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Neural Correlates of Individual Differences in Infant Visual Attention and Recognition Memory

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Abstract

Past studies have identified individual differences in infant visual attention based upon peak look duration during initial exposure to a stimulus. Colombo and colleagues (e.g., Colombo & Mitchell, 1990) found that infants that demonstrate brief visual fixations (i.e., short lookers) during familiarization are more likely to demonstrate evidence of recognition memory during subsequent stimulus exposure than infants that demonstrate long visual fixations (i.e., long lookers). The current study utilized event-related potentials to examine possible neural mechanisms associated with individual differences in visual attention and recognition memory for 6- and 7.5-month-old infants. Short- and long-looking infants viewed images of familiar and novel objects during ERP testing. There was a stimulus type by looker type interaction at temporal and frontal electrodes on the late slow wave (LSW). Short lookers demonstrated a LSW that was significantly greater in amplitude in response to novel stimulus presentations. No significant differences in LSW amplitude were found based on stimulus type for long lookers. These results indicate deeper processing and recognition memory of the familiar stimulus for short lookers.

Introduction

For over 50 years, researchers interested in cognitive development have measured infant visual behavior as a window into early perception and cognition. The habituation and paired comparison procedures are the most commonly used measures for examining the perceptual and cognitive capabilities of the human infant. Research has shown that performance on these tasks in infancy has significant predictive value for cognitive functioning later in childhood (e.g., Bornstein & Sigman, 1986; Fagan & Shepard, 1987; Rose & Feldman, 1995). Furthermore, look duration during performance on such tasks is negatively correlated with measures of cognitive performance in infancy and early childhood (Bornstein & Sigman, 1986; Colombo, 1993; Colombo & Mitchell, 1990; Colombo, Mitchell, & Horowitz, 1988; Colombo, Mitchell, Coldren, & Freese, 1991; McCall & Carriger, 1993; Rose, Slater, & Perry, 1986; Sigman, Cohen, Beckwith, & Parmelee, 1986; Tamis-LeMonda & Bornstein, 1989). Peak look-length during habituation or familiarization has been shown to provide a reliable and stable indicator of individual differences in infant attention and cognitive processing in that short-looking infants are more likely to demonstrate evidence of recognition memory for a familiar stimulus than long-looking infants (e.g., Colombo & Mitchell, 1990). Thus, the identification of mechanisms that could potentially explain individual differences in infant visual attention has emerged as an important topic of research.

Some possible mechanisms that have been proposed include overall integrity of the central nervous system, processing strategy, and ability to disengage and shift attention (e.g.,

Colombo, 1993; Colombo, Freeseaman, Coldren, & Frick, 1995; Colombo, Richman, Shaddy, Greenhoot, & Maikranz, 2001; Frick, Colombo, & Saxon, 1999). Colombo and colleagues (1995) tested processing strategy with 4-month-old infants using the paired comparison procedure. Infants were tested in paired comparisons involving simultaneous pairing of novel stimuli that differed from a familiar stimulus on either global or local stimulus properties. The rationale behind this design was based on the assumption that infants would prefer to look at the stimulus that appeared novel to them. Thus, if infants process global properties (i.e., configural aspects of a stimulus) prior to local details, then they should demonstrate a preference for the stimulus that differed from the familiar on global properties prior to demonstrating a preference for novel local elements. Short lookers demonstrated preferences based on global changes with brief familiarization (20 s) and shifted to demonstrating preferences based on local changes with longer familiarization (30 s). Long lookers required the longest familiarization time (50 s) to demonstrate any preference, and only demonstrated preferences for the novel local condition. The global-to-local processing sequence demonstrated by short lookers is consistent with the “global precedence” demonstrated by adults in visual processing (see review, Kimchi, 1992).

A neural mechanism that could possibly account for differences between short and long lookers relates to development of the posterior orienting network involved in disengaging fixation and voluntary shifts of visual attention (Colombo, 1995; Posner, 1980; Posner & Petersen, 1990). Structures involved in this system include the superior colliculus, posterior parietal cortex, and frontal eye-fields (Posner & Petersen, 1990). This system becomes functionally mature between 3 and 6 months postnatal age, a period of development characterized by decreases in look duration and more frequent shifts of fixation (see Colombo, 2001; Courage, Reynolds, & Richards, 2006). Delayed development of the posterior orienting network would be characterized by prolonged looking toward a single stimulus or toward individual local elements within a global pattern due to immature ability to voluntarily disengage and shift visual fixation.

Frick, Colombo, & Saxon (1999) found that long lookers demonstrate slower reaction times to localize a peripheral stimulus than short lookers on average. However, this delayed reaction to peripheral stimuli was only found on “competition” trials in which a central stimulus remained on the screen when the peripheral stimulus was presented, no differences were found between looker types on “non-competition” trials. The authors noted that long lookers’ latency scores were more variable than short lookers, and they found no differences in looker types in latency to disengage when using the participants’ shortest distraction latencies as the dependent variable. Thus, long lookers were capable of disengaging and shifting just as quickly as the short lookers but were more likely to have trials in which they continued looking at the central stimulus for relatively long periods of time before shifting fixation to the peripheral stimulus. This was interpreted as an indication that long look durations may represent slower visual processing or difficulties with attentional regulation.

The use of heart rate measures has also provided support for the possibility that ability to disengage fixation is one of the mechanisms that accounts for individual differences in infant visual attention. Richards (1988, 1997; Richards & Casey, 1991) identified several heart rate phases of attention that infants cycle through within a single look (see review, Reynolds & Richards, 2007). Two of these phases, termed sustained attention and attention termination, are of particular relevance. Sustained attention is the phase of attention when infants are actively engaged in information processing. This phase is proposed to reflect the activation of the alertness/arousal system of the brain and is characterized by a sustained decrease in heart rate during looking (Richards, 1997, 2002, 2008; Courage, Reynolds & Richards, 2006). Attention termination refers to periods when the infant continues to look at the stimulus but is no longer processing its information (i.e., is inattentive). Heart rate

returns to prestimulus levels during attention termination. Colombo, Richman, Shaddy, Greenhoot, and Maikranz (2001) measured heart rate and looking simultaneously and found that long and short lookers do not differ in the proportion of time spent in sustained attention; however, long lookers spend proportionately more time in attention termination than short lookers. Taken together, these findings indicate that long lookers may have problems disengaging fixation and support the possibility that functioning of the posterior orienting network may be related to individual differences in infant visual attention.

Examining the topography and latency of ERP components associated with attention would provide further answers to questions related to potential mechanisms behind individual differences in infant visual attention. In recent decades, significant advances have occurred through the use of EEG and ERPs. ERPs are scalp voltage oscillations recorded in the EEG that are time-locked with a specific physical or mental event (Fabiani, Gratton, & Coles, 2000; Picton, Bentin, Berg, et al., 2000). ERPs provide both topographical and temporal information. Although the topographical information is rather low in spatial resolution, ERPs can be combined with source analysis to determine areas of the brain that most likely produce the ERPs measured on the scalp (Huizenga & Molenaar, 1994; Reynolds & Richards, 2009; Scherg, 1990; Scherg, 1992; Scherg & Picton, 1991;). The temporal resolution of the ERP is excellent, providing millisecond accuracy in measuring the brain activity associated with cognitive events. This excellent temporal resolution allows for the analysis of specific component processes that contribute to cognitive processing. Thus, individual components associated different stages of visual processing (i.e., attention, recognition memory) that occur within a single look can be examined through the use of ERPs.

Early work on electrophysiological correlates of infant attention and recognition memory examined ERPs in infants exposed to oddball tasks (Courchesne, 1977; Karrer & Ackles, 1987; 1988; Karrer & Monti, 1995; Nikkel & Karrer, 1994). Oddball tasks involve the frequent presentation of a familiar (standard) stimulus randomly interspersed with the presentation of an infrequent unfamiliar (oddball) stimulus. A common finding across these studies was that a negatively-polarized component located over frontal and central electrodes was larger in amplitude to the oddball stimulus than the standard stimulus. Courchesne, Ganz, and Norcia (1981) labeled this component Nc, and concluded that the increased amplitude of Nc on oddball trials may reflect the infants' detection of a novel or discrepant, attention-getting stimulus.

Recent work has demonstrated that Nc amplitude is impacted by stimulus salience or level of attentional engagement (e.g., de Haan & Nelson, 1997, 1999; Reynolds & Richards, 2005; Reynolds, Courage, & Richards, 2010). By combining ERP and heart rate measures of attention, Richards (2003) showed that Nc is greater in amplitude during sustained attention than during attention termination. Reynolds and Richards (2005) used a high-density EEG recording system to record infant ERPs in an oddball task. This enabled the application of cortical source analysis of the ERP data for identification of locations in the cortex that could be potential generators of Nc (see: Reynolds, Courage, & Richards, 2010; Reynolds & Richards, 2005, 2009; Richards, Reynolds, & Courage, 2010). The results of the cortical source analyses identified areas of prefrontal cortex (in particular inferior prefrontal cortex and anterior cingulate) as likely cortical sources of Nc. These are areas of the brain consistently found to be active in a wide range of cognitive involving attention in adulthood (see review, Duncan & Owen, 2000).

Reynolds, Courage, and Richards (2010) designed a procedure with paired comparison trials embedded throughout an oddball ERP procedure. This allowed for the analysis of the distribution of infant visual preferences throughout ERP testing. Infants demonstrated

greater amplitude Nc to their preferred stimulus type (novel or familiar). Visual preference also interacted with attention. Infants that demonstrated a novelty preference showed greater amplitude Nc during attention than inattention. Infants that did not demonstrate a novelty preference showed no differences in Nc based on attention. The authors concluded that Nc amplitude is associated with activation of a general arousal/attention system in the brain (Richards, 2008). Activation of this system is initiated in the brainstem, which has subsequent descending effects on heart rate through parasympathetic innervation of the heart, and ascending effects on cortical activity through activation of the noradrenergic and cholinergic neurochemical systems. This arousal response is general in that it: occurs across multiple modalities, is a component of most attentional responding (orienting, selection, and maintenance), and impacts functioning in both the central and peripheral nervous systems. Thus, although Nc may reflect a specific component of attention, when this arousal system is activated, attention is enhanced and Nc increases in amplitude. The results of this study establish a strong relationship between Nc and behavioral correlates of infant attention and also indicate that individual differences may play a role in responsiveness of the Nc component to stimulus characteristics.

Attention can be conceptualized as having multiple components that serve multiple functions including attention as state (related to arousal), attention as selectivity, and attention as executive control (Ruff & Rothbart, 1996). Attention and arousal influence one another in a bidirectional manner such that level of arousal influences infant visual preferences in early development (Gardner & Karmel, 1984, 1995). Measuring sustained attention using heart rate gives an index of attention as state at the psychophysiological level. Colombo and colleagues (2001) found no differences based on looker type in proportion of time spent in sustained attention; however, heart rate is an indirect measure of activation of attention systems in the brain (Reynolds & Richards, 2008), and no study to date has examined individual differences in infant visual attention at the neural level. Failure to find group differences related to sustained attention at one level of analysis (i.e., heart rate) certainly does not rule out the possibility that differences may be apparent at different levels of analysis (e.g., behavioral, neural, etc.). Thus, an investigation of individual differences in infant attention utilizing the Nc ERP component as an electrophysiological correlate of attention is warranted.

Short and long lookers not only differ in looking during initial exposure to a novel stimulus, perhaps more importantly they differ in subsequent performance on recognition memory tasks. This indicates that short and long lookers not only differ in the ability to disengage and shift fixation, they also differ in ability to encode and subsequently recognize information presented to the visual modality. The late slow wave (LSW) is believed to reflect infant recognition memory and typically occurs from 1 to 2 s following stimulus onset over temporal, parietal, frontal, and central leads (see review, de Haan, 2007). The LSW can be either negative or positive in polarity depending on the electrode location, stimuli used, and amount of exposure to the stimulus presented. Past findings have been inconsistent in whether a negative-going slow wave (Nelson & Collins, 1991, 1992; Quinn, Westerlund, and Nelson, 2006; Reynolds & Richards, 2005; Richards, 2003) or positive-going slow wave (de Haan & Nelson, 1997, 1999; Snyder, 2010; Snyder, Webb, & Nelson, 2002; Snyder, Zolot, Garza, & Kresse, 2010; Webb, Long, & Nelson, 2005; Wiebe, Cheatham, Lukowski, Haight, Muehleck, & Bauer, 2006) occurs following novel or infrequent stimulus presentations; however, there appears to be overall consistency in that there is a reduction in the amplitude of the LSW (or return to baseline) with repeated presentations of a stimulus. Because short lookers are more likely to demonstrate evidence of recognition memory than long lookers at the behavioral level significant differences between short and long lookers may be found in the LSW.

The current study examined neural correlates of individual differences in infant visual attention and recognition memory. Infants of 6 and 7.5 months of age were tested in a procedure in which they were familiarized with a single stimulus, and then shown the familiar stimulus on 50% of the ERP trials, and novel stimuli on the other 50% of trials. We tested infants of 6 and 7.5 months of age because this age range represents a significant developmental transition in infant visual attention and looking behavior. Look duration is at its shortest at 6 months of age regardless of stimulus type as looking decreases with development of the posterior orienting system (Courage, Reynolds, & Richards, 2006; Posner & Petersen, 1990). From 6 to 12 months of age, look duration is influenced to a greater extent by stimulus characteristics possibly reflecting the emergence of higher-order (or executive) attention and the increased role of frontal brain areas in directing infant attention (see Colombo, 2001; Courage, Reynolds, & Richards, 2006; Ruff & Rothbart, 1996). Additionally, this is the age range when infant look duration has its greatest predictive value for later cognitive functioning (Colombo, 1995; McCall & Carriger, 1993). Peak look duration during familiarization was used to determine looker type. ERPs were used to provide insight into the point in the information processing stream at which differences emerge between looker types.

We examined the Nc component as a neural correlate of visual attention and early cognitive processing. Based on the finding that long lookers only demonstrate slower localization of peripheral stimuli in competition conditions (Frick, Colombo, & Saxon, 1999), we predicted no differences between groups on latency to peak of the Nc component. If the differences between looker groups were simply due to greater overall levels of attention in short lookers, then a main effect of looker type would be expected for Nc amplitude. However, given the finding that short and long lookers do not differ in proportion of time spent in sustained attention when measured using heart rate (Colombo et al., 2001), we predicted an interaction of looker type and stimulus type on Nc amplitude. Specifically, we expected that short lookers would demonstrate greater amplitude Nc to novel stimuli when compared to familiar reflecting a greater allocation of attention toward novel stimuli as well as discrimination of novelty versus familiarity. We expected no differences in Nc amplitude based on stimulus type (or possibly greater amplitude Nc to familiar) for long lookers indicating a lack of stimulus discrimination due to incomplete processing of the familiar stimulus. For the late slow wave, we again expected short lookers to demonstrate evidence of complete processing of the familiar stimulus. This evidence would come in the form of a return to baseline or reduction in amplitude of the LSW to the familiar stimulus compared to novel stimuli. In contrast, we predicted that the long lookers would not demonstrate significant differences in LSW responding based on stimulus type.

Method

Participants

A cross-sectional sample of 24 infants were tested at 6 ($N = 13$; 7m, 6f) or 7.5 ($N = 11$; 6m, 5f) months of age. All infants were tested within a week of their 26 or 32 week birthdates, respectively. Only infants born full term (at least 38 weeks gestation) without complications and of normal birth weight were recruited. Participants were drawn from a predominantly Caucasian and middle-class population. The ethnic/racial distribution of participants was: 21 Caucasian (not Hispanic), 1 Biracial, 1 Asian, 1 Caucasian (Hispanic). An additional 16 infants were tested, but not included in the final sample due to fussiness/distractibility ($N = 4$), excessive artifact in the EEG ($N = 10$), and technical problems ($N = 2$).

Apparatus

Participants were positioned on their parent's lap in a sound-attenuated room. They were seated 55 cm away from a 27" color LCD monitor (Dell 2707 WFP) with 60 Hz resolution. A digital camcorder (Sony DCR-HC28) was located just below the monitor in order to judge infant visual fixations. Fixations were judged online using a video feed to a computer in the experiment control room, adjacent to the testing room. The video was also recorded through use of Netstation software produced by Electrical Geodesics Incorporated (EGI). The Netstation was used to record EEG data and to synchronize this data with the video. The experimental procedure was controlled on a PC using E-Prime 2.0 software. The E-Prime program sent experimental events to the Netstation and utilized a single-clock system to time-lock these experimental events with the EEG and video data.

Visual Stimuli

Female face: A digital black-and-white photograph of an adult female face was presented in a 20° square on the monitor. This was used to obtain peak look duration and to determine looker type. **Object photographs:** Test stimuli consisted of 58 color digital photographs of objects (e.g. globe, lifejacket, Easter basket). The photographs were presented in a 20° square centered on the computer monitor. **Sesame Street characters:** Videos of Sesame Street characters were used to regain infants' interest and fixation on the monitor after becoming distracted. The video covered a 15° square area centered on the monitor.

Procedure

Following the informed consent process, infants were held on a parent's lap approximately 55 cm from the center of the computer monitor. They were fitted with an EGI sensor net and impedances were measured. The experiment was then completed in three phases. For consistency with previous work in the area, the first phase was based on Colombo and colleagues' method of determining looker type (Colombo, Freeseaman, Coldren, & Frick, 1995; Colombo & Mitchell, 1990; Colombo, Richman, Shaddy, Greenhoot, & Maikranz, 2001; Frick, Colombo, & Saxon, 1999). Specifically, infants were exposed to 20 s of accumulated looking to the female face and participants' peak look duration during this phase was used to determine looker group (short or long looker). Looking data was analyzed offline from this phase in order to determine peak look. The looker type groups were then determined by using a median split. The two age groups did not differ significantly on peak look duration, $t(22) .685; p = .50$; thus, the distribution of infants into short and long looker groups was accomplished with a median split using the median peak look from the entire dataset.² This resulted in 12 short lookers (seven 6-month-olds, five 7.5-month-olds) and 12 long lookers (six 6-month-olds, six 7.5-month olds). Descriptive statistics on the peak look duration data are shown in Table 1.

The second phase was a familiarization phase. Infants were exposed to 20 s of accumulated looking to one of the object stimuli. This stimulus served as the familiar stimulus for the remainder of the experiment. The object used for the familiar stimulus was randomly

¹Seventy-nine infants were tested prior to the infants included in the final dataset. However, we identified a problem with the synchronization of the timing of the video and EEG data files in Netstation 4.2, and were unable to accurately determine whether these infants were looking during many of the individual ERP trials. Thus, we elected not to use data collected from the first 79 participants and those participants are not included in our report of attrition in the body of the manuscript. The timing issue has since been addressed in Netstation updates.

²We also split infants into looker type groups based on a median split within each age group and determining looker type for the infant with the median score based on whether it was higher or lower than the overall median (this was necessary due to odd numbers of participants in each age group). This approach resulted in the same distribution as using the median score from the entire dataset to determine looker type. The distribution of infants into looker type groups was also identical when using the median score from a larger sample of infants (N = 53) to determine looker type groups. This larger sample included participants that did not contribute enough ERP data (due to fussiness, excessive artifact, or technical problems) to be included in the final dataset.

determined and varied between participants. The third phase consisted of the test trials, during which the familiar stimulus and novel stimuli were briefly presented, and EEG was recorded during this phase for ERP analysis. Novel stimuli consisted of the remaining 57 object photographs. The stimuli were presented for 500 ms, followed by a blank gray screen with a random duration of 2000 to 2500 ms. Novel and familiar stimulus presentations were equally distributed across trials (i.e., 50%). The stimuli were presented in random order in blocks of 20 stimulus presentations. Stimulus presentations were initiated only when the infant was judged to be looking at the monitor. During periods of distraction, the Sesame Street videos were presented as an attractor stimulus. Stimulus presentations continued for as long as the infant was not tired or fussy.

Inter-observer reliability

In addition to judging infant fixations online for the purpose of experimental control during testing, fixations were also judged offline by a trained rater to determine each participant's peak look to the female face for the purpose of determining looker type (see phase 1 of procedure above). For 20 participants, fixations were judged by a second trained rater in order to determine inter-rater reliability. The Pearson correlation coefficient indicated significant reliability between observers ($R = .954, p < .001$).

Infant fixations during phase 3 (ERP trials) were also judged offline to determine whether or not the participant was looking during each ERP trial. ERP trials in which the infant was not looking at stimulus onset or looked away during the stimulus presentation were not included in the data analysis.

EEG recording and analyses

The Electrical Geodesics Incorporated (EGI) Geodesic EEG System 300 (GES 300) 128 channel EEG recording system was used. The system consisted of the HydroCel Geodesic Sensor net, the NetAmps hardware, and the Netstation recording program. The 128 channel net used for infant recordings consisted of 124 electrodes mounted in a geodesic configuration of pedestals held in place with elastic connections. There were an additional 4 channels available for recording EOG and/or heart rate, these channels were not used in this experiment. Electrolytic sponges were located within the pedestals and the entire net was soaked in an electrolytic (saline-based) solution prior to use. Pedestals corresponding to the vertex, mastoids, and nasion locations were marked on the net and used to position the sensor net, while the elasticity of the net connections served to maintain the pedestals corresponding to the remaining 120 electrodes. The average interelectrode distance of the scalp electrodes was 21 mm.

The proper placement of the sensor net results in electrode impedances of about 10 to 50 k Ω . The EGI system utilized high-impedance amplifiers containing 128 channels connected to a computer A/D card in a Power PC-based computer system. A Mac OS computer program included with the EGI system was used for the A/D sampling, storing the data, the zero and gain calibration for each channel, and measuring impedances. The Netstation program received serial communication from a Dell Workstation used to control the experimental protocol with the use of E-Prime 2.0 software (Psychology Software Tools, Inc.). Communication between the two computers was temporally synchronized based on the sending of experimental information (e.g., trial type, trial onsets) from the experimental computer to the Netstation program using the E-Prime single-clock system. The sampling rate of the EEG was 250 Hz (4 ms samples) and band-pass filters were set from 0.1 to 100 Hz, with 20K amplification. EEG recordings were referenced to the vertex and algebraically re-referenced to the average reference. The application and adjustment of the net took about

10 min total, during which a second experimenter distracted the infant with rattles and infant-directed speech to keep the infant in a positive state prior to testing.

The EEG recordings were inspected for artifacts (i.e., blinks, saccades, movement artifact, and drift) and poor recordings using the Netstation review system. Individual channels were marked bad within trials if these occurred. Segments in which more than 10% of the channels were marked bad were eliminated from the analysis. For trials that were retained for the ERP analysis, individual channels marked bad were replaced using a spherical spline interpolation (Perrin, Pernier, Bertrand, Giard, & Echallier, 1987; Srinivasan, Tucker, & Murias, 1998). Only those participants who retained enough ERP trials per condition for stable ERP averages following EEG editing were included in the final dataset. On average, infants contributed 17.58 trials (range: 9 – 28) in the familiar condition and 17.08 trials (range: 8 – 33) in the novel condition. Descriptive statistics on the number of ERP trials included and number of times the attractor stimulus was used per group are included in Table 1.

ERP averages were created for producing waveform plots and topographical maps, and for the analysis of experimental effects. The ERP averages were calculated from 100 ms before stimulus onset through 2 s after onset. The Nc component is typically located at frontal, central, and parietal midline electrodes (i.e., Fz, Cz, Pz). We analyzed the mean data from clusters of electrodes of the EGI sensor net that corresponded to these regions. Nc peak amplitude and latency to peak were analyzed from 350 – 750 ms following stimulus onset at midline frontal (4, 10, 11, 16, 18, and 19; “FrontalZ”), left frontal (24, 27, 28, 33, 34; “FrontalL”), right frontal (116, 117, 122, 123, 124; “FrontalR”); and midline central (7, 31, 55, 80, and 106; “CentralZ”) and parietal (61, 62, 67, 72, 77 and 78; “ParietalZ”) electrode locations. For the late slow wave, mean amplitude from 1 – 2 s following stimulus onset was analyzed at left posterior temporal (51, 58, 59, 64, and 65; “TemporalL”), right posterior temporal (90, 91, 95, 96, and 97; “TemporalR”), left anterior temporal (34, 35, 39, 40, 41), right anterior temporal (103, 109, 110, 115, 116), FrontalZ, and CentralZ electrode clusters.

Design for Statistical Analysis

The design for the study included the experimental factors of testing age (2: 6, 7.5 months) and looker type (2: short looker, long looker) as between-subjects factors, and stimulus type (2: familiar, novel) as a repeated measures factor. We also analyzed electrode location as a within-subjects factor, the level for this factor varied by component (Nc or LSW). Repeated-measures ANOVAs were used in the analysis and the Greenhouse-Geisser correction was used in cases of violations of the assumption of sphericity. For significant effects, follow-up analyses were done using paired-samples *t*-tests (two-tailed). Effect sizes (η_p^2) are reported on all significant effects, and all significant tests are reported at $p < .05$.

Results

Grand Average Waveforms

Figure 1 displays the grand average waveforms (right panel) for each of the channel clusters (left panel) that demonstrated significant experimental effects. The Nc component is identified as a large negative peak in the midline frontal and central electrode clusters (FrontalZ and CentralZ) occurring approximately 500 ms after stimulus onset, and the LSW is identified as a negative-going slow wave at temporal electrode clusters and a positive-going slow wave at frontal and midline electrode clusters occurring from approximately 1 to 2 s after stimulus onset. For our statistical analysis of experimental effects, the Nc component was analyzed by examining peak (minimum) amplitude from 350 – 750 ms post stimulus onset. We also analyzed latency to peak of the Nc component in this same time-

window. The LSW was analyzed by examining mean amplitude occurring from 1 to 2 s post stimulus onset.

The Nc Component

Nc latency to peak—To analyze latency to peak of the Nc component, we ran two mixed ANOVAs (one for frontal electrode clusters and the other for midline electrode clusters). The first ANOVA included frontal electrodes (3: FrontalL, FrontalZ, FrontalR) and stimulus type (2: familiar, novel) as within-subjects factors; and age (2: 6 months, 7.5 months) and looker type (2: short looker, long looker) as between-subjects factors. The second ANOVA included midline electrodes (3: FrontalZ, CentralZ, ParietalZ) and stimulus type (2: familiar, novel) as within-subjects factors; and age (2: 6 months, 7.5 months) and looker type (2: short looker, long looker) as between-subjects factors. There were no significant effects found in the analysis of latency to peak for the Nc component.

Nc amplitude—We conducted our analysis of Nc amplitude similar to our analysis of Nc latency. We first conducted separate ANOVAs for frontal and midline electrode clusters on Nc peak amplitude (see above paragraph for specific factors). The ANOVA on midline electrode clusters was not significant. There was a significant frontal electrode by age interaction, $F(2, 40) 5.36; p = .009, \eta_p^2 = .211$; and a marginal three-way interaction between frontal electrodes, age, and stimulus type, $F(2, 40) 2.61; p = .086, \eta_p^2 = .115$. The 6-month-old group demonstrated an Nc that was greater in amplitude, $t(12) 2.683; p = .02$, at lateral frontal electrode sites ($M = -15.34 \mu V$) than midline frontal sites ($M = -10.23 \mu V$). In contrast, marginal differences were found for the 7.5-month-old group, $t(12) -1.888, p = .09$, with greater amplitude Nc at midline frontal ($M = -16.07 \mu V$) than lateral frontal electrode clusters ($M = -12.95 \mu V$). No significant differences were found, $F(1, 20) .006; p = .941, \eta_p^2 = .001$, on Nc amplitude at frontal electrodes for short lookers ($M = -13.80 \mu V$) compared to long lookers ($M = -13.59 \mu V$).

The Late Slow Wave

For the LSW analysis, we conducted a mixed ANOVA on mean amplitude from 1 – 2s following stimulus onset with electrode location (2: see below) and stimulus type (2: familiar, novel) as within-subjects factors; and age (2: 6 months, 7.5 months) and looker type (2: short looker, long looker) as between-subjects factors. We ran three ANOVAs examining the electrode factor at three different locations (posterior temporal, anterior temporal, and midline) with left and right hemisphere serving as the two levels of the electrode factor for both of the temporal electrode analyses, and frontal and central serving as the two levels of the electrode factor in the midline electrode analysis. There were no significant effects in the analysis of the LSW at anterior temporal sites.

In the analysis of posterior temporal sites, there was a significant three-way interaction of electrodes, stimulus type, and looker type, $F(1, 20) 4.51; p = .046, \eta_p^2 = .184$. Follow-up ANOVAs and t-tests were conducted separately for each posterior temporal electrode cluster. At TemporalL, there was a marginal main effect for stimulus type, $F(1, 20) 3.97; p = .060, \eta_p^2 = .166$. Infants demonstrated greater amplitude negative-going LSWs following novel ($M = -11.55 \mu V$) stimulus presentations than following familiar ($M = -6.96 \mu V$) stimulus presentations (see grand average waveform at TemporalL in figure 1). At TemporalR, there was a significant interaction of looker type and stimulus type, $F(1, 20) 5.74; p = .026, \eta_p^2 = .223$ (see figure 2). Short lookers demonstrated a LSW that was significantly greater in amplitude on novel trials ($M = -14.74 \mu V$) than familiar ($M = -4.84$

³We also conducted this analysis after using the McCarthy-Wood transformation as has been suggested for analyses of scalp distributions of ERPs (McCarthy & Wood, 1985), and found the same experimental effects using the transformed data.

μV) trials, $t(11) 2.57, p = .026$. No differences were found for long lookers in LSW amplitude on novel ($M = -8.63 \mu V$) and familiar trials ($M = -15.34 \mu V$) at temporal electrodes.

In the LSW analysis of midline electrodes, there was a three-way interaction of electrode, looker type, and stimulus type, $F(1, 19) 5.85, p = .026, \eta_p^2 = .235$. Follow-up analyses revealed there was an interaction of looker type and stimulus type at midline frontal electrodes, $F(1, 19) 4.49, p = .048, \eta_p^2 = .191$, that was similar to the LSW effect at TemporalR but with reversed polarity (see Figure 3). Short lookers demonstrated a positive-going LSW that was significantly greater in amplitude on novel trials ($M = 5.66 \mu V$) than familiar ($M = .02 \mu V$) trials, $t(10) -2.36, p = .024$. No differences were found for long lookers in LSW amplitude on novel ($M = 5.90 \mu V$) and familiar ($M = 10.24 \mu V$) trials at frontal electrodes.

Discussion

The purpose of the current study was to examine neural correlates of individual differences in infant visual attention. We focused on the mid-latency Nc ERP component associated with infant visual attention and the LSW associated with stimulus encoding and recognition memory. We predicted an interaction of looker type and stimulus type for Nc amplitude. We expected short lookers to demonstrate greater amplitude Nc to novel compared to familiar stimuli reflecting complete processing of the familiar stimulus and ability to discriminate novel from familiar. The results did not support this prediction. There were no significant effects on Nc amplitude related to looker type or stimulus type. The findings did support our prediction that there would be an interaction of looker type and stimulus type on the LSW reflecting discrimination of novel versus familiar stimuli for short lookers. The short lookers demonstrated greater amplitude LSWs at right temporal and midline frontal electrodes on novel trials when compared to familiar trials.

The Nc component

There were no significant experimental effects related to latency to peak of the Nc component. In a longitudinal analysis, Webb, Long, and Nelson (2006) found that the latency of Nc decreases with age across infancy. However, previous work by Reynolds and Richards (2005) utilizing a cross-sectional design and the same age groups as the current study also found no significant differences in Nc latency based on age. The lack of differences in short and long lookers on Nc latency is consistent with the behavioral finding that long lookers only demonstrate slower latencies to localize a peripheral stimulus in “competition” conditions in which the infant must disengage from a central stimulus prior to shifting fixation (Frick, Colombo, & Saxon, 1999). Long lookers shift to a peripheral stimulus just as quickly as short lookers on “non-competition” trials and their fastest shifts (shortest latency) on competition trials are equivalent to the fastest shifts of short-looking infants. The differences in latency to shift are only found when averaged across trials. Taken together, these findings suggest that individual differences in look duration are most likely not based on overall integrity of the central nervous system or efficiency of neural transmission.

There was a significant age by frontal electrode interaction effect on Nc amplitude. Six-month-olds demonstrated Nc that was greater in amplitude at lateral leads than at midline leads, whereas 7.5-month-olds' Nc was marginally lower in amplitude at lateral compared to midline leads. Reynolds, Courage, & Richards (2010) conducted source analysis in a study of infant attention and recognition memory and found that dipoles identified as probable cortical sources of Nc were broadly distributed throughout prefrontal cortex at 4.5 months of age and showed an increased localization toward midline prefrontal areas from 6 to 7.5

months. Consistent with Reynolds and Richards (2005), the dipoles from individual participants were most commonly localized to inferior prefrontal cortex and the anterior cingulate cortex indicating that these cortical areas play a key role in infant visual attention.

Our hypothesis that short lookers would demonstrate differences in Nc amplitude based on stimulus type whereas long lookers would not was not supported. The lack of a main effect of looker type or an interaction between looker type and stimulus type on Nc amplitude indicates that the differences in visual attention across these two groups may not be related to differences in overall magnitude of attention or the arousal aspect of attention. However, it is possible that the lack of a stimulus type effect on Nc amplitude for short lookers is due to the relatively complex stimuli used in the current study. Color photographs of objects were used as opposed to achromatic, computer-generated patterns. It is possible that short lookers maintained interest in the familiar object throughout testing. Using basic patterns similar to those used in previous studies (e.g., Colombo et al., 1995; Reynolds & Richards, 2005) instead of more complex stimuli may have produced the predicted looker type by stimulus type interaction. Reynolds and Richards (2005) found a main effect of stimulus type on Nc amplitude when using computer generated patterns with infants of these ages, thus we decided to use more complex stimuli in the current study to maximize the likelihood of finding differences between groups in discriminating novel from familiar stimuli. Another possibility is that the lack of differences in Nc amplitude is due to the sample size, and a study with increased power due to a larger sample may find significant differences between looker types. However, Nc amplitude in this dataset was almost equal for short ($-13.80 \mu V$) and long lookers ($-13.59 \mu V$), and the effect size for looker type on Nc amplitude was minimal ($\eta_p^2 = .001$).

Colombo and colleagues (2001) integrated looking and heart-rate measures and found that short and long lookers do not differ in the amount of time spent in sustained attention during looking, but do differ in the amount of time spent in attention termination. This finding indicates that the differences between short and long lookers in looking and information processing may be related to ability to disengage and shift visual fixation and attention, processes associated with development of the posterior orienting network (Posner & Petersen, 1990). The current ERP experimental procedure did not allow for the analysis of effects related to ability to disengage and shift attention; however, a study using the spatial-cueing procedure could potentially provide insight into differences between these groups in the ability to make planned as opposed to reactive saccades on competition and non-competition trials (see Richards, 2005).

The Late Slow Wave

As predicted, there was a significant interaction of looker type and stimulus type on the amplitude of the LSW at right temporal and midline frontal electrodes. Short lookers demonstrated LSWs that were significantly greater in amplitude for novel versus familiar stimuli. No significant differences in the LSW were found based on stimulus type for long-looking infants. Although the polarity of the LSW has varied across studies and can thus be hard to predict (de Haan, 2007), a common finding is a reduction in amplitude of the LSW that occurs with increased exposure to a stimulus leading to the conclusion that the LSW reflects stimulus encoding (e.g., de Haan & Nelson, 1997, 1999; Nelson & Collins, 1991, 1992; Nelson & Monk, 2001; Snyder, 2010; Snyder, Garza, Zolot, & Kresse, 2010). For example, Snyder (2010) found that the amplitude of the LSW decreases across repetitions during encoding and suggested that changes in amplitude of the LSW may be used to predict subsequent performance on the paired comparison task. Consistent with this conclusion and previous behavioral work in the area (e.g., Colombo & Mitchell, 1990; Colombo, Freese, Coldren, & Frick, 1995; Colombo, Richman, Shaddy, Greenhoot, & Maikranz, 2001; Frick, Colombo, & Saxon, 1999), the current findings indicate that short lookers fully

processed the familiar stimulus, thus demonstrating reduced amplitude slow waves on familiar trials.

It is worthwhile to note that Reynolds and Richards (2005) found a similar interaction effect of stimulus type and attention on the LSW at right temporal and frontal electrodes in infants from 4.5 to 7.5 months of age. Infants demonstrated greater amplitude LSWs to novel versus familiar stimuli in that study but these differences were only found on trials when the infants were engaged in sustained attention (measured with heart rate). It is possible that short lookers were more likely to be engaged in sustained attention during the period when the LSW is analyzed than long lookers; however, heart rate was not measured in the current study, so this possibility remains speculative.

Conclusion

The results of the current analyses of the Nc and LSW indicate that short lookers may not allocate greater levels of attention toward visual processing than long lookers; however, short lookers demonstrated evidence of encoding and recognition of the familiar stimulus and long lookers did not. This suggests that the differences between short and long lookers in ability to demonstrate evidence of recognition may be due to differences in the selective aspect of attention more so than the arousal aspect of attention. Because all infants are required to reach 20 s of accumulated looking to the familiar stimulus, this selection would refer to the focus of attention on specific features of a single stimulus (i.e., visual-intake strategy or scanning behavior). Colombo and colleagues (1995) found that short lookers process global properties of visual patterns prior to processing local elements, whereas long lookers appear to process local elements prior to global patterns. This global-to-local sequence of processing is a more efficient strategy for encoding than processing local elements first. Thus, it is likely that there are multiple mechanisms that account for variability in infant visual attention including visual-intake strategy and ability to inhibit, disengage, and shift visual attention.

The results of this study are the first to provide information on neural correlates of individual differences in infant visual attention. Differences in neural responding between looker types were not apparent until late stages of information processing associated with stimulus encoding. No differences were found on the mid-latency Nc component commonly associated with infant attention. Given that performance on looking measures of attention and recognition has been found to have significant predictive value for cognitive functioning in childhood (e.g., Bornstein & Sigman, 1986; Fagan & Shepard, 1987; Rose & Feldman, 1995), studies of individual differences in early cognitive development are of particular importance and continued research in the area is warranted.

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Grand Average Waveforms by Electrode Locations

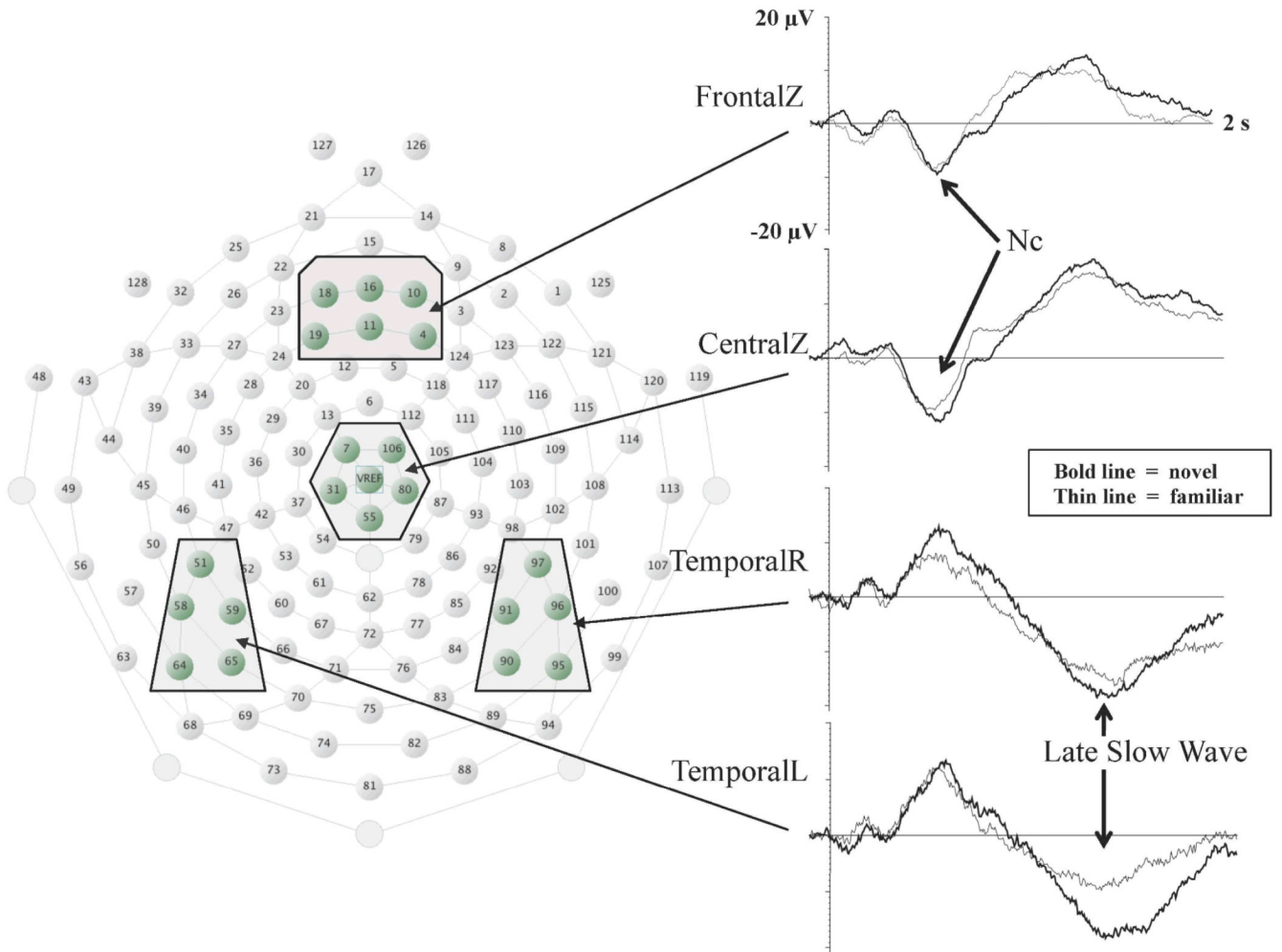


Figure 1. Layout of the EGI 128-channel sensor net, the electrode clusters that demonstrated significant experimental effects are indicated. The grand average waveforms for these electrode clusters are shown to the right. The Y-axis indicates change in amplitude from baseline and the X-axis indicates time following stimulus onset.

Late Slow Wave by Looker Type and Stimulus Type at TemporalR Electrodes

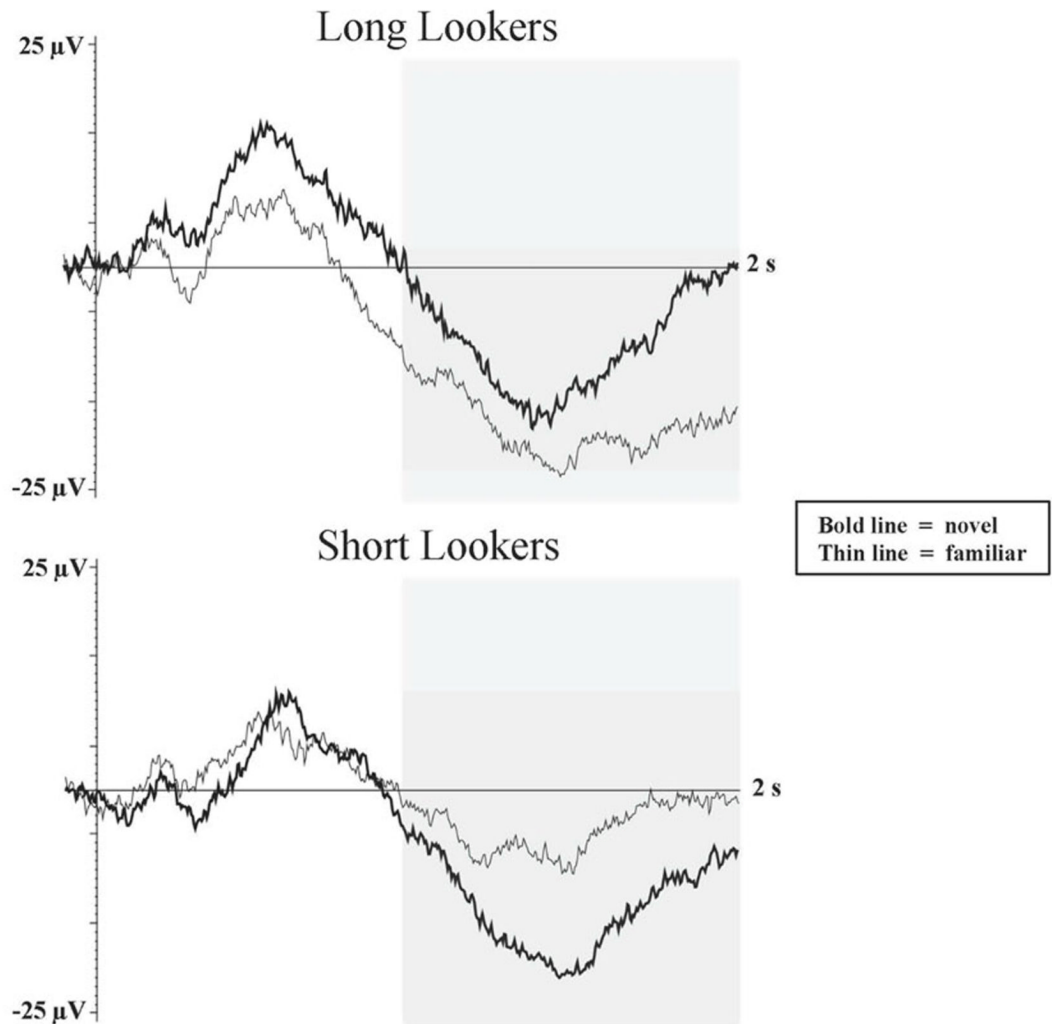


Figure 2.

Mean amplitude of the late slow wave by looker type and stimulus type at TemporalR. The Y-axis represents change in amplitude from baseline and the X-axis represents time following stimulus onset following familiar (thin line) and novel (bold line) stimulus presentations. The shaded area indicates the portion of the waveform examined in the LSW analysis from 1 to 2 s following stimulus onset.

Late Slow Wave by Looker Type and Stimulus Type at FrontalZ Electrodes

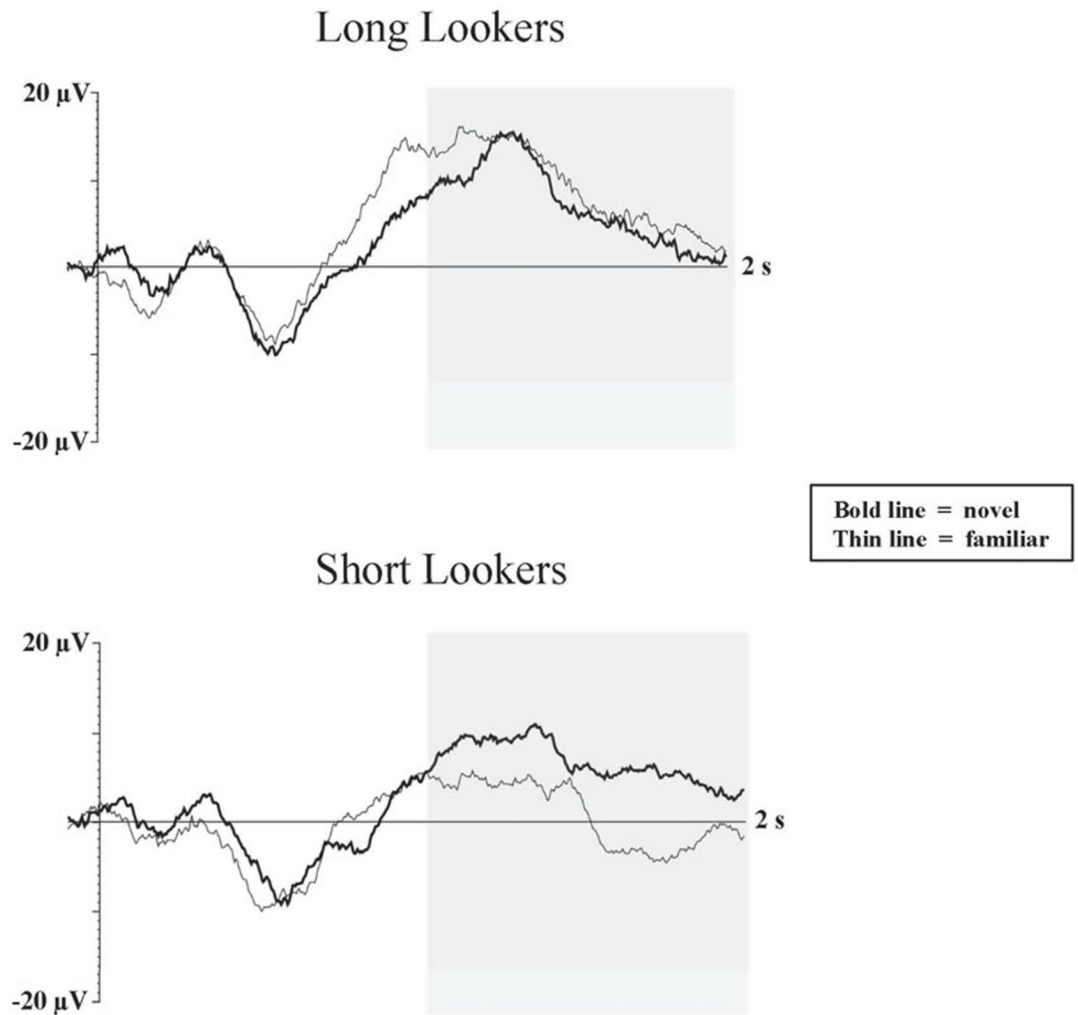


Figure 3.

Mean amplitude of the late slow wave by looker type and stimulus type at FrontalZ. The Y-axis represents change in amplitude from baseline and the X-axis represents time following stimulus onset following familiar (thin line) and novel (bold line) stimulus presentations. The shaded area indicates the portion of the waveform examined in the LSW analysis from 1 to 2 s following stimulus onset.

Table 1

Descriptive statistics on peak look data, numbers of ERP trials, and use of attractor stimulus per group.

Group	N	Mean peak look (SD)	Median peak look	Number of ERP trials (SD)	Use of attractor stimulus (SD)
Age:					
6 months	13	7.87 (4.37)	6.27	36.00 (14.71)	15.38 (12.64)
7.5 months	11	6.78 (3.20)	6.51	33.10 (11.80)	15.27 (11.78)
Looker Type:					
Short	12	6.14 (4.1)		33.67 (12.66)	15.50 (14.87)
Long	12	13.74 (5.8)		35.67 (11.97)	15.17 (11.89)
Total	24	7.37 (3.83)	6.39	34.67 (12.09)	15.33 (13.16)