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The Effect of Unique Labels on Face Perception in Infancy

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THE EFFECT OF UNIQUE LABELS ON FACE PERCEPTION IN INFANCY

A Dissertation Presented

by

HILLARY R. HADLEY

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ABSTRACT

THE EFFECT OF UNIQUE LABELS ON FACE PERCEPTION IN INFANCY

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Faces are universally important for a variety of reasons, ranging from identifying individuals to conveying social information. During the first year of life, infants' experience with commonly encountered face groups shapes how infants perceive familiar and unfamiliar faces. Between 6 and 9 months of age, infants become worse at differentiating among individual faces from unfamiliar face groups (e.g., other-species faces), a process known as "perceptual narrowing". Labeling faces from a previously unfamiliar face group has been found to promote individual-level differentiation, as well as expert neural processing for the face group. However, it is currently unclear what influences individual-level labels have on face perception at the neural level during the label learning process. The current study investigated effects of individual labels on neural responses to a previously unfamiliar face group by providing in-lab training experience and recording two types of neural responses – event-related potentials and steady state visual evoked potentials – during and immediately after label-face learning. Results indicate that 6- and 9-month-old infants use labels to learn about unfamiliar faces in different ways, such that labels impact face processing earlier in the learning period and across more stages of processing in older versus younger infants. Additionally, at 9 months, infants still differentiate among exemplars within an unfamiliar face group, and brief individuating experience localizes processing over face-related brain regions. The results of this study contribute to our understanding of what infants gain from a single labeling experience and how neural responses related to face processing change with learning and across the first year of life.

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CHAPTER 1

INTRODUCTION

Faces are arguably one of the most important stimuli infants gain experience with during the first year of life. They not only provide important social information such as referential attention (Farroni, Johnson, & Csibra, 2004; Maier, Glage, Hohlfeld, & Abdel Rahman, 2014; Striano, Reid, & Hoehl, 2006) and emotional cues (for review, see Leppänen & Nelson, 2006), but also scaffold learning in a variety of domains (e.g., speech perception and production, Lewkowicz & Hansen-Tift, 2012). As infants gain experience with certain face groups it shapes how infants perceive and respond to faces. The period between 6 and 9 months of age has been found to be particularly important in shaping face processing via experience. During this time, infants decline in their ability to discriminate individual faces within unfamiliar or infrequently encountered groups, a process known as “perceptual narrowing” (Kelly et al., 2007; Kelly et al., 2009; Pascalis, de Haan, & Nelson, 2002). Perceptual narrowing was originally reported for non-native speech contrasts (Werker & Tees, 1984), and recently has been suggested as a shared process for all forms of social communication (Pascalis et al., 2014). Although perceptual narrowing is a replicable and robust effect, the processes and mechanisms underlying perceptual narrowing are still unknown (for review, see Flom, 2014; Hadley, Rost, Fava, & Scott, 2014; Maurer & Werker, 2014; Pascalis et al., 2014). It is not only important to understand what types of experiences impact infants’ visual learning and development, but also the way in which experience changes visual perception (e.g., what brain regions are recruited, “online” influences of experiences). One prominent type of experience that has been found to influence perception of unfamiliar face groups is verbal labeling, or labeling faces with unique, individual labels. In a longitudinal training study, 6-month-old infants received 3 months of experience hearing individual labels paired with monkey faces in the context of a picture book (Scott & Monesson, 2009, 2010). After three months of individual-labeling experience, 9-month-olds maintained their ability to discriminate individual faces (Pascalis et al., 2005; Scott & Monesson, 2009) and also exhibited expert-like neural processing, indicating a powerful role of labeling (Scott & Monesson, 2010). In contrast, an equal amount of perceptual experience with a general category label or simple exposure (no label) to the faces did not result in behavioral or neural changes at 9 months of age (Scott & Monesson, 2009, 2010). However it is currently unclear what mechanisms underlie the beneficial role of unique labels and whether labels function differently across stages of development.

The current study investigated three currently unanswered questions. First, do the brain responses that support learning during a face-label association task differ at the beginning versus the end of perceptual narrowing? Second, does labeling enhance infants' immediate ability to differentiate individual faces as indexed by neural discrimination, and if so, do these effects vary by age? Finally, are the effects of perceptual narrowing measured at the neural level parallel to behavioral findings that show a decline in the ability to differentiate unfamiliar faces? To answer these questions, 6- and 9-month-old infants completed a brief, in-lab training session. Infants were presented with faces from an unfamiliar face group paired with unique individual-level labels or a non-speech noise. We examined neural responses to novel exemplars from the trained face group before and after training to assess how labeling impacts face perception and differentiation at the neural level. In addition, we examined neural differences during the label-learning task in order to determine if any age related processing differences exist.

The Development of Face Processing Biases

People are extraordinarily good at recognizing faces, however, this expertise is often diminished for faces of another species or race. These biases towards faces of the same species and race begin to develop over the first year of life, as infants learn from the faces present in their environment. While newborns do not show a visual preference for own- over other-race faces, by 3 months, infants exhibit a spontaneous preference for own-race faces (Kelly et al., 2005). Between 6 and 9 months of age, infants' visual perceptual systems tune to environmentally relevant categories, a process known as "perceptual narrowing" or "perceptual tuning." Perceptual narrowing refers to a relative decline in the ability to differentiate among faces within other races and species, while perceptual tuning references experience-dependent improvements in processing of own race and species face groups (for review, see Maurer & Werker, 2014). For example, from 6 to 9 months of age, infants move from equally discriminating faces of multiple races and species to failing to discriminate faces of other-races and species, as indexed by a behavioral visual discrimination task. At 9 months of age infants continue to easily differentiate human (Pascalis et al., 2002) and own-race (Kelly et al., 2007) faces, an effect present across cultures (Kelly et al., 2009). However, it is important to note that perceptual narrowing/tuning is dependent on experiences infants have with various face groups. For example, African infants who live in a predominantly Caucasian environment show no preference for African versus Caucasian faces at 3 months of age (Bar-Haim, Ziv, Lamy, & Hodes, 2006).

To complement the strong behavioral literature showing perceptual narrowing/tuning for face groups across the first year of life (Kelly et al., 2009; Kelly et al., 2007; Kelly et al., 2005;

Pascalis et al., 2002), a handful of studies have examined neural correlates of perceptual narrowing/tuning in infancy using event-related potentials (ERPs). In particular, studies have examined two face-sensitive perceptual ERP components, the N290 and the P400 (for review, see de Haan, Johnson, & Halit, 2003). Between 3 and 12 months of age, infants exhibit increased neural specificity to upright human faces (de Haan, Pascalis, & Johnson, 2002; Halit, de Haan, & Johnson, 2003). Twelve-month-old infants, but not 3- (Halit et al., 2003) or 6-month-old infants (de Haan et al., 2002) exhibit differential N290 amplitude responses for upright versus inverted human faces. Additionally, 12-month-olds do not exhibit differential N290 amplitudes for monkey faces (Halit et al., 2003). This pattern of response, known as a neural "inversion effect," is considered a marker for expert perceptual processing and typically occurs (in adults) for human faces or objects of expertise (Rossion & Curran, 2010). As such, the presence of a neural inversion effect at 12 but not 3 months of age demonstrates perceptual tuning to frequently experienced face groups. In addition, there is also neural evidence to support perceptual narrowing for unfamiliar face groups. For example, 9-month-olds exhibit a larger N290 (B. Balas, Westerlund, Hung, & Nelson, 2011) and larger P400 (Vogel, Monesson, & Scott, 2012) amplitude responses for own- versus other-race faces, whereas 5-month-olds do not show differential responses for own- and other-race faces (Vogel et al., 2012). These results indicate that after perceptual narrowing has occurred, infants process familiar and unfamiliar face groups differently at the neural level as well as the behavioral level, and may show enhanced responses to more familiar face groups.

Although a decline in face discrimination for unfamiliar face groups is the behavioral hallmark of perceptual narrowing (Kelly et al., 2009; Kelly et al., 2007; Pascalis et al., 2002), only one study to date has examined neural discrimination of faces within familiar versus unfamiliar face groups. Scott, Shannon, and Nelson (2006) examined neural discrimination of own- and other-species faces post-narrowing at 9 months of age by using a modified infant-controlled habituation task. After habituating to a single human or monkey faces, infants viewed the familiar face as well as a novel face, in frontal and profile orientations. The authors reported a marginally significant enhancement in discrimination for human faces (i.e., larger differential N290 amplitude response to familiar versus unfamiliar human faces) relative to monkey faces. In addition, infants exhibited differential P400 amplitude responses to familiar versus unfamiliar human faces, as well as differential P400 amplitude responses across different orientations of human faces (but not monkey faces). This pattern of response supports perceptual tuning for own-species faces such that by 9 months of age, infants have more specific neural processing of own-species faces.

Interestingly, Scott and colleagues (2006) also found that 9-month-olds exhibited larger N290 amplitude responses to familiar monkey faces and larger P400 amplitude responses to unfamiliar monkey faces, a finding that is in contrast to results from previous behavioral investigations (e.g., Pascalis et al., 2002; Pascalis et al., 2005). It is possible this finding is task-dependent, as infants were habituated to monkey faces before ERP responses were recorded. Recent work has shown that given enough exposure time even 12-month-old infants can behaviorally differentiate monkey faces (Fair, Flom, Jones, & Martin, 2012). Therefore, it is currently unclear whether individual-level discrimination of unfamiliar face groups is present in neural responses following the typical trajectory of perceptual narrowing or whether face-related neural responses continue to be sensitive to less familiar face identities, even when behavioral responses become less sensitive. Therefore one goal of the current study was to further investigate individual-level discrimination and the neural mechanisms that modulate discrimination of faces before and after the period of perceptual narrowing.

The Impact of Individual-level Label Learning of Face Processing

Experience with faces has, in some cases, been shown to attenuate perceptual narrowing. For example, studies giving infants experience with an unfamiliar face group (monkey faces) find that learning to match individual names (e.g., “Boris”, “Fiona”) with different monkey faces leads to a maintenance in ability to behaviorally differentiate untrained monkey faces at 9 months of age (Pascalis et al., 2005; Scott & Monesson, 2009). Scott and Monesson (2009) gave 6-month-old infants training books with pictures of monkey faces labeled at the individual level, the general category level (“monkey”), or that were not labeled, and parents were instructed to look at/read the book with their infant across a 3-month span. Following training, 9-month-olds trained with the individual-level labels successfully differentiated monkey faces. However, when all monkey faces were labeled with a general category label or when the faces were not labeled, 9-month-olds failed to discriminate monkey faces, showing the typical pattern of narrowing (Scott & Monesson, 2009). The ineffectiveness of a general category label in maintaining discrimination ability for a face group suggests that only specific types of experience (i.e., individual-level naming) influence the perceptual narrowing/tuning trajectory. Neural effects of book training experience were also explored using ERPs (Scott & Monesson, 2010). Infants given experience with monkey faces paired with individual labels exhibited an ERP inversion effect between the N290 and P400 components for monkey faces, while infants who received category-level or exposure book experience did not exhibit an inversion effect (Scott & Monesson, 2010). Together with behavioral findings, these results suggest that 3 months of individual-level experience with a previously unfamiliar face group results in more expert-like processing of faces within that group, both behaviorally and neurally.

Similar behavioral results have been found after 3 months of book training with other-race faces as well (Heron-Delaney et al., 2011). When Caucasian 6-month-olds received book training with other-race (Chinese) faces, matched with individual names, they successfully discriminated novel Chinese faces at 9 months of age, and also demonstrated recognition of the trained faces across different orientations. Although this study did not directly compare the use of individual versus category labels in the books (only individual names were used), the results compliment the previous studies that controlled for label type (Scott & Monesson, 2009, 2010) and lend support to the hypothesis that individual-level labels play an important role in shaping perceptual narrowing between 6 and 9 months of age.

To summarize, although infants typically decline in their ability to discriminate faces within unfamiliar groups (i.e., other-species, other-race), experience individuating faces within an unfamiliar group results in maintenance of discrimination abilities (Heron-Delaney et al., 2011; Pascalis et al., 2005; Scott & Monesson, 2009) and enhanced neural processing (Scott & Monesson, 2010). In particular, individuating experience is conferred through pairing faces with individual or unique labels. To date, studies experimentally examining the role of experience (particularly at the individual level) on face-related narrowing have provided experience across a multi-week to multi-month time frame. These studies have detailed the influence of extended experience on face processing, which reflects the important continuous experiences that infants receive across a period of perceptual refinement. However, this leaves open two questions. First, how do labels influence face processing in the moment, as infants are learning to associate faces and labels? Second, are there learning-related differences present before (6 months) relative to after (9 months) perceptual narrowing has occurred? The current study examined effects of individual-level learning within a face-label learning period at distinct points before and after perceptual narrowing in an effort to better understand how infants learn from labeling at different ages.

Label Learning in the Context of Categorization and Language Development

In order to investigate effects of labeling experience at discrete time points/ages in infancy, the label-face matching training must be largely condensed (e.g., into a single training session). One body of research beneficial for gaining an understanding of how relatively brief label-object learning can influence perception has examined how verbal labels affect object processing and category formation in infancy. Although this literature has focused almost exclusively on category-level labels (but see Best, Robinson, & Sloutsky, 2010), it presents a general understanding of how labels may affect object perception at behavioral and neural levels.

As early as 3 to 4 months of age, when multiple instances of an object category (e.g., dinosaurs) are paired with a shared label, infants differentiate a new member of the labeled category from a member of a separate category (e.g., fish), whereas pairing objects with tones fails to elicit categorization (Ferry, Hespos, & Waxman, 2010) (but see Ferguson & Waxman, 2016). Shared category labels can also override perceptually-based categories at 10 months of age (Plunkett, Hu, & Cohen, 2008). When 10-month-old infants viewed computer-generated cartoon pictures in silence, they formed two distinct categories based on visual perceptual differences. In contrast, when pictures were presented with a single verbal label, infants treated all pictures as part of a single, broad category, suggesting that a common label aided infants in forming categories in a way that superseded basic perceptual features.

Category-level labels have also been found to enhance visual processing of objects in 12-month-olds (Gliga, Volein, & Csibra, 2010). Infants were given a brief interactive experience, wherein the experimenter showed infants two novel objects, referencing one with a novel verbal label (e.g., “blicket”), and the other with a simple pronoun (e.g., “it”). Following this brief experience, infants viewed the familiarized objects in silence while EEG was recorded. Infants exhibited enhanced gamma-band oscillatory activity over the visual cortex in response to the labeled object relative to the non-labeled (“it”) object. The authors suggest that labeling an object changes how it is processed at a neural level and that increased gamma-band activity for the labeled object represents enhanced visual processing of the objects. Moreover, the authors suggest that the increased gamma activity supports behavioral evidence that labeling objects benefits categorization. In a similar study with adults (Maier et al., 2014), participants learned groups of novel objects labeled with category names. Adults then completed an ERP oddball task, where they viewed two side-by-side images of learned objects. On the majority of trials, the objects were identical. On oddball or deviant trials, adults viewed two different objects, which either belonged within the same labeled category, or belonged to different labeled categories. Adults exhibited a larger amplitude occipital P1 component (associated with low-level visual perceptual processing) for oddball trials from between-category objects relative to oddball trials from the same labeled category. The authors suggest that labels can enhance early visual processing of objects.

Word learning studies have also begun to investigate aspects of how infants learn to associate word labels with objects during the learning period. Friedrich and Friederici measured ERP responses in 14-month-old (2008) and 6-month-old (2011) infants as they were presented with novel object-novel word pairs. Half of the word-object pairs were “constant” (the same label always referred to the same object), and half were "rotated" (labels and objects were mixed such that each label was paired with each object). Fourteen-month-olds exhibited larger amplitude responses associated with word priming for the "constant" versus "rotated" pairing condition, suggesting that after very few learning trials, infants associate object-word pairs at 14 months (Friedrich & Friederici, 2008). Fourteen-month-olds (2008) and 6-month-olds (2011) also exhibited larger amplitude responses associated with semantic knowledge, as indexed by the central-parietal N400 component (Kutas & Hillyard, 1980), for the "constant" versus "rotated" pairing condition. These findings suggest that even at 6 months of age, infants are able to associate and form semantic representations for word-object pairs.

Best, Robinson, and Sloutsky (2010) extended this type of learning paradigm to investigate effects of individual-level labels on visual attention in 16- to 24-month-old infants. Infants viewed multiple novel objects paired with unique labels, a shared category label, or silence while visual fixations were recorded. Objects had features that were common across exemplars, as well as features that were unique. Infants who viewed objects paired with unique labels showed significantly greater looking to unique object features relative to infants who viewed in silence. These results suggest that pairing objects with individual labels may help infants tell objects apart by guiding attention to differentiating features.

Investigations of early word learning suggest that words and/or verbal labels shape the perception of and attention to visual object categories. The word-object learning literature has primarily focused on the effect shared category labels have on object perception (e.g., Ferry et al., 2010; Plunkett et al., 2008), although recent research has also examined effects of individuating labels (Best et al., 2010). The current study extended this line of research to investigate how labels shape *face* perception before and after a sensitive period in which face processing becomes tuned to familiar groups. Continuing to explore how different types of labels impact perception of various categories (e.g., objects, faces) will broaden our understanding of how infants can learn from labels and whether labels function similarly across different stimulus domains.

The previously reviewed neurophysiological studies have focused primarily on face-related occipital ERP components, such as the N290 and P400 (Balas et al., 2011; Scott & Monesson, 2010; Scott et al., 2006). However, a study examining infants' neural matching of cross-modal face and voice emotion stimuli also reported face-related processing for the infant negative central (Nc) component (Vogel et al., 2012). The Nc is a frontally and centrally distributed infant ERP component related to selective attention (Reynolds, Courage, & Richards, 2010). At 5 months of age, infants exhibited differential Nc amplitude responses to mismatching emotion information. In contrast, 9-month-olds exhibited responses to mismatched emotion information at the occipital N290 component. This change in response pattern suggests a possible shift across the course of perceptual narrowing from an attentional to a perceptual system. It is possible that the previous findings of a qualitative shift (Vogel et al., 2012) reflect a developmental change in processing emotion information or related to detecting incongruent information cross-modally. Therefore, another goal for the present study was to investigate whether there is a qualitative shift, from 6 to 9 months of age, in the neural regions underlying the learning of label-face pairings.

Neural measures

The present study employed two measures to examine neural responses to an unfamiliar face group before, during, and after a brief label-face training experience: event-related potentials (ERPs) and steady state visual evoked potentials (ssVEPs). The ERP measure was used to assess the influence of individual labels on face processing during the label-face learning period. ERP responses are time-locked to the presentation of stimuli and often rely on examining well-studied waveform components related to certain cognitive processes. The current study examined specific ERP components related to face-sensitive visual processing (P1, N290, P400) and selective attention (Nc). By using standard components, the findings of the current study can be directly compared and discussed in relation to previous electrophysiological studies (e.g., Balas et al., 2010; Balas et al., 2011; Scott et al., 2006).

The ssVEP measure was used in the context of a fast periodic visual stimulation (FPVS) task to assess neural discrimination of individual monkey faces before and after the label-face learning period. In FPVS paradigms, images are presented at a rapid, constant frequency (e.g., 6 faces per second) and as a result, neural responses to the images (ssVEP) oscillate at the presentation frequency (for review, see Norcia, Appelbaum, Ales, Cottereau, & Rossion, 2015). This technique is beneficial for use with developmental populations because many trials can be presented in a very short span of time and there is a high signal-to-noise ratio (S/N ratio). Additionally, ssVEP is an objective measure such that the expected response frequency is determined by the stimulus presentation frequency. The ssVEP measure has only recently been used to explore responses to high-level stimuli such as faces. To date, only two studies have used ssVEP to examine face processing in infancy, and both studies focused on the specificity of face and object category representations (de Heering & Rossion, 2015; Farzin, Hou, & Norcia, 2012). Farzin and colleagues (2012) reported that 4- to 6-month-old infants respond to the high-level structural information of faces and objects, and that face-related responses may be more widely distributed over occipital regions. Similarly, de Heering and Rossion (2015) found evidence that 4- to 6-month-old infants also form a category representation of faces that is separate from other objects, and that this face categorization is strongly present over the right occipital region. While both studies have important implications about the how faces are represented at the neural level, no FPVS studies thus far have examined face individuation in infancy. One recent adult study utilized FPVS with an oddball task design (e.g., infrequent changes in face identity) to investigate whether adults exhibited a response to face identity above and beyond a category response to faces (Liu-Shuang, Ales, Norcia, & Rossion, 2014). Liu-Shuang and colleagues found that in the context of an oddball FPVS task, adults exhibit a right-lateralized response to changes in face identity, suggesting that the oddball FPVS task is ideal for capturing face discrimination at the neural level.

In order to gain a more complete sense of how individual labels influence face processing at different points in development the current study addressed two major aims. First, the current study investigated whether or not 6- and 9-month-old infants show neural evidence of individual-level discrimination for previously unfamiliar monkey faces. As predicted by the behavioral perceptual narrowing literature (Pascalis et al., 2002; Scott & Monesson, 2009), we hypothesized that 6- but not 9-month-olds would exhibit neural discrimination for faces within an unfamiliar face group. However, if neural responses remain sensitive to unfamiliar face groups even after behavioral narrowing is present (Scott et al., 2006), we expected both 6- and 9-month-old infants to exhibit neural discrimination for an unfamiliar face group.

Second, the study investigated whether or not the brain responses that support learning during an individual-level face-label matching task differ at the beginning versus the end of perceptual narrowing and whether or not individual-level labeling enhances learning above and beyond a white-noise sound control condition. Given prior findings suggesting that labeling objects enhances visual perception of those objects (Gliga et al., 2010) and that consistently labeling objects can impact neural responses during the label-object learning period (Friedrich & Friederici, 2008, 2011), we predicted that labeling faces with unique labels, relative to pairing them with noise, would enhance neural processing of faces during in-lab training. As previous training studies have shown behavioral benefits (Heron-Delaney et al., 2011; Pascalis et al., 2005; Scott & Monesson, 2009) and specialized neural responses (Scott & Monesson, 2010) following experience with unique labels, we also predicted individual-level labeling would enhance neural discrimination within the previously unfamiliar face group post-training. Finally, we predicted that influences of labeling would be present in fronto-central regions at 6 months of age, and in occipital regions at 9 months of age, as prior works suggests that there may be an attention to perception shift in which systems infants use to process faces across development (Vogel et al., 2012).

CHAPTER 2

METHODS

Participants

All parents gave informed consent prior to testing. Participants were 26 6-month-old (12 males) and 20 9-month-old (11 males) infants. ERP analyses for the entire training period included data from 16 6- and 16 9-month-olds. ERP analyses for the separate first and second halves of training included data from a subset of infants with enough trials per condition for each separate half (6-month-olds: *n* = 12; 9-month-olds: *n* = 14). ssVEP analyses included data from 25 6- and 20 9-month-olds for the pre-training condition, 9 6- and 13 9-month-olds for the post-training label condition, and 7 6- and 11 9-month-olds for the post-training noise condition. An additional 10 6-month-olds and 4 9-month were excluded from ERP analyses because they did not contribute enough artifact-free trials per condition (6 months: *n* = 6; 9 months: *n* = 3) or because of excessive noise/drift in the data (6 months: *n* = 4; 9 months: *n* = 1). An additional single 6-month-old was excluded from all ssVEP analyses because they did not contribute enough useable trials per condition. Infants with a history of neurological, visual or auditory impairments were also excluded. Parents of participants were paid $10 and infants received a small toy for their participation.

Stimuli and apparatus

Visual stimuli consisted of 12 digitized color photographs of Barbary macaques (*Macaca sylvanus*) and 12 digitized color photographs of Tufted capuchins (*Cebus apella*) presented at a visual angle of approximately 13˚ (Figure 1). Each monkey identity had 5 versions of varying luminance including the original image, 20% increase and decrease, and 40% increase and decrease in luminance from the original. Variations in luminance were used to reduce low-level effects (Dzhelyova & Rossion, 2014). The set of macaque faces was used in prior infant training studies (Scott & Monesson, 2009, 2010).

Auditory stimuli consisted of words and a non-speech noise burst (referred to as “noise”) that were 610 ms in duration. Word stimuli were recorded and processed in Praat (Boersma & Weenink, 2014). Word stimuli included 6 disyllabic words/proper names: Boris, Carlos, Billy, Harry, Jamar, Bobby, spoken by a single female speaker and recorded at a rate of 96000 Hz. In order to ensure that all word stimuli were the same duration, samples from each word were clipped out until the word was the correct length. Clipped samples were selected primarily from continuants, then vowels, and were chosen on the basis that removing the samples did not change the overall sound of the words. When samples were clipped from vowels, they were taken from the center of the vowel and not from areas in the word where the formants changed. The noise stimulus was a burst of pink noise filtered with the spectrum of the speech stimuli. All auditory stimuli were presented with a peak intensity of 60-63 dB SPL (A-weighted).

Procedure

The study consisted of two parts: an in-lab training session, and a pre- and post-training assessment (Figure 2). During the training, infants viewed monkey faces paired with either unique verbal labels or a non-speech noise burst. Training was provided in-lab in an effort to more tightly control the perceptual nature of face and label matching experience. Infants also completed a pre- and post-training assessment in which they passively viewed faces in the context of an oddball paradigm. Electrophysiological data were recorded during the pre- and post-training tasks, as well as during training in order to examine neural discrimination of faces within the labeled versus noise conditions across age.

Training

During the training procedure, 6- and 9-month-old infants viewed two sets of a novel face group (monkey faces: Barbary macaques, Tufted capuchins), blocked by species. One set of faces (e.g., Barbary macaques) was matched with individual verbal labels (e.g., “Boris”, “Jamar”), while the other set of faces (e.g., Tufted capuchins) was presented with a non-speech noise (Figure 3). This noise control condition allowed us to determine whether verbal labels influenced face processing above and beyond what infants learn by simply viewing the faces. Infants received equal amounts of experience with the two face groups. In addition, the order of the face groups, exemplars within each face group, and the species assigned to each of the two sound conditions (individual label, noise) were counterbalanced across participants. The counterbalancing and control of experience allowed us to better control for potential influences of the perceptual input.

Training took place in the context of an ERP paradigm in order to examine neural responses to the face groups during training. Infants were trained with 4 monkey faces for each species group. During each trial, a face and sound (a label or non-speech noise) were presented with the same onset for a duration of 610 ms. The intertrial interval varied between 500-700 ms, and trials were presented when the experimenter judged infants to be looking at the screen. For analyses across the entire training period, within each species/face group, 6-month-olds viewed an average of 57 (*SD* = 10.2) trials and 9-month-olds viewed an average of 60 (*SD* = 1.2) trials out of 60 possible trials. Twenty-seven out of the thirty-two infants included in final analyses viewed all 60 possible trials per species/face group. For the subset of infants used in analyses for the first and second halves of trials, within each species/face group, 6-month-olds contributed an average of 18 (*SD* = 4.2) trials in the first half and 16 (*SD* = 5.7) trials in the second half of the training period. Nine-month-olds contributed an average of 20 (*SD* = 3.9) trials in the first half and 18 (*SD* = 4.1) trials in the second half of the training period.

Electrophysiological data were collected using a 128-channel Geodesic Sensor Net which is linked to a DC-coupled 128-channel high input impedance amplifier (Net Amps 300 TM, Electrical Geodesics Inc., Eugene, OR). Amplified signals were low-pass filtered online at 100 Hz and sampled every 2ms (at a rate of 500 Hz). All electrodes were referenced online to the vertex (Cz). Electrodes were adjusted until impedances were less than 50 kΩ.

ERP processing procedure

Data were processed using NetStation 4.3 (Electrical Geodesics Inc., Eugene, OR). Stimulus-locked ERPs were digitally band-pass filtered between 0.3 and 30 Hz and baseline-corrected with respect to a 100 ms pre-stimulus (onset of the face) baseline. Segmented trials were visually examined for excessive noise and/or drift. Channels were marked bad if they were excluded from more than 30% of all trials. Individual trials were excluded from analyses if they contained more than 12 bad channels. Individual channels that were constantly marked bad (off-scale on more than 70% of trials) were replaced using a spherical interpolation algorithm (Srinivasan, Nunez, Tucker, Silberstein & Cadusch, 1996). Datasets that had fewer than 15 artifact-free trials per condition were also excluded from analyses. Six-month-old infants contributed an average of 34 (*SD* = 8.59) trials for each condition and 9-month-old infants contributed an average of 38 (*SD* = 6.75) trials for each condition. An average reference was used in order to minimize noise at the reference site and to accurately estimate scalp topography.

Pre/post FPVS

Infants also completed a pre- and post-training fast periodic visual stimulation (FPVS) task for each face group to examine processing of novel exemplars of the trained face groups, and to examine neural discrimination of monkey faces prior to (6 months) and after (9 months) perceptual narrowing (Figure 4). Novel exemplars were used to assess generalization of learning within the trained face groups. Examining neural responses after training specifically assessed the effects of labeling on differentiation of individual faces at the neural level, which was meant to parallel the large behavioral literature on face differentiation. The use of an FPVS task allowed us to present many trials in a very short span of time, which is ideal for testing infants.

The FPVS task was structured as an oddball task in order to investigate exemplar-level discrimination. Oddball FPVS tasks have been used to investigate face processing in adults (Liu-Shuang et al., 2014) and recently in 6-month-old infants as well (de Heering & Rossion, 2015; Farzin et al., 2012). In the current study, one exemplar from a face group was presented at a rapid, constant frequency (6 times per second: 6 Hz) and every 5th stimulus (the oddball) was a different exemplar from the same group (e.g., AAAABAAAAC). Neural responses to the oddball stimulus oscillated at the same frequency as the oddball is presented (6 Hz/5 images = 1.2 Hz), making these responses easily identifiable in the data. Infants completed this task for each species/face group before and after training. Within each species/face group, infants viewed 10, 10-second “trials” that each included 11 oddballs. The total time for the pre-training assessment was approximately 3 to 5 minutes. Oddball stimuli consisted of 3 novel faces per face group that were repeated randomly with the criteria that the same face was not presented twice in a row. The size of all face stimuli was varied randomly across every face presentation, both for the frequent and oddball stimuli, from 95% to 105% of the original image size. Additionally, the luminance of all face stimuli varied randomly from a 40% decrease from the original image to an 40% increase from the original image. This variance in image size and luminance ensured that any responses at the oddball frequency were most likely due to changes in face identity, and not low-level image differences (Dzhelyova & Rossion, 2014). We examined pre- and post-training responses to the oddball stimulus within each of the trained species/face groups, and also investigated differences between infant age groups.

ssVEP processing procedure

Data were processed using EEGLAB (Delorme & Makeig, 2004) and customized Matlab scripts. EEG data were band-pass filtered between 0.1 Hz and 30 Hz. Filtered data were segmented into 10-second trials. Experimenters live-coded infants' duration of looking during each trial. Trials during which infants looked for less than 5 seconds were excluded from further processing and analyses. For each trial, bad channels were identified and replaced with average voltages from the nearest channels.[1] Six-month-old infants contributed an average of 7 (*SD* = 2.04) out of 10 trials per condition and nine-month-old infants contributed an average of 7 (*SD* = 1.65) out of 10 trials per condition. Data were re-referenced to the average reference to accurately estimate scalp topography. Data were averaged across trials and then converted into the frequency domain using a windowed[2] fast Fourier transform. Data were averaged before the fast Fourier transform in order to reduce non-phase-locked activity in measured responses. In order to create 0.1 Hz frequency bins for the exact frequencies of interest (1.2 Hz, 6 Hz), 102 ms were removed from the beginning of each participant's data. Bin resolution was determined by trial length and sampling rate. Data were visually inspected for a peak at 6 Hz, which indicated that data processing successfully reflected ssVEP responses at presentation frequency.

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[1] Bad channels were identified as outliers on a combination of three metrics (summed together to form a "quality metric"): the median absolute voltage value, the standard deviation of voltage values, and the maximum difference in voltage values at each channel. First, channels that fell more than 2.5 standard deviations away from the median quality metric were identified. A second quality metric was then calculated excluding these bad channels, and additional channels that fell more than 3.5 standard deviations away from the median quality metric were also identified as bad channels. Bad channels were replaced with average voltages from nearby channels. Up to 6 of the closest channels were used in interpolation, but fewer were used if any of the closest channels were also bad.

[2] A cosine window was applied to the first and last 20 data samples of the dataset due to each trial not corresponding to an integer number of frequency cycles. Windowing reduces the chance of aliasing and spectral leakage.

CHAPTER 3

ANALYSES

ERP

Time windows and electrode groupings were based on previous research and visual inspection of the data. Mean amplitude and latency to peak amplitude of the occipital P1, N290, and P400 components was analyzed, as well as the fronto-central Nc component. For occipital components, electrodes over left and right occipital regions were averaged for analysis (left region: 58, 59, 64, 65, 69; right region: 89, 90, 91, 95, 96). Mean amplitude of the P1 was measured between 95-180 ms after stimulus onset for 6- and 9-month-old infants. Mean amplitude of the N290 was measured between 215-280 ms after stimulus onset for 6- and 9-month-olds. Mean amplitude of the P400 was measured between 340-420 ms after stimulus onset for 6- and 9-month-olds. For the Nc component, electrodes over a single fronto-central region were averaged for analysis (5, 6, 11, 12). Mean amplitude for the Nc was measured between 350-600 ms after stimulus onset for 6-month-olds and between 350-550 ms after stimulus onset for 9-month-olds. Identical time windows and channel groups were used in analyses for the entire training period as well as the first and second halves of the training period.

Entire training period

Data for occipital components were entered into separate 2 x 2 repeated-measures ANOVAs for each age group and component. Each ANOVA included within-subjects factors of Condition (Label, Noise) and Region (Left, Right). Data for the fronto-occipital Nc component were entered into separate one-way repeated-measures ANOVAs for each age group. Each ANOVA included the within-subjects factor of Condition (Label, Noise). Significant interactions were followed up with Bonferroni-corrected t-tests.

First and second halves of training period

In order to look at the influence of labels during training in more detail, responses were also examined separately for the first and second halves of the training period. The first half of the training period consisted of the first 30 trials in each condition block (label, non-speech noise), and the second half of the training period consisted of the last 30 trial in each condition block. Only differences between the Label and Noise conditions that were significant for entire training period analyses were followed up. Each significant difference was followed up with paired-samples t-tests between conditions for the first as well as second half of trials.

ssVEP

In order to standardize responses across conditions and age groups, data were transformed into S/N ratios between the amplitude response at the frequency of interest (i.e., base: 6 Hz; oddball: 1.2 Hz) and amplitude response averaged across a range of frequencies from 0.2 to 1.2 Hz above and below the frequency of interest. Using a range of nearby frequencies is a beneficial way to estimate background noise in the spectrum and also provides a more accurate estimate for the noise that is occurring when the signal is measured relative to a temporally-separated baseline (Norcia et al., 2015). However, using bins both above and below the frequency of interest for calculating noise provides a more conservative rather than sensitive measure of signal presence and therefore may not reflect the presence of weak responses, particularly over lower frequency bins. For each condition and age group, responses were averaged across participants.

Single-sample t-tests

S/N ratios were compared to a threshold of 1 using single-sample t-tests in order to identify significant signals at the base and oddball frequencies. Measuring S/N ratios at the base frequency ensured that neural responses in each age group and condition were synchronized to general paradigm presentation rate (Farzin et al., 2012; Liu-Shuang et al., 2014). Similarly, determining whether S/N ratios at the oddball frequency were significant for a given age group, condition, and region allowed us to verify that a response was present in response to a change in face identity.

For the base frequency, individual single-sample t-tests were run for each age group (6 months, 9 months), condition (pre-training, post-training: label, post-training: noise), and occipital region (left, middle, right). For the oddball frequency, individual single-sample t-tests were run for each age group (6 months, 9 months), condition (pre-training, post-training: label, post-training: noise), and region (left occipital, middle occipital, right occipital, frontal, central). The significance level was set to a threshold of $p < .01$ due to the large number of t-tests being run.

ANOVAs

S/N ratio data were entered into separate 2 x 3 mixed-measures ANOVAs for each condition and region set. Separate ANOVAs were run for each condition (pre-training, post-training: label, post-training: noise) because each condition included different groups of participants. For occipital regions, each ANOVA included the within-subjects factor of Region (left, middle, right) and the between-subjects factor of Age (6 months, 9 months). For the frontal-to-occipital regions, each ANOVA included the within-subjects factor of Region (mid-occipital, frontal, central) and the between-subjects factor of Age (6 months, 9 months). Significant interactions were followed up with Bonferroni-corrected t-tests.

CHAPTER 4

RESULTS

ERP

See Tables 1-6 for component means and standard errors for each age group. Tables 1-2 summarize main effects for the entire training period, Tables 3-4 summarize interactions for the entire training period, and Tables 5-6 summarize follow up tests for the first and second halves of training.

P1: 6-month-olds

Entire training period

Amplitude analyses revealed a significant main effect of Region, $F(1,15) = 12.06$, $p = .003$, $\eta^2 = .446$, due to a larger P1 amplitude recorded over the right versus left hemisphere.

First and second halves

No follow-up tests were conducted for 6-month-olds' P1 response.

P1: 9-month-olds

Entire training period

Amplitude analyses revealed a significant main effect of Region, $F(1,15) = 6.70$, $p = .021$, $\eta^2 = .309$, due to a larger P1 amplitude recorded over the right versus left hemisphere. Latency analyses revealed a significant main effect of Condition, $F(1,15) = 17.81$, $p = .001$, $\eta^2 = .543$, where 9-month-olds exhibited a faster latency to peak P1 for the label relative to the noise condition. There was also a marginally significant interaction of Condition and Region, $F(1,15) = 4.31$, $p = .055$, $\eta^2 = .223$, driven by a faster latency to peak P1 for the label versus the noise condition over the left hemisphere, $t(15) = 3.23$, $p = .006$, but not the right hemisphere, $t(15) = 1.59$, $p = .133$ (Figure 5).

First and second halves

Nine-month-olds exhibited a significantly faster latency to peak P1 for the label relative to the noise condition, averaged across hemispheres, for both the first, $t(13) = 3.28$, $p = .006$, and second, $t(13) = 2.39$, $p = .033$, halves of training (Figures 6-7). Additionally, the latency to peak P1 was significantly faster for labeled faces over the left hemisphere for the first, $t(13) = 2.52$, $p = .025$, and second, $t(13) = 2.44$, $p = .030$, halves of training.

N290: 6-month-olds

Entire training period

Amplitude analyses revealed a significant interaction between Condition and Region, $F(1,15) = 5.17$, $p = .038$, $\eta^2 = .256$. Follow-up paired-samples t-tests indicated that this interaction was driven by a significantly larger N290 amplitude in response to faces paired with labels relative to those paired with a non-speech noise over the right hemisphere, $t(15) = 2.64$, $p = .019$, but no significant difference between conditions over the left hemisphere, $t(15) = .84$, $p = .413$ (Figure 8). There were no significant latency differences.

First and second halves

There were no significant N290 amplitude differences in response to the label versus noise conditions over the right hemisphere in the first half of trials. In the second half of trials, infants exhibited a significantly larger N290 amplitude in response to faces paired with labels relative to those paired with a non-speech noise over the right hemisphere, $t(11) = 2.58$, $p = .026$.(Figures 9-10).

N290: 9-month-olds

Entire training period

Amplitude analyses revealed a significant main effect of Condition, *F*(1,15) = 10.44, *p* = .006, η^2 = .410, such that 9-month-olds exhibited a larger N290 amplitude in response to faces paired with labels versus those paired with a non-speech noise (Figure 11). Latency analyses revealed a significant main effect of Region, *F*(1,15) = 17.85, *p* = .001, η^2 = .543, due to a faster latency to peak N290 over the right versus left hemisphere.

First and second halves

In the first half of trials, 9-month-olds exhibited a marginally larger N290 amplitude, collapsed across hemispheres, in response to labeled faces relative to those paired with a non-speech noise, *t*(13) = 2.13, *p* = .053. There were no significant condition differences in the second half of trials. (Figures 6-7).

P400: 6-month-olds

Entire training period

Amplitude analyses revealed a significant main effect of Region, *F*(1,15) = 6.25, *p* = .025, η^2 = .294, such that 6-month-olds exhibited a larger P400 amplitude over the right versus left hemisphere. There were no significant latency differences.

First and second halves

No follow-up tests were conducted for 6-month-olds' P400 response.

P400: 9-month-olds

Entire training period

Amplitude analyses revealed a significant main effect of Condition, *F*(1,15) = 7.57, *p* = .015, η^2 = .335, due to a larger P400 amplitude in response to faces paired with a non-speech noise relative to those paired with labels (Figure 11). There was also a significant main effect of

Region, $F(1,15) = 5.48$, $p = .033$, $\eta^2 = .268$, due to a larger P400 amplitude response over the right versus left hemisphere. There were no significant latency differences.

First and second halves

There were no significant condition differences at the P400 component in the first half of trials. In the second half of trials, infants exhibited a larger P400 amplitude in response to faces paired with a non-speech noise versus those paired with labels, $t(13) = 2.62$, $p = .021$. (Figures 6-7).

Nc: 6-month-olds

Entire training period

There were no significant amplitude differences. Latency analyses revealed a significant main effect of Condition, $F(1,15) = 10.23$, $p = .006$, $\eta^2 = .405$, such that 6-month-olds exhibited a faster latency to peak Nc for faces paired with a non-speech noise relative to those paired with labels (Figure 12A,12C).

First and second halves

In the first half of trials, 6-month-olds exhibited a significant faster latency to peak Nc for faces paired with a non-speech noise compared to those paired with labels, $t(11) = 2.69$, $p = .021$. There were no significant condition differences in the second half of trials (Figure 13).

Nc: 9-month-olds

Entire training period

There were no significant amplitude or latency differences (Figure 12B-C).

First and second halves

No follow-up tests were conducted for 9-month-olds' Nc response.

ssVEP

Single-sample t-tests

See Tables 7-8 for exact *p*-values and t-statistics for 6-month-old (Table 7) and 9-month-old (Table 8) responses.

<u>6-month-olds</u>

Pre-training

T-tests revealed significant responses at the base frequency over left, middle, and right occipital regions (*p*s < .001) (Figure 14). There were no significant responses at the oddball frequency (Figure 15).

Post-training: Label

Significant responses at the base frequency were found over left, middle, and right occipital regions (*p*s < .01) (Figure 14). There were no significant responses at the oddball frequency (Figure 16).

Post-training: Noise

Significant responses at the base frequency were found over the right occipital region (*p* = .006). Marginally significant responses at the base frequency were found over left (*p* = .012) and middle (*p* = .013) occipital regions (Figure 14). There were no significant responses at the oddball frequency (Figure 17).

<u>9-month-olds</u>

Pre-training

T-tests revealed significant responses at the base frequency over left, middle, and right occipital regions (*p*s < .001) (Figure 14). Infants exhibited significant responses at the oddball frequency over all regions (left occipital, middle occipital, right occipital, frontal, central) (*p*s < .01) (Figure 15).

Post-training: Label

Infants exhibited significant responses at the base frequency over left, middle, and right occipital regions (*p*s < .01) (Figure 14). There was a significant response at the oddball frequency over the right occipital region (p = .008) (Figure 16).

Post-training: Noise

T-tests revealed significant responses at the base frequency over left, middle, and right occipital regions (*p*s < .01) (Figure 14). There were no significant responses at the oddball frequency (Figure 17).

ANOVAs for oddball frequency response

Pre-training

Analyses for occipital regions revealed a significant main effect of Age, $F(1,43) = 7.650$, $p = .008$, $\eta^2 = .151$, such that 9-month-olds exhibited a significantly larger response at the oddball frequency than 6-month-olds (Figure 18A, 18C). There was also a significant main effect of Region, $F(2,42) = 4.407$, $p = .018$, $\eta^2 = .173$, due to larger responses over the right occipital compared to the middle occipital (p = .015, corrected) region (Figure 18B-C). Analyses for midline regions revealed a significant effect of Age, $F(1,43) = 5.151$, $p = .028$, $\eta^2 = .107$, such that 9-month-olds exhibited a significantly larger response at the oddball frequency than 6-month-olds (Figure 19).

Post-training: Label

Analyses for occipital regions revealed no significant differences in response at the oddball frequency. Analyses for midline regions revealed a significant interaction of Age and Condition, $F(2,19) = 4.704$, $p = .022$, $\eta^2 = .331$. Follow-up one-way ANOVAs for each age group revealed that this interaction was driven by 9-month-olds exhibiting differential responses across regions, *F*(2,11) = 5.270, *p* = .025, η^2 = .489. Specifically, 9-month-olds exhibited a larger response over the frontal versus central region (*p* = .036, corrected) (Figure 20).

Post-training: Noise

There were no significant differences in response at the oddball frequency for the post-training noise condition.

Summary

During the label-face training period, both 6- and 9-month-olds exhibited differential ERP responses to faces paired with labels relative to those paired with noise. At 6 months, infants exhibited a larger N290 amplitude to labeled faces. This N290 difference was only present over the right hemisphere and driven by the second half of trials. At 9 months, infants exhibited a faster latency to peak P1 and a larger N290 amplitude to labeled faces during the first half of trials, and a larger P400 amplitude to faces paired with a non-speech noise during the second half of trials. All differential responses at 9 months were present over both left and right hemispheres. Additionally, 6-month-olds showed a faster latency to peak Nc to faces paired with a non-speech noise versus those paired with labels during the first half of training, while 9-month-olds showed no difference in Nc response between sound conditions. However, it should be noted that 6-month-olds did not show a clearly peaked Nc component across the entire training period or within either separate half of trials. Results of the Nc latency analyses should therefore be interpreted cautiously.

Prior to label-face training, 6- and 9-month-old infants exhibited identifiable ssVEP responses at the base frequency (6 Hz) over all occipital regions. Six-month-olds did not show any significant responses at the oddball frequency (1.2Hz), while 9-month-olds showed identifiable responses at the oddball frequency over occipital, central, and frontal regions. After training, 6-month-olds exhibited identifiable responses at the base frequency over all occipital regions, but did not exhibit significant responses at the oddball frequency. Nine-month-olds also exhibited responses at the base frequency over all occipital regions. Nine-month-olds exhibited significant responses at the oddball frequency over the right occipital region for faces paired with individual labels during training, and did not exhibit any significant responses at the oddball frequency for faces paired with a non-speech noise.

CHAPTER 5

DISCUSSION

The current study had two overarching aims: (1) to determine whether or not 6- and 9-month-old infants show neural individual-level discrimination for previously unfamiliar monkey faces, and (2) to determine whether or not the brain responses that support learning during an individual-level face-label matching task differ at the beginning versus the end of perceptual narrowing and whether or not individual-level labeling enhances learning above and beyond a white-noise sound control condition. To address these aims, this study tested separate groups of 6- and 9-month-old infants in the context of an in-lab training study. During an ERP training task, faces from an unfamiliar group (monkey faces) were presented with either unique labels or a non-speech noise. Neural discrimination of monkey faces was assessed prior to and after training using an FPVS paradigm.

The results of this study suggest that while both 6- and 9-month-olds' face-related responses are influenced by the presence of unique labels, older and younger infants learn from labeling experience in different ways. At 9 months, labels influence multiple stages of processing and have an effect earlier in the learning period, while at 6 months labels only influence an earlier stage of processing and do so later in the learning period. Further, the current findings demonstrate that neural differentiation of an unfamiliar face group does not directly parallel behavioral perceptual narrowing, as 9-month-olds, but not 6-month-olds, showed evidence of face discrimination. This discrepancy between previous behavioral findings and the current results suggests that narrowing is a multi-faceted process. Finally, the present results suggest that at older ages, when infants have gained more language-related experience, brief labeling experience can localize face identity responses over face-sensitive brain regions.

Influence of labels during training period

Responses to monkey faces paired with individual labels and those paired with a non-speech noise were examined across the entire training period, as well as in the first and second halves of trials in order to more closely examine the learning process. Both 6- and 9-month-old infants exhibited enhanced visual ERP components in response to monkey faces paired with individual labels relative to those paired with a non-speech noise. This result is consistent with previous work that reports 12-month-olds exhibit enhanced visual perception of objects that have been explicitly labeled (Gliga et al., 2010). The current study not only suggests that labels may impact visual perception earlier than 12 months of age, but also clarifies *how* labels can impact processing due to the high temporal resolution of the ERP technique. With such high temporal resolution, different ERP components can index different stages of processing (Münte et al., 1998) and provide a clearer picture of when in processing labels exert an influence. While both age groups showed the same general pattern of enhancement for labeled faces, there were notable timing and topography differences in responses between age groups.

Early visual processing

Nine-month-old infants exhibited a faster latency to peak P1 amplitude over the left hemisphere for the label versus non-speech noise condition (Figure 5), suggesting that at 9 months, hearing a verbal label facilitates very early perceptual processing of visual stimuli. This faster processing of labeled faces was apparent in both the first and second halves of trials. In contrast 6-month-olds did not exhibit differences in P1 latency between sound conditions across the training period. This early modulation due to labels seen at 9 months is consistent with a recent finding in the adult literature (Maier et al., 2014). After learning to associate category names with groups of novel objects, adults exhibited a larger P1 amplitude in response to objects from different categories versus objects from the same category, indicating that category labels influenced early visual processing. Therefore the current findings suggest that labeling visual stimuli can impact early visual processing even in infancy.

Face-sensitive visual processing

Across the entire training period, 6-month-old infants exhibited a larger N290 amplitude in response to labeled faces (Figure 8). However 6-month-olds, infants showed no differential processing at the N290 in the first half of training and the overall N290 effect was driven by a larger N290 amplitude in response to labeled faces in the second half of training alone. In contrast, across the entire training period, 9-month-olds exhibited both a larger N290 amplitude as well as a differential P400 amplitude in response to faces paired with labels versus those paired with a non-speech noise (Figure 11). Interestingly, 9-month-olds exhibited a larger N290 in response to labeled faces within the first half of trials. In the second half of trials, 9-month-olds no longer showed a significant differential N290 response to the label versus non-speech noise condition, but instead showed differential amplitude responses at the P400 component, such that faces paired with a non-speech noise elicited a larger P400 amplitude than faces paired with labels (Figures 6-7). The shift in differences between sound conditions from the N290 to the P400 suggests that as 9-month-olds are gaining experience hearing labels paired with monkey faces during the training, the influence of labels shifts from an earlier (N290) to a later (P400) stage of processing.

It is unclear of how the directionality of the P400 response (larger amplitude in response to faces paired with a non-speech noise) should be interpreted in the present study, particularly since the lower amplitude P400 in response to labeled faces appears to be driven by the absolute larger negativity of the waveform response to labeled faces. The P400 has previously been found to be larger in response to unfamiliar versus familiar human faces (Scott et al., 2006), and so the differential P400 response in the current study may be related to 9-month-olds' growing familiarity with labeled monkey faces. Although the P400 component is influenced by features such as familiarity (Balas et al., 2010; Scott et al., 2006) or inversion (de Haan et al., 2002; Scott & Monesson, 2010), the directionality of response is not consistent across studies. However, the shift in response from the N290 to P400 component at 9 months provides an important insight into the learning process, and indicates that language can impact visual processing in complex ways that may change even within a single learning period.

In a previous ERP study that taught 6-month-olds to associate a novel word with a novel object (Friedrich & Friederici, 2011), the authors reported that infants did not show differential responses between consistent and rotating word-object pair conditions in the first half of training, but did so in the second half of training. Thus, it is not entirely surprising that in the present study, 6-month-olds did not show differential responses to the label versus non-speech noise condition until the second half of training. In addition, the finding that 6-month-olds exhibit differences between the label and non-speech noise conditions in the second half of training, while 9-month-olds show differential responses in the first half of training may reflect increases in myelination that occur across the first year of life (Deoni et al., 2011), which have been associated with faster encoding (Richmond & Nelson, 2007).

It is unclear whether the differential P400 response seen at 9 months but not 6 months in the current study is also reflective of slower encoding at 6 months, or whether this age-related difference is indicative of a qualitative change in how labels influence visual processing. It is possible that 9-month-olds' additional experience with word learning and referential labeling may cause labels to influence visual processing in more complex ways. Specifically, the current findings suggest that with additional language experience, labeling a face or object may continue to influence later stages of visual processing, possibly allowing for more feedback from other cortical regions (Garrido, Kilner, Kiebel, & Friston, 2007). It is also possible that the differential P400 response seen at 9, but not 6, months of age may simply reflective a quantitative difference associated with changes in rates of encoding. That is, if 6-month-olds were given additional label-face training trials, they may eventually also show a differential P400 response between faces paired with labels and those paired with a non-speech noise. While future work should determine whether it is a qualitative or quantitative change, the current results indicate that labels influenced an early stage of face-related processing at 6 months of age – as indexed by the N290 component – and influenced both early and later stages of face-related processing at 9 months – as indexed by the N290 and P400 components.

Attention

Across the training period, 6-month-olds exhibited a faster latency to peak Nc amplitude for faces paired with a non-speech noise relative to those paired with labels. This latency difference was driven by responses during the first half of training (Figure 13), as this latency difference was not present in the second half of trials. Particularly since this effect was only present in the first half of trials, it is possible that the differential Nc response is a result of the non-speech noise being a somewhat novel sound (especially relative to human speech), and therefore orienting infants' attention more quickly. Six-month-olds did not exhibit any differences in Nc amplitude between sound conditions, which appears to contradict a previous suggestion that younger infants recruit an attentional system when processing faces (Vogel et al., 2012). However, Vogel and colleagues found differential Nc responses in the context of multimodal face-voice emotion matching, which might have been driven by one of many factors not present in the current study (e.g., emotion information, matching information across modalities). Therefore the present findings do not rule out the hypothesis that younger infants recruit an attentional system for face processing. Unlike younger infants, 9-month-olds did not show any differences in onset time of the Nc component between conditions. These results also contrast eye-tracking results with older infants that suggest hearing unique labels draws infants' attention to unique features (Best et al., 2010). However, it is possible that eye movements may not directly correspond to Nc amplitude, the most commonly used index of attention allocation at the neural level.

Hemispheric differences

Another notable difference in response pattern between 6- and 9-month-olds was the distribution of responses over occipital scalp regions. Differential processing of faces paired with labels relative to those paired with noise was only present over the right hemisphere in 6-month-olds, while condition differences were apparent over both left and right hemispheres in 9-month-old infants. While responses over the right hemisphere were expected due to right lateralization of face-related responses (for review, see de Haan et al., 2003), it is currently unclear what the diffuse processing at 9 months may signify.

It is possible that responses over both hemispheres at 9 months of age reflect 9-month-olds' additional experience with language and word learning. Infants begin to produce speech-like sounds after 6 months of age (Jusczyk, 1997; Oller, 2000) and begin to demonstrate word comprehension around 9-10 months (Benedict, 1979; but see Bergelson & Swingley, 2012). It has been suggested that word learning between 6 and 9 months of age acts as a top-down influence on face perception and helps to shape the perceptual narrowing process (Hadley et al., 2014). While enhanced responses to labeled faces at 6 and 9 months of age suggest that word learning acts as a top-down influence on face perception at both ages, the presence of enhanced responses over both left and right hemispheres at 9 months may reflect the interaction of word learning and increases in language experience. Left lateralization of speech processing has been hypothesized to be partially driven by increases in language experience (Minagawa-Kawai, Cristià, & Dupoux, 2011). Therefore, we suggest that the bilateral responses present at 9 months in the current study reflect a qualitative change in neural responses to faces in the presence of verbal labels that is related to language experience.

Discrimination of faces before and after label training

Pre-training

Prior to any label-face training, infants completed a Fast Periodic Visual Stimulation (FPVS) oddball face individuation task to assess neural discrimination of monkey faces as indexed by steady state visual evoked potential (ssVEP). Both 6- and 9-month-olds infants exhibited significant responses at the base frequency (i.e., the rate at which all faces were presented), suggesting that the technique functioned properly and brain responses identifiably oscillated at the presentation frequency (Figure 14). However only 9-month-olds exhibited significant responses at the oddball frequency, which marked changes in monkey face identity (Figure 15). This suggests that 9-month-olds, but not 6-month-olds, showed neural discrimination of monkey faces. Comparing responses at the oddball frequency between age groups and regions revealed that prior to training, 9-month-olds exhibited larger responses than 6-month olds across all occipital and frontal (Figure 18) regions. Additionally, regardless of age, infants exhibited larger responses at the oddball frequency over the right occipital region versus the left and middle occipital regions (Figure 18), although this lateralization appears to be primarily driven by 9-month-old infants. In a recent FPVS study investigating face individuation in adults, Rossion and Boremanse (2011) propose that such localization over right occipito-temporal channels reflects a high-level “identity response”. This suggests that in the current study, 9-month-olds may be demonstrating a similar, high-level face response, even for a relatively unfamiliar face group.

While previous behavioral work reports that 9-month-olds fail to differentiate among unfamiliar monkey faces (Pascalis et al., 2002), 9-month-olds do show evidence of neural discrimination of monkey faces in the current study. This finding is surprising given not only the behavioral literature, but also prior ERP studies that reported evidence of perceptual narrowing/tuning in 9-month-old infants (Balas et al., 2011; Vogel et al., 2012). However, the findings in these previous ERP studies reflect an aspect of perceptual narrowing/tuning related to enhanced responses for familiar versus unfamiliar face groups. In contrast, the present FPVS task was designed to assess the decline or failure to differentiate face identities in an unfamiliar group typically associated with perceptual narrowing. A similar ERP study (Scott et al., 2006) reported that following brief familiarization, 9-month-olds showed differential ERP responses to familiar versus unfamiliar monkey faces, suggesting that neural discrimination for an unfamiliar face group may remain sensitive even after behavioral perceptual narrowing. The current findings are in line with Scott and colleagues’ (2006) findings and further support the idea that perceptual narrowing/tuning are complex processes that may not be fully explained by behavioral measures. In addition, the contrasting findings between studies examining face identity discrimination and enhanced responses for familiar versus unfamiliar face groups suggest that different aspects of the perceptual narrowing/tuning process may occur at different rates.

It is alternatively possible that responses at the oddball frequency were driven by low-level cues such as fur and skin hue, and that the “face identity response” found in the current study may not reflect high-level face processing, but may instead reflect low-level cues inherent between monkey identities. Following suggestions from previous adult studies (Dzhelyova & Rossion, 2014), low-level differences were controlled for here by varying image size and luminance on every presentation, reducing this possibility. Future work could clarify the nature of the reported neural discrimination response by presenting infants with inverted monkey faces in the same paradigm, which should not generate a high-level "identity" response (Liu-Shuang et al., 2014).

Given previous findings that 6-month-olds can behaviorally discriminate monkey faces (Pascalis et al., 2002; Scott & Monesson, 2009), it is somewhat surprising that they do not also show neural discrimination of monkey faces in the present study. One possibility is that paradigm differences between the present study and previous behavioral studies contributed to the lack of a significant response at the oddball frequency in 6-month-olds. One commonly used measure of face discrimination is the visual paired-comparison paradigm in which infants are familiarized to a single face identity and then view the familiarized face and a novel face in a side-by-side presentation (Pascalis et al., 2002; Pascalis et al., 2005; Scott & Monesson, 2009). This behavioral paradigm may reduce memory load since the initial familiarization period can last 20-30 seconds and faces are presented simultaneously at test (for discussion, see Nelson, 1995). These task details may facilitate behavioral perceptual discrimination in 6-month-olds.

In contrast, the FPVS paradigm in the current study did not include an initial familiarization period or the chance for side-by-side comparison, and also presented multiple novel identities within each 10-second trial. Therefore it is possible that 6-month-olds did not exhibit responses related to changes in face identity because of the increased task demands. A recent rapid repetition ERP-priming task failed to show individual-level human face discrimination in 9-month-olds and similarly suggested that differences in paradigm setup and demands may explain these discrepant results (Peykarjou, Pauen, & Hoehl, 2014). Future work should continue to explore task constraints on young infants' capacity to differentiate stimuli across different levels of measurement.

Post-training

Neural discrimination responses were also measured after training to determine whether brief label-face training had an influence on neural discrimination of a face category. In a post-training FPVS task, infants completed trials with the monkey species paired with labels during training, as well as the monkey species paired with a non-speech noise during training. Importantly, this post-training FPVS task used novel monkey face identities and therefore assessed changes in discrimination ability for the face category in general, and not for explicitly learned faces.

Six-month-old infants did not show a significant oddball response for the species trained with labels or a non-speech noise (Figures 16 and 17). This suggests that brief label training with an unfamiliar face group was not sufficient to elicit neural face discrimination for that face group in younger infants. Similar to the lack of differentiation response prior to training, this is somewhat surprising given the strong behavioral differentiation that 6-monsth-olds routinely demonstrate (Pascalis et al., 2002; Pascalis et al., 2005; Scott & Monesson, 2009). It is possible that if tested on the trained faces instead of novel exemplars from the trained category, 6-month-olds may show a discrimination response and that young infants require more exposure (e.g., 3 months of training: Scott & Monesson, 2009, 2010) to reliably differentiate novel face identities. It is also possible, as discussed above, that the task design (e.g., multiple novel identities, no familiarization period) may limit 6-month-olds' differentiation ability. Finally, as suggested by

Vogel and colleagues (2012), younger infants may recruit fronto-central attentional processes when perceiving faces and it may be the case that the FPVS task is not optimal for capturing such attentional processes. Therefore, labeling faces may draw 6-month-olds' attention to unique features (Best et al., 2010), but this effect of labels is not reflected in ssVEP responses.

In contrast, 9-month-olds did exhibit a significant response at the oddball frequency following training, indicating neural discrimination of monkey faces. Although 9-month-olds showed neural discrimination of monkey faces prior to training, the pattern of results following training suggests that training did impact 9-month-olds' responses. Specifically, 9-month-olds exhibited a significant oddball response for the monkey species paired with individual labels during training (Figure 16), but failed to show a significant oddball response for the species paired with a non-speech noise (Figure 17). Comparisons between regions revealed that, following label training, 9-month-olds showed a significantly larger response at the oddball frequency over frontal versus central regions (Figure 20). However, it is important to note that responses at the oddball frequency over these regions were not significant when compared to the threshold S/N ratio of 1.

Additionally, following label training the response at the oddball frequency was only localized over the right occipital region, whereas prior to training, 9-month-olds showed a widespread response over all regions, as well as a strong response over the right occipito-temporal region. This suggests that learning to match faces with unique labels not only maintained neural discrimination for the face group, but also honed this response to face-related regions. Although strong conclusions about neural generators cannot be made using electrophysiological techniques, the right occipital cortex includes regions that are highly responsive to faces in adults (e.g., fusiform gyrus, inferior occipital cortex) (Gauthier, Tarr, Moylan, Skudlarski, & Gore, 2000; Kanwisher, McDermott, & Chun, 1997; Rossion et al., 2000). Further, many electrophysiological studies report strong face-related responses over right occipital regions in infants (de Haan et al., 2003; de Heering & Rossion, 2015). Therefore, the present results suggest that following individual-level label training, 9-month-olds' neural discrimination responses may become more constrained to face-selective regions rather than recruiting multiple regions and neural processes. Previously, it has been suggested that right lateralization of face responses is closely tied to left lateralization of responses to words as children learn to read (Dundas, Plaut, & Behrmann, 2014). The current findings suggest that other aspects of language development – namely brief word-face learning – may also drive lateralization of face responses and do so much earlier than the onset of reading.

The finding that 9-month-olds exhibit neural discrimination of unfamiliar faces following label training, but not following training with a non-speech noise suggests that the *type* of experience is important for promoting face differentiation. As previous training studies (e.g., Pascalis et al., 2005; Scott & Monesson, 2009, 2010) suggest, experience with individual-level labels facilitates face individuation, while experience with a shared label does not. The current study extends these findings by demonstrating that unique labels seem to have a powerful impact even after relatively brief experience.

Limitations

One limitation of the ERP training task is that a non-speech noise was used as the categorical label. It is possible that enhanced responses for faces paired with individual verbal labels were driven by the presence of a speech sound in general, and not necessarily the individuating nature of the labels. In a previous training study (Scott & Monesson, 2009, 2010), a shared verbal category label was used ("monkey"). Therefore, we may see slightly different results if comparing responses in the presence of individual- versus category-level speech labels. However, the use of a non-speech noise provides an initial, more conservative comparison and serves as an important first step to demonstrating the unique effects of individuating labels. Additionally, infants can use non-speech sounds (e.g., tones) to shape object categorization when these sounds are used with communicative intent (Ferguson & Lew-Williams, 2014). Therefore, our results are not necessarily driven solely by the speech versus non-speech comparison. Future work should compare responses to individual versus category speech labels to further discern how important the impact of *unique* labels are. Similarly, it is possible that the differences between sound conditions reflect responses to the auditory stimuli that would be present even in the absence of visual stimuli. In this case, the reported differential responses would not indicate enhanced visual processing, but instead reflect differences between sound conditions driven by auditory processing. Future work examining responses in an auditory-only paradigm could clarify this issue.

One notable limitation of the post-training ssVEP findings is the small sample size. Many infants did not complete the post-training FPVS task and therefore the current post-training results reflect subsets of infants who contributed enough trials in a given condition. In order to achieve somewhat reasonable sample sizes for analyses, separate subsets of participants were used for the post-training label condition and the post-training noise condition analyses.[3] While this method requires caution when interpreting results and comparing conditions, it is comparable to a between-subjects design and therefore retains overall validity.

Conclusions

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[3] Only five 6-month-olds and nine 9-month-olds contributed data to the pre-training ssVEP and both label and non-speech noise post-training ssVEP datasets. See the Participants subsection of the Methods section for specific *n*s for each condition and age group.

In conclusion, the present study provides evidence for three important aspects of the development and tuning of face perception in the first year of life. First, unique labels influence visual processing *during* learning. As infants hear labels paired with unfamiliar faces, face-sensitive neural responses are enhanced over occipital regions. Additionally, there may be qualitative differences in the influence of labels emerging between 6 and 9 months of age, such that younger infants exhibit label-related effects at an early stage of processing while older infants demonstrate a shift in label-related effects from earlier to later stages of processing, as indexed by a shift from the N290 to P400 ERP component. The label-related effects at 6 months suggest that even young infants use words to shape their perception of the world around them, although the additional components and regions seen at 9 months indicate that the way in which words influence learning and perception may change across development to involve additional brain regions and stages of processing.

Second, in contrast to behavioral findings (Pascalis et al., 2002; Pascalis et al., 2005; Scott & Monesson, 2009), 9-month-olds, but not 6-month-olds, show neural discrimination of an unfamiliar face group as measured by ssVEP. Along with a previous ERP study (Scott et al., 2006), these findings indicate that perceptual narrowing/tuning is a complex process that cannot be fully captured by behavioral measures. Interestingly, the finding that 6-month-olds do not show robust neural discrimination of an unfamiliar face group demonstrates that narrowing/tuning involves more than perceptual processes and should guide future research towards exploring other mechanisms (e.g., selective attention) that drive narrowing/tuning.

Finally, brief experience matching unique labels with unfamiliar faces was sufficient to influence 9-month-olds' neural discrimination of the face group. Specifically, individuating experience may reduce the need for multiple brain regions and processes to be involved in differentiating among faces and hone the face identity response to face-related occipital regions. This post-training change suggests that labels not only function as a tool to shape face perception in the moment, but also may help to reorganize how faces are processed during future encounters. Ultimately, the results of this study will serve to broaden our understanding of how experience can shape learning and face perception across development.

Table 1: Significant main effects for 6-month-olds: Means with standard errors in parentheses

Component	Entire training period		1st half of trials		2nd half of trials	
	Label	Noise	Label	Noise	Label	Noise
P1 mean amplitude/µV	5.91 (1.18)	4.43 (1.56)	7.57 (1.63)	6.71 (1.64)	5.52 (2.02)	6.32 (1.05)
P1 latency/ms	147.90 (4.52)	154.25 (4.61)	150.10 (4.92)	154.55 (4.24)	**144.17 (5.15)***	**153.07 (4.91)***
N290 mean amplitude/µV	-0.15 (1.52)	3.38 (1.99)	2.20 (2.95)	2.69 (2.68)	**-2.08 (1.52)***	**4.21 (2.33)***
N290 latency/ms	264.23 (4.45)	264.65 (6.12)	264.33 (5.14)	266.03 (5.63)	256.93 (4.91)	262.65 (5.44)
P400 mean amplitude/µV	11.10 (1.89)	10.40 (2.47)	9.48 (3.14)	7.17 (2.55)	10.19 (2.78)	13.38 (3.66)
P400 latency/ms	387.46 (4.84)	385.29 (3.97)	382.80 (5.51)	383.02 (4.24)	382.08 (4.75)	382.87 (3.48)
Nc mean amplitude/µV	-1.51 (1.46)	0.57 (1.44)	0.10 (2.10)	-0.08 (1.70)	-0.07 (2.14)	-1.77 (1.40)
Nc latency/ms	**509.75 (18.70)****	**443.28 (15.18)****	**490.08 (22.04)***	**444.25 (22.41)***	499.29 (22.15)	465.33 (19.13)

* and bolded text denotes significant differences (* denotes *p* < .05; ** denotes *p* < .01)

Table 2: Significant main effects for 9-month-olds: Means with standard errors in parentheses

Component	Entire training period		1st half of trials		2nd half of trials	
	Label	Noise	Label	Noise	Label	Noise
P1 mean amplitude/µV	6.10 (1.36)	6.81 (1.19)	5.75 (1.57)	7.55 (1.48)	5.83 (1.81)	5.78 (1.48)
P1 latency/ms	**140.00 (3.79)****	**152.30 (2.69)****	**136.70 (4.69)****	**151.83 (3.41)****	**139.71 (3.74)***	**148.90 (3.37)***
N290 mean amplitude/µV	**2.17 (1.76)****	**7.12 (1.24)****	**2.62 (2.19)**	**7.33 (1.59)**	1.01 (2.33)	4.81 (1.43)
N290 latency/ms	257.33 (3.11)	254.11 (3.56)	258.24 (4.27)	258.86 (4.14)	255.79 (4.72)	251.96 (4.95)
P400 mean amplitude/µV	**14.96 (2.60)***	**19.28 (2.10)***	14.40 (2.49)	16.43 (2.69)	**13.22 (3.09)***	**20.25 (2.05)***
P400 latency/ms	386.88 (3.33)	382.41 (3.63)	388.44 (3.95)	382.70 (4.70)	384.87 (4.11)	383.86 (3.81)
Nc mean amplitude/µV	-4.50 (2.18)	-7.56 (0.84)	-5.54 (2.65)	-5.46 (1.44)	-2.20 (3.47)	-10.02 (1.39)
Nc latency/ms	452.22 (10.86)	427.44 (12.10)	444.68 (13.08)	435.04 (11.98)	458.32 (13.71)	432.54 (12.16)

* and bolded text denotes significant differences (* denotes *p* < .05; ** denotes *p* < .01); bolded alone indicates marginally significant differences

Table 3: Significant interactions for 6-month-olds: Means with standard errors in parentheses

Component	Left region		Right region	
	Label	Noise	Label	Noise
P1 mean amplitude/µV	4.24 (1.27)	2.44 (1.55)	7.57 (1.45)	6.42 (1.84)
P1 latency/ms	150.30 (6.06)	155.75 (5.41)	145.50 (4.74)	152.75 (5.14)
N290 mean amplitude/µV	0.98 (1.71)	2.78 (2.18)	**-1.28** **(1.67)***	**3.97** **(2.19)***
N290 latency/ms	265.78 (4.63)	270.25 (6.06)	262.68 (5.23)	259.05 (7.31)
P400 mean amplitude/µV	9.73 (2.23)	7.84 (2.63)	12.64 (1.93)	12.94 (2.59)
P400 latency/ms	388.10 (4.93)	389.33 (4.69)	386.83 (5.87)	381.25 (5.05)

* and bolded text denotes significant differences (* denotes $p < .05$; ** denotes $p < .01$)

Table 4: Significant interactions for 9-month-olds: Means with standard errors in parentheses

Component	Left region		Right region	
	Label	Noise	Label	Noise
P1 mean amplitude/µV	3.56 (1.10)	4.32 (1.00)	8.63 (2.00)	9.29 (2.16)
P1 latency/ms	**134.43** **(5.62)****	**154.78** **(4.21)****	145.55 (4.00)	149.83 (3.31)
N290 mean amplitude/µV	-0.27 (1.95)	4.32 (1.62)	4.62 (2.54)	9.91 (2.26)
N290 latency/ms	269.30 (4.48)	263.63 (5.33)	245.35 (3.99)	244.60 (4.91)
P400 mean amplitude/µV	11.55 (3.07)	15.84 (2.64)	18.36 (3.17)	22.72 (2.40)
P400 latency/ms	390.78 (3.56)	385.35 (6.05)	382.98 (6.07)	379.48 (4.42)

* and bolded text denotes significant differences (* denotes $p < .05$; ** denotes $p < .01$)

Table 5: Significant follow ups for 6-month-olds: Means with standard errors in parentheses

Component	Hemisphere	1st half of trials		2nd half of trials	
		Label	Noise	Label	Noise
N290 mean amplitude/µV	Right hemisphere	0.54 (3.72)	1.68 (3.07)	**-1.93** **(1.76)***	**7.02** **(2.96)***
Nc latency/ms	Collapsed across hemispheres	**490.08** **(22.04)***	**444.25** **(22.41)***	499.29 (22.15)	465.33 (19.13)

* and bolded text denotes significant differences (* denotes $p < .05$; ** denotes $p < .01$); bolded alone indicates marginally significant differences

Table 6: Significant follow ups for 9-month-olds: Means with standard errors in parentheses

Component	Hemisphere	1st half of trials		2nd half of trials	
		Label	Noise	Label	Noise
P1 latency/ms	Collapsed across hemispheres	**136.70 (4.69)***	**151.83 (3.41)***	**139.71 (3.74)***	**148.90 (3.37)***
P1 latency/ms	Left hemisphere	**130.74 (7.13)***	**152.83 (4.88)***	**137.77 (5.05)***	**153.17 (5.34)***
N290 mean amplitude/µV	Collapsed across hemispheres	**2.26 (2.19)**	**7.33 (1.58)**	1.01 (2.33)	4.81 (1.43)
P400 amplitude/ms	Collapsed across hemispheres	14.40 (2.49)	16.43 (2.67)	**20.25 (2.05)***	**13.22 (3.09)***

* and bolded text denotes significant differences (* denotes $p < .05$; ** denotes $p < .01$); bolded alone indicates marginally significant differences

Table 7: 6-month-olds' ssVEP responses

Frequency	**Condition**	**Region**	**S/N ratio**	**SE**	**p-value**
Base (6 Hz)	Pre-training	Left occipital	2.635*	.260	< .001
		Middle occipital	3.437*	.377	< .001
		Right occipital	3.247*	.293	< .001
	Post-training: Label	Left occipital	2.798*	.434	.003
		Middle occipital	4.134*	.892	.008
		Right occipital	3.427*	.620	.004
	Post-training: Noise	Left occipital	2.353^{+}	.380	.012
		Middle occipital	4.136^{+}	.903	.013
		Right occipital	3.306*	.554	.006
Oddball (1.2 Hz)	Pre-training	Left occipital	1.092	.056	.113
		Middle occipital	1.088	.060	.158
		Right occipital	1.131	.080	.115
		Frontal	1.116	.067	.096
		Central	1.093	.068	.183
	Post-training: Label	Left occipital	1.249	.106	.047
		Middle occipital	1.097	.108	.398
		Right occipital	1.001	.126	.993
		Frontal	0.868	.152	.410
		Central	1.070	.119	.573
	Post-training: Noise	Left occipital	1.344	.118	.026
		Middle occipital	1.083	.160	.624
		Right occipital	1.003	.079	.972
		Frontal	0.846	.103	.184
		Central	0.980	.097	.844

Compared to a $p < .01$ threshold: * $p < .01$, $^{+}$ $p < .02$ (marginal)

Table 8: 9-month-olds' ssVEP responses

Frequency	**Condition**	**Region**	**S/N ratio**	**SE**	**p-value**
Base (6 Hz)	Pre-training	Left occipital	2.407*	.305	< .001
		Middle occipital	3.275*	.306	< .001
		Right occipital	2.807*	.234	< .001
	Post-training: Label	Left occipital	2.405*	.256	< .001
		Middle occipital	3.088*	.476	.001
		Right occipital	2.692*	.407	.001
	Post-training: Noise	Left occipital	2.384*	.332	.002
		Middle occipital	3.568*	.602	.002
		Right occipital	3.156*	.449	.001
Oddball (1.2 Hz)	Pre-training	Left occipital	1.318*	.101	.005
		Middle occipital	1.301*	.088	.003
		Right occipital	1.561*	.126	< .001
		Frontal	1.182*	.063	.001
		Central	1.310*	.083	.001
	Post-training: Label	Left occipital	1.180	.150	.256
		Middle occipital	1.219	.112	.075
		Right occipital	1.409*	.130	.008
		Frontal	1.306	.175	.106
		Central	0.895	.103	.329
	Post-training: Noise	Left occipital	1.007	.122	.954
		Middle occipital	0.883	.104	.285
		Right occipital	0.976	.085	.786
		Frontal	0.865	.064	.060
		Central	0.904	.097	.346

Compared to a p < .01 threshold: * p < .01, $^{+}$ p < .02 (marginal)

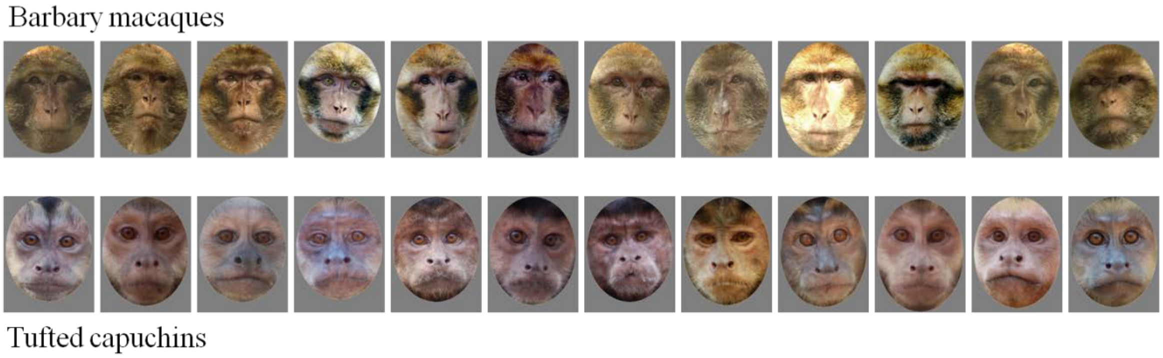

Figure 1. Stimulus set of monkey faces.

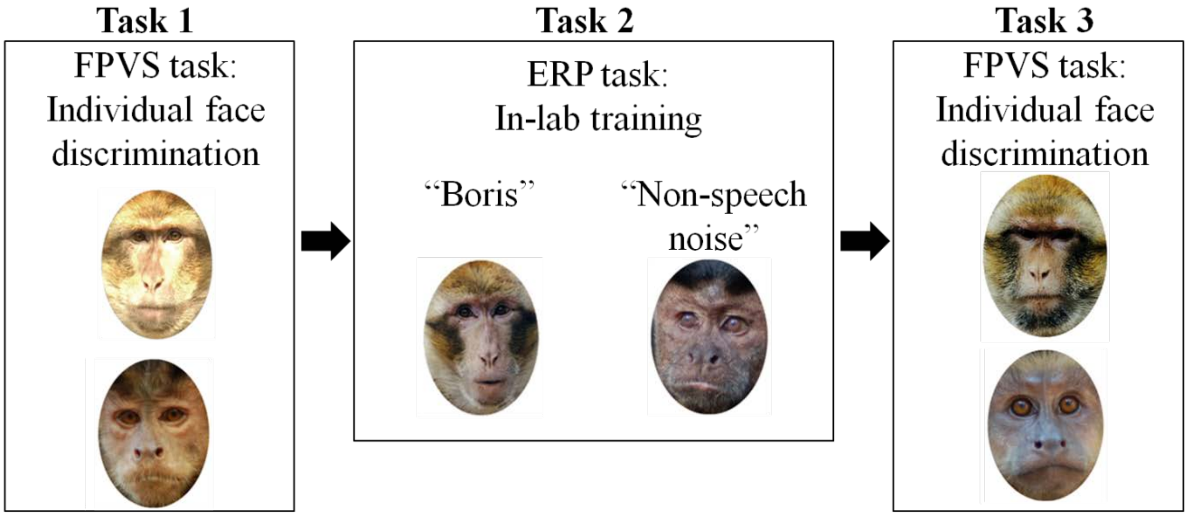

Figure 2. Overview of experimental session. Infants completed training and a pre-/post-training assessment with two face groups. During training, one set of faces was paired with individual-level verbal labels, and the other set was paired with a non-speech noise.

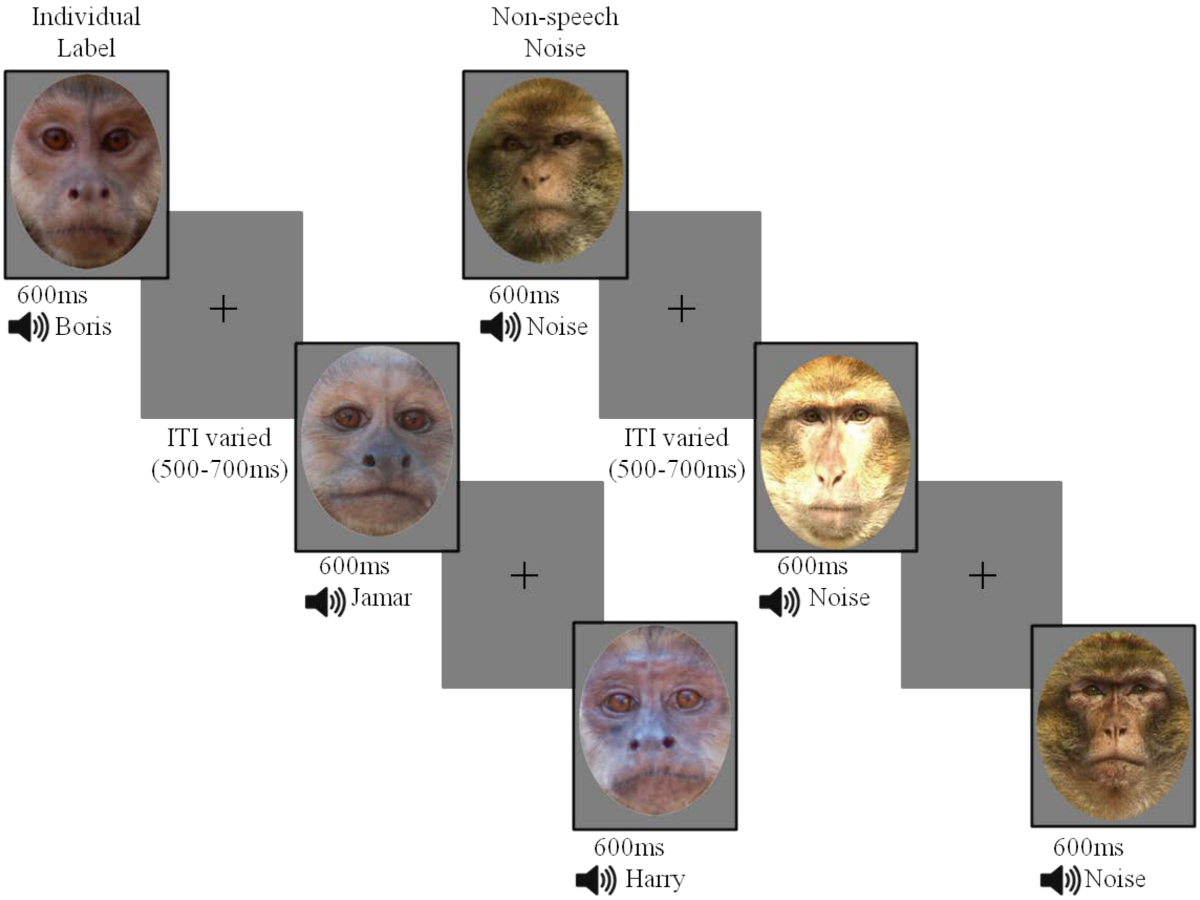

Figure 3. ERP training task. Infants completed two “blocks” of training: Individual-level labels, and a non-speech noise. Infants viewed 4 unique faces paired with a label (or noise). Faces were repeated up to 15 times throughout the training block, in a randomized order with no immediate exemplar repetitions.

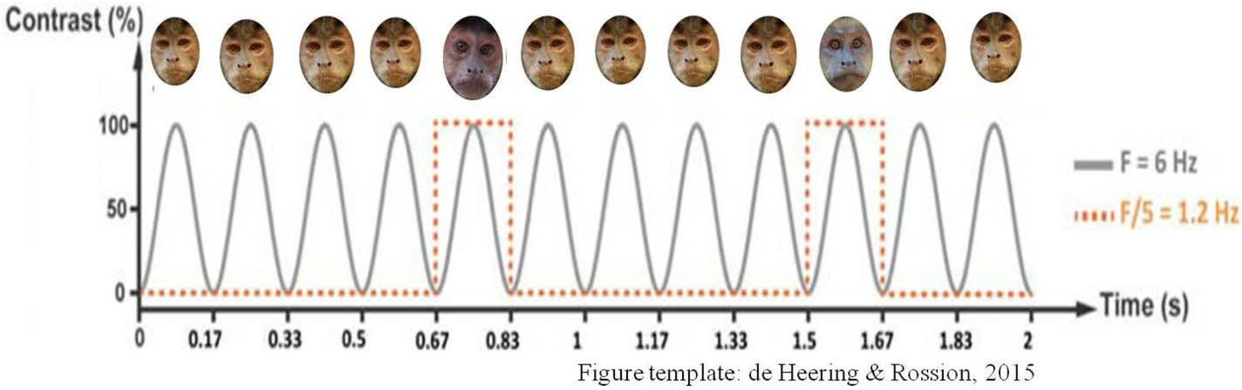

Figure 4. FPVS pre-/post-training oddball task. Infants completed up to 10 “trials” of the oddball task for each of the trained face groups, and viewed novel exemplars relative to the training task. Faces were presented at a rate of 6 faces per second (base rate: 6 Hz). Every 5th face was a different face identity (oddball rate: 1.2 Hz).

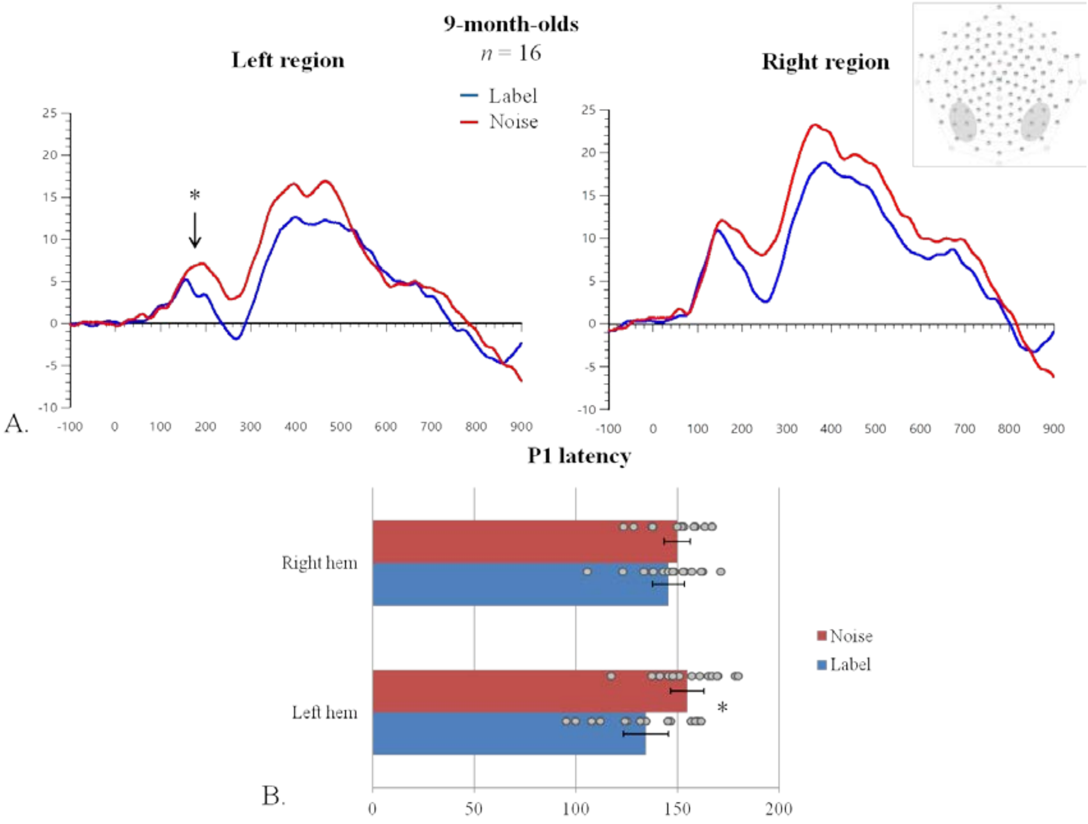

Figure 5. (A) ERP waveforms in response to label and non-speech noise conditions for 9-month-olds. The latency to peak P1 amplitude over the left hemisphere is faster in response to monkey faces paired with labels versus those paired with a non-speech noise. Significant latency differences are marked with an arrow. (B) Bar graph displaying the latency to peak differences between conditions for each hemisphere. Error bars represent 95% confidence intervals and circles represent individual subject data.

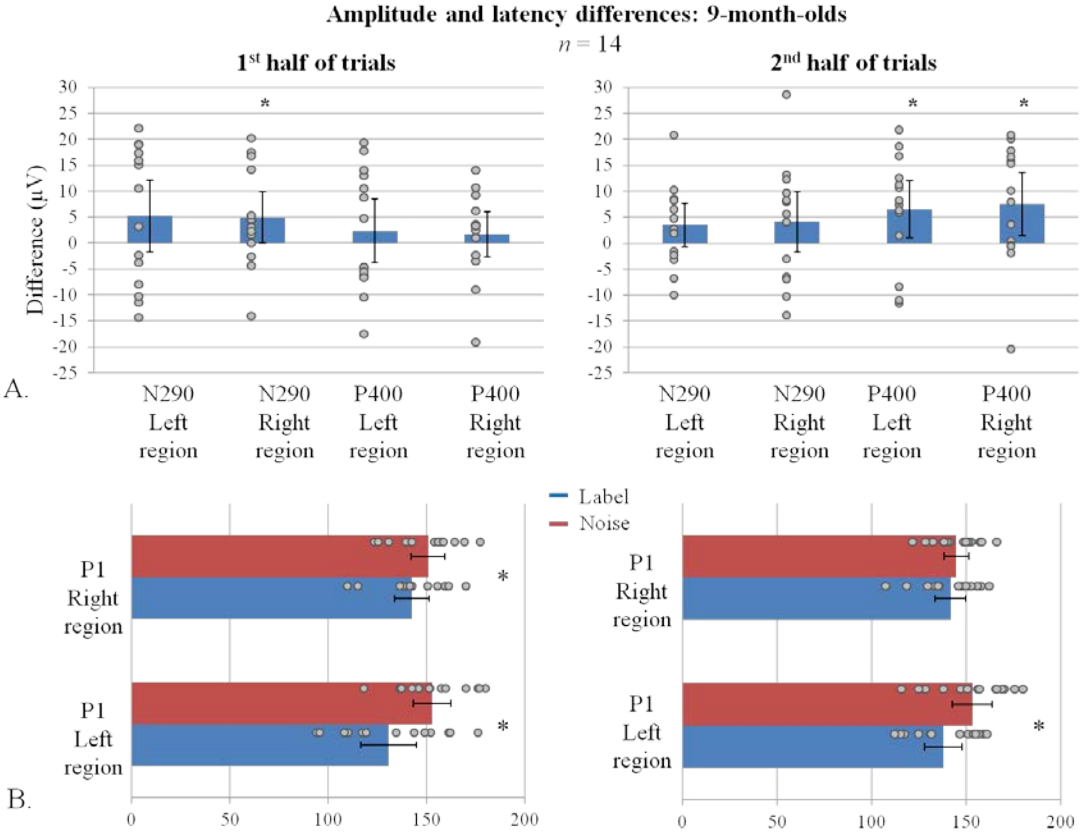

Figure 6. Difference and individual variability in 9-month-olds' ERP response between Noise and Label conditions for the first and second halves of the training period. (A) Amplitude differences are computed as Noise – Label for the first and second halves of the training period. (B) Latency differences are displayed with bars representing latency to peak in each condition. Error bars represent 95% confidence intervals and circles represent individual subject data. Significant differences between conditions are marked with asterisks.

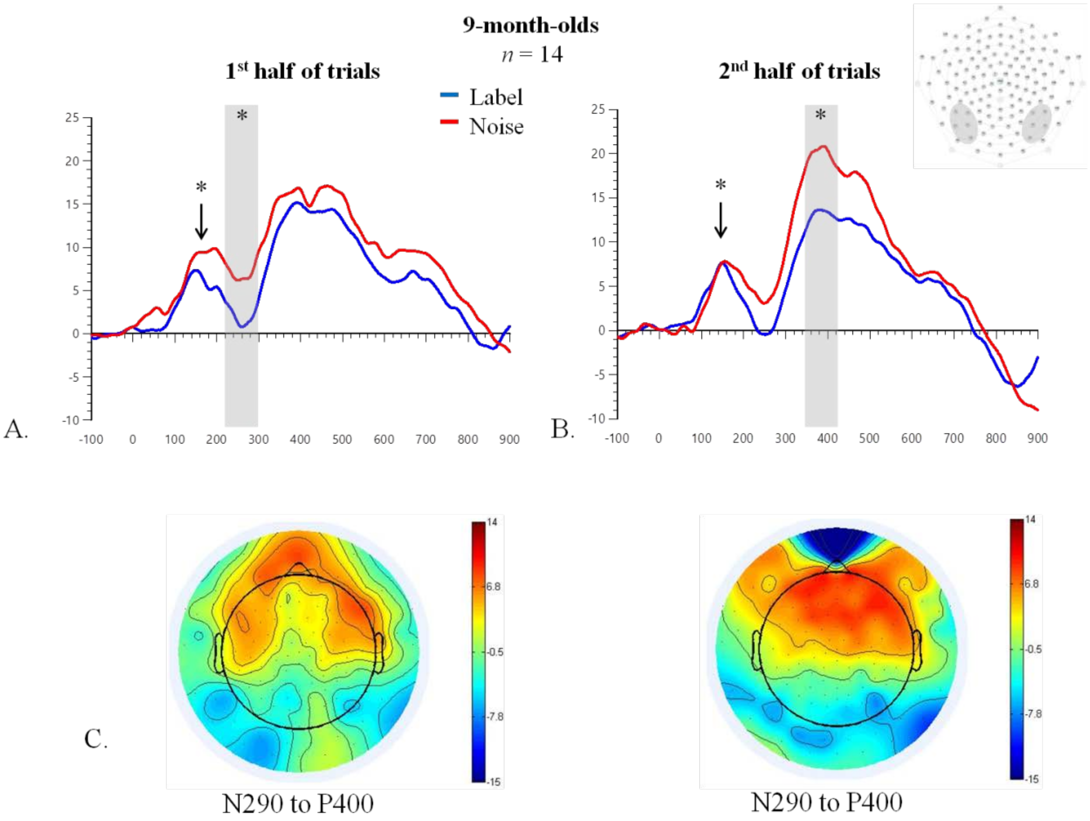

Figure 7. ERP waveforms in response to label and non-speech noise conditions for 9-month-olds for the first (A) and second (B) half of the training period. Nine-month-old infants exhibited a larger N290 amplitude in response to the label versus noise condition during the first half of trials, and a larger P400 amplitude in response to the noise versus label condition during the second half of trials. Nine-month-olds also exhibited a faster latency to peak P1 amplitude in response to the label versus noise conditions in both the first and second halves of trials. Significant amplitude differences are marked with a box. Significant latency differences are marked with an arrow. (C) Headplot displaying the difference in amplitude response between the label and non-speech noise conditions for the first and second half of the training period, for time period between the N290 and P400 components. Larger negative values (cooler colors) represent a larger negative amplitude in the label versus noise condition.

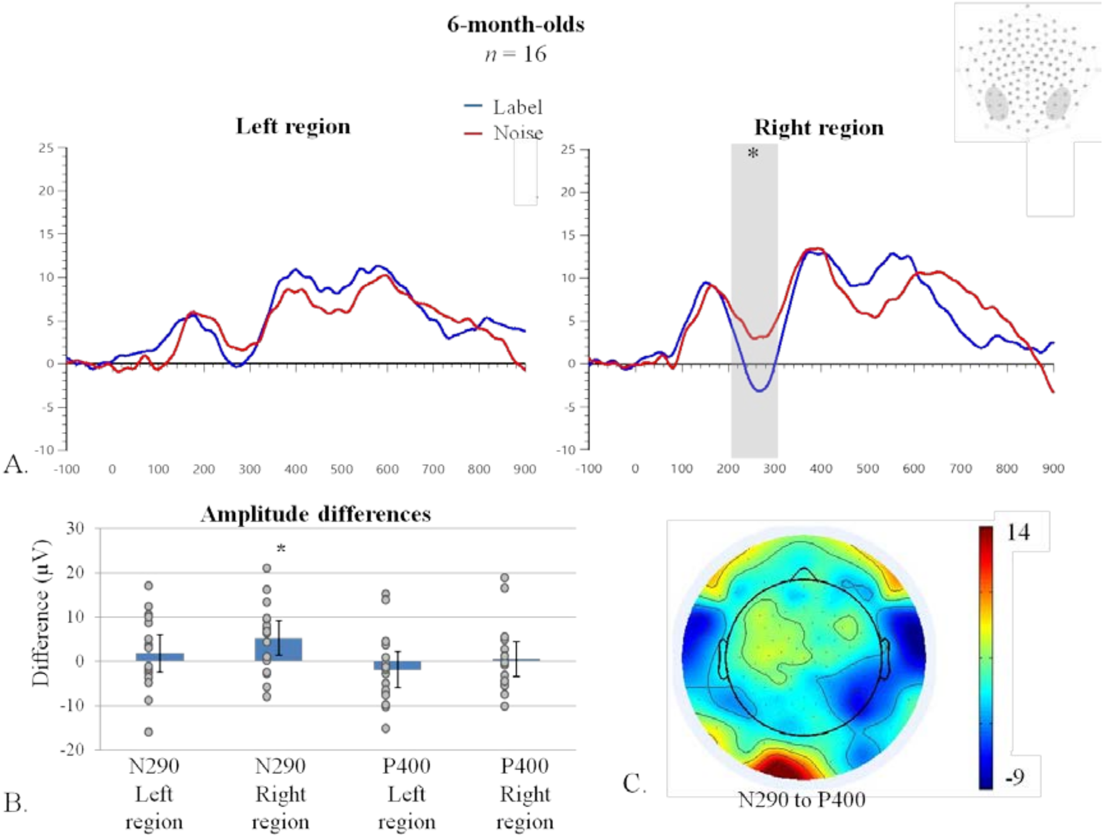

Figure 8. (A) ERP waveforms in response to label and non-speech noise conditions for 6-month-olds. The N290 amplitude over the right hemisphere is larger in response to monkey faces paired with labels versus those paired with a non-speech noise. Significant amplitude differences are marked with a box. (B) Difference and individual variability in 6-month-olds' ERP amplitude response between Noise and Label conditions. Amplitude differences are computed as Noise – Label for the entire training period. Error bars represent 95% confidence intervals and circles represent individual subject data. Significant differences between conditions are marked with asterisks. (C) Headplot displaying the difference in amplitude response between the label and non-speech noise conditions from the beginning of the N290 window to the end of the P400 window. Larger negative values (cooler colors) represent a larger negative amplitude in the label versus noise condition.

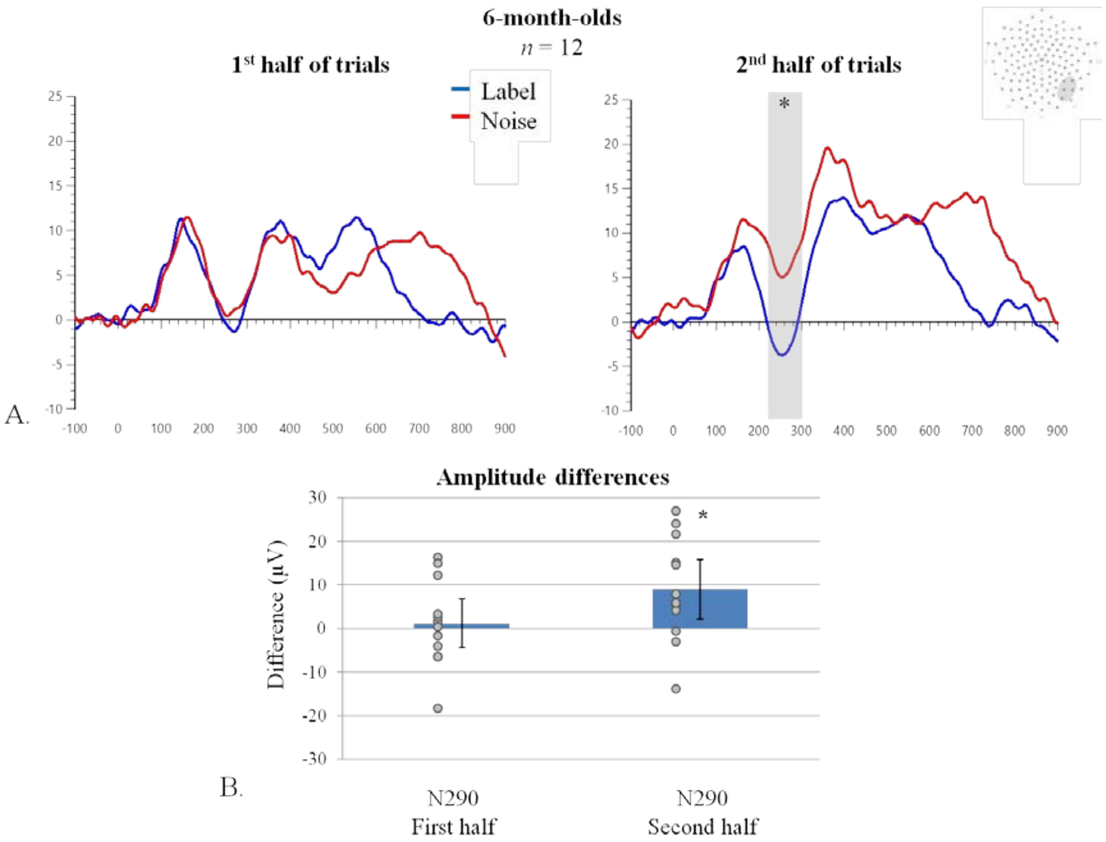

Figure 9. ERP waveforms in response to label and non-speech noise conditions for 6-month-olds during the first and second half of trials. (A) Consistent with the entire training period results, during the second half of trials, 6-month-olds exhibit a larger N290 amplitude in response to the label versus noise condition over the right region, but not the left region. (B) Difference and individual variability in 6-month-olds’ ERP amplitude response between Noise and Label conditions. Amplitude differences are computed as Noise – Label for the first and second half of the training period over the right region. Error bars represent 95% confidence intervals and circles represent individual subject data. Significant differences between conditions are marked with asterisks.

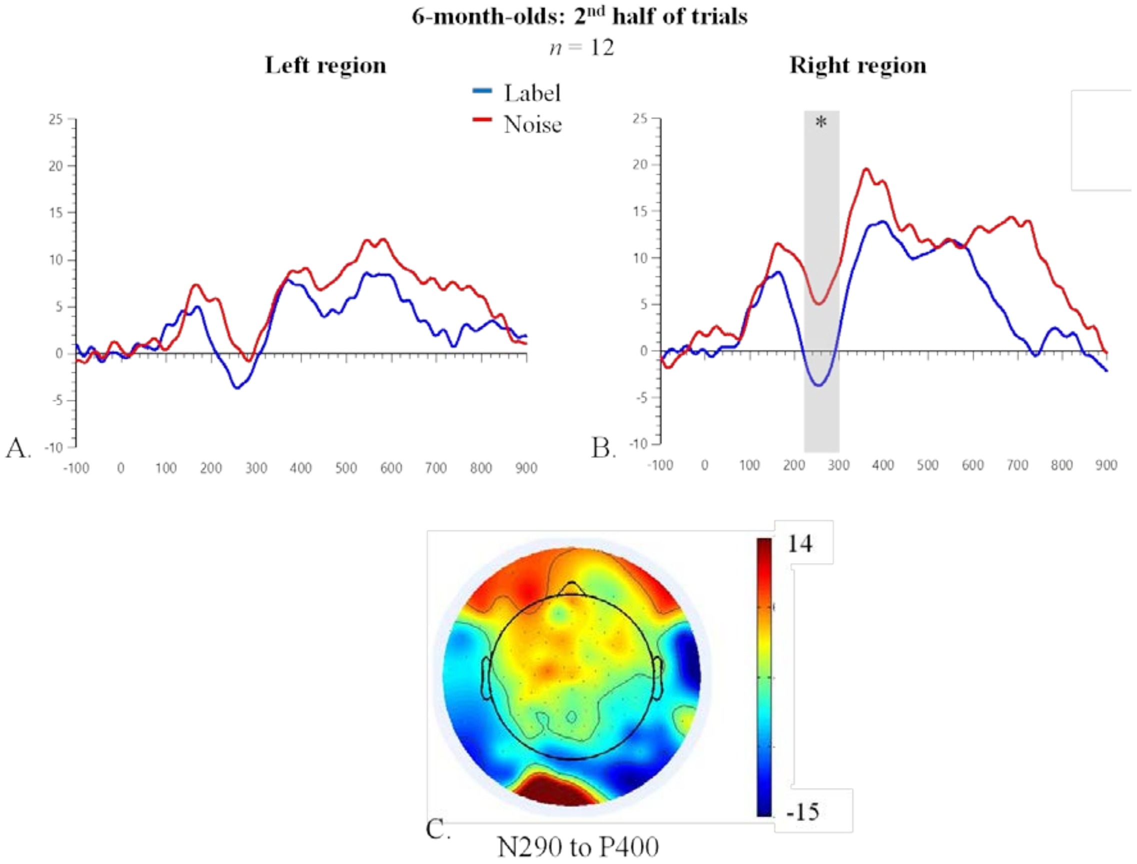

Figure 10. ERP waveforms in response to label and non-speech noise conditions for 6-month-olds during the second half of trials, over the left (A) and right(B) scalp regions. Consistent with the entire training period results, during the second half of trials, 6-month-olds exhibit a larger N290 amplitude in response to the label versus noise condition over the right region, but not the left region. (C) Headplot displaying the difference in amplitude response between the label and non-speech noise conditions for the second half of the training period, for time period between the N290 and P400 components. Larger negative values (cooler colors) represent a larger negative amplitude in the label versus noise condition.

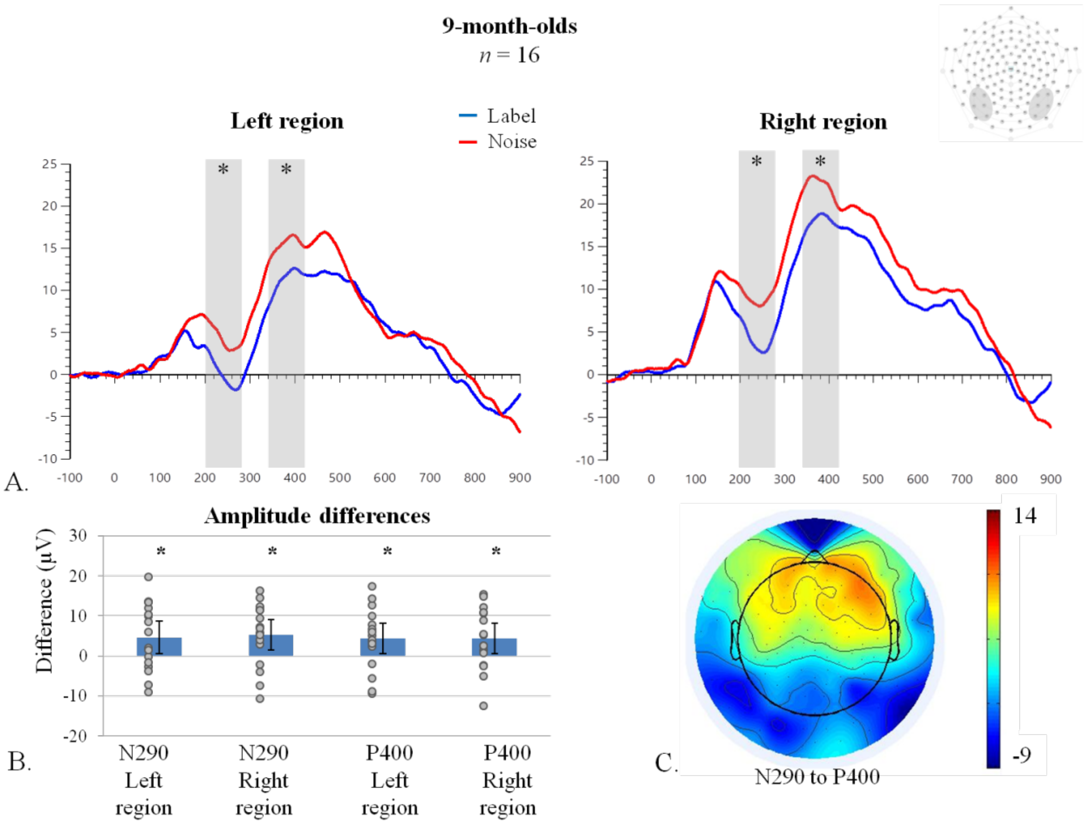

Figure 11. (A) ERP waveforms in response to label and non-speech noise conditions for 9-month-olds. The N290 amplitude over left and right hemispheres is larger in response to monkey faces paired with labels versus those paired with a non-speech noise. Additionally, the P400 amplitude over both hemispheres is larger in response to the noise versus label condition. Significant amplitude differences are marked with a box. (B) Difference and individual variability in 9-month-olds' ERP amplitude response between Noise and Label conditions. Amplitude differences are computed as Noise – Label for the entire training period. Error bars represent 95% confidence intervals and circles represent individual subject data. Significant differences between conditions are marked with asterisks. (C) Headplot displaying the difference in amplitude response between the label and non-speech noise conditions for the time period between the N290 and P400 components. Larger negative values (cooler colors) represent a larger negative amplitude in the label versus noise condition.

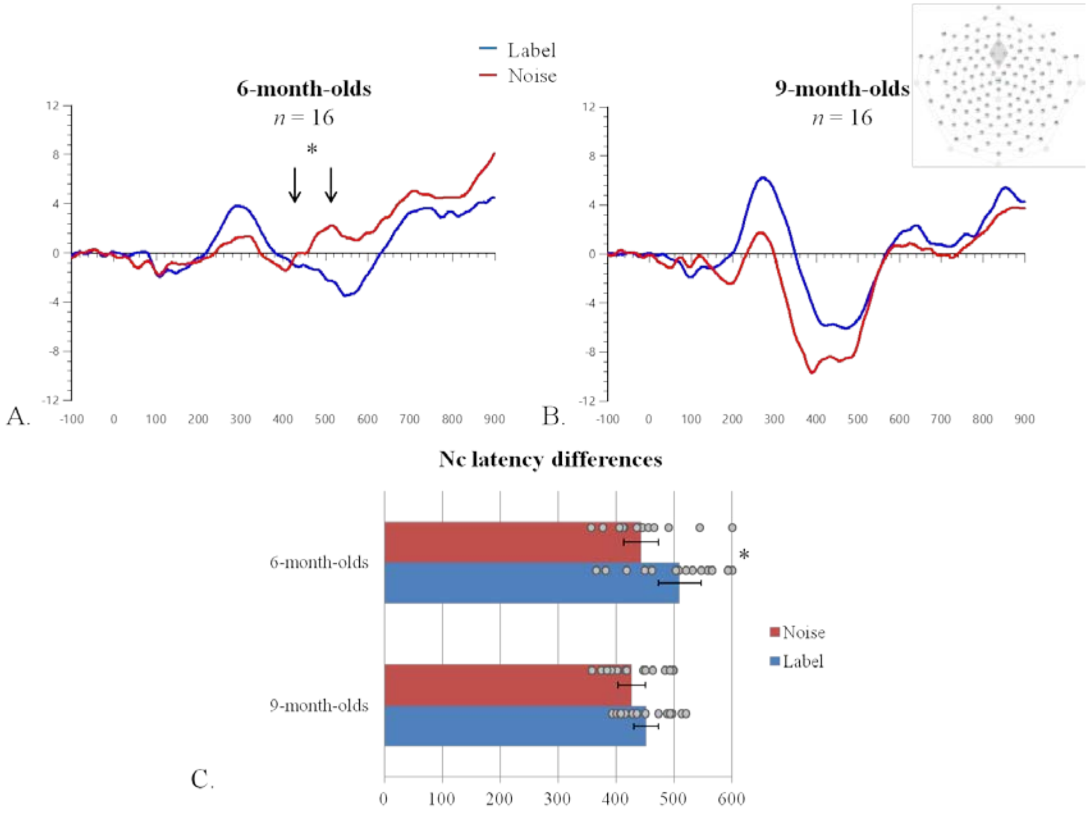

Figure 12. (A-B) ERP waveforms in response to label and non-speech noise conditions for 6-month-olds (A) and 9-month-olds (B). At 6 months, the latency to peak Nc amplitude is faster in response to monkey faces paired with a non-speech noise versus those paired with labels. Significant latency differences are marked with an arrow. (B) Bar graph displaying the latency to peak differences between conditions for each age group. Error bars represent 95% confidence intervals.

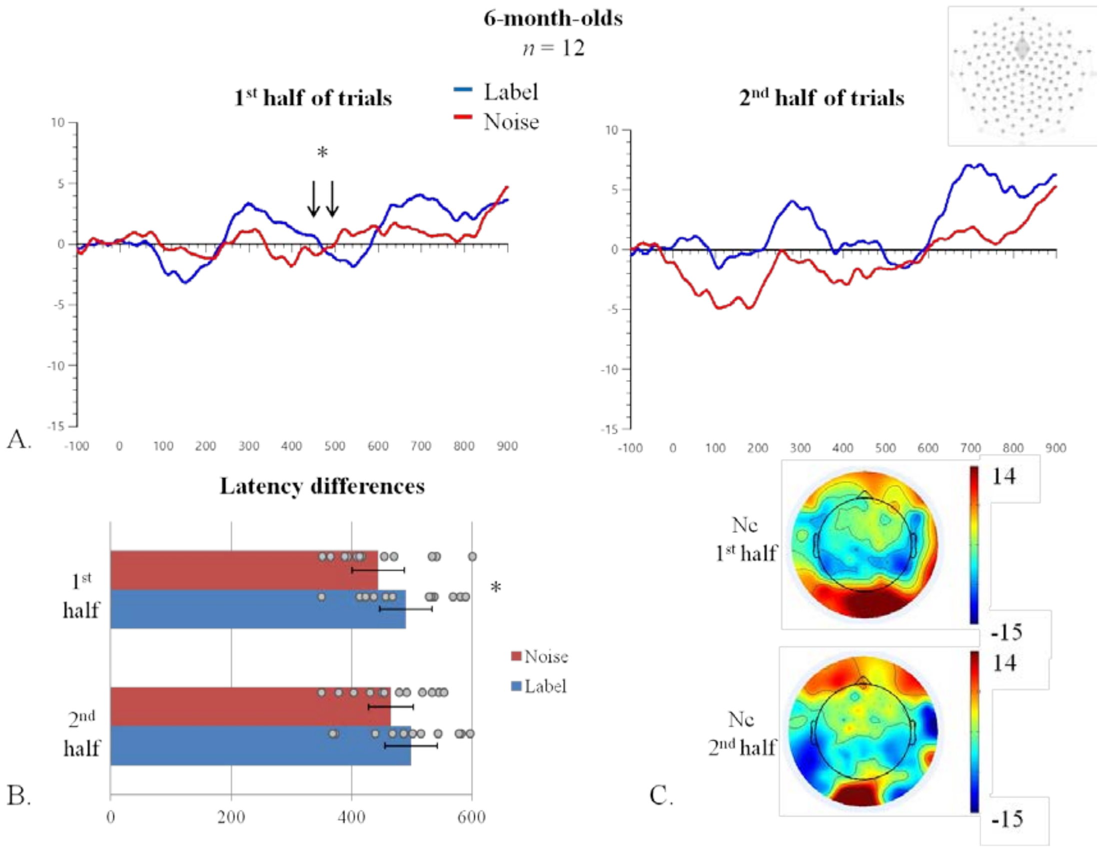

Figure 13. ERP waveforms in response to label and non-speech noise conditions for 6-month-olds for the first and second halves of the training period. (A) Six-month-old infants exhibit a faster latency to peak Nc amplitude in response to the noise versus label condition in the first half of trials. Significant latency differences are marked with an arrow. (B) Latency to peak differences between conditions for 6-month-olds in each half of the training period. Error bars represent 95% confidence intervals and circles represent individual subject data. Significant differences between conditions are marked with asterisks. (C) Headplots displaying the difference in amplitude response between the label and non-speech noise conditions for the first and second half of the training period, for time period of the Nc component. Larger negative values (cooler colors) represent a larger negative amplitude in the label versus noise condition.

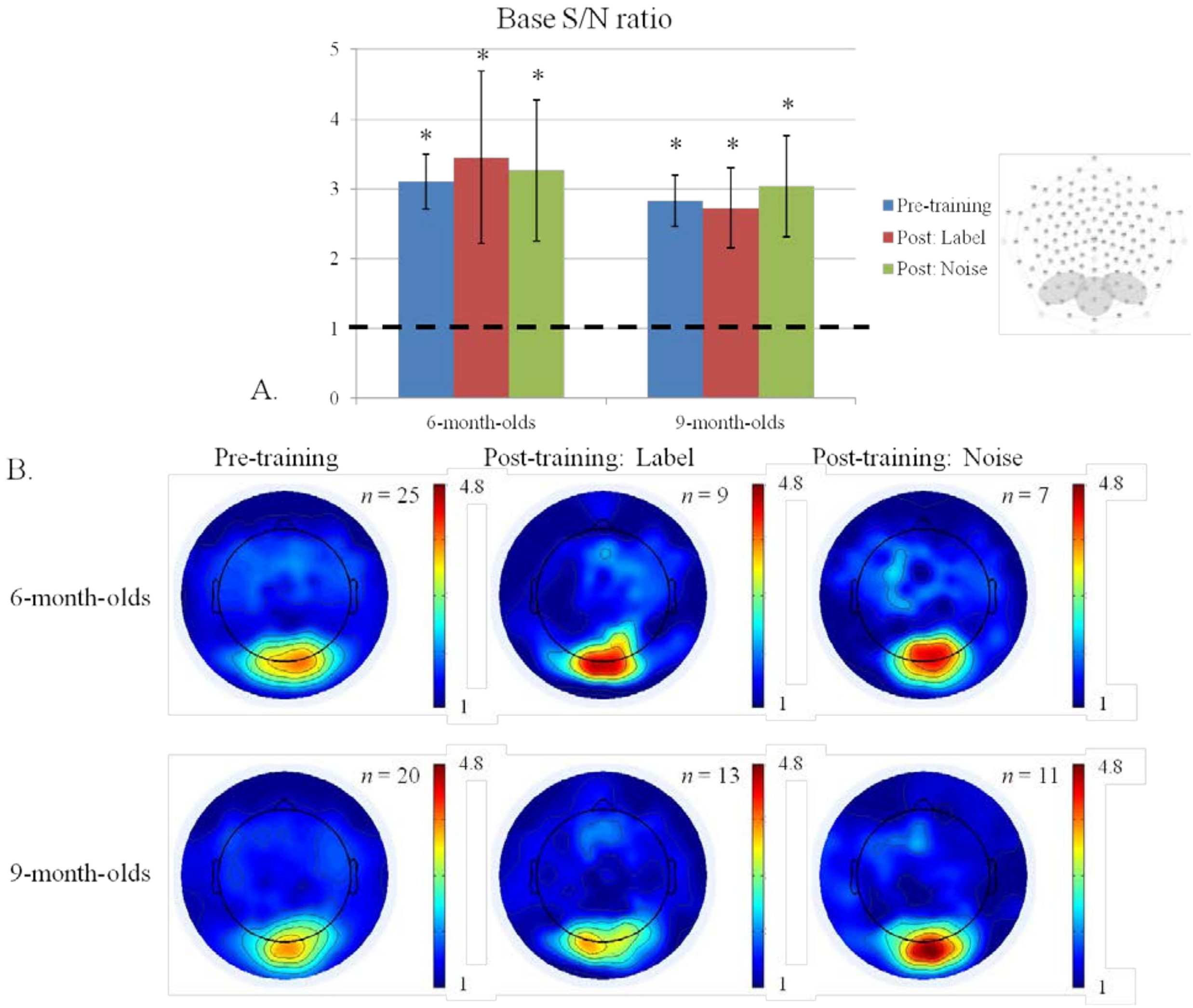

Figure 14. S/N ratios at the base frequency for each age group and time point, collapsed over occipital regions. (A) Bar graph of S/N ratios for each age group and time point. At all time points, 6- and 9-month-olds exhibited a significant S/N ratio (relative to 1). Error bars represent 99% confidence intervals to reflect the $p < .01$ threshold used in these analyses. (B) Headplots displaying S/N ratios for each age group and time point. Larger numbers (warmer colors) indicate a higher S/N ratio relative to 1.

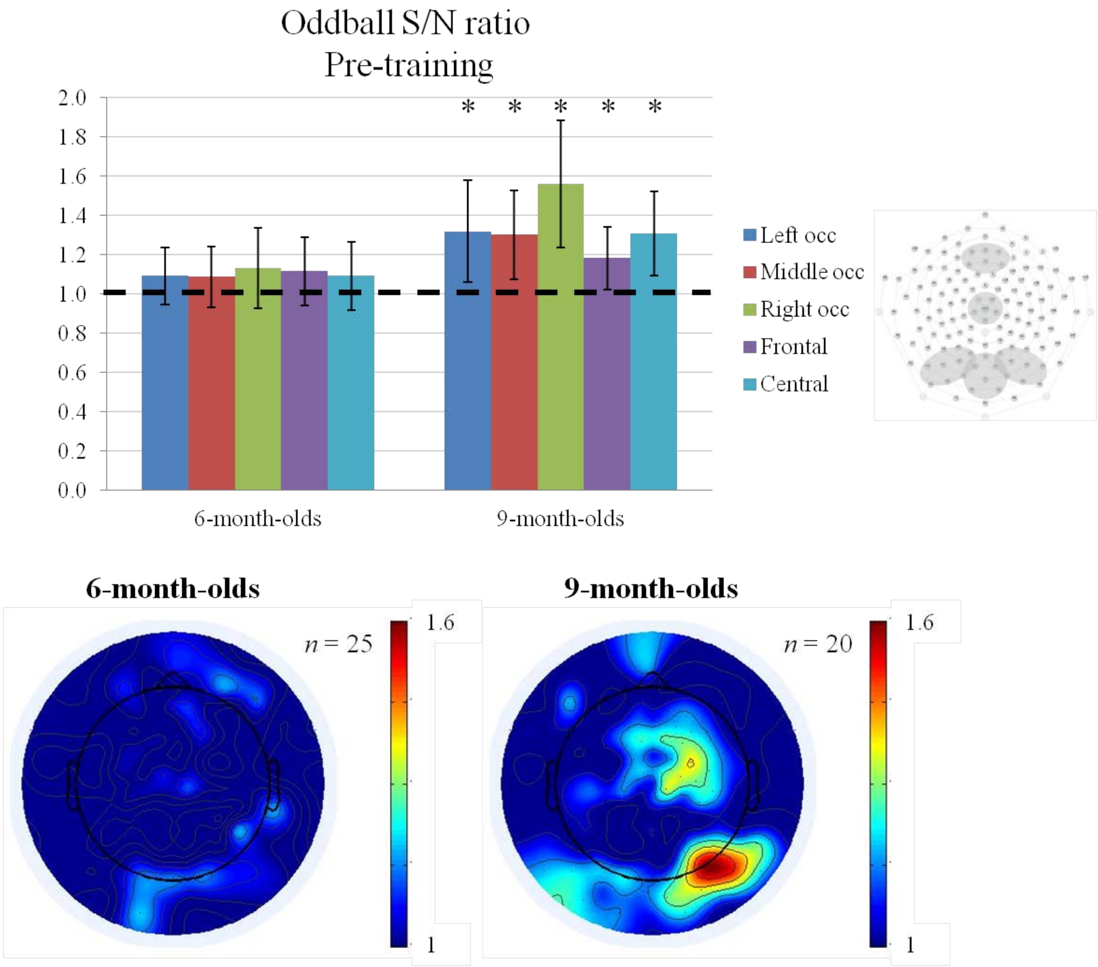

Figure 15. S/N ratios at the oddball frequency for each age group and region at the pre-training time point. (A) Bar graph of S/N ratios for each age group and region. Nine-month-olds exhibited a significant S/N ratio (relative to 1) over all regions. Error bars represent 99% confidence intervals to reflect the *p* < .01 threshold used in these analyses. (B) Headplots displaying S/N ratios for each age group. Larger numbers (warmer colors) indicate a higher S/N ratio relative to 1.

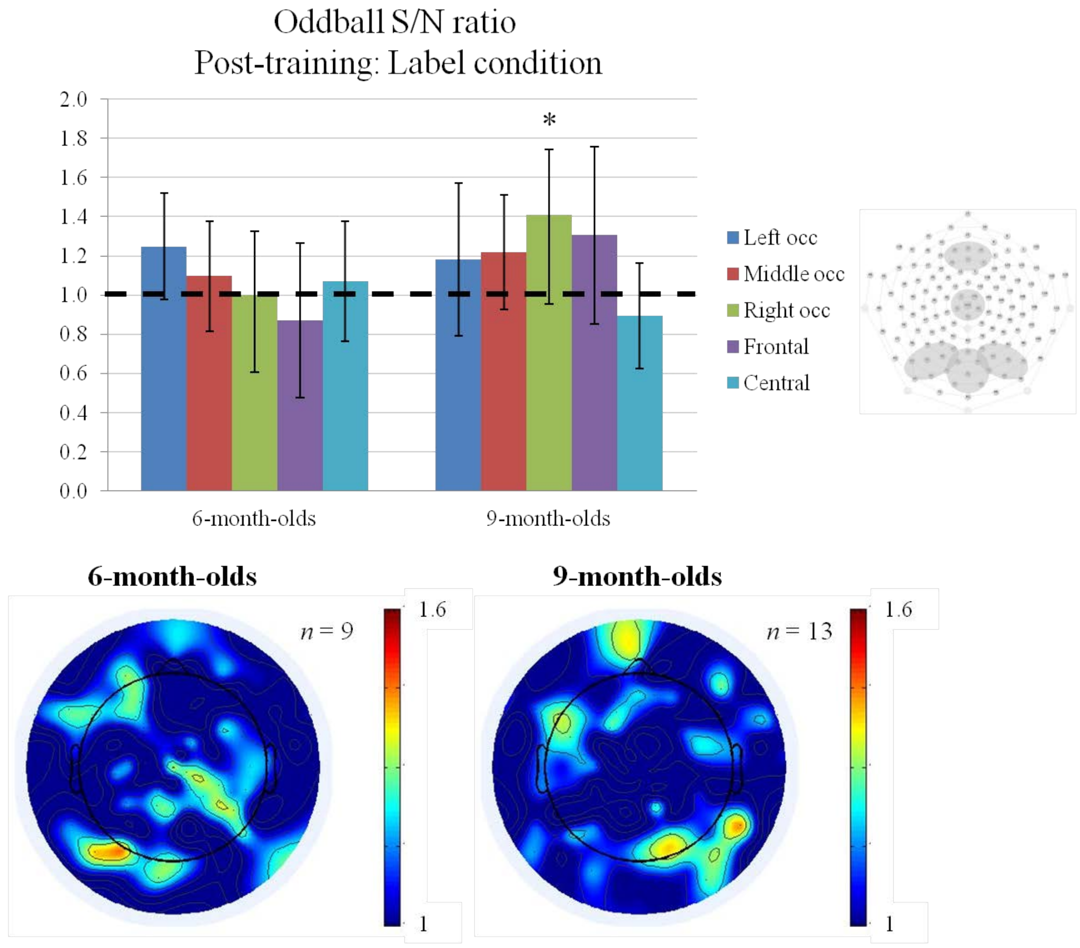

Figure 16. S/N ratios at the oddball frequency for each age group and region at the post-training: Label condition time point. (A) Bar graph of S/N ratios for each age group and region. Nine-month-olds exhibited a significant S/N ratio (relative to 1) over the right occipital region. Error bars represent 99% confidence intervals to reflect the *p* < .01 threshold used in these analyses. (B) Headplots displaying S/N ratios for each age group. Larger numbers (warmer colors) indicate a higher S/N ratio relative to 1.

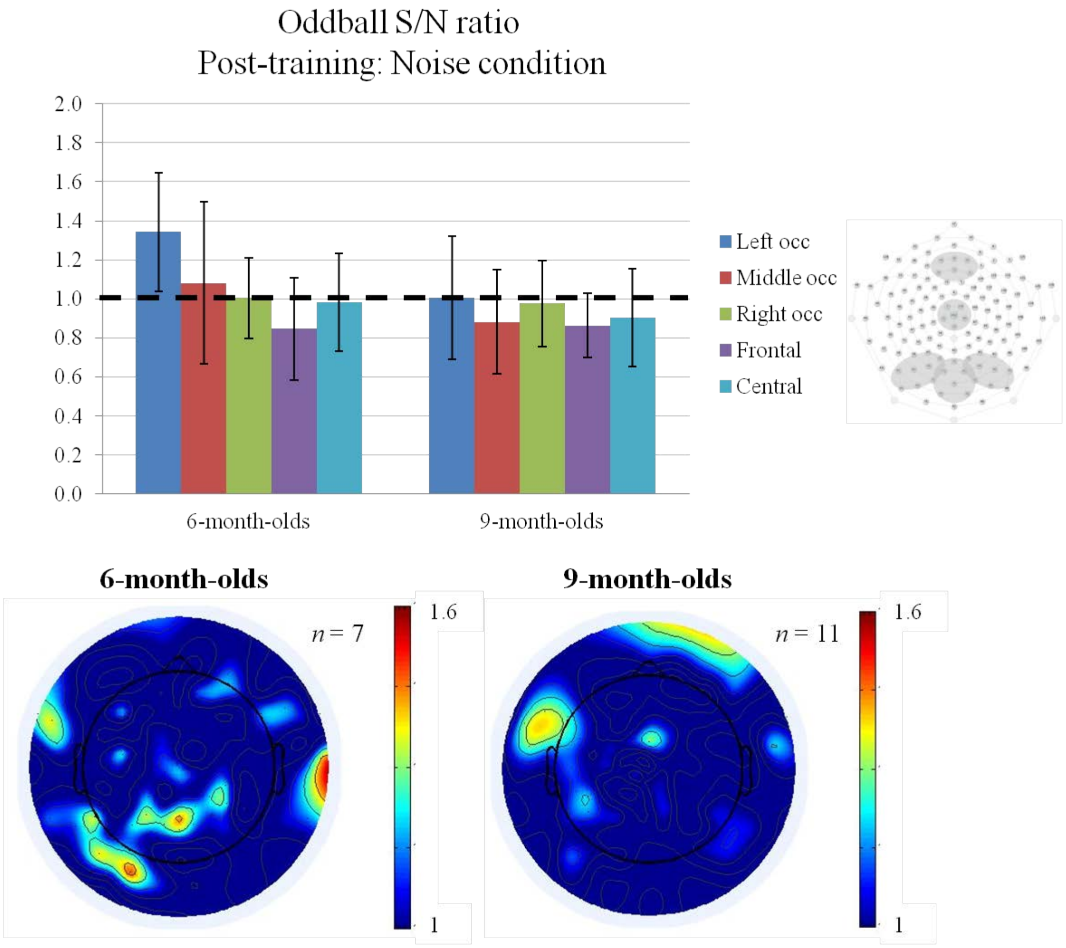

Figure 17. S/N ratios at the oddball frequency for each age group and region at the post-training: Noise condition time point. (A) Bar graph of S/N ratios for each age group and region. Error bars represent 99% confidence intervals to reflect the $p < .01$ threshold used in these analyses. (B) Headplots displaying S/N ratios for each age group. Larger numbers (warmer colors) indicate a higher S/N ratio relative to 1.

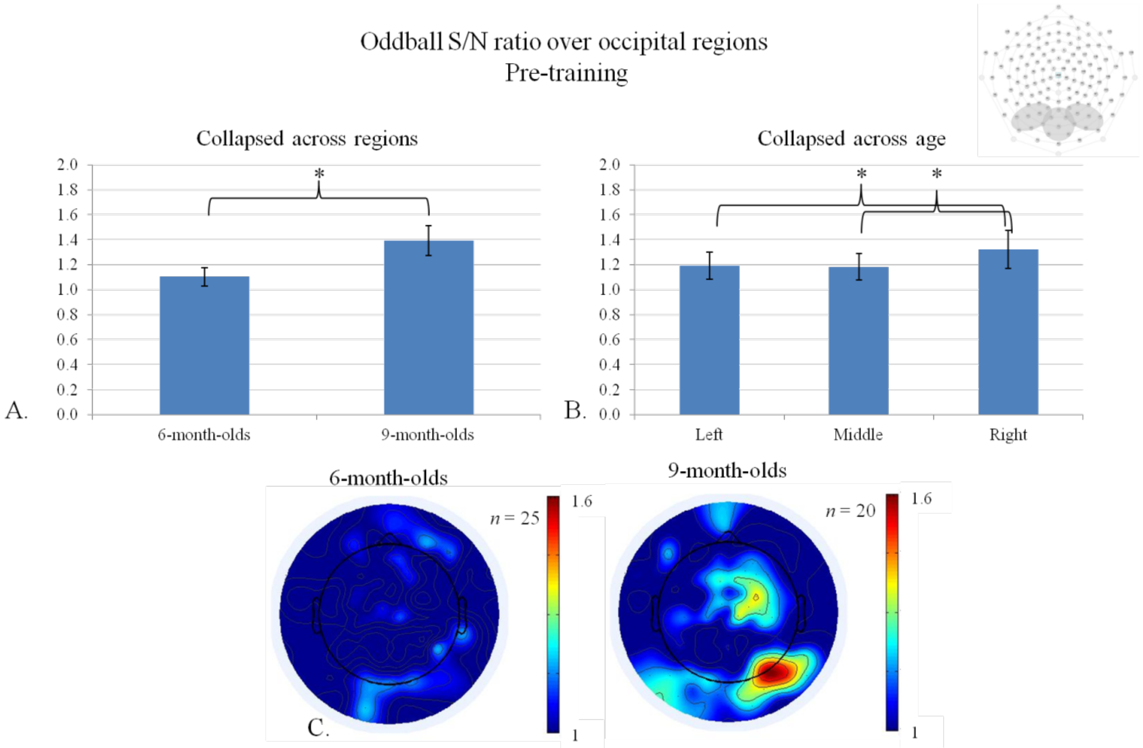

Figure 18. S/N ratios at the oddball frequency over occipital regions at the pre-training time point. (A) Bar graph of S/N ratios for each age group, collapsed across occipital regions. At the pre-training time point, 9-month-olds exhibited a significantly larger S/N ratio at the oddball frequency than 6-month-olds. Error bars represent 95% confidence intervals. (B) Bar graph of S/N ratios for each occipital region, collapsed across age group. At the pre-training time point, there was a significantly larger S/N ratio at the oddball frequency over the right region compared to the left and middle regions. Error bars represent 95% confidence intervals. (C) Headplots displaying S/N ratios for each age group at the pre-training time point. Larger numbers (warmer colors) indicate a higher S/N ratio relative to 1.

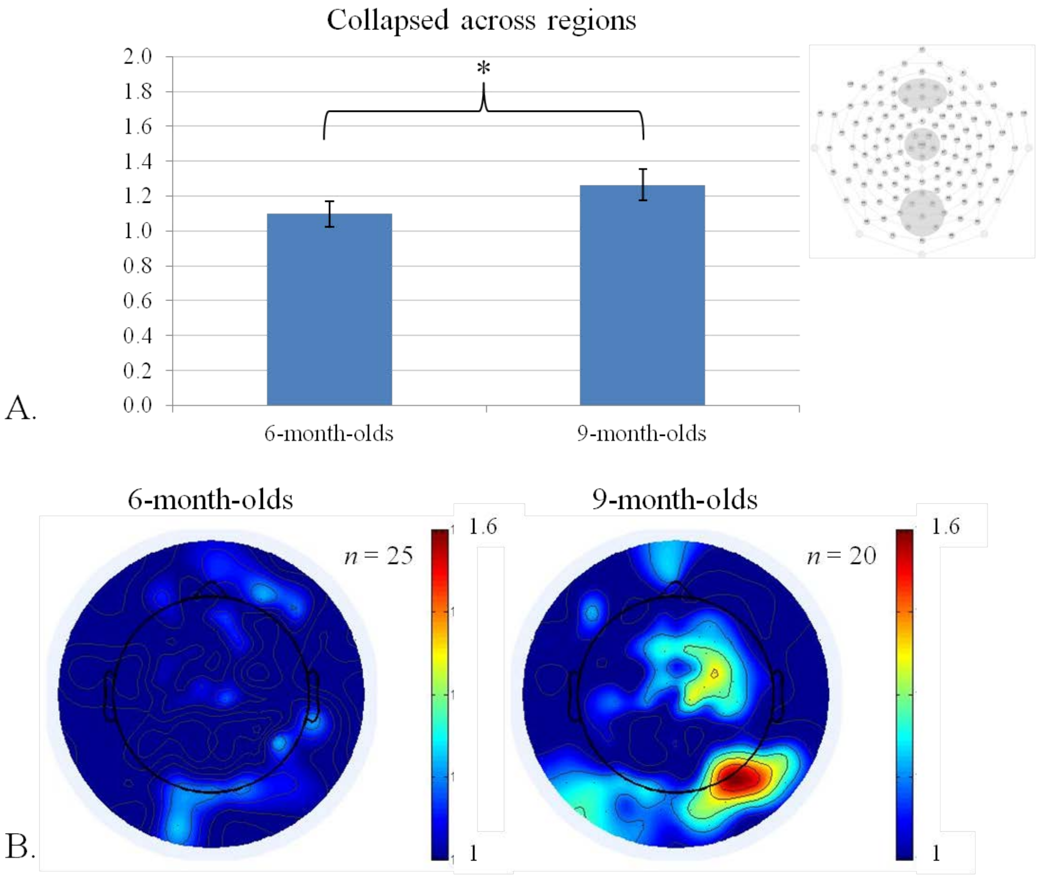

Figure 19. S/N ratios at the oddball frequency over midline regions at the pre-training time point. (A) Bar graph of S/N ratios for each age group, collapsed across midline regions. At the pre-training time point, 9-month-olds exhibited a significantly larger S/N ratio at the oddball frequency than 6-month-olds. Error bars represent 95% confidence intervals. (B) Headplots displaying S/N ratios for each age group at the pre-training time point. Larger numbers (warmer colors) indicate a higher S/N ratio relative to 1.

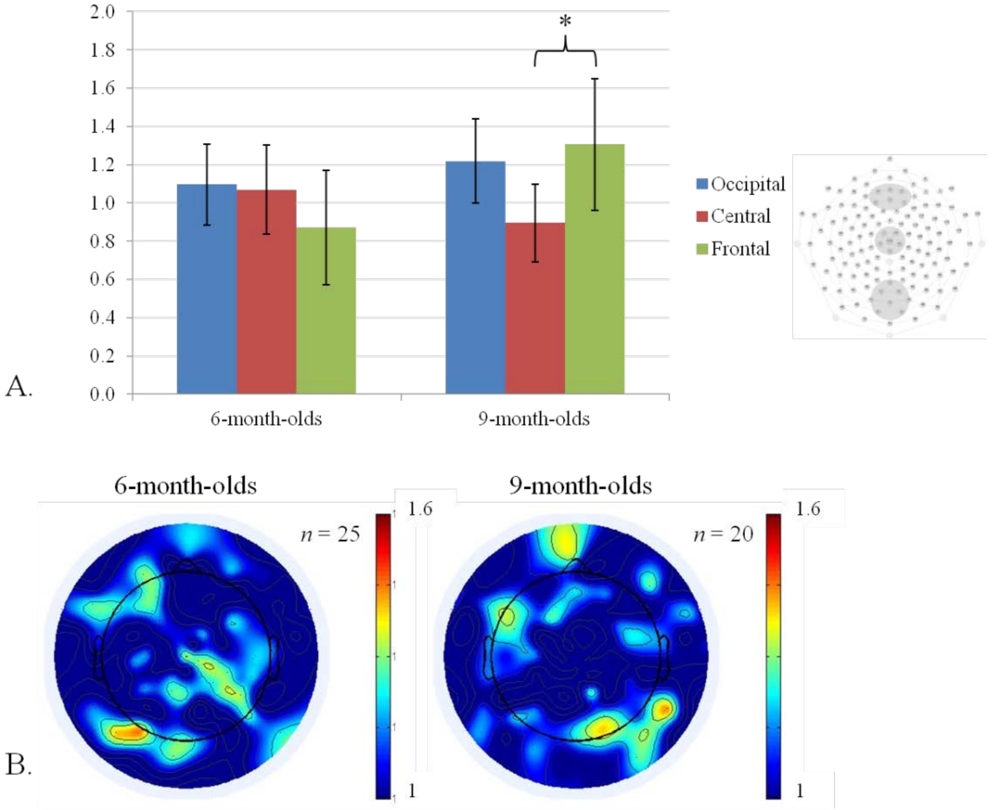

Figure 20. S/N ratios at the oddball frequency over midline regions at the post-training: Label condition time point. (A) Bar graph of S/N ratios for each age group and occipital region. At the pre-training time point, 9-month-olds exhibited a significantly larger S/N ratio over the frontal versus central region. Error bars represent 95% confidence intervals. (B) Headplots displaying S/N ratios for each age group at the post-training: Noise condition time point. Larger numbers (warmer colors) indicate a higher S/N ratio relative to 1.

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