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Effects of interstimulus intervals on behavioral, heart rate, and event-related potential indices of infant engagement and sustained attention

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Abstract

Maximizing infant attention to stimulus presentation during an EEG or ERP experiment is important for making valid inferences about the neural correlates of infant cognition. The present study examined the effects of stimulus presentation interstimulus interval (ISI) on behavioral and physiological indices of infant attention including infants' fixation to visual presentation, the amount of heart rate (HR) change during sustained attention, and ERP components. This study compared an ISI that is typically used in infant EEG/ERP studies (e.g., 1,500–2,000 ms) with two shorter durations (400–600 ms and 600–1,000 ms). Thirty-six infants were tested cross-sectionally at 3, 4.5, and 6 months. It was found that using the short (400–600 ms) and medium (600–1,000 ms) ISIs resulted in more visually fixated trials and reduced frequency of fixation disengagement per experimental block. We also found larger HR changes during sustained attention to both of the shorter ISIs compared with the long ISI, and larger ERP responses when using the medium ISI compared to using the short and long ISIs. These data suggest that utilizing an optimal ISI (e.g., 600–1,000 ms), which increases the presentation complexity and provides sufficient time for information processing, can promote infant engagement and sustained attention during stimulus presentation.

Descriptors: Interstimulus intervals, ERPs, Infant sustained attention

Infant sustained attention is an endogenous attentional function that is affected by the intrinsic properties of stimulus presentation. Increased information (e.g., visual stimulus) load and stimulus complexity during a given unit of time of visual presentation benefits infant sustained attention and improves infant engagement (Courage, Reynolds, & Richards, 2006; Stets, Burt, & Reid, 2013). Studies with infant participants often use EEG and ERPs as measures of infant attention and cognitive processes. One issue in this research is the relatively high attrition rate of participants (~50%; Stets, Stahl, & Reid, 2012) compared to that in adult research (Luck, 2014). Infants' fussiness and poor data quality are two frequent contributors to the high attrition rate in infant EEG/ERP research (Stets et al., 2012). Maximizing infant attention and engagement to stimulus presentation should enhance the processing quality and minimize the probability of a study being terminated early because of infants' fussiness, which should in turn reduce the attrition rate. We hypothesized that accelerating the presentation rate of visual stimuli that enhances the complexity of information load would facilitate infant sustained attention. In the current study, we manipulated the presentation rate by using different interstimulus intervals (ISIs) that refer to the periods between the offset of a visual presentation and the onset of the next one. We found that the length of ISIs of visually presented stimuli affected both behavioral and psychophysiological measures of infant attention.

Sustained attention represents a period of voluntary attention engagement that affects infants' behavioral and psychophysiological responses. Studies have consistently found that sustained attention is associated with maintaining fixation on a focal stimulus in the presence of a peripheral distracting stimulus, which means that infants are less likely to be distracted by a peripheral stimulus during sustained attention than inattention (Casey & Richards, 1988; Pérez-Edgar et al., 2010; Richards & Hunter, 1997; Richards & Turner, 2001). This pattern of visual fixation in infant sustained attention has also been found during infants' toy play (Lansink & Richards, 1997; Oakes, Madole, & Cohen, 1991; Oakes & Tellinghuisen, 1994; Ruff, 1986). The period when infants show focused concentration on an object or toy is referred to as focused attention. During focused attention, infants are engaged in active examination of the object and take longer to shift from the object to a distracting stimulus (e.g., Lansink & Richards, 1997; Oakes & Tellinghuisen, 1994). Greater engagement in stimulus presentation and toy play during sustained attention reflects increased brain arousal and allocation of attention (Richards, 2008, 2009). The enhancement of general arousal and attentional allocation during sustained attention is accompanied by heart rate (HR) changes (see Colombo, 2002; Reynolds & Richards, 2008, for reviews). Richards and colleagues

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have measured HR derived from electrocardiogram (ECG) recordings to identify infant attention phases during infants' looking. Sustained attention is the phase when infants' HR declines significantly and remains at this lower level compared to their prestimulus baseline. Functional assessments of HR-defined sustained attention have been obtained in infants as young as 8 weeks (Richards, 1989), and sustained attention develops dramatically in depth, amount, and frequency from 3 to 6 months (see Colombo, 2001; Richards, 2008, for reviews). Sustained attention also affects infant ERP responses. For example, the negative central (Nc) component is a large negative deflection in the ERP prominent at frontal-central scalp regions occurring about 350 to 750 ms after a briefly presented visual stimulus (Courchesne, Ganz, & Norcia, 1981; Goldman, Shapiro, & Nelson, 2004). The amplitude of the Nc component has been found to be larger during sustained attention than during inattention (Guy, Zieber, & Richards, in press; Reynolds, Courage, & Richards, 2010; Reynolds & Richards, 2005; Richards, 2003).

Intrinsic properties of visual stimuli, such as stimulus complexity and amount of information presented during a certain period, have been found to impact infant sustained attention and infants' engagement in the presentation. Infants may engage in sustained attention for only 2–3 s, or not at all, when presented with simple stimuli, but may spend 20 s or more in sustained attention when the visual presentation is complex and dynamic (Reynolds & Richards, 2008; Richards, 2010; Richards & Casey, 1992). For example, Courage et al. (2006) observed longer durations of sustained attention in response to complex stimuli (e.g., faces, Sesame Street) compared with achromatic patterns. The authors also found larger changes in the interbeat interval (IBI; or HR deceleration) when infants were watching dynamic compared to still video presentations. The IBI has an inverse association with HR, such that the lengthening of IBI corresponds to HR deceleration and the shortening of IBI corresponds to HR acceleration.

The effects of the intrinsic properties of visual stimuli on infants' engagement and sustained attention have been recently replicated in an infant ERP experiment (Stets et al., 2013). Stets and colleagues examined whether increasing the variety of the stimuli presented in the experiment would facilitate infants' visual fixation and engagement. A paradigm with increased stimulus variety resulted in an attrition rate of 22.2% (Stets et al., 2013), which was much lower than the average attrition rate (~50%) in infant EEG and ERP studies (see Stets et al., 2012, for review). The authors argued that the increased stimulus complexity led to extended periods of sustained attention in comparison to the typical procedures used in infant EEG and ERP studies, which in turn improved the data quality and reduced the possibility for early termination of a study due to infants' fussiness.

The relation between the properties of visual presentation and infant sustained attention suggests the potential effect of presentation rate on infant performance in an ERP experiment. Presentation rate of stimuli is positively related to information load and stimulus complexity during a given period of presentation. A slow presentation rate (e.g., using a long ISI between event presentations) may not provide sufficient information to start and maintain infant sustained attention. During visual information processing, infants go through multiple attention phases. At the onset of stimulus presentation, there is a period called *stimulus orienting* that is hypothesized to be an initial evaluation of stimulus properties and lasts for 2 to 5 s (Reynolds & Richards, 2008). Additional processing resources are recruited to stimulus presentation based on the novelty and complexity of the presented information (Reynolds & Richards, 2008). If the stimulus is simple or has been fully processed, attention wanes, which results in a fixation toward another location. Alternatively, if the information is sufficiently novel, or dynamic and complex, the stimulus-orienting phase is followed by sustained attention. Sustained attention begins 4 to 5 s following the stimulus onset and lasts from 2 s to about 20 s depending on the intrinsic properties of the stimuli presented (Courage et al., 2006; Richards & Casey, 1992). A typical presentation paradigm used in infant ERP studies consists of a 500-ms stimulus presentation followed by an ISI of 1,000–2,500 ms (e.g., Courchesne et al., 1981; de Haan & Nelson, 1999; Reynolds & Richards, 2005; Richards, 2003). This typical ISI allows only one or two presentations during the period of stimulus orienting, and may not be optimal for further stimulus processing and initiating the sustained attention phase. At the end of a period of sustained attention, the infant disengages from the stimulus presentation, and the probability increases of being distracted from the fixated location by a stimulus in another location. Enhanced stimulus novelty or presentation complexity may result in sufficient information flow to extend the period of sustained attention. Shortening the ISI during stimulus presentations would increase the amount of information that infants are being exposed to, eliciting sustained attention, increasing stimulus complexity, which then facilitates infant sustained attention and engagement in the experiment, and extending the period of sustained attention.

Increasing the presentation rate by shortening the ISI would also increase the signal-to-noise ratio in the EEG/ERP data by obtaining more artifact-free trials. The minimum requirement of artifact-free trials in infant ERP research varies from 5 to 10 trials per condition (DeBoer, Scott, & Nelson, 2007; Stets & Reid, 2011; Stets et al., 2012). Although the minimum requirement for artifact-free trials is much less strict in infant compared with adult ERP research (cf. Luck, 2014), it still leads to a high attrition rate (~50%), especially when there are multiple experimental conditions (DeBoer et al., 2007; Stets et al., 2012). If the presentation rate were designed to maximally elicit and maintain sustained attention, then fixation toward the stimulus events would last longer and be less likely to be discontinued and more likely to enhance processing at the "target" location. Thus, greater number of visual fixated trials would be obtained by using shorter ISIs for stimulus presentation, which in turn would increase the signal-to-noise ratio in the ERP data and reduce the attrition rate.

The primary goal of this study was to examine the effects of ISI duration on behavioral and physiological indices of infant sustained attention in an ERP experiment. Specifically, this goal was to examine the effects of shortening the ISI for presentation on infants' fixation to presentation, HR-defined attention, and ERP components, with the goal of eliciting better fixation and attention patterns than with the typical presentation rate. We used a 500-ms stimulus presentation that was accompanied by an ISI duration typically used in ERP research (1,500–2,000 ms), or with two shorter ISIs (400–600 ms and 600–1,000 ms). The Nc ERP component is a large negative deflection in the ERP in frontal-central regions of the scalp that occurs between 350–750 ms following stimulus onset. The duration of the presentation sequence for the short ISI (500-ms stimulus, 400–600 ms) was chosen so that it would cover the time window for the Nc component. However, it is possible that the Nc components elicited by two consecutive stimuli might slightly overlap with one another when the short ISI is used. Utilizing this short ISI might also provide insufficient time for processing the visual stimuli in young infants, so an ISI of medium duration was also chosen (600–1,000 ms), which was also shorter than the typical ISI. We tested infants at 3, 4.5, and 6 months of age to cover a key period for the development of infant sustained attention and information processing (Colombo, 2001, 2002; Richards, 2008). We hypothesized that the shorter ISIs would increase the frequency of visual fixation, decrease the frequency of disengagement, increase the amount of IBI change during sustained attention, and extend the duration for sustained attention. Given an overall increase in attentiveness and the relation between attention and the amplitude of the Nc ERP component, we also expected that using the short and medium ISIs would elicit greater Nc amplitude than using the long ISI.

A second goal in the current study was to examine whether the facilitation effect of shortening the ISI duration on infant sustained attention would benefit infant face-sensitive ERPs. The relation between infant sustained attention and ERP indices of infant face processing has been recently addressed in Guy et al. (in press). The authors found that the amplitudes of two infant face-sensitive ERP components, the N290 and P400, were larger during HR-defined sustained attention than inattention. More importantly, the N290 amplitude was found to be greater to faces than toys during sustained attention, but this effect was not shown during inattention. In the current study, we tried to replicate the relation found between infant sustained attention and infant and face-sensitive ERPs. We used three types of stimuli, including female faces, infant faces, and objects to test the second goal. One rationale for choosing these three types of stimuli was to elicit different face-sensitive ERPs (the N290, P400) responses (e.g., de Haan & Nelson, 1999; Guy et al., in press; Peykarjou & Hoehl, 2013). In addition, using multiple types of stimuli allowed us to examine whether the effects of ISI are due to the improvement of infant attentional state without being limited to a specific stimulus category. The hypothesis regarding the second goal was that using the short and medium ISIs that are expected to enhance sustained attention would lead to greater amplitude of the N290 and P400 responses.

Method

Participants

Thirty-six infants were tested at 3 (*M* = 105 days, *SD* = 7.85, 3 female [F]/9 male [M]), 4.5 (*M* = 143 days, *SD* = 8.4, 8 F/4 M), or 6 (*M* = 194 days, *SD* = 9.47, 6 F/6 M) months of age, which means that 12 infants each were tested at these three ages. All infants were full term (at least 38 weeks gestation, birth weight at least 2,500 g), and healthy at birth with no known developmental anomalies. An additional 10 infants were tested but excluded from final analyses and reports. In particular, six infants' data were excluded due to fussiness/distractibility before 5 min data collection; one infant's data were excluded due to equipment failure (i.e., no video was recorded); and three infants' data were excluded due to excessive artifacts (e.g., eye or body movements and noise) in their EEG data.

Apparatus and Stimuli

A 29-in. color video monitor (Hanns.G HG281D) was used to present the stimuli. The center of the monitor was located approximately 55 cm away from the infant's eyes. The display was set to 1,280 horizontal and 1,024 vertical pixels. A video camera located above the monitor was used to record the infant's face. The recording from this camera was shown on a TV screen in an adjacent room for the experimenter to monitor the infant. E-Prime 2.0 (Psychology Software Tools, Inc.) software residing on a Dell Precision 690 PC was used for controlling stimulus presentations.

Three types of visual stimuli were included in the ERP presentations. These included pictures of female faces taken from the NimStim set (Tottenham et al., 2009), infant faces obtained from the Internet, and small toylike objects selected from the object images used in Guy et al. (in press). There were 12 images for each stimulus category. The visual stimuli were presented with a 17° visual angle in the center of the screen.

Moving videos of Sesame Street characters were used as dynamic attractors. The Sesame Street characters were taken from the movie, "Sesame Street's 25th Birthday: A Musical Celebration!" The videos were edited to retain segments with only a single character from dancing scenes and contained just the character with dynamic movements (Guy et al., in press). The characters were presented in a $2° \times 3°$ area in the center of the screen.

The visual stimuli and attractors were presented over a background image that covered the entire screen. There were five background images including scenes of the sky, greenery, pool water, ocean, and sand (Guy et al., in press). The background images had the most visual clarity in the center of the screen, and gradually were blurred from the center of the screen to the edge. The background images were used to improve infants' engagement (Mallin & Richards, 2012), and the change in visual clarity was designed to keep the infant fixated toward the center of the screen when the presentation stimulus was absent (Guy et al., in press).

Procedure

A block of stimulus presentations began with a Sesame Street attractor at the center of the screen overlaid on a background image. An experimenter judged if the infant was looking toward the attractor, and the computer program initiated a sequence of brief image presentations. If the infant looked away from the visual presentation, a Sesame Street attractor was presented and lasted until the infant looked back to the center of the screen. The brief stimulus presentations then resumed. Each experimental block lasted for 55 s. A 5-s black screen was presented between experimental blocks. The experiment continued as long as the infant was not fussy in order to obtain as many trials as possible. The entire experiment lasted for about 9 to 12 min.

The brief stimulus presentations consisted of a stimulus presentation for 500 ms followed by an ISI. The ISI duration for any stimulus presentation was randomly selected within the minimum and maximum range for an ISI type. The three types of stimuli (female faces, infant faces, toys) were presented randomly with equal probability in an experimental block. Figure 1 shows an example of one experimental block with three images randomly selected from the infant faces, female faces, and toys.

One of the three types of ISIs (400–600 ms, 600–1,000 ms, 1,500–2,000 ms) was chosen at the beginning of an experimental block and used for the brief stimulus presentations during the entire block. When there were equal numbers of trial presented for any of the three ISI types, the type of ISI was chosen randomly. Otherwise, the ISI type with the fewest number of presentations was chosen. The semirandom selection of ISI types was designed to obtain close numbers of stimulus presentations for each ISI duration over the entire course of the experiment. The total number of trials presented with the short ISI (*M* = 91.81, 95% CI [84.26, 99.34]) was very close to the number for the medium ISI (*M* = 88.31, 95% CI

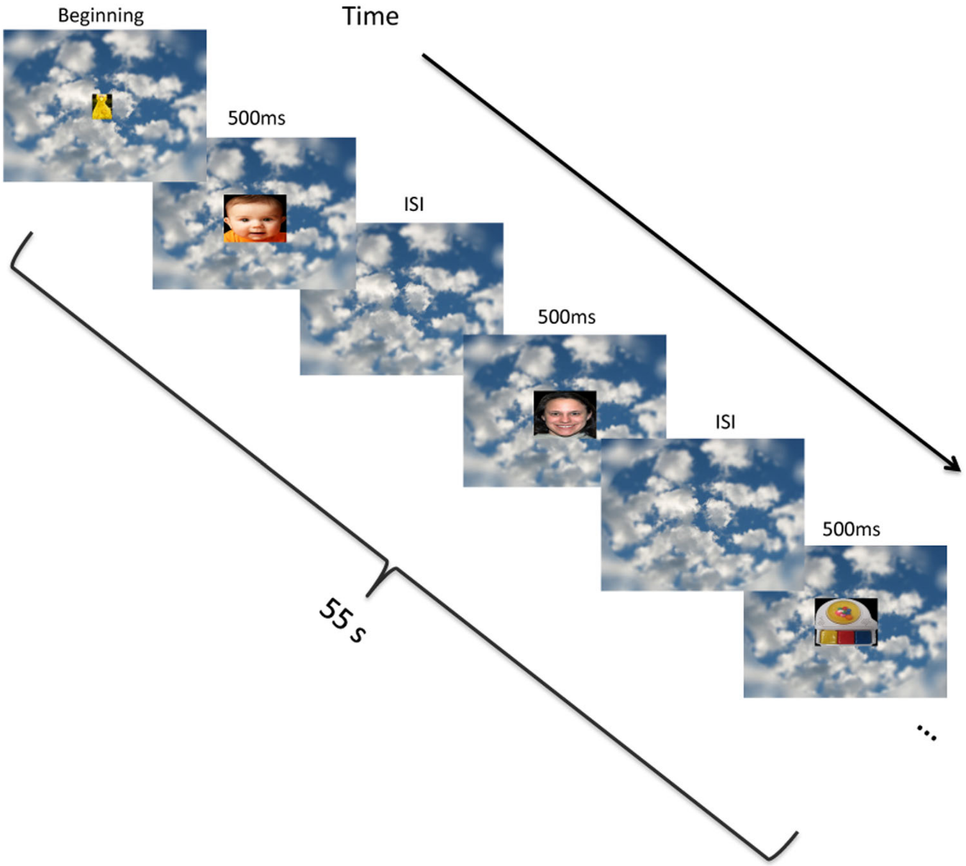

Figure 1. Example for the design of experimental blocks that each lasts for 55 s. Each experimental block started with a Sesame Street character that was used as an attractor. The infant face, female face, and toy shown in this figure were randomly selected from the three sets of images used in the current study. The background (water) shown in this figure was one of five background images used in the study. One ISI type (short, medium, or long) was consistently used in one experimental block.

[81.26, 95.35]), and both were slightly higher than that for the long ISI (*M* = 81.75, 95% CI [75.02, 88.48]).

Judgment and Quantification of Visual Fixation

Infants' fixation on the stimulus presentation was judged offline based on review of the video recording. A single observer who was blind to the ISI condition determined whether the infant was fixating on the brief stimulus presentation for its entire duration (500 ms) without an eye movement. If this criterion was not met, the trial was excluded from further analyses. The offline judgment of visual fixation was completed for each trial in the experiment.

The average number of fixated trials, ratio of fixated trials to total number of brief stimulus presentations, and number of attractors used in each ISI block were calculated after the judgment of infants' fixations. These variables were utilized as the behavioral measures of infant engagement and attention and compared among the three ISI blocks.

Measurement and Quantification of HR

Attention phases were determined from the changes in HR that occurred during viewing of the stimulus presentations. Two Ag-AgCl electrodes were placed on the infant's chest with disposable electrode collars for the recording of the ECG. The Electrical Geodesics Incorporated (EGI, Eugene, OR) system was used to amplify and digitize the ECG recording. The R-R intervals refer to the latency between the R waves of two heartbeats. These were identified offline for the ECG data and used to compute the IBIs. The IBI has an inverse association with HR, such that the lengthening of IBI corresponds to HR deceleration and the shortening of IBI corresponds to HR acceleration. The phase of stimulus orienting was defined as the time period before the significant HR deceleration occurred during infants' looking. The phase of sustained attention was defined as the time when there was a significant deceleration of HR below the prestimulus level and the HR remained at the lowered level during infants' looking. The criterion for a significant HR deceleration was five successive beats with IBIs longer than the median of the five preceding beats. The phase of attention termination was defined as an acceleration of HR that brought the HR back to the prestimulus level during infants' looking. The criterion for HR acceleration was five successive beats with IBIs shorter than the median of the five preceding beats. Details about using ECG data to define attention phases in a continuous presentation paradigm have been described elsewhere (e.g., Mallin & Richards, 2012; Pempek et al., 2010).

The mean amount of IBI change during the three attention phases was calculated for each block, and overall for the experiment. The proportion of time spent in each attention phase was calculated as the ratio of the overall duration of that phase to the overall looking time for each ISI block. The amount of IBI change and the proportion of duration for each ISI type were utilized as HR (physiological) measures of infant sustained attention.

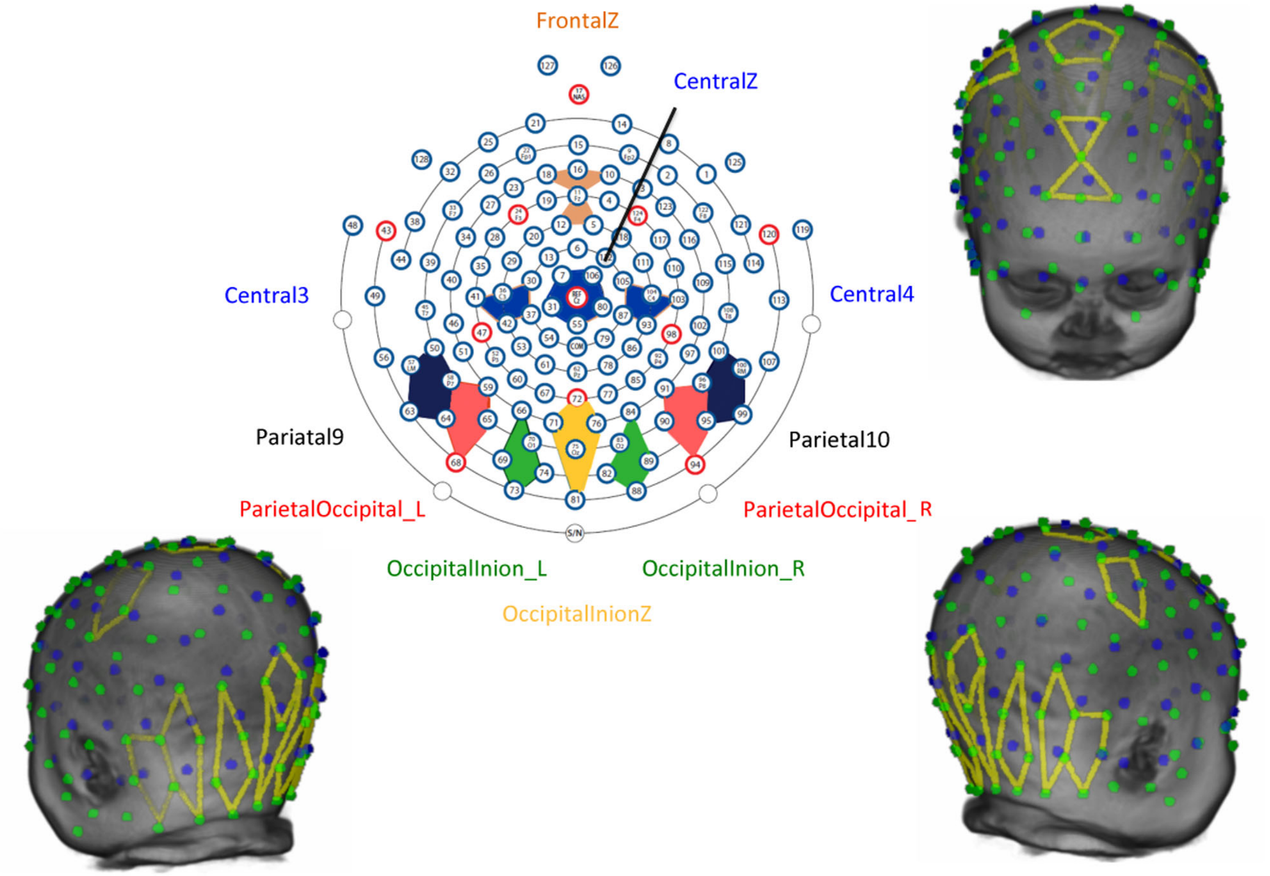

Figure 2. Bird's eye view and 3D view of the electrode clusters created with HGSN electrodes. The 2D map shows the locations and the names of the 11 electrode clusters, as well as the HGSM clusters used to create the electrode clusters. The 3D (MRI) images were displayed on a 3-month average MRI template. The green dots stand for HGSN electrodes on the scalp and the blue dots represent the 10-10 positions. Yellow lines connected the HGSN electrodes used to create the 11 electrode clusters.

EEG Recording, Segmenting, and Channel Manipulation

The EGI system was used to amplify and digitize the EEG recording. A high-density 128-channel HydroCel Geodesic Sensor Net (HGSN) produced by EGI was used for EEG recording. The size of the HGSN was chosen based on the infant's head circumference. EEG was measured from 124 channels in the electrode net and two Ag-AgCl electrodes that were used to measure electrooculogram (EOG). The EEG signal was referenced to the vertex, recorded with 20 K amplification at a 250 Hz sampling rate with band-pass filters set from 0.1–100 Hz and 100 kΩ impedance. The vertex-referenced EEG was algebraically recomputed to an average reference.

The EEG recordings were inspected for eye movements and artifacts, and if these occurred, individual channels within trials were eliminated from the analyses or substituted with adjacent channels when the number of bad channels was fewer than 12. Eye movements were defined on the basis of the difference between the two EOG channels ($\Delta\text{EOG} > 40\ \mu\text{V}$ within 40 ms). The EEG recordings were inspected for artifacts ($\Delta\text{EEG} > 200\ \mu\text{V}$ or $\Delta\text{EEG} > 100\ \mu\text{V}$ within 40 ms). If there were fewer than 12 channels that were missing or had bad data, a linear interpolation was conducted using the five closest channels. At least seven artifact-free trials in an experiment cell (3 ISI Types × 3 Stimulus Types) were required for a participant's data to be included in the further analyses. This minimum number of artifact-free trials per condition is slightly lower than the usual criterion (e.g., ~10; DeBoer et al., 2007) used in infant ERP research, but may be acceptable given clean trials, number of conditions in this study, and our quantification procedure (cf. Stets & Reid, 2011). The segmenting of the EEG was done based on target onset. The segments were from 100 ms before target onset through 900 ms following target onset. EEG segments were averaged for ERP analyses on the basis of the nine experimental conditions. The EEG and ERP data processing procedure was completed using the EEGLAB and ERPLAB toolboxes (Delorme & Makeig, 2004; Lopez-Calderon & Luck, 2014) within MATLAB (MATLAB R2014a, The Mathworks, Inc.).

The HGSN electrodes were combined into 11 electrode clusters that cover most of the scalp regions used in the examination of the N290, P400, and Nc components. The 11 clusters were created based on examination of studies analyzing infant face-sensitive ERPs (e.g., de Haan Pascalis, & Johnson, 2002; de Haan & Nelson, 1997, 1999; Guy et al., in press; Halit, Csibra, Volein, & Johnson, 2004; Halit, de Haan, & Johnson, 2003; Leppänen, Moulson, Vogel-Farley, & Nelson, 2007; Luyster, Powell, Tager-Flusberg, & Nelson, 2014; Cassia, Kuefner, Westerlund, & Nelson, 2006; Peykarjou, Westerlund, Cassia, Kuefner, & Nelson, 2013; Scott & Nelson, 2006) and attention-related ERPs (e.g., Goldman et al., 2004; Guy et al., in press; Richards, 2003; Reynolds et al., 2010; Reynolds & Richards, 2005). Figure 2 shows the locations of these clusters via a 2D HGSN map and a 3-month-old average MRI head image. The 11 clusters were named based on the 10-10 electrode

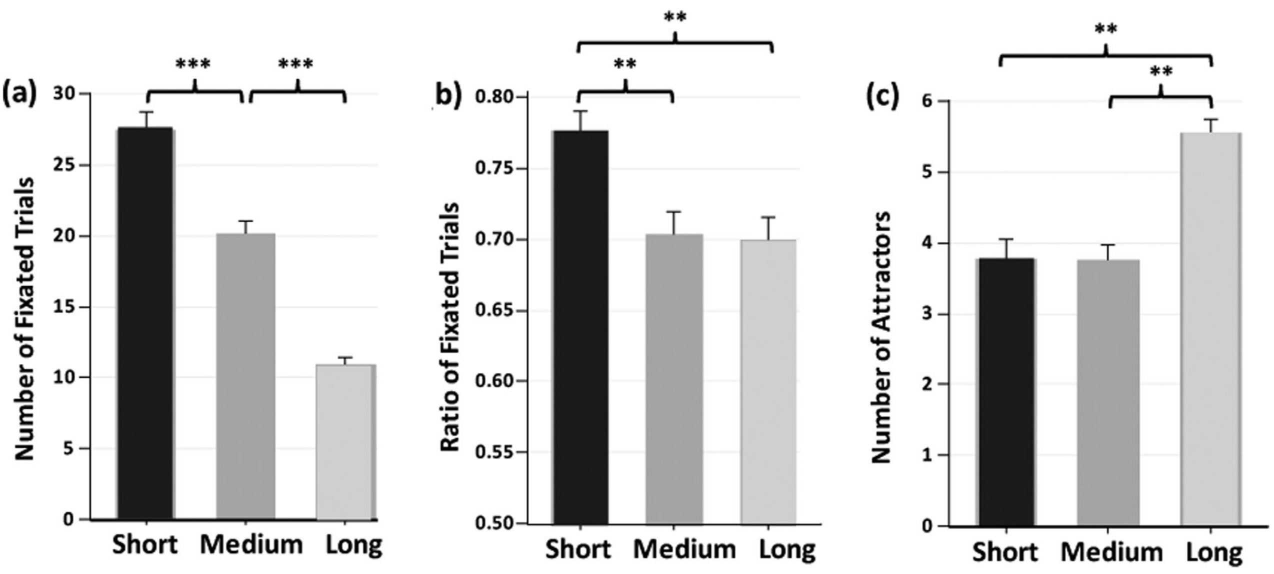

Figure 3. Illustration of the average fixated trials obtained (A), average ratio of fixated trials relative to total number of trials presented (B), and average number of attracter used, i.e., frequency of looking away (C) in one experimental block, separately for the three ISI blocks. $^{**}p < .01$; $^{***}p < .001$.

positions (Jurcak, Tsuzuki, & Dan, 2007) surrounded by the cluster of HGSN electrodes. Each of the clusters, "FrontalZ," "CentralZ," "Central3," "Central4," "Parietal9," "Parietal10,"covered one 10-10 position. The "ParietalOccipital_L" and "ParietalOccipital_R" clusters covered more than one 10-10 position in the lateral parietal occipital regions (PO7, PO9, and PO8, PO10, respectively), while the "OccipitalInion_L," "OccipitalInionZ," and "OccipitalInion_R" each covers more than one 10-10 position in the occipital inion regions (O1, I1, and O2, I2, and Oz, Iz, respectively).

Design for Statistical Analysis

The design for statistical analysis included the ISI type (3 levels: 400–600 ms, 600–1,000 ms, 1,500–2,000 ms), stimulus type (3 levels: female face, infant face, toy), and channel location (4 levels: ParietalOccipital_L, Parietal9, ParietalOccipital_R, Parietal10 for the N290; 3 levels: OccipitalInion_L, OccipitalInionZ, OccipitalInion_R for the P400; 4 levels: FrontalZ, Central3, CentralZ, Central4 for the Nc) as within-subject factors, and age (3 levels: 3, 4.5, 6 months) as a between-subjects factor. Analyses of the behavioral measurements tested the fixated trials, the ratio of fixated trials to total presented trials, and the number of video attractors used in one experiment block as dependent variables. Analyses of the HR measurements tested the amplitude of IBI change and the proportion of time spent in the attention phases as dependent variables. The N290 was examined from 200–400 ms after stimulus onset, the P400 was analyzed from 350–650 ms after stimulus onset, and the Nc was analyzed from 350–750 ms after stimulus onset. Peak-to-trough differences between the N290 peak and the preceding positive peak were calculated in order to control for the potential effect of slow waves (Guy et al., in press; Kuefner, de Heering, Jacques, Palmero-Soler, & Rossion, 2010; Peykajou et al., 2013). Mean amplitude was measured for the P400 and the Nc components. Mixed-design analyses of variance (ANOVAs) were conducted with a general linear models approach, which was performed using the Proc GLM of SAS (version 9.4) software (SAS Institute Inc., Cary, NC). Separate mixed-design analyses were performed for the different dependent variables. All statistical tests were conducted on a .05 level of significance (two-tailed). Simple effects following significant interactions and post hoc tests following main effects were Bonferroni corrected.

Results

Behavioral Results

The number of fixated trials and the ratio of this number to the total presentations in an experimental block (55 s) were analyzed to examine the effects of ISI type on infant focused attention and engagement in an ERP experiment. We conducted two ISI Type (short, medium, long) × Age (3, 4.5, 6) mixed-design ANOVAs. Stimulus type was not included in this analysis because the semi-random presentation paradigm resulted in a very close number of visually fixated trials for the three types of stimuli in each experimental block. There was a main effect of the ISI type on fixated trials, $F(2,66) = 118.67$, $p < .001$. A post hoc test showed that using the short ISI resulted in greater number of fixated trials than using the medium ISI, which resulted in greater number of fixated trials than using the long ISI, $ps < .001$ (Figure 3A). The analysis for the ratio of fixated trials to the total presentations in a block also revealed an effect of the ISI type, $F(2,66) = 10.68$, $p < .001$. In particular, the ratio of visual fixations to the total presented trials in an experimental block was significantly higher when using the short compared to the medium and long ISIs, $ps < .01$ (Figure 3B). No main effect or interaction involving age were found in these two analyses.

Frequency of looking away from the presentation in an experimental block was analyzed to determine whether shorter ISIs would benefit infants' fixation to the presentation. A mixed-design ANOVA was conducted to analyze the frequency of looking away as a function of ISI type and age. There was a main effect of the ISI type, $F\ (2,66) = 32.21$, $p < .0001$. A post hoc test showed that the frequency of disengagement in the blocks using the long ISI was higher than those using the short and medium ISIs, $ps < .01$ (Figure 3C). No main effect or interaction involving age were found in this analysis.

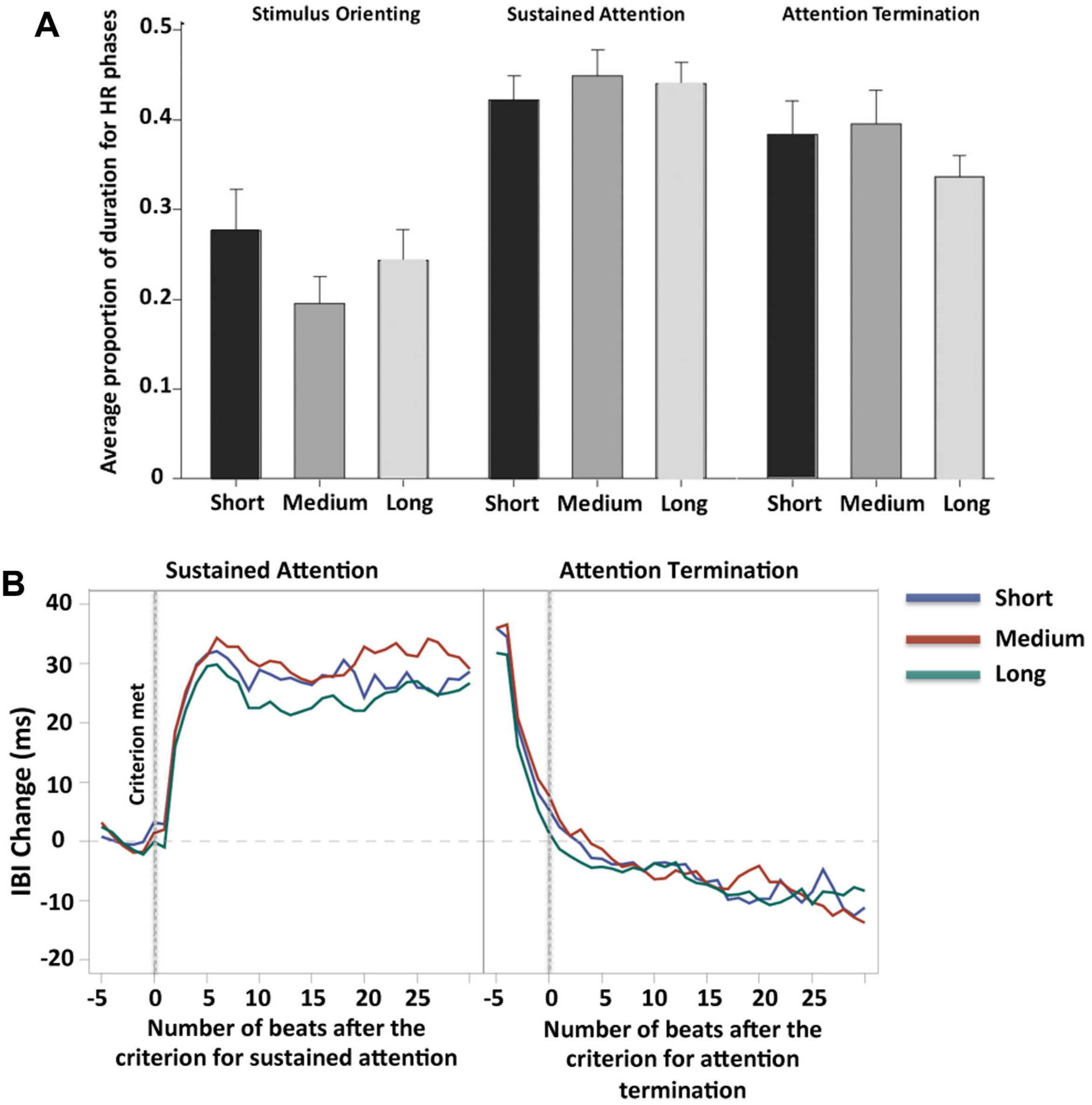

Figure 4. A: Average proportion of the time spent in the three HR-defined attention phases (stimulus orienting, sustained attention, attention termination), compared between the short (black), medium (dark gray), and long (light gray) ISIs. Error bars represent standard errors of means. B: Average amount of IBI changes (ms) during sustained attention (left panel) and attention termination (right panel), compared between the short (blue), medium (red), and long (green) ISIs. The IBI change shown in the *y* axis has an inverse association with HR. Thus, the HR deceleration in sustained attention is shown by the lengthening of IBI values, and the return of HR to prestimulus level in attention termination is shown by the shortening of IBI values. The *x* axis shows the number of beats (−5 to 30) following the criterion of HR deceleration or acceleration is met. Thirty beats in infancy from 3 to 6 months lasts about 12s.

HR Results

One analysis was conducted to examine the effect of the ISI type on the duration of HR-defined sustained attention while infants were looking at the presentation. The overall duration of sustained attention was divided by the overall looking time to obtain the proportion of attention, separately for the three ISI types. Since the sum of the proportion of time spent in all attention phases equals one, we only analyzed the proportion of time spent in the phase of sustained attention. The proportion of the duration spent in sustained attention was analyzed with an ISI Type (3) × Age (3) mixed-design ANOVA. There were no statistically significant main effects or interactions involving ISI type. Figure 4A shows the proportion of time spent in the three attention phases across the three ISI types. The three attention phases include stimulus orienting (looking period before HR deceleration), sustained attention (HR deceleration), and attention termination (HR acceleration). It can be seen in Figure 4A that the proportion of time spent in sustained attention did not differ across the three ISI types or the other two attention phases.

A second analysis was conducted to test whether the ISI type affected the amplitude of IBI change during sustained attention (HR deceleration) and attention termination (HR acceleration). The mean IBI change during the two attention phases was analyzed with two ISI Type (3) × Age (3) mixed-design ANOVAs. The analysis of the mean IBI change during sustained attention resulted in a significant effect of the ISI type, $F(2,66) = 10.69$, $p < .001$. A post hoc test showed that the short and medium ISIs resulted in greater IBI changes during sustained attention than the long ISI, $ps < .01$. The

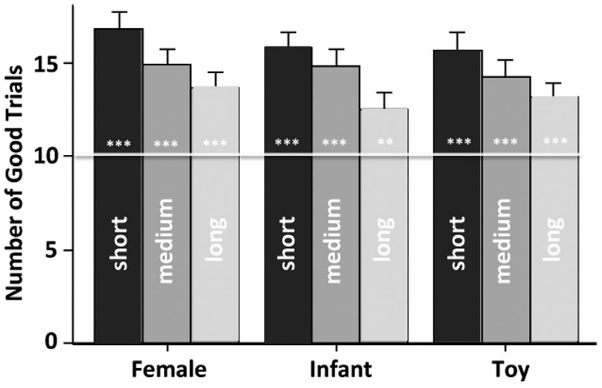

Figure 5. Number of artifact-free (good) trials obtained for the nine experimental conditions (3 Stimulus Types × 3 ISI Types). Error bars represent standard errors. The number of good trials obtained for each experimental condition was significantly higher than 10 (white horizontal line). **$p < .01$; ***$p < .001$.

interaction of ISI type and age was not significant. The analysis of the mean IBI change during attention termination revealed no effect of the ISI type or age. Figure 4B illustrates the average IBI changes for sustained attention (left panel) and attention termination (right panel) separately for the three ISI types, with the x axis showing the number of heart beats from the last precriterion beat through 30 beats after the onset of the deceleration or acceleration. The duration of 30 beats is approximately 12 s, which covers the majority (78.32%) of attention periods for sustained attention and attention termination (cf. Mallin & Richards, 2012). Employing the short and medium ISIs elicited greater IBI changes than the long ISI during sustained attention (i.e., HR deceleration; Figure 4B).

ERPs Results

The average number of clean trials that infants contributed to the final ERP average after artifact detection was 131.44, 95% CI [118.63, 144.26]. One mixed-design ANOVA was performed to test the number of clean trials that infants contributed to the final ERP average as a function of ISI type (3) and age (3). There was a significant effect of the ISI type, $F(2,66) = 10.57$, $p < .001$. A post hoc test showed that the number of trials obtained with the short ISI ($M = 48.19$, 95% CI [43.07, 53.32]) was significantly larger than the number of trials obtained with the long ISI ($M = 39.30$, 95% CI [34.74, 43.87]). Neither of them was significantly different than the average number of trials obtained with the medium ISI ($M = 43.94$, 95% CI [39.22, 48.67]). Figure 5 depicts the distribution of the artifact-free trials in the nine experimental conditions (3 ISI Types × 3 Stimulus Types). It can be seen in Figure 5 that the average number of clean trials in each condition was higher than 10. Individual t tests verified this information, $p\text{s} < .01$ (Figure 5). Figure 5 also shows that the number of clean trials obtained from the short ISI was slightly greater than the number of trials obtained from the long ISI. This difference was due to the more frequent eye movements that occurred in the experimental blocks using the long ISI, as well as slightly fewer trials presented with the long ISI. Similar numbers of trials were obtained for the three stimulus types (female faces, infant faces, and toys; Figure 5).

Figure 6 shows the overall ERP responses at the 11 electrode clusters averaged across the three age groups separately for the short, medium, and long ISI conditions. The N290 occurs at about 300 ms following the stimulus onset. It can be seen in Figure 6 that the N290 is evident in both lateral and medial posterior regions. However, the N290 response in the three medial posterior channels (Occipital-Inion1, Occipital-InionZ, Occipital-Inion2) was affected by or mixed with the N1 component that was most prominent in these regions (Richards, 2005; Xie & Richards, 2016). In contrast, the N290 component in the four lateral electrode clusters (Parietal9, Parietal10, Parietal-Occipital7–9, Parietal-Occipital8–10) was not influenced by the N1 component and appeared to have clearer peaks (cf. Guy et al., in press). The P400 is the positive peak following the N290, and it was most prominent in the medial posterior regions (Figure 6). The Nc is evident as a negative deflection that occurred in the time window of 350–750 ms following the stimulus onset. The Nc was most prominent in the four frontal and central electrode clusters (Figure 6).

The N290 amplitude was analyzed to determine the effect of the ISI type on an ERP correlate of infant face processing. One mixed-design ANOVA was performed to test the peak-to-trough difference of the N290 as a function of ISI type (3), stimulus type (3), age (3), and channel locations (4: Parietal9, ParietalOccipital_L, Parietal10, ParietalOccipial_R). Analysis of the N290 peak amplitude revealed no effects or interactions involving ISI type. Results included significant main effects of the stimulus type, $F(2,66) = 10.71$, $p < .0001$; age, $F(2,33) = 5.83$, $p = .0068$; channel location, $F(3,99) = 4.80$, $p = .0036$, and an interaction between stimulus type and age, $F(4,66) = 3.11$, $p = .0208$. Simple effects tests following the interaction showed that the stimulus type only impacted the N290 response in 6-month-olds, $F(2,66) = 14.83$, $p < .0001$. Post hoc tests for the main effect of the stimulus type showed that the N290 peak amplitude to female faces was larger than that to infant faces, $p < .05$, which in turn was larger than that to toys, $p < .05$. Post hoc tests for the main effect of age showed that the N290 amplitude increased with age. Post hoc tests for the main effect of channel location showed that the N290 peak amplitude in right electrode clusters (Parietal10, PO8–PO10) was larger than that in left electrode clusters (Parietal9, PO7–PO9), $p\text{s} < .05$. Figure 7 depicts the N290, P400, and Nc responses in the 11 electrode clusters averaged across the ISI types, separately for the three stimulus types. It can be seen that the N290 amplitude elicited by female faces was larger than that elicited by infant faces, which was in turn larger than that elicited by toys, especially in the right lateral electrode clusters (ParietalOccipital_R and Parietal10). Figure 7 also shows the right hemisphere asymmetry in that the N290 responses in the right lateral electrode clusters were larger than those in the left lateral electrode clusters.

The P400 amplitude was analyzed to determine the effect of ISI on a second face-sensitive ERP component. A mixed-design ANOVA was performed to test the mean amplitude of the P400 as a function of ISI type (3), stimulus type (3), age (3), and channel locations (3 levels: OccipitalInion_L, OccipitalInionZ, OccipitalInion_R). Analysis of the P400 mean amplitude revealed a main effect of the ISI type, $F(2,66) = 10.54$, $p < .0001$. Post hoc tests showed that the P400 amplitude for the medium ISI was larger than that for the short and long ISIs, $p\text{s} < .05$. Age was found to influence the amplitude of the P400 component, $F(2,33) = 4.01$, $p = .0276$. Post hoc tests showed that the P400 amplitude increased with age. Figure 8 shows the P400 responses in the three medial posterior electrode clusters as a function of the ISI type for the three age groups. The P400 amplitude was larger for the medium ISI compared with the short and long ISIs (cf. Figure 6), and the P400 amplitudes develop with age.

The mean amplitude of the Nc was analyzed to determine the effects of the ISI type on infant attention-related brain activity. The

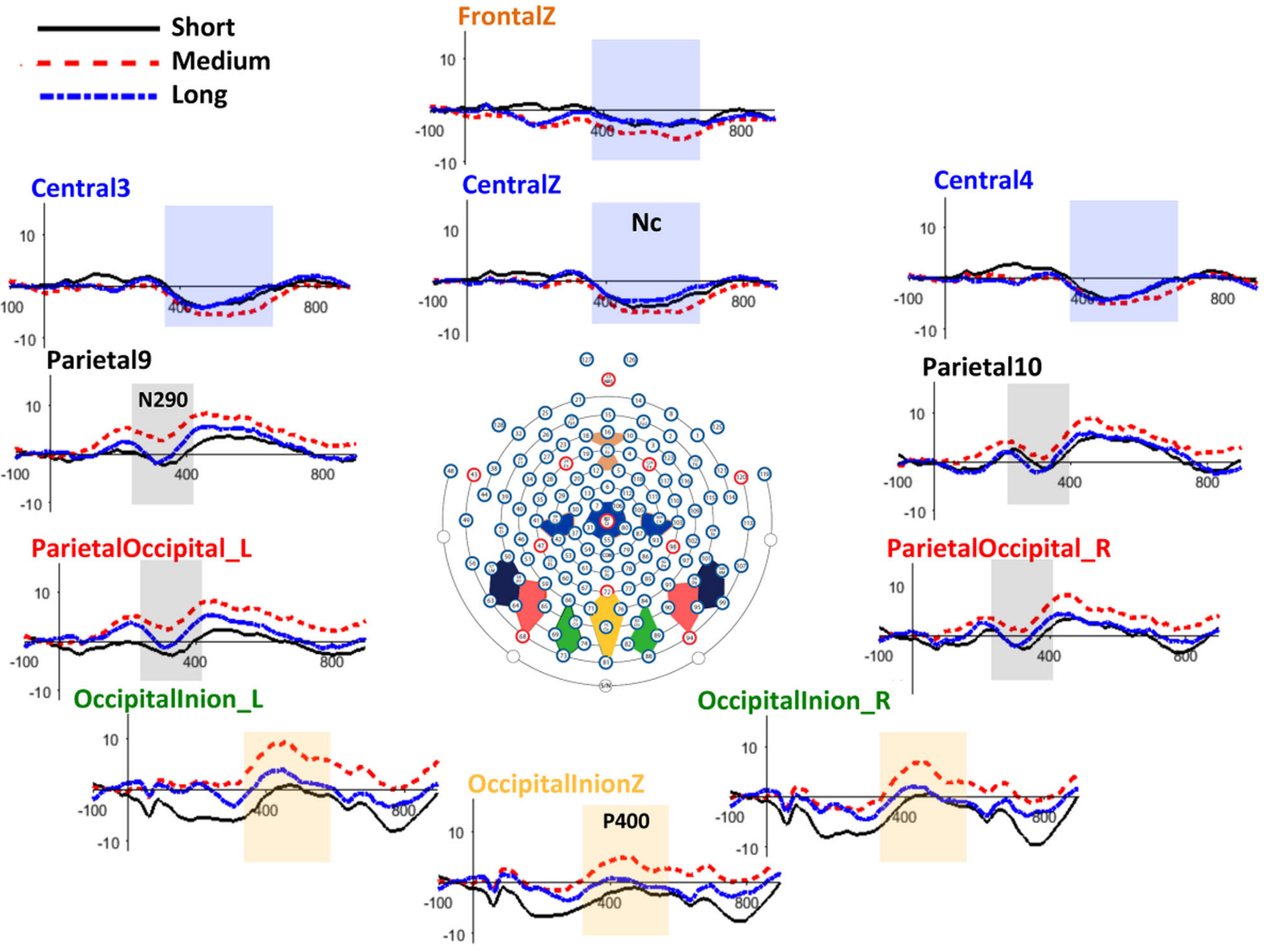

Figure 6. The N290, P400, and Nc responses for the short (black), medium (red), and long (blue) ISIs in the 11 electrode clusters. The 2D map in the middle of the figure shows the locations of the 11 electrode clusters and the HGSM clusters used to create the electrode clusters. Each ERP figure consists of the name of the virtual channel and the ERP responses (from −100 to 900 ms following target onset) in that virtual channel. The relative locations of ERP figures and the colors of the channel names are consistent with the relative locations and the colors of the electrode clusters shown in the 2D electrodes map.

Nc mean amplitude was analyzed with an ISI Type (3) × Stimulus Type (3) × Channel Location (4: Frontalz, Centralz, Central3, Central4) × Age (3) mixed-design ANOVA. Results included main effects of the ISI type, $F(2,66) = 4.04$, $p = .022$; stimulus type, $F(2,66) = 4.23$, $p = .018$; and age, $F(2,33) = 7.37$, $p = .0023$. No interactions were found among these factors. Post hoc tests for the effect of the ISI type showed that the Nc amplitude for the medium ISI was greater than that for the long and short ISIs, $ps < .05$. No difference was found between the Nc amplitude for the short and long ISIs. Post hoc tests for the stimulus type main effect showed that Nc responses to female faces were larger than to infant faces and toys, $ps < .05$. Post hoc tests for the age effect showed that the Nc amplitude increased with age, $ps < .05$. Figure 9 illustrates the average Nc responses in the four frontocentral electrode clusters separately for the three ISI conditions and the three ages. The medium ISI evoked the largest Nc component, whose amplitude increased with age.

Discussion

The present study investigated the effect of ISI duration on infant engagement and sustained attention in an ERP study. Our primary goal was to examine the effect of the ISI type on the behavioral, HR, and ERP indices of infant engagement and attention. We hypothesized that using the short (400–600 ms) and medium (600–1,000 ms) ISIs would facilitate infant fixation, enhance the amount of IBI change in sustained attention and extend the duration of sustained attention, and lead to greater Nc amplitude compared to using the long (1,500–2,000 ms) ISI. Our results lent support to most of these hypotheses. Infants had more visual fixations to the presentation and reduced frequency of looking away from the presentation when using the short and medium ISIs compared to using the long ISI. The amount of the IBI change during sustained attention was larger when using the short and medium ISIs than using the long ISI. The effect of the ISI type on infant sustained attention was reflected in the ERP data as well. The medium ISI evoked a greater amplitude Nc component than the short and long ISIs. Given the important role that sustained attention plays in infant cognitive processes including face processing (e.g., Guy et al., in press), our second goal was to determine whether ISI duration would affect infant face-sensitive ERPs. We found larger P400 amplitude for the medium ISI than the short and long ISIs, but no effect of ISI on the N290 component. The N290, P400, and Nc ERP components that were examined in the current study showed an increase in their amplitude from 3 to 6 months of age.

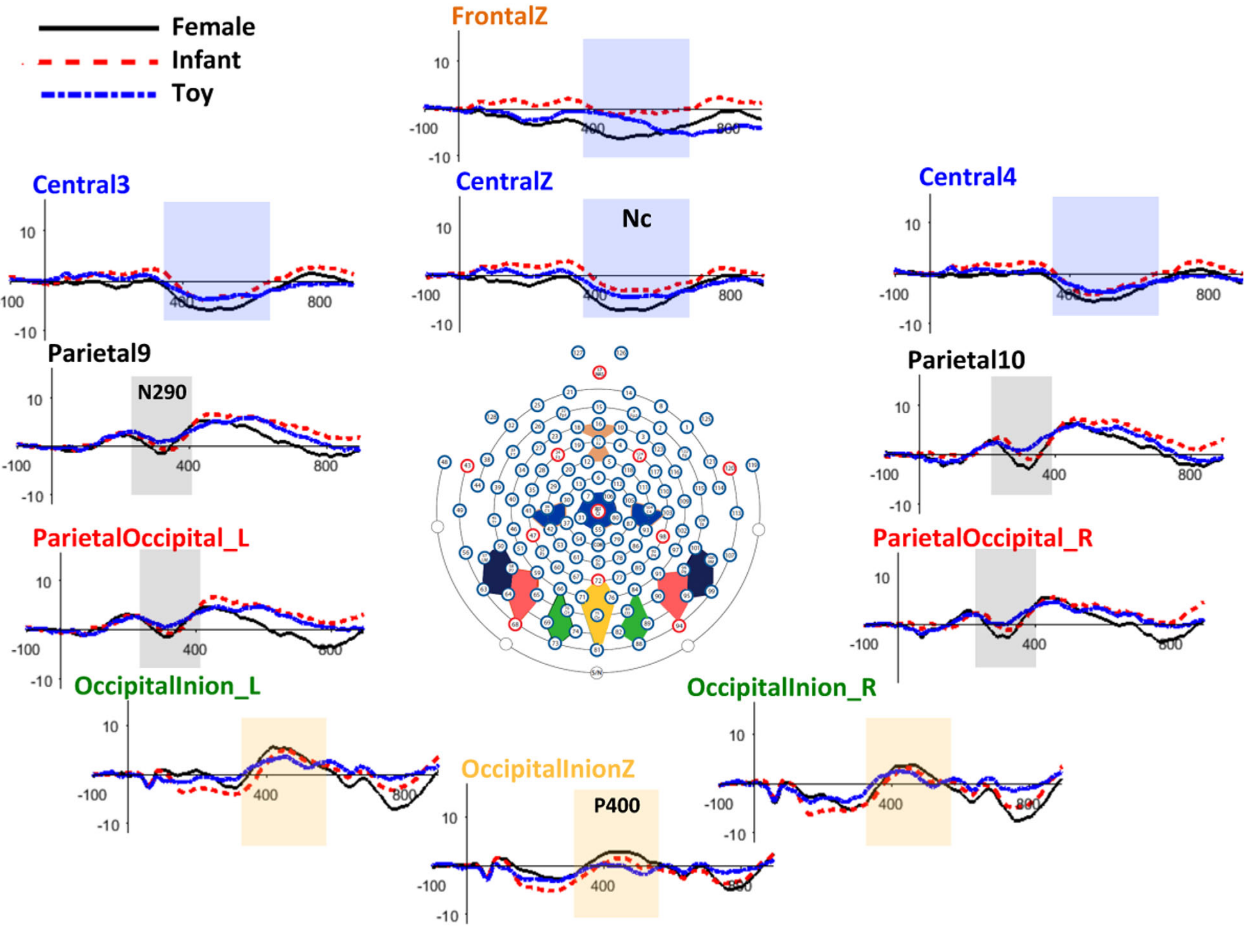

Figure 7. The N290, P400, and Nc responses for the female faces (black), infant faces (red), and toys (blue) in the 11 electrode clusters. The 2D map in the middle of the figure shows the locations of the 11 electrode clusters and the HGSM clusters used to create the electrode clusters. Each ERP figure consists of the name of the virtual channel and the ERP responses (from −100 to 900 ms following target onset) in that virtual channel. The relative locations of ERP figures and the colors of the channel names are consistent with the relative locations and the colors of the electrode clusters shown in the 2D electrodes map.

Effects of ISI on Infant Engagement and Attention

Behavioral measures of infant attention supported our hypothesis that shorter (short and medium) ISIs would improve infant engagement in an ERP experiment. The facilitative effects of shorter ISIs on infant engagement were shown through the higher ratio of visually fixated trials and the lower frequency of disengagement in the experimental blocks with the short and the medium ISIs. These findings suggest that infants show more continuous looking and are more likely to look at the screen when shorter ISIs are used than the conventional ISI. These facilitation effects of the short and medium ISIs are comparable with previous research that reported improved engagement in presentation paradigms that provided more complex and interesting visual presentations (Courage et al., 2006; Stets et al., 2013). Infant visual fixation measured in the current study has been regarded as a behavioral index of infant sustained attention (e.g., Lansink & Richards, 1997; Oakes & Tellinghuisen, 1994; Ruff, 1986). Previous studies have shown that infants were far less distractible during sustained attention in both experimental (e.g., Pérez-Edgar et al., 2010; Richards & Hunter, 1997; Richards & Turner, 2001) and naturalistic settings (Oakes & Tellinghuisen, 1994; Tellinghuisen & Oakes, 1997). Our behavioral measurements of sustained attention and engagement show that using an optimal ISI benefits infant sustained attention and improves infants' engagement in an ERP experiment.

Analysis of the average amount of IBI change provides converging evidence for the facilitation effect of shortening the ISI duration on infant attention. Our finding of increased IBI change (i.e., greater HR deceleration) during sustained attention when using the short and medium ISIs establishes a connection between behavioral measures of visual fixation and physiological measures of HR (Mallin & Richards, 2012; see Colombo, 2001; Reynolds & Richards, 2008, for reviews). The facilitative effect of shorter ISIs on infant HR-defined sustained attention is consistent with Courage and colleagues' finding that infants showed greater IBI change during sustained attention when watching dynamic visual presentations (e.g., Sesame Street) compared with static visual stimuli (e.g., pictures of faces and toys). Taken together, the findings from Courage et al. (2006) and the present study suggest the important effect of stimulus properties and style of presentation on infant sustained attention. The pattern of HR changes during attention termination did not differ across the short, medium, and long ISI durations, which provides further evidence for the central role that sustained attention plays in infants' continuing fixation to the presentation stimuli.

Our hypothesis that shorter ISIs would result in longer periods of sustained attention was not supported, as results showed that duration of sustained attention did not vary across the ISI types. Courage et al. (2006) found that infants spent a larger proportion of time in sustained attention when Sesame Street materials or

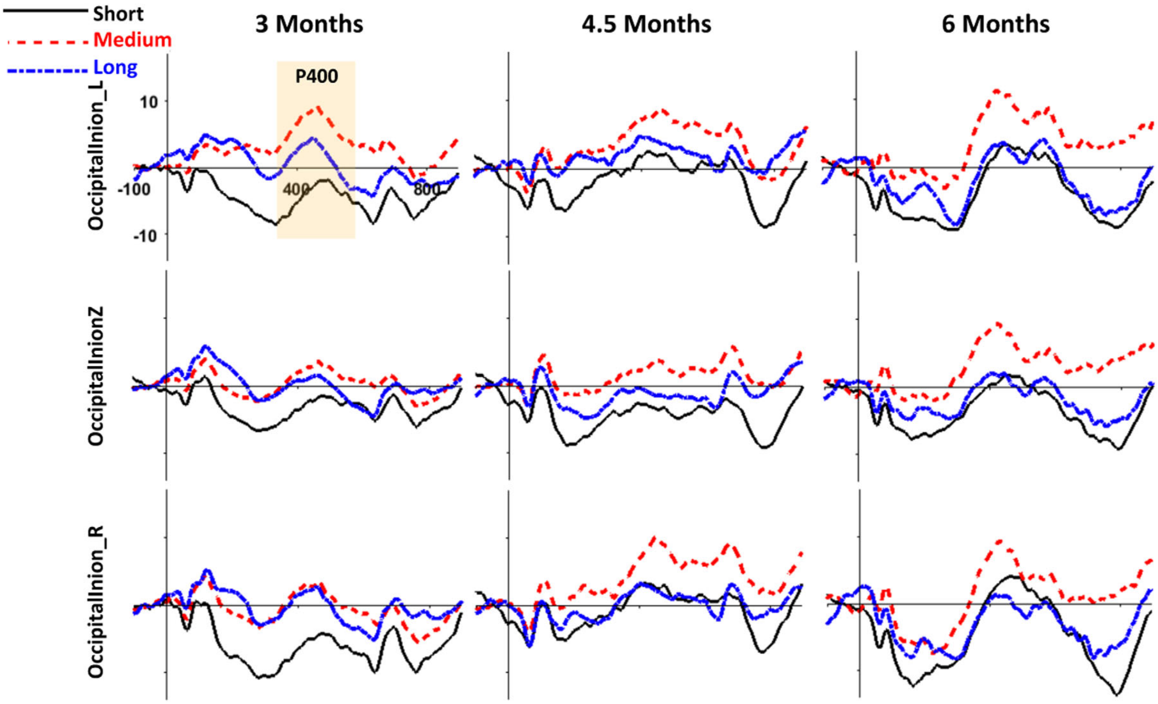

Figure 8. ERP responses for the short (black), medium (red), and long (blue) ISIs in the three electrode clusters (OccipitalInion_L, OccipitalInionZ, OccipitalInion_R) that were used for the P400 analyses, separately for the three age groups. The ERPs are shown from 100 ms preceding stimulus onset through 900 ms following stimulus onset averaged over the three stimulus types

pictures of faces were presented compared with achromatic geometric stimuli. We failed to find extended duration of sustained attention or different patterns of attention phases when using the shorter ISIs (Figure 4A). The absence of the ISI effect might be due to the more frequent usage of attractors due to higher rates of disengagement in the experimental blocks with the long ISI. We utilized dynamic Sesame Street characters to attract infants' attention back to the presentation and to preserve the quality of our ERP data. The more frequently used visual attractors for the long ISI condition (Figure 3C) might attenuate the effect of the ISI type on the duration of infant sustained attention.

The Nc ERP results suggest the effect of shortening the ISI duration on infants' brain responses to visual presentations. The medium ISI elicited larger Nc responses to visual stimuli than the short and the long ISIs regardless of the stimulus type. Previous research has shown that the Nc component serves as an index of attention allocation and brain arousal, where greater arousal elicits larger Nc responses (Reynolds & Richards, 2005; Richards, 2003). The current finding that the Nc amplitude is modulated by ISI duration indicates that using an optimal ISI for presentation optimizes infants' attention allocation and increases brain arousal. We did not find increased Nc amplitude in the shortest ISI condition. This may be because infants at these ages (3 to 6 months) cannot sufficiently process information presented at such a fast rate (e.g., with the 400–600 ms ISI). Infant information processing relies on the development of infant sustained attention (Colombo, 2001, 2002; Reynolds & Richards, 2008; Richards & Gibson, 1997). Information processing and sustained attention appear to show intertwined rapid changes across the first year of life (Colombo, 2001, 2002; Richards & Casey, 1992). Less-developed information processing capabilities at 3 to 6 months of age might lead to the contrary effect of using the short ISI on the Nc component. Future research may investigate whether using the shortest ISI would enhance the Nc response in older infants who have more developed abilities in attention allocation and information processing.

The finding of the substantial increases in the amplitude of the Nc component from 3 to 6 months is consistent with previous research that has examined the development of the Nc component at various ages (e.g., Luyster et al., 2014; Reynolds et al., 2010; Richards, 2003; Webb et al., 2005). In the current study, we found that the Nc amplitude increased (i.e., became more negative) significantly from 3 to 6 months (Figure 6). These results are comparable to those of Webb, Long, & Nelson (2005), which included a linear increase of the Nc amplitude longitudinally from 4 to 12 months. Our current findings, together with the previous research, suggest a rapid development of infant sustained attention and its neural correlates in the first few months of life.

Effects of ISI on Face-Sensitive ERPs

Our finding of greater P400 amplitude for the medium ISI than the short and long ISIs suggests the relation between infant sustained attention and face perception. Employing the medium ISI elicited the greatest P400 amplitude, regardless of the stimulus type. It is plausible that increased arousal during sustained attention enhances face processing in 3- to 6-month-old infants. This finding was partially consistent with the report by Guy et al. (in press) that sustained attention has an impact on 4.5- to 7.5-month-old infants' N290 and P400 responses. In that study, both the N290 and P400 responses were found to be larger during sustained attention than inattention. The N290 amplitude was greater to faces than toys during sustained attention, but this N290 effect was not shown during inattention. The P400 amplitude was significantly greater to toys than faces during sustained attention. The present study, together with Guy et al. (in press), indicate that the increased brain arousal

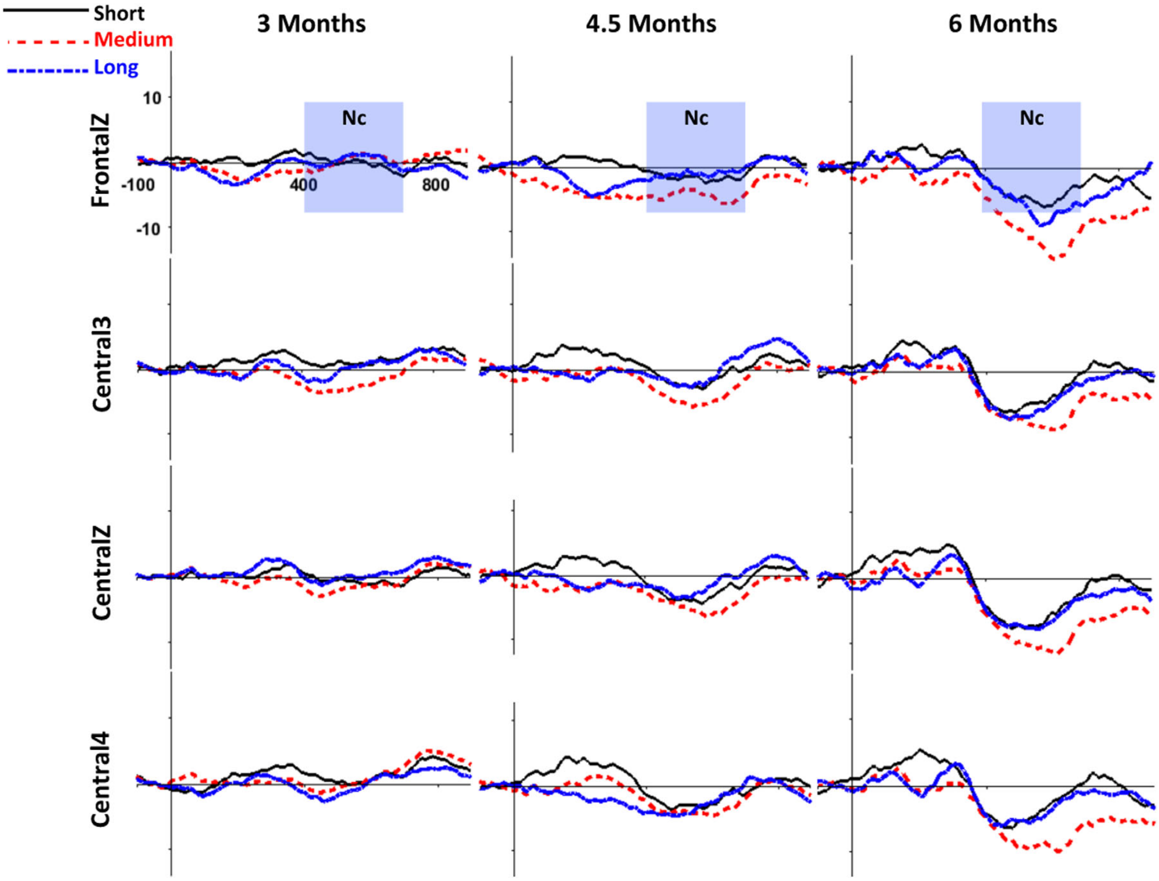

Figure 9. ERP responses for the short (black), medium (red), and long (blue) ISIs in the four electrode clusters (FrontalZ, Central3, CentralZ, Central4) that were used for the Nc analyses, separately for the three age groups. The ERPs are shown from 100 ms preceding stimulus onset through 900 ms following stimulus onset averaged over the three stimulus types.

during sustained attention may facilitate face processing at these young ages, before it becomes a more automatic process.

An alternative explanation for the greatest P400 response when using the medium ISI is that sustained attention enhances infants' visual processing in general, given that there was no interaction between the ISI type and the stimulus type on the P400 response. This explanation is in line with previous research that has reported the effects of sustained attention on infants' visual processing of target stimuli (Hunter & Richards, 2003; Mallin & Richards, 2012; Richards, 2004; Xie & Richards, 2016). In these studies, infants' reaction time and their ERP responses to the visual targets were improved during sustained attention. Thus, the facilitation effect of sustained attention on infants' visual processing may lead to the elevated P400 response when using the medium ISI that has been observed to benefit sustained attention.

The face-sensitive N290 and P400 ERP components developed dramatically from 3 to 6 months of age. The greater N290 response to faces versus objects found in the current study is consistent with most of the previous literature on the N290 component in infants' face perception (e.g., de Haan & Nelson, 1999; de Haan et al., 2002; Guy et al., in press). We found that differences in N290 amplitude to faces compared with objects were more prominent at 6 months than 3 and 4.5 months of age. We also found that the amplitude of the N290 and P400 increased substantially with age (Figure 8), which is comparable with the existing literature (e.g., Guy et al., in press; Luyster et al., 2014). These two findings suggest that rapid changes occur in the neural mechanisms underlying infants' face perception between 3 and 6 months of age.

The P400 component may represent different neural mechanisms than the N290 component. Although there was an N290 effect in infants' face processing, no difference in the P400 component was found between the responses to faces and toys in the current study. The absence of the P400 effect is consistent with previous studies that either found no P400 effect or only P400 latency effect in response to human faces versus nonhuman faces (e.g., Cassia et al., 2006; Guy et al., in press; Halit et al., 2003, 2004; Parise, Handl, & Striano, 2010; Peykarjou & Hoehl, 2013). In contrast, some other studies have reported greater P400 response to human faces versus nonhuman faces (e.g., de Haan & Nelson, 1997; de Haan et al., 2002). The inconsistency between the P400 findings may be due to the difference in the experimental design between these studies and the large individual variability at these ages. However, an alternative explanation is that infant P400 plays a different role than the N290 in infants' face processing, with the possibility that the P400 indexes infant attention similar to the Nc. The ERP averages in the posterior P400 regions appear to show a distinct peak at 400–450 ms that is not clearly shown in the fronto-central Nc regions (Figure 6–9; also see Guy et al., in press). The positive potential of the P400 then continues through the period of the Nc (Figure 6–9; also see Luyster et al., 2014). The length of ISI was found to have similar effects on the P400 and Nc responses in the current study. It is possible that there is early P400 activity that is independent of the neural activation for the Nc, but that much of the activity in the P400 region is merely the positive expression of the generators of the Nc (Guy et al., in press). The roles that the N290, P400, and Nc components play in infant face perception and attention allocation deserves future attention and thorough investigations using cortical source analysis techniques, which is out of the scope of the current research.

Application of the ISIs Examined in the Current Study

Increasing infant engagement and visual fixation during stimulus presentation allows for maximizing the acquisition of artifact-free trials for the ERPs analyses. The mean number of usable trials obtained for each of the nine conditions was significantly greater than 10, and the average total number of artifact-free trials was 131.44 (Figure 5). The average duration of the current experiment was around 10 min, which was within the typical time range of an infant EEG or ERP experiment. The large number of clean trials obtained in this study most likely resulted from increased infant attention and engagement when using the short and medium ISIs for presentation. This explanation is supported by the recent finding from Stets et al. (2013). The authors also found that significantly more numbers of artifact-free trials were obtained from 1-year-old infants by increasing the variability and complexity of the visual presentation. Because infant engagement and attention were improved in the current study, the attrition rate was reduced to a much lower level (21.74%) compared to the average attrition rate (~ 50%) in infant EEG and ERP studies (Stets et al., 2012).

The ISIs tested in the current study should be applicable to infant visual ERP experiments with various types of stimuli. Three types of prevalent visual stimuli (female faces, infant faces, and objects) were utilized in the current study to determine whether the effects of ISIs on infant ERPs would differ with stimulus type. No interaction effects were found between ISI type and stimulus type for any ERP component. Thus, the effect of the medium ISI on infant ERP responses should be attributed to improved attention allocation and general arousal and not restricted to the presentation of a certain type of stimulus. We expect that the facilitation effect of the medium ISI would also be found with other types of stimuli used in infant ERP research, such as geometric patterns, animal faces, scrambled faces, inverted stimuli, and even noise.

The interaction between infant sustained attention and information processing indicates that the optimal ISI duration for an infant ERP experiment might change with age. Our behavioral and HR measures indicate that using both short and medium ISIs facilitate infant sustained attention. However, the short ISI (400–600 ms) might not provide sufficient time for infants younger than 6 months to fully process the visual stimuli. Consequently, the Nc amplitude was not differentiated between the short and the long ISIs. This ERP finding suggests that overload of information presented with the short ISI might have a negative effect on information processing at these early ages. The medium ISI (600–1,000 ms) not only facilitated infant engagement and sustained attention but also provided an appropriate duration for information processing at these ages. Future infant ERP research with subjects around 6 months should consider utilizing an ISI similar to the medium ISI tested in this study to obtain higher quality EEG and ERP data. We expect that there should be an improvement of the adaptation to a very short ISI with age, along with the dramatic development of the efficiency of information processing during infancy.

One limitation in the current study is that the short and medium ISIs tested here may not be applicable to studies aimed at examining slower ERP components lasting for 1 to 2 s following stimulus onset. Some ERP components with slow wave frequency changes occur between 1s and 2 s following stimulus onset (Courchesne et al., 1981). These slow waves have been argued to reflect infant novelty detection and recognition memory (e.g., de Haan & Nelson, 1997, 1999; Reynolds & Richards, 2005). The short and medium ISIs tested in the current study may not provide a sufficient duration to cover the entire period of the slow waves. One caveat is that these slow waves may overlap with the early evoked (i.e., time- and phase-locked to the stimulus) ERP components. However, the jitter in slow waves across epochs is small compared to the time scale of the signal and should be consistent across different experimental conditions. Thus, the overlapping issue should not show an impact on hypothesized comparisons between conditions. Some adjustment of the high-pass filter may eliminate the potential effects of the overlapping components, but any change in the filtering process needs to be made cautiously. Our current findings suggest that increasing the information load and stimulus complexity by shortening the ISI facilitates infant engagement and sustained attention in general. Therefore, future research on infant slow waves may still modify their ISIs to reach a compromise between the benefit of improving infant attention and the practicability in examining the slow waves.

Conclusion

The present study tested the effects of ISI duration on infant engagement and attention in an ERP experiment. We compared the typical presentation rate often used in ERP studies of a 500-ms stimulus presentation followed by a 1,500–2,000 ms ISI, with two shorter ISIs (400–600 ms and 600–1,000 ms). We found that using the shorter ISIs resulted in more visually fixated trials and reduced the frequency of disengagement per experimental block. We also found larger HR changes during sustained attention for the two shortest ISIs, and larger Nc and P400 ERP component amplitude for the medium ISI. The two face-sensitive ERP components were differentially affected by the ISI manipulations. The earlier N290 was relatively unaffected, but the P400 was largest for the medium ISI. This difference suggests that the neural mechanisms underlying the N290 and P400 components play different roles in infant face processing and attention allocation (cf. Guy et al., in press). In conclusion, this study shows that increasing the presentation rate by shortening the ISI increases the amount, complexity, and novelty of visual information presented in a fixed period of time, which in turn enhances infant engagement and attention in an ERP study.

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