in interpreting the “state” of the infant during data collection. Since data were collected until the infant became “too fussy” or “too bored,” it is possible that experimenters may have differed in their judgment of these states. This may have resulted in either experimenter termination of the test session before the infant had fully encoded the stimuli, or continuation of the test session past the point in which the infant had fully encoded the stimuli. In other words, judging an infant to be “too fussy” or “too bored” is a subjective decision and may have differed across the experiments.

Another possible explanation is that the treatment of the study populations was influenced by the characteristics of the “at-risk” populations to which the data presented here served as a control. For instance, infants in the “at-risk” population for Study 1 (i.e., infants of diabetic mothers) were frequently observed to be highly compliant with the testing procedures, often sitting through all 100 of the possible trials. In an implicit attempt to equate the testing procedures, and provide appropriate comparisons between the “at-risk” and control samples, testing of the control infants in Study 1 may have been less likely to be terminated prior to reaching 100 trials. In contrast, infants in the “at-risk” population for Study 3 (i.e., healthy, premature infants) were frequently observed to be easily aroused, harder to comfort, and more likely to become fussy earlier in the procedure. These infants tended to complete fewer than 100 trials. Thus, testing of the control infants in Study 3 may have been *more* likely to be terminated prior to reaching 100 trials. Since Study 2 compared longitudinal and cross-sectional samples of healthy, full-term infants, effects due to the characteristics of an “at-risk” population would not be relevant.

So, while an infant’s inattention or fussiness while viewing repeated presentations of a visual stimulus may theoretically indicate habituation to the stimulus, the number of trials infants completed in the data from the three studies reported here was not strictly “infant-controlled.” Thus, group differences reflect some combination of intrinsic psychological variables (i.e., individual differences in encoding, etc.) and extrinsic factors (i.e., experimenter bias, “at-risk” population characteristics). For this reason, caution must be taken in interpreting group effects in this analysis. It is important to note, however, that the experimenter’s influence on the number of trials completed appears to primarily effect the composition of Group 3 (81–100); Groups 1 and 2 appear to contain an even distribution of subjects from the three study populations.

This may be because the experimenters influence over whether to stop or continue testing most likely occurred near an infant's "threshold" of cooperation, and that this "threshold" occurred more frequently near the boundary between Groups 2 and 3.

It is also important to note that these issues are not unique to infant ERP research, but are an unavoidable consequence of comparing the work of different experimenters, both within the same lab and across labs. This is also true for behavioral paradigms such as habituation. For example, not only have different experimenters used different procedures for assessing habituation (e.g., fixed-trials vs. infant-controlled), but even within the same procedure there is no general consensus as to what habituation criteria are most appropriate (e.g., a decline in looking relative to the first three looks or the three longest looks, etc.).

Thus, with respect to the hypotheses regarding whether individual differences in number of trials completed reflects individual differences in the rate or extent of stimulus encoding, our findings appear to be mixed. First, there was a group effect in the amplitude and latency of the Nc,² a component thought to reflect attentional processes. Since the amplitude of a component is thought to reflect the degree or amount of activation of a neural circuit and the latency of a component is thought to reflect speed of processing, this finding would suggest group differences in both the amount and speed of attentional processing of the stimuli. Since the Nc is thought to reflect attention, however, findings regarding the Nc do not likely provide information about individual differences in stimulus encoding. Second, there was a condition by group interaction in the SW, although post hoc tests failed to reach significance. Since the SW is thought to reflect a form of stimulus encoding, and it was argued that a condition by group interaction would simultaneously support one hypothesis and refute the other, this finding appears to be more consistent with the hypothesis that individual differences in number of trials completed reflect differences in the extent of stimulus encoding. Caution must be taken in reaching this conclusion, however, due to the fact that post hoc tests failed to reach significance, and that group effects may be confounded with experimenter effects. Thus, the effects for the Nc may reflect group differences in the amount and speed of attentional processing, while the effects for the SW may reflect group differences in the extent of stimulus encoding. Theoretically, these two findings are not inconsistent with one another: individual differences in the quality of attentional processing may result in differences in the extent to which a stimulus is encoded. Our data, however, do not speak to this relationship directly.

Finally, it is not surprising that amplitude effects, but not latency effects, differed between the equated and unequated analyses of inter-subject variability. That is, the signal-to-noise ratio of an ERP is known to influence the amplitude of the components (Picton et al., 2000), as well as the likelihood of obtaining statistical significance, since the poorer the S/N ratio, the greater the variance due to noise. In the present analysis, equating the S/N ratios resulted in the emergence of effects that were null findings in the analysis of unequated S/N ratios. This took the form of a main effect of group for the amplitude of the Nc, and a condition by hemisphere by group interaction for the amplitude of the slow wave. Both of these effects reflect modulation of the ERP by group, which is the variable confounded with S/N ratio in the unequated analysis. Thus, equating the signal-to-noise ratios between the three groups appeared to allow amplitude effects to emerge where they were previously obscured.

5. General discussion

There are several major findings of the analyses reported here. First, two separate components of the infant ERP, the Nc and SW, were found to dissociate cognitive processes associated with familiarity from processes associated with stimulus repetition. The Nc was observed to be modulated by familiarity alone, whereas the slow wave was observed to be modulated by stimulus repetition alone. Second, individual differences in the number of trials an infant completes in an ERP session were observed to be associated with differences in the amplitude and latency of the Nc, possibly reflecting individual differences in both the magnitude and speed of attentional processing. Finally, individual differences in the number of trials an infant completes also appear to reflect differences in the extent to which the familiar and novel faces are encoded.

5.1. Implications for theoretical models of habituation and infant memory

The topography of the Nc was found to be modulated by the a priori familiarity of the stimulus in both Study 1 and Study 2. Differences in topography are thought to reflect different underlying neural generators and hence different cognitive processes (Nunez, 1981). Thus, these results suggest that the familiar and novel stimulus are being processed differently (i.e., possibly by different neural circuits). Although the Nc is modulated by familiarity, it is unlikely that the Nc itself reflects recognition per se, since the Nc is observed in response to both familiar and novel stimuli. It may, however, reflect the influence of recognition on attention.

The slow wave component was found to be modulated by repetition. Specifically, the amplitude of the slow wave decreased with greater exposure to the stimulus. In a general sense, then, the slow wave component can be said to reflect a form of habituation to the stimulus. Whether this habituation reflects encoding per se, or some other process, is a matter of debate. Numerous other studies have reported a reduction in neural activation in response to stimulus repetition during visual short-term memory tasks, including decrements in (a) ERP amplitude over temporal scalp regions in adults (Begleiter, Porjesz, & Wang, 1993; Pietrowsky et al., 1996); (b) response of inferior temporal cortex neurons in single-cell recordings in monkeys (Miller, Li, & Desimone, 1991; Mikami & Kubota, 1980; Riches, Wilson, & Brown, 1991), and (c) cerebral blood flow to posterior cortex in adults (Squire et al., 1992). Furthermore, these findings are all in accord with computational evidence that repetition of a specific visual pattern results in changes in the efficiency by which the pattern is processed such that the number of units required to process the stimulus is reduced (McClelland & Rumelhart, 1986).

In contrast, several studies have demonstrated an *increase* of neuronal activation in the hippocampus as a result of learning in monkeys (Berger & Thompson, 1978) and memory in human adults (Squire et al., 1992). It is likely, therefore, that the observed decrement in amplitude of the slow wave component over temporal scalp regions in response to stimulus repetition reflects the activity of structures in the temporal lobe other than the hippocampus. This is an important distinction since evidence from amnesic patients and animal studies suggest that short-term memory may be subserved by neocortical structures in the temporal lobe responsible for the processing of specific stimulus information, whereas long-term memory depends on the interaction between neocortex and medial temporal lobe structures, including the hippocampus (Squire & Zola-Morgan, 1991).

Interestingly, however, the effect of repetition on the slow wave component did not appear to be influenced by the familiarity of the stimulus. If the slow wave component reflects the updating of memory for a partially encoded stimulus, then this null finding seems counter-intuitive since the familiar and novel stimulus appear to have been updated to an equal extent. This may simply reflect a null finding and, thus, a type II error in this report. On the other hand, it is possible that the processes of encoding and recognition are independent (i.e., encoding does not cease once recognition occurs), and/or the effect of repetition on the slow wave component reflects the updating of a specific representation of the two-dimensional static image of the familiar face versus the updating of a more general representation of the familiar face. The second interpretation is in agreement with the argument presented above that the modulation of the slow wave component reflects the processing of *specific* stimulus information by neocortical structures in the temporal lobe. Updating of a more general representation of the familiar face would require interactions with long-term memory and, hence, the hippocampus. Although it is still possible that this occurs, it does not appear to be reflected in the modulation of the slow wave component.

In conclusion, the evidence and arguments presented above suggests that the habituation of an infant's visual attention may be due, in part, to the decrement in neuronal activation of structures in the temporal lobe which encode specific perceptual properties of a stimulus, a form of short-term perceptual memory.

5.2. *Implications for infant ERP methodology*

There are several implications of the present work for infant ERP methodology, particularly with respect to the issues of replication and the effects of variability due to individual differences on the study of normative cognitive development. First, the behavior of both the Nc and SW reported here differs from previous findings. Specifically, the present study observed a difference in the topography, but not the amplitude, of the Nc in response to the familiar and novel face. The basic finding that the Nc is modulated by familiarity appears to be consistent across studies, although the specific form that the modulation takes differs. Consideration of the group effects found in the analysis of inter-subject variability may help shed light on this inconsistency.

Individual differences in the number of trials completed were found to influence both the amplitude and latency of the Nc, suggesting individual differences in both the magnitude and speed of stimulus processing. These findings, in general, are consistent with a large body of literature reporting individual differences in infant performance on behavioral measures of cognition (see [Colombo & Mitchell, 1990](#) for review). Furthermore, the effect of individual differences in the number of trials completed on the Nc may have interacted with the familiarity of the stimulus, although this effect was argued to be difficult to interpret. This raises the possibility that, across conditions, effects in one group of infants may cancel effects in another group. Thus, if the final sample includes large individual differences in the number of trials completed, it may be less likely that amplitude or latency effects will occur.

This possibility is supported by a comparison of individual differences in number of trials completed across studies using the same experimental manipulation. As seen in [Table 5](#), the total number of possible trials and the mean number of trials completed are similar across

Table 5

Comparison of means (SD) of trials completed and included in averages across studies employing the face recognition paradigm

Report	Total infants tested	Total infants included	Maximum no. of trials	Mean trials completed	Mean trials included in average
de Haan & Nelson (1997)	61	39	70	63 (9)	17 (5)
de Haan & Nelson (1999)	99	45	70	66 (7)	28 (5)
Nelson et al. (2000)	85	25	100	78 (-*)	33 (-*)
Analysis of intra-subject variability	54	19	100	78 (14)	13 (2)
Analysis of inter-subject variability	95	51	100	72 (20)	20 (0)

* Not reported.

the three published reports using the face recognition paradigm and the present report. One important difference, however, is in regard to variability in the number of trials completed. In de Haan and Nelson (1997, 1999) the standard deviation of the number of trials completed was 9 and 7, respectively. In contrast, the standard deviation of number of trials completed was 14 in Study 1 and 20 in Study 2. Thus, there is less variability in the number of trials completed in the published reports in which there was an effect of familiarity on the amplitude of the Nc.

If this is the case, it has important implications for infant ERP methodology. Indeed, many studies using infant ERPs exclude infants who do not complete a pre-set number of trials (e.g., Ackles & Cook, 1998; Nelson & Collins, 1991). Although these constraints were imposed in order to control variability due to differences in exposure to stimuli, the attrition of infant participants as a result may have resulted in a selective sample. Constraining the sample in such a way may not only limit the generalizability of the findings, but may also limit the conditions under which we may expect to replicate the results.

The observed behavior of the slow wave component has been inconsistent across previously published reports using the same experimental manipulation. Specifically, in the original (de Haan & Nelson, 1997) as well as current reports, the slow wave component was not found to be modulated by the familiarity of the stimulus when the two faces were dissimilar in appearance. In contrast, the two studies published subsequent to the original study reported that the slow wave component was modulated by the familiarity of the stimulus when the two faces were dissimilar in appearance. One possibility is that the lack of effect in the original and current reports simply reflects a null finding and, thus, a type II error.

Another possibility is that the extent to which the familiar/novel pair was actually dissimilar in appearance differed across these four studies. This is a crucial factor, since the modulation of the slow wave component was found to depend on the perceptual similarity between the familiar and novel stimulus: the slow wave differentiated “similar-looking,” but not “dissimilar-looking” familiar and novel faces in the original report. In this report (de Haan & Nelson, 1997), the faces chosen by the experimenter were rated for perceptual similarity by four independent observers after the experiments were completed. The ratings were reported to match closely with the experimenter’s original decisions. Subsequent studies did not undertake these ratings, but relied on the experimenter’s judgment in choosing “dissimilar-looking” faces. Thus, it is possible that these subsequent studies differed in their judgments of similarity such that some of the face pairs were more “similar” in appearance than “dissimilar.”

The probability of this is severely undermined, however, by two facts. First, the independent observers' ratings in the original study were not used to modify the participant samples in any way, they were simply provided to validate the judgment of the experimenter. In this respect, then, the four studies do not differ in the method used to pair a "dissimilar-looking" novel face with the familiar face (i.e., subjective experimenter judgment was the sole determining factor). Second, and most importantly, both the original report and one of the subsequent reports, each of which reports different results for the slow wave, were conducted by the same experimenter. Furthermore, this is the same experimenter whose judgments of similarity were validated by independent raters in the original report. Thus, it does not seem likely that differences in judgments about perceptual similarity between the familiar and novel face can account for the discrepancy in findings regarding the behavior of the slow wave component.

5.3. Implications for developmental processes

In this paper we examined two kinds of variability in infant brain activity: variability in the brain's response to a stimulus over time as a function of stimulus repetition, and variability in the brain's response between subjects as a function of the total number of trials completed in an ERP session. We will now consider the implications of this variability for developmental processes.

Infancy and childhood represent a time of enormous change in the structure and functioning of the human brain, yet most measures used to study the development of cognitive processes (such as memory or attention) rely on behaviors such as looking or reaching. While such measures are used extensively and successfully and have provided important information regarding cognitive development, the behaviors themselves necessarily reflect only the end state of the process of interest. In contrast, the ERP contains information about both the extent and timing of neuronal responses to a stimulus. Thus, ERPs can be used to study cognitive processes as they are occurring in the individual, as well as the state and functioning of the brain over the course of development.

Variability in ERP responses across individuals, then, may reflect fundamental differences in the capacity and/or the temporal qualities of the way the brain processes information. In the infant, this variability may additionally reflect variability across stages or a continuum of development. Thus, individual differences in ERPs may represent individual qualities that remain stable or represent different points in the development of an ability or process.

With respect to the first type of variability examined, variability in the brain's response as a function of stimulus repetition, it was found that the processes of stimulus repetition and familiarity can be dissociated at the level of neuronal responses. This is an important finding for several reasons. First, differentiating these processes through a measure such as habituation or preferential looking is not possible, since stimulus repetition (or the amount of exposure to the stimulus) is necessarily confounded with familiarity in these methods. Second, in a visual habituation paradigm, the decrement in looking to a stimulus over time is commonly considered to result from the construction of a "neuronal model," and hence memory, of the stimulus. In most models of habituation (e.g., [Berlyne, 1963](#); [Sokolov, 1963](#); but see [Cohen, 1973](#)), the "construction of the neuronal model" and "memory" are used interchangeably, implying that they are the same process. What our data suggest, however, is the possibility

that the process underlying recognition of a stimulus (which, by definition, requires a memory trace) and the process of constructing a neuronal model (via stimulus repetition) may involve different neural subsystems and relatively independent processes. This idea, if correct, has important implications for theories regarding the development of visual recognition memory that would not likely result from research limited to the use of behavioral measures.

Despite the existence of a large body of literature demonstrating age-related differences in habituation and preferential looking, most models of and theories about habituation and infant visual attention do not address development (e.g., Sokolov, 1963; Cohen, 1973; Bahrick & Pickens, 1995). Our findings suggest that the decrement in visual attention in response to stimulus repetition (or exposure) during a habituation paradigm, and a novelty preference demonstrated after a very brief retention interval, may reflect the activity of neocortical structures in the temporal lobes that implement a form of short-term perceptual memory. By definition, then, a novelty or familiarity preference following a lengthy delay (i.e., several minutes, hours, days, etc.) between familiarization and test would not reflect the contents of short-term perceptual memory, but a memory trace stored in long-term memory stores. Thus, the novelty preference itself may not reflect a unitary process, or a single type of memory. While these ideas in themselves are not necessarily new, it is generally assumed that information flows from a short-term store into a long-term store via some intermediary process, and that attention is inhibited (and encoding ceases) once recognition (or a match) occurs. Our data, however, demonstrated a dissociation in the processes of familiarity and stimulus repetition, raising the possibility that these processes may operate somewhat independently of one another. In other words, the recognition of a stimulus as familiar does not necessarily terminate the construction of a neuronal model in short-term perceptual memory, and the contents of short-term perceptual memory are not necessarily transferred to long-term memory stores. The implication for development, therefore, is that age-related differences in the amount of time a stimulus can be remembered may result from (a) the development of structures (i.e., the hippocampus, the neocortex) and/or processes related to long-term memory storage, (b) the development of neocortical structures in the temporal lobes and/or processes related to short-term perceptual memory, or (c) the development of anatomical and/or functional connections between these neural subsystems. Furthermore, each of these separate subsystems, as well as the functional connections between them, may have different developmental trajectories.

Variability in the brain's response between subjects as a function of the total number of trials completed in an ERP session was also examined. Group effects were found to modulate both the amplitude and latency of the Nc, a component thought to reflect an obligatory attentional response. Specifically, the Nc of infants who completed between 61 and 80 trials was faster to peak and larger in amplitude compared to infants who completed fewer than 60 trials. In general, differences in latency of ERP components are interpreted to reflect differences in speed of processing, whereas differences in the amplitude of a component is thought to reflect differences in the size of a response or amount of processing resources. Thus, the group differences in the Nc found here suggest that the attentional response of infants who completed between 61 and 80 trials occurred faster and was of greater magnitude than infants who completed fewer than 60 trials (see Note 2). As previously discussed, differences in ERP components across infants may reflect either trait-like, stable individual differences, or different

points along the developmental continuum of some cognitive process. The data presented here cannot distinguish between these possibilities as it represents a one-time measure in a single age-cohort.

In research using habituation and preferential looking methods, individual differences in the rate at which infants habituate to visual stimuli has been interpreted to reflect individual differences in the speed of stimulus encoding (Colombo & Mitchell, 1990). Thus, one possibility is that infants who complete fewer trials in an ERP visual recognition paradigm may encode stimuli faster and habituate more quickly. Yet, it has long been noted that memory for a stimulus and interest in a stimulus are confounded in habituation and preferential looking procedures (Sophian, 1980). Thus, another possibility is that infants who habituate faster do so because they are less engaged by the stimuli or their interest decreases more quickly. Our data appears to support this alternative hypothesis in that infants who completed fewer trials actually appeared to process the stimuli slower and with fewer processing resources. These findings seem to be in conflict with the idea of faster encoding. Furthermore, the group differences in the Nc likely reflect group differences in an attentional process rather than encoding or memory. These findings must be interpreted with caution, however, since the studies reported here provided no direct measure of the relationship between number of trials completed and memory as assessed by habituation or preferential looking.

One shortcoming of the data reported here is that the studies in which they were collected were not specifically designed to evaluate variability in infant ERPs. Nevertheless, the findings reported here demonstrate that examining variability in infants' brain responses to stimuli and events both within the individual and across individuals can help to inform our understanding of information processing in several ways. First, examining variability in the brain's response to a stimulus over time provides an on-line evaluation of information processes such as stimulus detection, attention, encoding, and recognition. The ERP measure, in particular, can help relate such general processes to the neural systems which implement them, and on-going improvements in the number of electrodes from which we can record and source localization methods will continue to improve our ability to investigate such structure/function relationships. An understanding of the neural systems involved in a particular cognitive process has important implications, since our increasing knowledge from other areas of research regarding the function of specific neural structures will help to inform our understanding of how general processes (such as encoding) are implemented in the brain. This, in turn, may lead to important revisions to existing theories. In the present report, for example, contrasting the topography of neural responses which reflect the way the brain responds to individual stimuli over time versus the way the brain responds to differences between stimuli led to the conclusion that the neural systems involved in encoding and recognition may involve different neural subsystems, and the hypothesis that encoding and recognition may, therefore, be relatively independent processes. This, in turn, led to the hypothesis that novelty preferences may reflect different forms of memory under different delay conditions, and that under immediate test conditions may reflect a form of short-term perceptual memory implemented in structures within the temporal lobe (i.e., the fusiform gyrus for faces, areas TE and TEO for other objects). While further research will be needed to evaluate such hypotheses, the hypotheses themselves represent a level of specificity not currently reflected in most models of habituation and infant visual recognition memory.

Second, examining variability in the brain's response across individual infants can help to inform our theories of cognitive development by providing evidence that may help to distinguish between alternative hypotheses regarding the basis for individual differences in infant behavior. For example, in the present report we found that individual differences in the number of trials an infant completed was related to amplitude and latency differences in an ERP component thought to reflect attention. This finding led to the hypothesis that individual differences in habituation may reflect differences inattention or interest rather than speed of encoding. Further research will be needed to evaluate this hypothesis as well.

In conclusion, the results presented here suggest that a consideration of individual differences in infant brain response may have an especially important application to theories and models of the development of normative cognitive processes in infancy, given the relatively large individual differences and rapid change in biological maturation and emergence of function during this period compared to later in life.

Notes

1. In [de Haan and Nelson \(1997\)](#), the authors present area scores for the slow wave. Because they are difficult to interpret as an absolute value, we have chosen to present the as average amplitude instead. To confirm that area scores were functionally similar to average amplitude for the positive slow wave, the results from all analyses were undertaken with both values. There were no differences in the results between the two measures.
2. It is interesting to note that while main effects of group were obtained for both the amplitude and latency of the Nc, post hoc tests reached significance for comparisons between Group 1 (fewer than 60) and Group 2 (61–80) only. As noted above, the distribution of study populations in Group 3 was uneven and likely reflected experimenter and cohort effects confounded with individual differences in infant behavior. The confound of these influences on the data for Group 3 may explain the non-significance of comparisons with this group. That is, if the main effect of group largely reflects individual differences in some underlying psychological process, then the strength of this effect may not have been large enough in Group 3 due to the presence of other effects. We also noted the apparent even distribution of study populations across Groups 1 and 2, suggesting that assignment to these groups may have been minimally influenced by confounding variables. The finding of significant post hoc comparisons between Groups 1 and 2 in two different measures may support this idea. For these reasons, it seems appropriate to interpret the effects obtained for Groups 1 and 2 as most likely reflecting individual differences in infant variables.

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References

- Ackles, P. K., & Cook, K. G. (1998). Stimulus probability and event-related potentials of the brain in 6-month-old human infants: A parametric study. *International Journal of Psychophysiology*, *29*, 115–143.
- Bahrnick, L. E., & Pickens, J. N. (1995). Infant memory for object motion across a period of 3 months: Implications for a four-phase attention function. *Journal of Experimental Child Psychology*, *59*, 343–371.
- Begleiter, H., Porjesz, B., & Wang, W. (1993). A neurophysiologic correlate of visual short-term memory in humans. *Electroencephalography and Clinical Neurophysiology*, *87*, 46–53.
- Berger, T. W., & Thompson, R. F. (1978). *Proceedings of the National Academy of Sciences*, *75*, 1472–1576.
- Berlyne, D. E. (1963). Motivational problems raised by exploratory and epistemic behavior. In S. Koch (Ed.), *Psychology: A study of a science. The process areas, the person, and some applied fields: Their place in psychology and in science* (Vol. 5, pp. 284–364). New York: McGraw-Hill.
- Bornstein, M. H. (1985). Habituation as a measure of visual information processing in human infants: Summary, systematization, and synthesis. In G. Gottlieb & N. A. Krasnegor (Eds.), *The measurement of audition and vision in the first year of postnatal life: A methodological overview* (pp. 253–300). New Jersey: Ablex Press.
- Cohen, L. B. (1973). A two process model of infant visual attention. *Merrill-Palmer Quarterly*, *19*, 157–180.
- Colombo, J., & Mitchell, D. W. (1990). Individual and developmental differences in infant 5 visual attention. In J. Colombo & J. W. Fagen (Eds.), *Individual differences in infancy* (pp. 193–227). Hillsdale, NJ: Lawrence Erlbaum.
- Courchesne, E., Ganz, L., & Norcia, A. (1981). Event-related potentials to human faces in infants. *Child Development*, *52*, 804–809.
- de Haan, M., & Nelson, C. (1997). Recognition of the mother's face by 6-month-old infants: A neurobehavioral study. *Child Development*, *68*, 187–210.
- de Haan, M., & Nelson, C. (1999). Brain activity differentiates faces and object processing in 6-month-old infants. *Developmental Psychology*, *35*, 1113–1121.
- Gratton, G., Coles, M. G. H., & Donchin, E. (1983). A new method of off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*, *55*, 468–484.
- Jasper, H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology*, *10*, 371–375.
- Karrer, R., & Ackles, P. K. (1987). Visual event-related potential of infants during a modified oddball procedure. *Electroencephalography and Clinical Neurophysiology*, *40*, 603–608.
- McClelland, J., & Rumelhart, D. (1986). *Parallel distributed processing* (Vols. 1 and 2). Cambridge, MA: MIT Press.
- Mikami, A., & Kubota, K. (1980). Inferotemporal neuron activities and color discrimination with delay. *Brain Research*, *182*, 65–78.
- Miller, E. K., Li, L., & Desimone, R. (1991). A verbal mechanism for working and recognition memory in inferior temporal cortex. *Neuroscience Abstracts*, *2*, 1377–1379.
- Nelson, C. (1994). Neural correlates of recognition memory in the first postnatal year. In G. Dawson & K. Fischer (Eds.), *Human behavior and the developing brain* (Chap. 9, pp. 269–313). New York: Guilford Publications.
- Nelson, C. (1996). Electrophysiological correlates of early memory development. In H. W. Reese & M. D. Franzen (Eds.), *Proceedings of the thirteenth West Virginia university conference on life span developmental psychology: Biological and neuropsychological mechanisms* (pp. 95–131). New Jersey: Lawrence Erlbaum.
- Nelson, C., & Collins, P. (1991). An event-related potential and looking time analysis of infants' response to familiar and novel events: Implications for visual recognition memory. *Developmental Psychology*, *27*, 50–58.

- Nelson, C. A., Wewerka, S., Thomas, K. M., Tribby-Walbridge, S., deRegnier, R., & Georgieff, M. (2000). Neurocognitive sequelae of infants of diabetic mothers. *Behavioral Neuroscience*, *114*, 950–956.
- Nikkel, L., & Karrer, R. (1994). Differential effects of experience on the infant's ERP and behavior. *Developmental Neuropsychology*, *10*, 1–11.
- Nunez, P. (1981). *Electrical fields of the brain*. New York: Oxford University Press.
- Picton, T. W., Bentin, S., Berg, P., Donchin, E., Hillyard, R., Johnson, R., Jr., Miller, G. A., Ritter, W., Ruchkin, D. S., Rugg, M. D., & Taylor, M. J. (2000). Guidelines for using human event-related potentials to study cognition: Recording standards and publication criteria. *Psychophysiology*, *37*, 127–152.
- Pietrowsky, R., Kuhmann, W., Krug, R., Molle, M., Fehm, H. L., & Born, J. (1996). Event-related brain potentials during identification of tachistoscopically presented pictures. *Brain and Cognition*, *32*, 416–428.
- Riches, I. P., Wilson, F. A. W., & Brown, M. W. (1991). The effects of visual stimulation and memory on neurons of the hippocampal formation and the neighboring parahippocampal gyrus and inferior temporal cortex of the primate. *Journal of Neuroscience*, *11*, 1763–1779.
- Snyder, K., & Nelson, C. (in preparation). *Electrophysiological correlates of novelty preferences in human infants*.
- Sokolov, E. (1963). *Perception and the conditioned reflex*. Oxford: Pergamon Press.
- Sophian, C. (1980). Habituation is not enough: Novelty preferences, search, and memory in infancy. *Merrill-Palmer Quarterly*, *26*, 239–257.
- Squire, L. R., Ojemann, J. G., Miezin, F. M., Petersen, S. E., Videen, T. O., & Raichle, M. E. (1992). Activation of the hippocampus in normal humans: A functional anatomical study of memory. *Proceedings of the National Academy of Sciences USA*, *89*, 1837–1841.
- Squire, L. A., & Zola-Morgan, S. (1991). The medial temporal lobe memory system. *Science*, *253*, 1380–1385.
- Stolarova, M., Whitney, H., deReigner, R., Georgieff, M., & Nelson, C. (in preparation). *Recognition memory and priming in healthy premature infants*.
- Webb, S., & Nelson, C. (2001a). Perceptual priming for upright and inverted faces in infants and adults. *Journal of Experimental Child Psychology*, *79*, 1–22.
- Webb, S., & Nelson, C. (submitted for publication). *A longitudinal investigation of face and object recognition memory across the first year of life*.