



SHORT REPORT

Neural correlates of infant accent discrimination: an fNIRS study

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Abstract

The present study investigated the neural correlates of infant discrimination of very similar linguistic varieties (Quebecois and Parisian French) using functional Near InfraRed Spectroscopy. In line with previous behavioral and electrophysiological data, there was no evidence that 3-month-olds discriminated the two regional accents, whereas 5-month-olds did, with the locus of discrimination in left anterior perisylvian regions. These neuroimaging results suggest that a developing language network relying crucially on left perisylvian cortices sustains infants' discrimination of similar linguistic varieties within this early period of infancy.

Introduction

The neural bases allowing infants to acquire language have long been the object of scientific interest. Over the first year of life, infants accumulate linguistic knowledge allowing them to preferentially attend to speech dimensions that are relevant in their native language. One of the earliest achievements in this attunement process is accent discrimination, the ability to distinguish two varieties of the same language (e.g. French spoken in Paris or in Quebec, henceforth referred to as 'regional accents'). Here, we document that discrimination between two accents involves a brain network relying crucially on left perisylvian cortices (including inferior frontal gyrus and superior temporal gyrus), as well as on linguistic experience and/or maturation.

Two competing answers have been proposed in the literature as to how the infant brain processes language (for a recent summary, see Petitto, Berens, Kovelman,

Dubins, Jasinska & Shalinsky, 2012). The first view holds that infants rely on *auditory-general* processes when learning the sound patterns of their language, thus predicting that linguistic expertise would be associated with larger activations in increasingly anterior cortices within the superior temporal gyrus and sulcus (cf. Rauschecker & Scott, 2009). The second view proposes that *language-specific* processes may make a substantial contribution (cf. Dehaene-Lambertz & Gliga, 2004). Consequently, it predicts that left perisylvian cortices will play a key role, as they do in *adult* linguistic processing. According to much of the literature on the neural bases of perceptual attunement, processing a sound contrast that is present in the infants' native language comes to engage a left-dominant network towards the end of the first year of life (e.g. Y. Sato, Mori, Furuya, Hayashi, Minagawa-Kawai & Koizumi, 2003; Y. Sato, Sogabe & Mazuka, 2010; Petitto *et al.* 2012; a review in Minagawa-Kawai, Cristia & Dupoux, 2011a), an age at which

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infants' discrimination of sound contrasts becomes clearly affected by their ambient language (e.g. Werker & Tees, 1984). A key question that remains open is whether other benchmarks of language development are also associated with primary activations in left perisylvian regions. One such benchmark is the discrimination of close linguistic varieties.

Discriminating very different languages does not depend on linguistic experience. In fact, both newborns and rats are able to discriminate languages as dissimilar as Japanese and English, which greatly differ in their rhythms (Ramus, 2002; Toro, Trobalon & Sebastián-Gallés, 2003). In contrast, discrimination of rhythmically similar linguistic varieties has only been documented for human infants, and only at later ages (Bosch & Sebastián-Gallés, 1997, 2001; Nazzi, Juszyk & Johnson, 2000; Vicenik, 2011; see also Kinzler, Dupoux & Spelke, 2007).

Infants also find it more difficult to discriminate two regional accents if they do not have experience with either of them. For example, 5- and 7-month-olds exposed to South-West English can discriminate between this variety and Welsh English, but not between the equally unfamiliar Welsh English and Scottish English (Butler, Floccia, Goslin & Panneton, 2011). Since accent discrimination appears to vary with age and language exposure, it has been proposed that accumulating experience with the native language is necessary (although perhaps not sufficient) for this process. Does accent discrimination at the early age of 5 months also engage left perisylvian cortices, suggesting a language-specific learning process?

While there is no previous neuroimaging evidence on infant accent discrimination *per se*, studies have been conducted on neural responses while listening passively to blocks of speech in the native language, an unfamiliar language, and/or non-speech versions of such auditory stimuli. Much of this work has employed functional Near-Infrared Spectroscopy (fNIRS) to study the localization of brain networks in awake, mobile infants (see Cristia, Dupoux, Hakuno, Lloyd-Fox, Schuetze, Kivits, Bergvelt, van Gelder, Filippin, Charron & Minagawa-Kawai, 2013, for a review of infant fNIRS research). For instance, H. Sato, Hirabayashi, Tsubokura, Kanai, Ashida, Konishi, Uchida-Ota, Kunishi and Maki (2012) reported that left temporal cortices of newborn Japanese infants exhibited greater activation for forward than backward (time-reversed) versions of Japanese, whereas no such difference was evident when forward and backward English was presented. This was interpreted as an indication that left perisylvian cortices were coding for acquired knowledge, as they responded differently to the native and the foreign language. However, these findings were not replicated in May,

Byers-Heinlein, Gervain and Werker (2011), where forward and backward English elicited similar patterns of activation in English-exposed newborns, whereas forward and backward Tagalog did not (with no lateralization differences). It must be noted that May *et al.* (2011) used low-pass filtered stimuli, while Sato *et al.* (2012) used normal, broadcast speech. This difference might in part explain the differences in the findings.

Research on older infants reveals differences in overall activation, and not degree of left-dominance. For example, 4-month-old Japanese learners exhibited overall greater activation in auditory cortices when listening to Japanese phrases than English phrases, with an equally left-dominant response in both cases (Minagawa-Kawai, van der Lely, Ramus, Sato, Mazuka & Dupoux, 2011c). In the only study not using fNIRS, Peña, Pittaluga and Mehler (2010) documented different electroencephalographic responses to the native language from a rhythmically different language in both preterm and full-term infants at 12 months post-conception (i.e. 3 months for infants born full-term), and to the native than a rhythmically similar language at 15 months post-conception (i.e. 6 months of age for full-terms). Importantly, a group of preterm infants was also tested at 12 months post-conception and with 6 months of *ex utero* language experience. This last group failed to show a differential response to the native language and a rhythmically similar non-native one. These results indicate that *ex utero* linguistic exposure is not the only factor impacting infants' perception of language varieties, since a certain degree of neural maturation was also necessary for these brain responses to differ between the native and a similar language variety. Unfortunately, these electroencephalographic data were not interrogated in terms of the specific brain regions that sustained processing of each linguistic variety, or of their discrimination.

Overall, this previous work suggests that the infant brain can process linguistic varieties differently, but sheds little light on whether a left-dominant, language-specific network is involved in discriminating close varieties such as two regional accents of the same language (see Zhao, Shu, Zhang, Wang, Gong & Li, 2008, for adult fMRI results on language discrimination). To address this question, the present study employed a variation of the change detection paradigm that has been used to study the neural correlates of perceptual attunement. In this paradigm, infants are presented with blocks where the same kind of stimuli are repeated (non-Alternating or Homogeneous) and blocks where two different types of stimuli are played in alternation (Alternating). Change detection is typically indicated by significantly greater activation in Alternating as compared to Homogeneous blocks

(Minagawa-Kawai, Mori, Naoi & Kojima, 2007; Sato *et al.*, 2003, 2010). In our study, each block included speech of either two talkers of different varieties (Alternating blocks) or two talkers of the same variety (Homogeneous blocks). Given that both Alternating and Homogeneous blocks involved an alternation between *talkers*, a difference in brain activation in Alternating compared to Homogeneous blocks would most likely be due to the detection of the *change in language variety*, which is absent from the Homogeneous blocks. We tested infants exposed to Parisian French with Parisian and Quebecois French, two similar linguistic varieties that should require infants to use their incipient language knowledge (rather than innate rhythmic sensitivities that are available to newborns and non-human animals, as discussed above). As in previous perceptual attunement work, we used fNIRS, which uses near-infrared light traveling from a group of sources to a group of detectors placed on the child's head. The light traveling from a given source to a given detector forms a channel. Changes in light intensity reflect changes in the concentrations of oxygenated and deoxygenated hemoglobin (which accompany local neural activity) found in the brain tissue sampled by that channel. We positioned our channels bilaterally to sample from several structures spanning from anterior to posterior perisylvian cortices.

To track the developmental trajectory of emergent regional accent discrimination, we tested one group of infants at 3 to 4 months of age, and another at about 5 months of age. Following the language-specific hypothesis, we predicted that a brain network involving left perisylvian cortices would come to be involved with increasing age. In contrast, if accent discrimination relies only on an auditory-general network, then discrimination will be evident bilaterally.

Experiment

Materials and methods

Participants

Caregivers signed an informed consent form approved by the Ile-de-France III Ethics Board (No. ID RCB (AFSSAPS) 2007-A01142-51). Thirty 3-month-olds ($M = 3$ months and 21 days or 3:21, range 3:9–4:3; 20 females) and 31 5-month-old French monolinguals ($M = 5:6$, range 4:24–5:18; 14 females) were tested. Infants were full-term, in good health, and without developmental, language, or hearing problems according to parental report. Primary caregivers were asked to estimate what proportion of the time infants heard

Parisian, Quebecois, and other accents of French (and other languages). Among the 3-month-old group, information was missing for two children; none of the children had any exposure to speakers of Quebecois French; two recurrent caregivers of one infant had a southern French accent (Parisian exposure estimated at 30% of their waking time). For the remaining 27 3-month-olds, exposure to Parisian accent was estimated at an average of 100% of their waking time. Among the 5-month-old group, information was missing for one child; none of the children had any exposure to speakers of Quebecois French; both parents of one infant had a southern French accent. For the remaining 29 5-month-olds, exposure to Parisian accent was estimated at an average of 91% of their waking time. Eight 5-month-olds and six 3-month-olds who had data for less than a quarter of the study were dropped from further analyses.

Stimuli

There are three main phonological differences between Parisian and Quebecois accents of French that should be salient to infants (all examples are from Walker, 1984, cross-validated against the more recent Durand, Laks & Lyche, 2009). First, some vowels are diphthongized (*neige* 'snow' is pronounced [nəʒ] in Quebecois, and [nɛʒ] in Parisian), which will create overall differences in average vowel length and vowel-internal formant movement evident even before language-specific vowel categories have been learned. Second, consonant clusters may be simplified to a greater extent in Quebecois ('table' may be pronounced [tab]), which should affect perceptual rhythm. Finally, it has been argued that Quebecois French has a different phrasal rhythm, since sometimes non-final syllables are lengthened (*il va neiger* 'it will snow' would be pronounced [i#va#nɛɪ:ʒɛ] in Quebecois, [i#va#nɛʒɛ] in Parisian). In addition to the aforementioned well-established phenomena, naïve Parisian and Quebecois listeners sometimes report hearing differences in prosody across the two varieties.

Given the longer duration and repetitive nature of the study required to gather sufficient fNIRS data, we sought to make the test more ecological and less challenging by using audiovideos, which should enhance arousal and direct infants' attention towards the stimulation. Audio-visual recordings of infant-directed speech were gathered from two Quebecois and two Parisian female talkers (cf. Butler *et al.*, 2011; Toro *et al.*, 2003, who used between one and four voices). Each talker received a different list of 20 brief passages (1–3 sentences; see the project website, Cristia, 2013). Recordings were performed with the talker speaking one passage at a time facing the camera/infant in a natural

fashion (not reading out loud). The videos of two passages were lost. As a result, there were 78 different videos, two of which were repeated, for a total of 80 videos. The Quebecois and Parisian samples did not differ in pitch characteristics known to affect infants' attention (average pitch in ERB [*SD*] Quebecois 6.2 [.6], Parisian 6.4 [.7]; maximum pitch in ERB [*SD*] Quebecois 9.1 [1.7], Parisian 9 [1.7]), nor in duration (average duration [*SD*] Quebecois 3.2 s [.7 s], Parisian 3.4 s [.7 s]).

Paradigm

Infants heard a maximum of five sets; each set was composed of four blocks of stimulation during which fNIRS data were analyzed (depicted in Figure 1) and two behavioral trials. Each block of stimulation began with an attention-getting sound, followed by four videos (each including one passage), and ended with a silent screensaver. The four videos always alternated between two different talkers, and they were separated by 200 ms of blank screen, for a stimulation duration of each block 14.3 s on average (range 12–20 s). The silent screensavers varied in duration between 15 and 25 s pseudo-randomly. In half of the blocks, both talkers spoke with the same accent (either Parisian French or Quebecois French); and in the other half the two talkers spoke with different accents (*Alternating* blocks). The video-to-block type attribution was counterbalanced across infants (i.e. a video that appeared as *Alternating* for infant A, was part of a *Homogeneous* block for infant B). Given the counterbalancing of the video-to-block attribution, random preferences for one or another talker or video are not a major concern. Nonetheless, we had also interspersed a number of behavioral trials to measure, if there was one, infants' preference for one over another talker using infants' looking times to paired presentation of still frames of the talkers' faces. No significant preferences were obtained. Finally, the order of talkers within the block and the order of block

types were also carefully counterbalanced across children.

Equipment and data acquisition

The infant sat on a caregiver's lap in a soundproof testing booth, at about 1 m from a 17" Dell LCD monitor, behind which Logitech speakers S-0264B were hidden. A camera placed above the screen recorded the child for offline coding of looks. Stimuli were presented using Psycoscope B55 (Bonatti, 2009). The fNIRS system UCL-NTS continuously emits near-infrared light of two wavelengths (for further technical details, see Everdell, Coulthard, Crosier & Keir, 2005; Minagawa-Kawai, Cristià, Vendelin, Cabrol & Dupoux, 2011b). There was a left pad and a right pad, each with a configuration that provided data from a total of 14 channels (see Figure 2). Adjacent source-detector pairs were at a distance of 25 mm, and they thus defined 10 'shallow' channels; non-adjacent pairs were at a distance of 56 mm, which defined 'deep' channels because given the source–detector separation they were able to penetrate deeper into the brain.

Probe placement

Following previous infant work, we used anatomical landmarks to align the bottom of the pad with the T3-T5 line of the 10/20 system, and used the ear as a midpoint reference (see Figure 2). Head circumference measurements and localization estimations suggested that channels tapped similar cortical regions across different infants, and across different infant groups.

Data analysis

Light intensity signals measured by the fNIRS machine were converted into oxygenated hemoglobin (oxyHb) and deoxygenated hemoglobin (deoxyHb) concentration

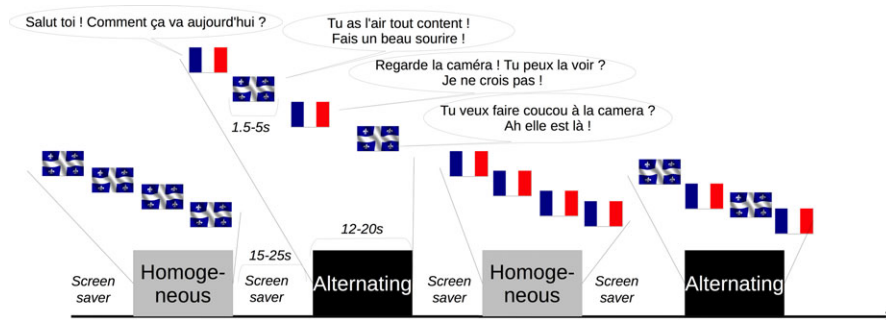


Figure 1 Paradigm. One stimulus set is represented here (compliant infants saw up to five sets).

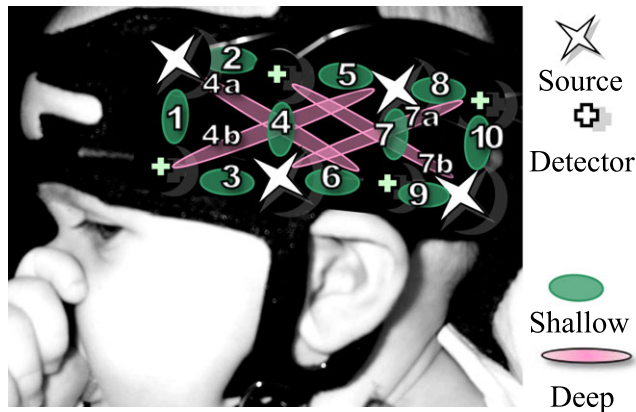


Figure 2 Pad placement. Location of the pad relative to surface landmarks on a typical 5-month-old infant's head. In fNIRS, the light emitted by a given source and picked up in a given detector forms a channel. Sources and detectors that were 25 mm apart defined 'shallow' channels and those 56 mm apart 'deep' channels (because the light can travel deeper into the tissue in the latter case). Shallow channels here are arbitrarily numbered 1 to 10 from front to back. Deep channels are noted with the number of a neighboring shallow channel and a letter index (4a, 4b, 7a, 7b).

using the modified Beer-Lambert Law. Artifacts, resulting from head movement, etc., were defined as concentration changes larger than 0.15 millimolars per millimeter (mM.mm) in 100 ms (one sample) at the level of individual detectors (Kotilahti, Nissilä, Näsi, Lipiäinen, Noponen, Meriläinen, Huotilainen & Fellman, 2010). Artifacts stretches of the signal were removed from the analyses. Activation was assessed using General Linear Models (GLM, as in Kotilahti *et al.*, 2010; Minagawa-Kawai *et al.*, 2011b). The GLM also included regressors that modeled baseline changes following major artifacts, and slow nonlinear trends, thus regressing out signal changes due to physical and physiological noise. This analysis assesses the correlation between the signal observed and the signal expected based on a model of the hemodynamic response elicited by the experimental stimulation. The application of the adult HRF model to oxyHb was justified by its excellent fit ($R > .91$). As in most previous work we focus on oxyHb (for a discussion, see Lloyd-Fox, Blasi & Elwell, 2010, p. 280; results using deoxyHb are provided on the project website, Cristia, 2013).

To answer our main research question, we declared the contrast between Alternating and Homogeneous conditions as a regressor for each channel within each age group. (The contrast between the two types of Homogeneous conditions, Parisian and Quebecois, was not significant; see the project website, Cristia, 2013.) The resulting β values for each condition and channel were

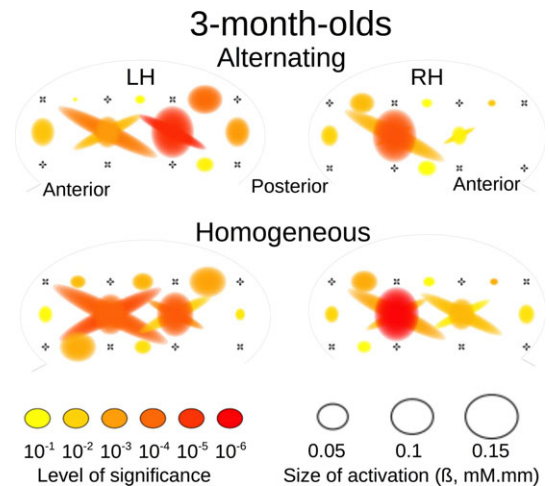


Figure 3 Activations during Alternating and Homogeneous blocks in the 3-month-old group. The surface of the oval indicates the size of the activation, namely the β value (the estimate of oxygenated hemoglobin concentration changes in the regression). The color of the oval represents the uncorrected p -value. Channels whose responses are significantly greater to Alternating than Homogeneous blocks (after correction) are circled in blue. (This comparison was not significant in any channel in the 3-month-old age group).

tested against zero with a t -test, using a conservative bootstrap resampling approach to correct for multiple comparisons (Westfall & Young, 1993).

Results

As illustrated in Figure 3, the contrast between Homogeneous and Alternating conditions was not significant at $p_{corr} < .05$ for any channel in the 3-month-old group.

As shown in Figure 4, the contrast between Homogeneous and Alternating conditions was significant at $p_{corr} < .05$ for 1 channel in the left hemisphere in 5-month-olds. Specifically, responses for Alternating blocks were greater than those for Homogeneous blocks in the left deep Channel 4a. This channel most probably samples from the middle superior temporal gyrus and inferior frontal gyrus, in addition to the insula given the depth of maximal sensitivity.

An analysis confirmed that the lateralization and age differences suggested by the previous analyses emerged from a significant difference in activation across the groups and hemispheres. In a linear mixed model predicting activation level (β in channel 4a), Hemisphere (left, right) and Group (3-month-olds, 5-month-olds) were declared as fixed factors, and Participant as random factor. The only significant factors were a main effect of Group (HPD lower bound estimate .046, higher

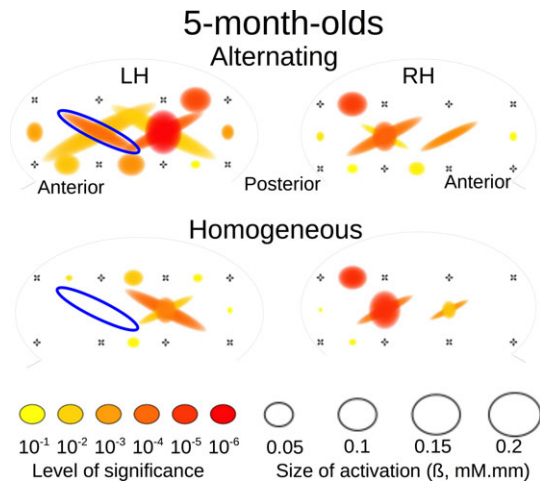


Figure 4 Activations during Alternating and Homogeneous blocks in 5-month-old group. See caption of Figure 3 for explanations.

bound .170, $p = .001$, with overall larger responses for 5- than 3-month-olds) and an interaction Hemisphere by Group (HPD lower bound estimate $-.181$, higher bound $-.004$, $p < .05$). The interaction was due to the fact that the two groups differed to a greater extent in the left hemispheric responses than in right hemispheric responses.

Discussion

In the present paper, we explored activation in perisylvian structures as infants use their budding linguistic knowledge to discriminate close linguistic varieties. There was strong evidence for regional accent discrimination in one channel that sampled left perisylvian structures in 5-month-olds. Furthermore, such a difference was not present in slightly younger infants, who lacked the linguistic and maturational development necessary to distinguish such close linguistic varieties. A mixed model confirmed the presence of an age by hemisphere interaction. Overall, these results are consistent with the idea that discriminating close linguistic varieties involves a brain network that crucially depends on left perisylvian structures, and which emerges in French learners at some point between 3 and 5 months of age due to maturation and/or additional linguistic experience (see below). Such a conclusion is in line with much fNIRS work suggesting that language processing, even in infancy, not only engages auditory-general, bilateral networks, but may involve a left-dominant, plausibly language-specific network in the infant brain (e.g. Bortfeld, Fava & Boas, 2009; Peña, Maki, Kovacic,

Dehaene-Lambertz, Koizumi, Bouquet & Mehler, 2003; Petitto *et al.*, 2012; Sato *et al.*, 2003).

Additional work suggests that the role that left perisylvian cortices play varies with age. For example, while the contrast between forward versus backward speech more strongly engages left than right cortices at birth (Peña *et al.*, 2003; Sato *et al.*, 2012), by 3 months of age such hemispheric differences in temporal cortices' processing of forward over backward speech are no longer evident (Dehaene-Lambertz, Dehaene & Hertz-Pannier, 2002). In contrast, automatic change detection involving speech sounds comes to engage a left-dominant perisylvian network only after infants gather enough experience with the sounds, such that lateralization is evident later for harder contrasts (see discussion in Minagawa-Kawai *et al.*, 2011a). Obviously, structures are many and varied in the left hemisphere, and it is likely that many different mechanisms, plausibly instantiated in diverse structures within the perisylvian regions, will be variably engaged as the infant becomes an expert language perceiver.

An interesting question is what information enabled 5-month-olds to detect the change in accent. Previous behavioral research using low-pass filtered auditory stimuli (where much consonantal information is removed) suggests that suprasegmental information alone can be sufficient to effect discrimination between similar linguistic varieties (Spanish and Catalan, in Bosch & Sebastián-Gallés 1997; American English and German, in Vicens 2011). Nonetheless, 5-month-olds in the current study had access to the unfiltered acoustic information as well as the visual signal, and thus could have made use of numerous cues in the speech presented to them (including visual ones, cf. Weikum, Vouloumanos, Navarra, Soto-Faraco, Sebastián-Gallés & Werker, 2007). We believe that the strength of the discrimination responses uncovered by our audio-visual paradigm would allow an investigation of this question, as the information provided to infants could be neutralized (e.g. by low-pass filtering the audio signal, or inverting the visual image). It is important to bear in mind that whatever cues may have been recruited, they cannot have been evident to the novice/inexperienced eye and ear, as demonstrated by the 3-month-olds' results.

While this change in performance with age is consistent with linguistic experience playing a key role, other interpretations remain open. Indeed, accent differences often depend on small acoustic changes, and thus improvements in audition could also be necessary, as suggested by the preterm versus experience-matched term results discussed in the Introduction (Peña *et al.*, 2010). Similarly, although the precise localization cannot be ascertained with fNIRS, the suggested engagement of

the left insula could indicate that crossmodal integration (Calvert, Hansen, Iversen & Brammer, 2001) and short-term memory (Bamiou, Musiek & Luxon, 2003) might also play an important role, particularly given the varied and audio-visual nature of the stimuli used. Thus, many perceptual and cognitive skills could be involved in infants' accent discrimination, and teasing apart their contribution is an important research question to address in the future.

An additional open question that awaits further research concerns the networks involved in accent discrimination as well as linguistic processing in the face of accent variation. Recent behavioral work suggests that older infants come to ignore accent variation when performing linguistic tasks (Kitamura, Panneton & Best, 2013), possibly as a result of assigning accent differences between talkers to their individual social identity. This interesting possibility could be put to test with fNIRS, as such a reassignment should result in a pattern of activation that is markedly different from the one found here. Indeed, functional Magnetic Resonance Imaging on adults suggests that recognizing words while ignoring talker voice engages a bilateral, more posterior network (including posterior superior and middle temporal gyrus and inferior parietal regions; Wong, Nusbaum & Small, 2004).

While a great deal of work remains to be done, the present study provides a key piece of the puzzle regarding the brain networks that subtend early language acquisition. We document that young infants' discrimination between close language varieties is associated with activation of left perisylvian structures. These results complement previous work on the comparison between speech and non-speech in newborns, and that on perceptual attunement in 1-year-olds, two strands of research documenting fundamental contributions of left perisylvian cortices as infants achieve different benchmarks of early language development.

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References

- Bamiou, D.E., Musiek, F.E., & Luxon, L.M. (2003). The insula (Island of Reil) and its role in auditory processing: literature review. *Brain Research Reviews*, **42**, 143–154.
- Bonatti, L. (2009). Psyscope X Build 55 [Computer Program], <http://psy.ck.sissa.it/>.
- Bortfeld, H., Fava, E., & Boas, D.A. (2009). Identifying cortical lateralization of speech processing in infants using near-infrared spectroscopy. *Developmental Neuropsychology*, **34**, 52–65.
- Bosch, L., & Sebastián-Gallés, N. (1997). Native-language recognition abilities in 4-month-old infants from monolingual and bilingual environments. *Cognition*, **65**, 33–69.
- Bosch, L., & Sebastián-Gallés, N. (2001). Evidence of early language discrimination abilities in infants from bilingual environments. *Infancy*, **2**, 29–49.
- Butler, J., Floccia, C., Goslin, J., & Panneton, R. (2011). Infants' discrimination of familiar and unfamiliar accents in speech. *Infancy*, **16**, 392–417.
- Calvert, G.A., Hansen, P.C., Iversen, S.D., & Brammer, M.J. (2001). Detection of audio-visual integration sites in humans by application of electrophysiological criteria to the BOLD effect. *Neuroimage*, **14**, 427–438.
- Cristia, A. (2013). Supplementary materials to 'Neural correlates of infant accent discrimination: an fNIRS study'. Last accessed 24 October 2013. https://sites.google.com/site/acrsta/talks/fnirs_infant_accent
- Cristia, A., Dupoux, E., Hakuno, Y., Lloyd-Fox, S., Schuetze, M., Kivits, J., Bergvelt, T., van Gelder, M., Filippin, L., Charron, S., & Minagawa-Kawai, Y. (2013). An online database of infant functional Near InfraRed Spectroscopy studies: a community-augmented systematic review. *PLoS One*, **8**, e58906. Last accessed 28 February 2013. <https://sites.google.com/site/dbifnirs/>
- Dehaene-Lambertz, G., Dehaene, S., & Hertz-Pannier, L. (2002). Functional neuroimaging of speech perception in infants. *Science*, **298**, 2013–2015.
- Dehaene-Lambertz, G., & Gliga, T. (2004). Common neural basis for phoneme processing in infants and adults. *Journal of Cognitive Neuroscience*, **16**, 1375–1387.
- Durand, J., Laks, B., & Lyche, C. (2009). *Phonologie, variation et accents du français*. Paris: Hermès.
- Everdell, N.L., Coulthard, M.G., Crosier, J., & Keir, M.J. (2005). A machine for haemodialysing very small infants. *Pediatric Nephrology*, **20**, 636–643.
- Kinzler, K.D., Dupoux, E., & Spelke, E.S. (2007). The native language of social cognition. *Proceedings of the National Academy of Sciences, USA*, **104**, 12577–12580.

- Kitamura, C., Panneton, R., & Best, C. (2013). The development of language constancy: attention to native versus nonnative accents. *Child Development*, **84**, 1686–1700.
- Kotilahti, K., Nissilä, I., Näsi, T., Lipiäinen, L., Noponen, T., Meriläinen, P., Huotilainen, M., & Fellman, V. (2010). Hemodynamic responses to speech and music in newborn infants. *Human Brain Mapping*, **31**, 595–603.
- Lloyd-Fox, S., Blasi, A., & Elwell, C.E. (2010). Illuminating the developing brain. *Neuroscience Biobehavioral Reviews*, **34**, 269–284.
- May, L., Byers-Heinlein, K., Gervain, J., & Werker, J.F. (2011). Language and the newborn brain: does prenatal language experience shape the neonate neural response to speech? *Frontiers in Psychology*, **2**, 222.
- Minagawa-Kawai, Y., Cristià, A., & Dupoux, E. (2011a). Cerebral lateralization and early speech acquisition: a developmental scenario. *Developmental Cognitive Neuroscience*, **1**, 217–232.
- Minagawa-Kawai, Y., Cristià, A., Vendelin, I., Cabrol, D., & Dupoux, E. (2011b). Assessing signal-driven mechanisms in neonates: brain responses to temporally and spectrally different sounds. *Frontiers in Psychology*, **2**, 135.
- Minagawa-Kawai, Y., Mori, K., Naoi, N., & Kojima, S. (2007). Neural attunement processes in infants during the acquisition of a language-specific phonemic contrast. *Journal of Neuroscience*, **27**, 315–321.
- Minagawa-Kawai, Y., van der Lely, H., Ramus, F., Sato, Y., Mazuka, Y., & Dupoux, E. (2011c). Optical brain imaging reveals general auditory and language-specific processing in early infant development. *Cerebral Cortex*, **21**, 254–261.
- Nazzi, T., Jusczyk, P.W., & Johnson, E.K. (2000). Language discrimination by English-learning 5-month-olds. *Journal of Memory and Language*, **43**, 1–19.
- Peña, M., Maki, A., Kovacic, D., Dehaene-Lambertz, G., Koizumi, H., Bouquet, F., & Mehler, J. (2003). Sounds and silence: an optical topography study of language recognition at birth. *Proceedings of the National Academy of Sciences, USA*, **110**, 11702–11705.
- Peña, M., Pittaluga, E., & Mehler, J. (2010). Language acquisition in premature and full-term infants. *Proceedings of the National Academy of Sciences, USA*, **107**, 3823–3828.
- Petitto, L.A., Berens, M.S., Kovelman, I., Dubins, M.H., Jasinska, K., & Shalinsky, M. (2012). The ‘Perceptual Wedge Hypothesis’ as the basis for bilingual babies’ phonetic processing advantage: new insights from fNIRS brain imaging. *Brain and Language*, **121**, 130–143.
- Ramus, F. (2002). Language discrimination by newborns: teasing apart phonotactic, rhythmic, and intonational cues. *Annual Review of Language Acquisition*, **2**, 85–115.
- Rauschecker, J.P., & Scott, S.K. (2009). Maps and streams in the auditory cortex: nonhuman primates illuminate human speech processing. *Nature Neuroscience*, **12**, 718–724.
- Sato, H., Hirabayashi, Y., Tsubokura, H., Kanai, M., Ashida, T., Konishi, I., Uchida-Ota, M., Kunishi, Y., & Maki, A. (2012). Cerebral hemodynamics in newborn infants exposed to speech sounds. *Human Brain Mapping*, **33**, 2092–2103.
- Sato, Y., Mori, K., Furuya, I., Hayashi, R., Minagawa-Kawai, Y., & Koizumi, T. (2003). Developmental changes in cerebral lateralization to spoken language in infants. *Japanese Journal of Logopedia and Phoniatrics*, **44**, 165–171.
- Sato, Y., Sogabe, Y., & Mazuka, R. (2010). Development of hemispheric specialization for lexical pitch-accent in Japanese infants. *Journal of Cognitive Neuroscience*, **22**, 2503–2513.
- Toro, J.M., Trobalon, J.B., & Sebastián-Gallés, N. (2003). The use of prosodic cues in language discrimination tasks by rats. *Animal Cognition*, **6**, 131–136.
- Vicenic, C.J. (2011). The role of intonation in language discrimination by infants and adults. Doctoral dissertation, UCLA Los Angeles.
- Walker, D.C. (1984). *The pronunciation of Canadian French*. Ottawa, Canada: University of Ottawa Press.
- Weikum, W.M., Vouloumanos, A., Navarra, J., Soto-Faraco, S., Sebastián-Gallés, N., & Werker, J.F. (2007). Visual language discrimination in infancy. *Science*, **316**, 1159.
- Werker, J.F., & Tees, R.C. (1984). Cross-language speech perception: evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development*, **7**, 49–63.
- Westfall, P.H., & Young, S.S. (1993). *Resampling-based multiple testing*. New York: John Wiley & Co.
- Wong, P.C., Nusbaum, H.C., & Small, S.L. (2004). Neural bases of talker normalization. *Journal of Cognitive Neuroscience*, **16**, 1173–1184.
- Zhao, J., Shu, H., Zhang, L., Wang, X., Gong, Q., & Li, P. (2008). Cortical competition during language discrimination. *NeuroImage*, **43**, 624–633.

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