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Author(s)	Sulpizio, Simone; Doi, Hirokazu; Bornstein, Marc H.; Cui, Joy; Esposito, Gianluca; Shinohara, Kazuyuki
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fNIRS Reveals Enhanced Brain Activation to Female (versus Male) Infant Directed Speech (relative to Adult Directed Speech) in Young Human Infants

Simone Sulpizio[1], Hirokazu Doi[2], Marc H. Bornstein[3], Joy Cui[3], Gianluca Esposito[4,5], Kazuyuki Shinohara[2]

[1] Faculty of Psychology, Vita-Salute San Raffaele University, Milan, Italy

[2] Department of Neurobiology and Behavior, Nagasaki University, Graduate School of Biomedical Science, Japan

[3] Child and Family Research, *Eunice Kennedy Shriver* National Institute of Child Health and Human Development, USA, and Institute for Fiscal Studies, London, UK

[4] Department of Psychology and Cognitive Science, University of Trento, Italy

[5] Psychology Program, School of Social Sciences, Nanyang Technological University, Singapore

Running Head: IDS v. ADS in fNIRS

Highlights: (i) fNIRS Reveals Enhanced Brain Activation to Infant Directed Speech over Adult Directed Speech in Young Human Infants; (ii) fNIRS Reveals Enhanced Brain Activation to Female Speech over Male Speech in Young Human Infants

Corresponding authors: Marc H Bornstein (Marc_H_Bornstein@nih.gov)

Kazuyuki Shinohara (kazuyuki@nagasaki-u.ac.jp)

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Abstract

We hypothesized an association between auditory stimulus structure and activity in the brain that underlies infant auditory preference. In a within-infant design, we assessed brain activity to female and male infant directed relative to adult directed speech in 4-month-old infants using fNIRS. Results are compatible with the hypothesis that enhanced frontal brain activation, specifically in prefrontal cortex that is involved in emotion and reward, is evoked selectively by infant directed speech produced by female voices and may serve as a neuronal substrate for attention to and preference for “motherese” displayed by infants.

Keywords: fNIRS; IDS; ADS; female voice; male voice

1. Introduction

Infants do not command adequate skills to fully comprehend speech, but infants still respond to speech directed to them. Indeed, adults commonly speak to infants in a special register called "Infant Directed Speech" (IDS; also known as "baby talk") that is distinguished from Adult Directed Speech (ADS). IDS has unique vocal and acoustic characteristics and is thought to promote attention, cognition, and social interaction. In this fNIRS study, we examined and compared brain responses in infants' left and right frontal cortical hemispheres to female versus male voices speaking in IDS and ADS. In the next sections, we briefly review studies that describe differences between IDS and ADS, motherese versus fatherese, infant preferences for IDS, fNIRS, and hemispheric development in infancy.

1.1 IDS-ADS

Compared to ADS, IDS has higher pitch ($f0$), a larger pitch range ($f0$ range), slower tempo (longer phoneme duration), and more rhythm (Fernald et al., 1989; Kaplan et al., 1995; Soderstrom, 2007; Song et al., 2010). IDS can be found in a wide variety of languages, such as English, German, Italian, Japanese, Korean, Sri Lankan Tamil, Tagalog, and Thai (Inoue et al., 2011; Narayan & McDermott, 2016; Sulpizio et al., 2017), even if cross-language comparisons show IDS is subject to some cross-linguistic adaptations (Fernald et al., 1989). The exaggerated acoustics of IDS are thought to make it more attractive to infant listeners than ADS (Fernald & Kuhl, 1987; Kitamura & Lam, 2009; Papoušek et al., 1991; Trainor et al., 2000): Young infants, even newborns, prefer listening to IDS over ADS (Cooper & Aslin, 1990; Fernald, 1985; Werker & Mcleod, 1989; Pegg et al., 1992). IDS is also believed to aid infant language learning by facilitating speech segmentation (Thiessen et al., 2005) and amplifying lexical and grammatical structure (Fernald & Mazzie, 1991; Nelson et al., 1989). Infants whose mothers use such exaggerations in speech show correspondingly better speech discrimination (Liu et al., 2003). Finally, IDS emerges in the vocal expression of emotion and is a likely pathway to emotional bonding (Saint-Georges et al., 2013; Trainor et al., 2000). Infants use IDS as a cue to select appropriate social partners, attending preferentially to an interlocutor who uses IDS (Schachner & Hannon, 2011). Thus, IDS stands at the core of the infant's perceptual, linguistic, emotional, and social development.

1.2. Motherese versus Fatherese

Two principal vocal properties are intensity (loudness) and frequency (pitch). The larynx (voice box which holds the vocal folds) is more descended in males, so when the vocal folds generate a sound wave (via vibration), the wavelength is longer (because it has further to travel along the vocal tract), generating lower pitch. In general, male voices (MV) fall at an octave lower than female voices (FV). In consequence, mothers speaking in IDS ("motherese") and fathers speaking in IDS ("fatherese") share several features, albeit with some differences. Gergely, Faragó, and Topál (2017) noted that mothers exaggerate vowels more than do fathers when speaking to infants, and the pitch characteristics of motherese are stable across infant development (see also Amano et al., 2006). Additionally, reading and conversing in fatherese involves different patterns of prosodic modification from motherese (Shute & Wheldall, 1989). Others have reported that motherese also utilizes a wider pitch (*f*0) range than fatherese (Fernald et al., 1989; but see Warren-Leubecker & Bohannon,1984).

Mothers and fathers also vary in caregiving behaviors (Murry et al., 2013; Pleck, 2010). Because mothers' and fathers' parenting separately predict children's language and cognitive skills (Tamis-LeMonda et al., 2004), motherese and fatherese could have independent effects on child development. However, mothers are more frequently the primary caregiver and principal socializer of infants (Bornstein, 2015; Greenfield et al., 2006). Moreover, Johnson, Caskey, Rand, Tucker, & Vohr (2014) found that female adults respond to infant vocalizations more than do male adults. Differences between female-infant and male-infant interactions underscore that females may provide vocal cues, sociality, and language input different from males.

For their part, infants respond to IDS differently depending on the gender of the speaker. Niwano & Sugai (2003) reported that infants respond at a greater rate to motherese than fatherese. Infants become familiar with their mother's voice while in utero and hear vocalizations from their mothers most frequently. Not surprisingly, infants prefer their own mothers' IDS (Fernald, 1985; Grieser & Kuhl, 1988), and newborns prefer female voices (their mothers and strangers) over male voices (their fathers and strangers), suggesting that prenatal experience might also influence voice preferences (Brazelton, 1978; DeCasper & Prescott, 1984). Furthermore, infants show advantages in matching female faces to voices in contrast to matching male faces to voices (Richoz et al., 2017). Thus, the infant brain may respond differently to IDS vocalized by females and males.

1.3 Infant Preferences

What is the basis of infants' preference for IDS, especially when produced by a female voice? The present study attempts to answer the question why infant attention to IDS exceeds infant attention to ADS. One hypothesis suggests that attention in infants is mediated by the amount of excitation of neural tissue in the brain (Bornstein, 1978; Haith, 1980). It has long been recognized that neurons, and neuronal network aggregations, respond preferentially to different specific types of stimulation (Hubel & Wiesel, 1962). When the appropriate stimulus or "trigger feature" for a given neuron or network is presented in its receptive field, the rate of neural electrical activity increases. Stimuli that deviate from the neuron's preferred feature structure produce lower rates of neural firing or may even inhibit neuronal excitation from its spontaneous level. This relation between specific stimulation and central nervous system activity is today unchallenged.

1.4. fNIRS

Advances in behavioral testing techniques have permitted strong inferences about infant perception (Bornstein et al., 2014). However, the neural underpinnings of infants' developing capacities have remained elusive, in large measure because of limited methods available to study brain development in human infants. Functional near-infrared spectroscopy (fNIRS) is a viable tool for measuring brain activation in awake, engaged infants (Jobsis, 1977). fNIRS is noninvasive and nonionizing and so is safe to use with infants repeatedly and for extended periods of time. fNIRS also has good temporal resolution: Brain signals can be routinely observed with a temporal sampling resolution up to 0.01 s. Furthermore, behavioral measures of infant looking time and head turning may show similar responses to different stimuli, whereas neuroimaging data may reveal different patterns of cortical responses to those same stimuli, suggesting that stimuli are actually perceived or processed differently, such as with mobile objects and checkerboard patterns in infants as young as 3 months old (Watanabe et al., 2008). fNIRS neuroimaging technology can also localize function in the brain. A longitudinal fNIRS study revealed that localized patterns of activation in the temporal and frontal cortex to visual and auditory social stimuli arise across the first 2 years of life (Lloyd-Fox et al., 2016).

In fNIRS, near-infrared light is projected through the scalp and the skull into the brain, and the intensity of the light that is diffusely refracted is recorded. Neural activation in response to a stimulus results in increased blood flow to the area activated. Change in blood flow leads to an increase in blood volume and can be assessed by measuring local concentrations of oxyhemoglobin (Oxy-Hb) and deoxyhemoglobin (DeOxy-Hb). Typically, during cortical activation, local concentrations of Oxy-Hb increase and those of DeOxy-Hb decrease (Chance et al., 1993; Hoshi & Tamura, 1993; Kato et al., 1993; Villringer et al., 1993). The low tissue absorption of near-infrared light between 650 and 950 nm is utilized to capitalize on the changes in local concentrations of the two (Boas et al., 2004; Sato, et al., 2004; Strangman et al., 2003). Light intensity modulation during stimulus presentation (here IDS) is compared with that during a baseline in which no stimulus or a control stimulus (here ADS) is presented. Change in brain activation relative to the baseline or control provides information about the hemodynamic response to the stimulus. A linear relation obtains between hemodynamics and neural activity (Gratton et al., 2001).

Although behavioral responses of infants to IDS have been assessed, much less is known about whether IDS produced by females versus males prompts different patterns of activation in the infant brain.

fNIRS allows us to expand our understanding of IDS and early development of neural areas associated with language and emotion by tracking the changes in infant cerebral blood flow in response to different auditory and visual stimuli (Lloyd-Fox et al., 2010). Using fNIRS, Saito et al. (2007) found that infants demonstrate greater increases in oxygenated blood flow to the frontal area when presented with IDS than ADS produced by female voices, suggesting that IDS and ADS produce different levels of activation in frontal brain. Their study also supports the ideas that infants can differentiate between the two types of speech registers and might prefer IDS over ADS. However, to date and to our knowledge, there has been no study that answers the question of whether there are differences in hemodynamic activity elicited by IDS relative to ADS spoken by female versus male speakers.

1.4. Hemispheric Development and Functionality in Infants

Speech-based computation of linguistic processing is generally lateralized to left (temporal, parietal, and frontal) cortices in adults (Binder et al., 2000; Hickok & Poeppel, 2000; Boatman, 2004; Indefrey & Levelt, 2004; Scott & Wise, 2004). Some evidence suggests that neural specialization in left temporal areas for language processing is also present early or develops quickly over the first years of life. Speech played to newborns tends to elicit greater left-hemisphere than right-hemisphere activation (Dehaene-Lambertz et al., 2006); newborns also hemodynamically respond differently to repetitive syllabic sequences (/*gamama*/) compared to non-repetitive ones (/*gamada*/), suggesting their preparedness to respond differently to sounds with higher probabilities of occurrence, and left temporal and frontal areas appear to govern this sensitivity (Gervain et al., 2008). However, a collection of neuroimaging studies has reported significant right frontal activity in the brain when participants were tasked with detecting emotional prosody in audio recordings (Buchanan et al., 2000; George et al., 1996; Imaizumi et al., 1997). The right hemisphere, specifically the right prefrontal cortex, has a role in judging variations in pitch of speech in adults (Zatorre et al., 1992) and the tempoparietal region of the right hemisphere in infants as young as 3 months (Homae, Watanabe, Nakano, Asakawa, & Taga, 2006). None of these studies focused on IDS. However, voice-sensitive activation in 3- to 7-month-olds in a right-hemisphere location that is similar to that described in the adult brain suggests that the infant temporal cortex shows some right-hemispheric functional specialization which is congruent with right hemisphere voice sensitivity in adulthood (Blasi et al., 2011). Because IDS has a different pitch and pitch range from ADS, we were interested in determining if there would be a difference in hemispheric sensitivity to female and male IDS in the infant brain.

1.5 *Study Goal*

The primary aim of the current study was to analyze hemodynamic activity in the frontal lobes of young infants in response to hearing female and male IDS relative to ADS. We sought to determine if infants selectively prefer motherese or fatherese via hemodynamic activity in the brain. To achieve our objectives, we presented awake infants of 4-5 months with audio recordings of female and male strangers reading the same story in IDS and ADS. We chose to study hemodynamic responses of the frontal area, specifically the lateral frontopolar area 1 (Fp1) and medial frontopolar area 2 (Fp2), as these regions are implicated in emotions, social cognition, and affective processing in young children (Brink et al., 2011) and adults (Bludau et al., 2014). In a mature brain, the frontopolar area is connected to the superior temporal sulcus and gyrus which are associated with the interpretation of social signals, including emotions of others (Boschin et al., 2015; Wicker, Perrett, Baron-Cohen, & Decety, 2003). Moreover, the oribitofrontal cortex has extensive connections with the limbic system, including the amygdala, giving the frontal area a vital role in emotion regulation (Banks et al., 2007; Rempel-Clower, 2007). Saito et al. (2007) proposed that hemodynamic activation of the frontal area by IDS reflects that IDS is a source of emotional stimulation for infants. Therefore, we sought to examine if the infant brain utilizes the same areas as more developed brains in processing social stimuli that may hold emotional value.

We predicted that a relatively greater increase in Oxy-Hb would be seen in response to IDS relative to ADS produced by female speakers in comparison to IDS relative to ADS produced by male speakers. Because lateralization is an ongoing process in infancy, we assessed but made no predictions about hemispheric differences.

2. Materials and methods

2.1 Participants

A total of 16 normally developing 4-5 month infants participated. Seven infants were excluded from the analysis following refusal to wear the NIRS probe or failure to obtain more than one useable block of trials due to excessive motion artifacts. This attrition rate is within the normal range for published NIRS studies with awake infants (e.g., Lloyd-Fox et al., 2011; Naoi et al., 2012); on average, about 40% of infants tested in NIRS are excluded from data analysis because of failure to accommodate to the apparatus or meet processing criteria (Lloyd-Fox et al., 2010). The final sample included 9 infants, aged 4 months (range = 122-154 days), a sample size effectively used in previously published fully within-subjects NIRS experiments with infants (e.g., Kusaka et al., 2004; Minagawa-Kawai et al., 2011). All parents provided written informed consent prior to the study, which was approved by the Ethics Committee at the Course of Medical and Dental Sciences in Nagasaki University, Japan.

2.2 Stimuli

The voices of two female and two male parents provided stimuli. The voices were extracted from the voice database of the Department of Neurobiology and Behavior, Nagasaki University, which contains recordings of mothers and fathers reading stories either to their baby (IDS sample) or to an adult (ADS sample). The stimuli involved the first sentences of *Iiokao*, a Japanese story for infants. The two female and two male voices were selected to maximize contrast in acoustic features in IDS and ADS (Fernald et al. 1989). Acoustic measures were calculated using PRAAT (Boersma & Weenik, 2012). Mean pitch (Hz) for female voices (~223 Hz) was ~116 Hz greater than for male voices (~106 Hz) in IDS and ~219 Hz vs. ~141 Hz or a difference of ~78 Hz for ADS. The pitch range (Hz) for female voices (~200 Hz) was ~112 Hz greater than for male voices (~88 Hz) in IDS and ~406 Hz vs. ~391 Hz for a difference of ~15 Hz for ADS. Mean intensity of stimuli was equalized between 66 and 69dB by adjusting the energies of the sounds, and speaking rates did not differ by more than .04 words/sec.

2.3 Procedure

The experiment took place in the baby lab of the Department of Neurobiology and Behavior, Nagasaki University. Infants were tested while seated in their mother's lap. After the placement of NIRS probes on the infant's frontal sites, infants participated in two sessions: female voice (FV) and male voice (MV). Stimuli were presented through speakers 1 m front of the infant. Each infant listened to only one FV and one MV. In the FV session, 15 s of female ADS were presented as the baseline and 20 s of IDS were presented as the target (for the use of ADS as baseline, see Naoi et al., 2012). With trial lengths of 20 s, most infants can successfully complete 6-10 trials, which is consistent with that reported by other researchers (Lloyd-Fox et al., 2010). MV sessions were identical to FV sessions. The two sessions were repeated 4 times in counterbalanced order across infants. All experiments were videorecorded to assess the infant movements.

2.4 fNIRS measurement and analysis. Changes in Oxy-Hb and Deoxy-Hb hemogloblin concentrations for blood in the frontal sites of the brain were measured using a 2-ch NIRS system (NIRO-200, Hamamatsu Photonics, Japan). The sampling rate was 6 Hz. The NIRS probes, consisting of 2 sets of one detector and one emitter (distanced ~4 cm from one other) with the emission probe emitting near-infrared light with wavelengths of approximately 735 nm and 850 nm. The probes were attached at FP1 and FP2, respectively, according to the international 10–20 EEG electrode system; these sites cover left and right sites of the frontal lobes.

First, trials with large motion artifacts were excluded. Infants averaged 3.2 (*SD* = 0.9) and 3.3 (*SD* = 0.7) blocks in the FV and MV sessions, respectively (Wilcoxon test, *W* = 39.5, *p* >.9). Thus, analyses were perfomed on a total of 59 observations (out of a maximum of 72; i.e., 9 participants x 2 sessions (FV, MV) x 4 blocks). Across infants, we collected a total of 30 and 29 blocks for FV and MV, respectively. The Oxy-Hb and DeOxy-Hb concentrations of each block were averaged and smoothed with a 5-s moving average (Naoi et al., 2012) that was calculated for each session and for each channel. A baseline correction was performed by subtracting activation in the baseline (ADS) block from that in the target (IDS) block. That is, we obtained an IDS relative to ADS measure by calculating the difference in Oxy-Hb to IDS relative to ADS for FV and MV sessions; after correction, we compared infants' brain activation to IDS produced in the FV session with IDS produced in the MV session. We focused on changes in the Oxy-Hb concentration because it is the more sensitive parameter of the hemodynamic response (e.g., Strangman et al., 2003). Deoxy-Hb was also analyzed. We interpret a hemodynamic change relative to the control (Lloyd-Fox et al., 2009). The advantage of this approach is that patterns of relative activation are directly assessed. The disadvantage is loss of information about patterns of activation that are common to the two events. Finally, corrected data belonging to the same condition were averaged.

3. **Results**

Changes in Oxy-Hb and Deoxy-HB were analyzed by means of two-way ANOVAs, with voice type (FV vs. MV) and hemisphere (right vs. left) as within-infant factors. The ANOVA on the Oxy-HB change showed a main effect of voice type, F (1, 8) = 5.61, p = .04, η^2 = .11: Infants exhibited a significantly larger response to FVs than to MVs. This result is illustrated in Figure 1. Neither the main effect of hemisphere, nor the Voice type by Hemisphere interaction was significant (both *F*s < 1). No effects emerged in the ANOVA of Deoxy-Hb changes (voice type: F <1; Figure 1; hemisphere: F <1; Hemisphere x Voice type: F (1, 8) = 3.62, p >.09).

< Figure 1 About here>

4. Discussion

We found that frontal areas of young infants' brains show an increase in Oxy-Hb (but not in Deoxy-Hb) for IDS relative to ADS when produced by female voices relative to male voices. Female voiced IDS relative to ADS activated brains of infants more than male voiced IDS relative to ADS and did so equally in the two hemispheres.

Our results suggest that gender-specific characteristics of speech contribute to the hemodynamic response in infants listening to speech. Prior to birth, fetuses hear their mother's voice most frequently. Considering that most infants spend the majority of their time with their mothers or other female figures (e.g., babysitter, nanny, grandmother, nurse), they are regularly exposed to more female IDS. As a result, infants are often more familiar with female gendered voices and behaviors, which may facilitate social interactions more than male voices. Infants also respond with greater Oxy-Hb changes in the frontal cortex when listening to IDS relative to ADS of their mothers than female strangers (Hepper et al., 1992; Naoi et al., 2012). It is important to note that infants prefer female strangers' IDS behaviorally over female strangers' ADS (Cooper & Aslin, 1990; Fernald, 1985). Therefore, our results suggest that, in general, female IDS relative to ADS evokes more powerful neural responses than male IDS, although the hemodynamic response to IDS vocalized by an unfamiliar female may be less powerful than that evoked by IDS vocalized by their mother.

Soderstrom (2007) hypothesized that, because infants are exposed to their father's (male) voice less than to their mother's (female) voice, preference for the male voice may develop more slowly than for the female voice. Even postnatal exposure to male voices may not be enough to evoke similar female-male levels of hemodynamic change in infants. DeCasper and Fifer (1980) reported that newborns prefer their mother's voice over an unfamiliar female's voice, and DeCasper and Prescott (1984) found that newborns with significant postnatal experience to their father's voice did not prefer their father's voice when they listened to recordings of their father and an unfamiliar male reading a story, even though they were able to differentiate the two.

Intrauterine auditory experiences, as well as prenatal and postnatal bonding between mother and child, may contribute to infants' relatively heightened sensitivity to the female voice in the frontal lobe. Unique mother-child interactions offer infant consistent, warm, and rewarding socioemotional experiences, which provide input to the orbitofrontal cortex, our recording site. Schore (1997) emphasized that affective experiences during the first 2 years of life between infant and caregiver influence neurodevelopment of the prefrontal cortex, including the orbitofrontal area. As such, our results further support Saito et al. (2007) in that female IDS may offer positive socioemotional stimulation to infants.

We observed no difference in hemispheric sensitivity. It is possible that cerebral lateralization has not yet progressed far in 4-month-old infants. In parallel, early electrophysiological work identified waveforms associated with language comprehension present in children with relatively high levels of word comprehension, but absent in children with relatively little evidence of word comprehension (Mills et al., 1993, 1997); the topological distribution of this component changed with development from a bilateral distribution to a distribution that was more prominent over the left frontal cortex. ERP studies confirm that the bias toward left-hemisphere processing for language develops over infancy (Cheour-Luhtanen et al., 1995; Kuhl, 1998; Molfese et al., 1991), and there is a greater left than right hemispheric response over frontal and temporal cortex (to known words) in infants aged 19 to 22 months (Conboy & Mills, 2006).

4.1 *Limitations and Future Directions*

fNIRS is unsuitable for investigation of neural activation in structures deeper than about 1 cm below the surface of the brain. As fNIRS measures only from surface cortical areas, we do not have information about activation in subcortical areas that might be part of a processing circuit. Moreover, our study used a small sample with associated limitations on power to detect small effects (Yu, Cheah, Hart, & Yang, 2018), yet we found an effect of female relative to male IDS relative to ADS. Additionally, our audiorecordings of IDS derived from a voice database, rather than from each infant's actual mother and father. Naoi et al. (2012) reported greater activation of the frontal area using fNIRS when infants were presented with IDS of their own mothers than IDS of female strangers. It is possible that greater hemodynamic responses could have resulted had we used recordings of each infant's actual parents. Future research directions might also include administering female and male IDS relative to ADS at various points across the first year of infancy to determine when hemispheric sensitivity to language appears in the frontal area or lateralizes. IDS has unique prosodic characteristics that could involve and engage the prefrontal cortex in unique ways.

4.2 *Conclusions*

fNIRS has been implemented in a variety of ways to analyze changes in Oxy-Hb and Deoxy-Hb in response to auditory and visual stimuli in infants. fNIRS produces imaging results consistent with other imaging techniques (i.e., fMRI and PET) used simultaneously (Huppert et al., 2006; Kleinschmidt et al., 1996; Strangman et al., 2002; Villringer & Chance, 1997), providing evidence that fNIRS offers a reliable and valid measure of brain activity. The use of fNIRS in infant studies allows us to delve more deeply into the functioning and organization of the developing brain. For example, fNIRS has allowed investigators to pinpoint cortical responses in the temporal lobe within the first half year of life that may be associated with the later development of autism (Lloyd-Fox et al., 2017). Here, we used fNIRS to ascertain if infants show differential hemodynamic responses or levels of activation when presented with female and male IDS relative to ADS. We focused on the prefrontal cortex, specifically the orbitofrontal cortex, for its associations with emotion regulation and affective experiences. In accord with our hypothesis, we found that IDS relative to ADS of female voices evokes a greater change in Oxy-Hb concentration than IDS relative to ADS of male voices in the frontal brain area of infants, but no difference in hemispheric sensitivity to female or male voices at 4 months.

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Figure 1. Mean relative values of oxygenated (a) and deoxygenated (b) hemoglobin (averaged for channels) for IDS relative to ADS produced by female and male voices. Error bars indicate standard errors. *$p < .05$.