Newborn's brain activity signals the origin of word memories

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Edited by Mortimer Mishkin, National Institute for Mental Health, Bethesda, MD, and approved August 24, 2012 (received for review April 3, 2012)

Recent research has shown that specific areas of the human brain are activated by speech from the time of birth. However, it is currently unknown whether newborns' brains also encode and remember the sounds of words when processing speech. The present study investigates the type of information that newborns retain when they hear words and the brain structures that support word-sound recognition. Forty-four healthy newborns were tested with the functional near-infrared spectroscopy method to establish their ability to memorize the sound of a word and distinguish it from a phonetically similar one, 2 min after encoding. Right frontal regions—comparable to those activated in adults during retrieval of verbal material—showed a characteristic neural signature of recognition when newborns listened to a test word that had the same vowel of a previously heard word. In contrast, a characteristic novelty response was found when a test word had different vowels than the familiar word, despite having the same consonants. These results indicate that the information carried by vowels is better recognized by newborns than the information carried by consonants. Moreover, these data suggest that right frontal areas may support the recognition of speech sequences from the very first stages of language acquisition.

neonate's memory | right frontal lobe | sound encoding | speech perception | oxyhemoglobin

Previous studies have shown that newborns and human fetuses are able to remember word sounds (1–3) as well as to extract prosodic properties of speech (4) or identity relations between syllables (5, 6). However, neither the specific elements newborns encode from speech, nor the brain structures that mediate speech recognition at birth have been precisely characterized. Building on a functional near-infrared spectroscopy (fNIRS) paradigm used to test memory in newborns (7), the present study asks whether the newborn can remember all of the sounds [consonants (C) and vowels (V)] that form a bisyllabic CVCV word, or whether some of these segments are better encoded than others.

Judging by the number of studies reporting early abilities to discriminate fine phonetic contrasts (8), one might be inclined to ascribe to newborns a very detailed representation of the sound of words. In fact, newborns appear to discriminate all phonetic contrasts of the languages of the world, including those that their parents can no longer distinguish. Newborns distinguish consonants differing in one feature—for example, place of articulation, voicing, manner of articulation (9–11), duration (12)—as well as vowel quality contrasts (13, 14). Do the representations newborns hold in memory contain the full range of segmental details suggested by these discrimination capacities?

Different studies suggest that in adults (15–18), and in infants older than 12 mo (19–23), consonantal sequences are encoded more robustly than vocalic sequences for the representation of words. It is possible that a similar bias (namely, preference for consonantal information when encoding words) is already present at birth. Alternatively, it is possible that throughout development, maturation and experience modify the dimensions of speech that are privileged for encoding words. In fact, there are a number of reasons to predict that newborns, unlike adults and older infants, rely more on vowels than on consonants when recognizing the sound of a familiar word. First, infants learn native vocalic categories earlier than consonantal categories (24–28), suggesting that vocalic information might be available to infants earlier than consonantal information. Second, because vowels are longer and louder than consonants, they may be more noticeable in the speech signal and easier for newborns to process (29). Third, vowels are a rich source of information about the prosodic structure of the language. Encoding vowels—the main carriers of prosody—might facilitate parent–infant interactions (30), which in turn contributes to the infants' linguistic development (31). Moreover, prosodic cues play an important role in identifying indexical information, such as speakers' identity (32, 33), and are essential, early in development, for acquiring the syntactic structure of the language of exposure (34–37). Finally, given that prosodic processing involves mainly the right hemisphere (38, 39), and that certain areas of the right hemisphere implicated in speech processing appear to develop earlier in development than the corresponding areas of the left hemisphere (40, 41), the information carried by vowels may become available to infants earlier than the information carried by consonants.

The present study uses fNIRS (for reviews related to the technique see refs. 42–45) to explore whether newborns' memory relies mainly on the vocalic or consonantal content of a word-sound. Forty-four newborns participated in this study, which consisted of a familiarization phase and a test phase, separated by a silent retention interval. During familiarization, neonates were presented with 10 blocks, each composed of six identical words (Fig. 1*B*). During the test phase, composed of five blocks, brain responses to consonantal changes for half of the participants, and to vocalic changes for the other half were assessed in six regions of interest (ROIs) (Fig. 1*A*). Crucially, the interval between familiarization and test lasted 2 min, which allowed testing memory for word-sounds rather than mere sensory discrimination. [Auditory sensory representations decay in about 1.5 s in newborns (46).] The contrast between the brain responses to consonant and vowel changes enables a comparison of early word-sound memories to more mature word-representations that are known to rely mainly on consonantal information (15–23). In addition, the present study investigates whether brain areas that support memory for verbal information in adults also support memory in newborn infants.

Results

Because there were no significant differences between the newborns that were familiarized with the word */lili/* and those

Author contributions: S.B.-V., J.-R.H., M.N., and J.M. designed research; S.B.-V. and F.M. performed research; S.B.-V. analyzed data; and S.B.-V., J.-R.H., M.N., and J.M. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1205413109/-/DCSupplemental.

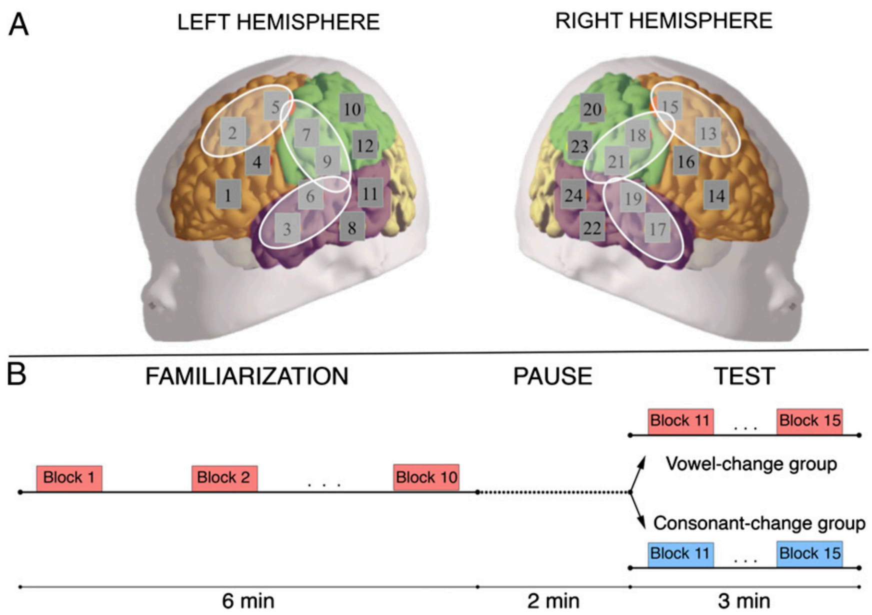

Fig. 1. Details of the procedure used in the study. (*A*) Location of channels (gray squares) and regions of interest (white ellipses) on a schematic neonate brain. (*B*) The experimental design. Each rectangle represents a block consisting in a series of six words separated by short pauses of 0.5 or 1.5 s.

familiarized with the word /*mimi*/ (permutation test, $P > 0.35$), data from all participants were pooled for the analyses.

Permutation tests performed over each of the ROIs showed a significant difference between the groups in the right frontal area in the first block of the test phase. Neonates in the vowel-change group displayed a greater response than neonates in the consonant-change group (permutation test, $P < 0.001$) (Fig. 2*A*). This pattern was verified both for infants familiarized with the word /*mimi*/ and tested with either /*mama*/ or /*sisi*/ (permutation test, $P < 0.01$), and for newborns familiarized with the word /*lili*/ and tested with either /*lala*/ or /*titi*/ (permutation test, $P < 0.05$). No other area showed significant differences between the groups. [Similar analyses for deoxyhemoglobin yielded no significant differences (*SI Text* and Fig. S1). As previously pointed out (5, 43), this might be because oxyhemoglobin measures are more sensitive and have better signal-to-noise ratio than deoxyhemoglobin measures.]

Moreover, to evaluate the change in response from the familiarization to the test phase, we computed the difference between the activation in the last block of the familiarization phase minus the activation in the first block of the test phase. An ANOVA with Group (consonant-change/vowel-change) as a between-subject factor, and ROI as within-subject factor showed a main effect of Group [$F(1,22) = 7.839$; $P < 0.01$] because of an increment in the response from the familiarization to the test phase in the vowel-change group, and a decrement in the response in the consonant-change group (Fig. 2 *B* and *C*). We found no main effect of ROI [$F(5,18) = 1.566$; not significant], but a significant interaction between ROI and Group factors [$F(5,18) = 2.870$; $P < 0.05$]. (As stated in *Materials and Methods*, specific channels showing artifacts were rejected in each block. For this reason, the degrees-of-freedom vary from one comparison with another.) Post hoc *t* tests showed a significant difference between the consonant-change and vowel-change groups [$t(27) = 4.387$; $P < 0.0001$] because of a decrement in oxyhemoglobin concentration in the consonant-change group and an increment in the vowel-change group in the right frontal area. The same pattern was also observed in the left temporal [$t(29) = 2.324$; $P < 0.05$] and the right parietal areas [$t(28) = 2.322$; $P < 0.05$] (Fig. 3). A binomial test revealed that the majority of neonates displayed the effect in the right frontal area, showing either increment or decrement from the familiarization to the test phase according to the group to which they were assigned ($P < 0.01$). This finding was also true for the left temporal area ($P < 0.01$), but not for the right parietal area ($P = 0.05$).

Discussion

The present study shows differential brain activations between the consonant-change group and the vowel-change group in the recognition test. In particular, there was a significant decrease in oxyhemoglobin when participants were tested with a word that contained novel consonants and a significant increase when the word contained novel vowels. This effect was observed most strongly in the right frontal areas and, to a lesser degree, in the left temporal and right parietal areas.

For newborns, no standard physiological explanation currently exists to account for the direction of changes in the hemodynamic responses measured by NIRS (43). This problem has probably persisted in the field because of the scarcity of experiments manipulating type and complexity of the stimuli within similar paradigms, which would make the studies directly comparable among themselves. However, the pattern of activation observed in the present study avoids this problem. These responses can be interpreted in light of the characteristic brain activation observed in our previous fNIRS studies assessing memory in newborns (3), which used experimental paradigms and stimuli similar to the ones used in the present study. In our previous studies, participants showed a decrease of oxyhemoglobin when presented with a familiar word-sound in the recognition test (e.g., the pseudoword "*mita*" presented in the familiarization and also in the test phase), and an increase in the oxyhemoglobin when they listened to a novel word-sound differing in both consonants and vowels (e.g., "*mita*" presented in the familiarization and "*pelu*" in the test phase). Therefore, the activations observed in the present study suggest that vowel information is privileged in newborns' encoding and/or recognition of word-sounds. These data contrast with previous studies in adults and older infants, showing that participants rely primarily on consonants during lexical processing and word learning (15–23).

The present results can be attributed to the newborns' ability to maintain the familiarization word-sound in memory, and not

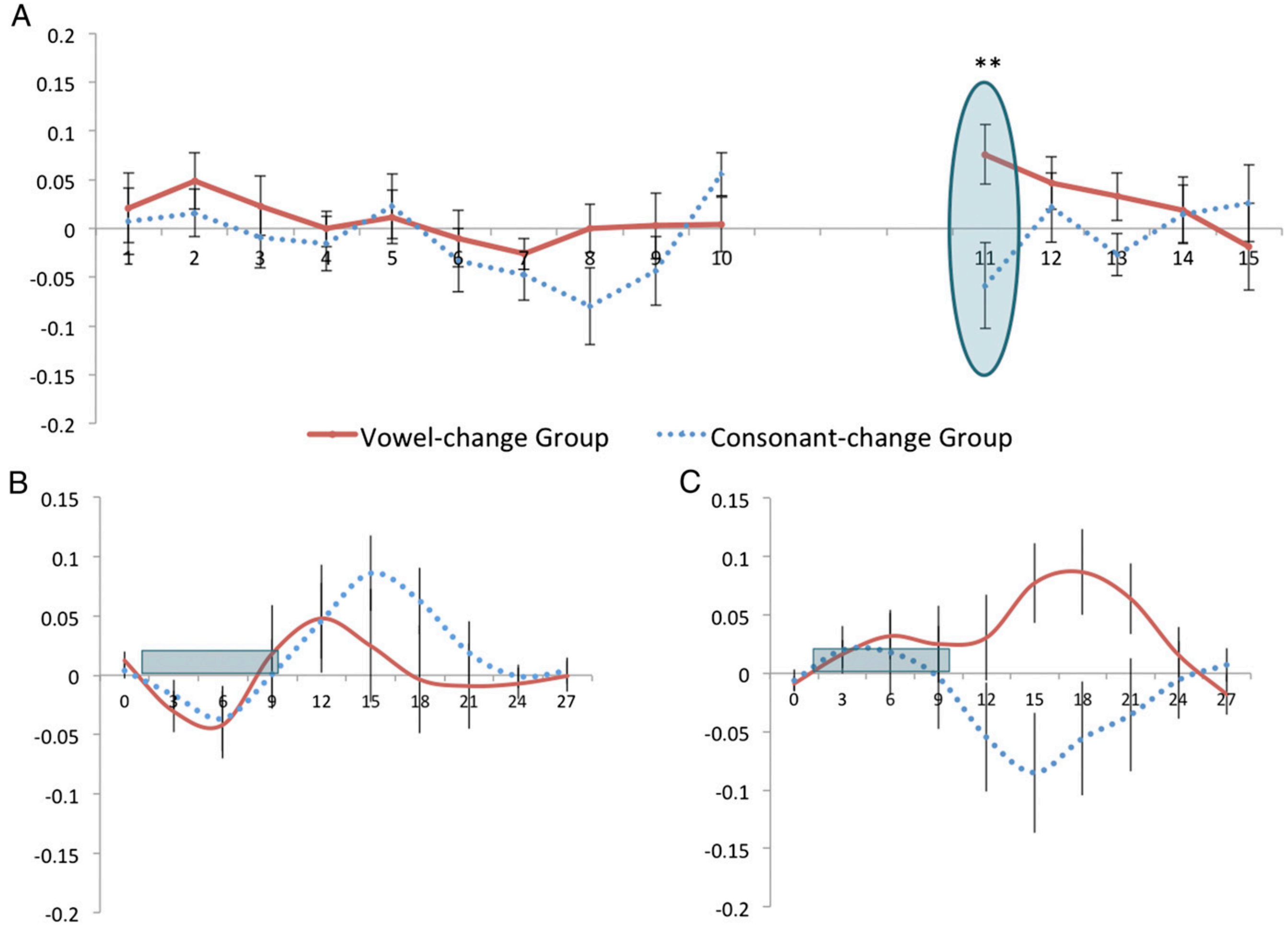

Fig. 2. Time course of the relative hemodynamic changes in the right frontal area averaged across subjects per group. (*A*) Mean concentration changes across the experiment. The *x* axis shows number of blocks. (*B*) Hemodynamic curve in the last block of the familiarization phase and (*C*) first block of the test phase. The *x* axis displays time in seconds. The rectangle along the *x* axis indicates the time of stimulation. In all of the graphs, the *y* axis shows the changes in concentration of oxyhemoglobin in mmol·mm. Error bars indicate SEM (permutation test, $^{**}P < 0.001$).

merely to the traces maintained in their sensory systems. Newborns' sensory memory lasts at most 1.5 s (46), and even adults' temporary traces of speech information (short-term storage) decay in a few seconds in the absence of a vocal or subvocal rehearsal (47). Therefore, the ability to retain the sound of a word for 2 min (i.e., the duration of the retention interval in our study) vastly exceeds the limits of sensory systems and may instead rely on memory representations.

In addition, the regions exhibiting differential activation to previously heard vowels versus novel vowels (i.e., left temporal, right parietal, and right frontal areas) constitute further evidence that basic memory processes, sustaining the retention of speech information for several minutes, are functional from birth. In fact, the right frontal (48–50) and parietal areas (51–53) are usually activated in adult participants when they retrieve information from memory. Moreover, the right frontal activation has been reported when 3-mo-old infants listen to the same sentence repeatedly (54). Finally, the observed activation of the left temporal region aligns with previous reports on early speech processing (54–56), and with the notion that anatomical (41) and functional (3) precursors of memory for speech sounds emerge in very young infants.

These results have a number of implications for theories of speech processing, early memory, language acquisition, and development. First and foremost, the present study provides evidence that the newborn's memory for word-sounds differs from the purely auditory-sensory representations reported in previous studies. In fact, the present findings suggest that newborns' well-attested ability to discriminate vocalic as well as consonantal contrasts need not imply a longer-term memorization of all of the segments of a CVCV word. Differential recognition of repeated vowels and repeated consonants might occur because newborns disregard or fail to fully encode consonantal information when storing the sound of a word in memory. Alternatively, consonants might be encoded during the familiarization phase, but not recognized by newborns at test. At this point of our research, it is difficult to distinguish between these accounts. It seems clear, however, that vowels are privileged over consonants in the newborns' memory system, despite their ability to perceive both fine vocalic and fine consonantal contrasts.

It is premature to draw firm conclusions about whether the newborn's memory for word-sounds is structured into phonetic segments. The recognition of a familiar word at birth might be based either on the representation of the segmental qualitative properties of the vowels (e.g., height and roundedness), or on suprasegmental properties of vowels (e.g., pitch and duration). It is difficult to fully separate the quantitative and the qualitative aspects of vowels. In fact, front vowels, such as /*i*/, are intrinsically pronounced with a higher pitch than back vowels, such as /*a*/ (57, 58). Changes in pitch are salient for newborns (59, 60), and so are

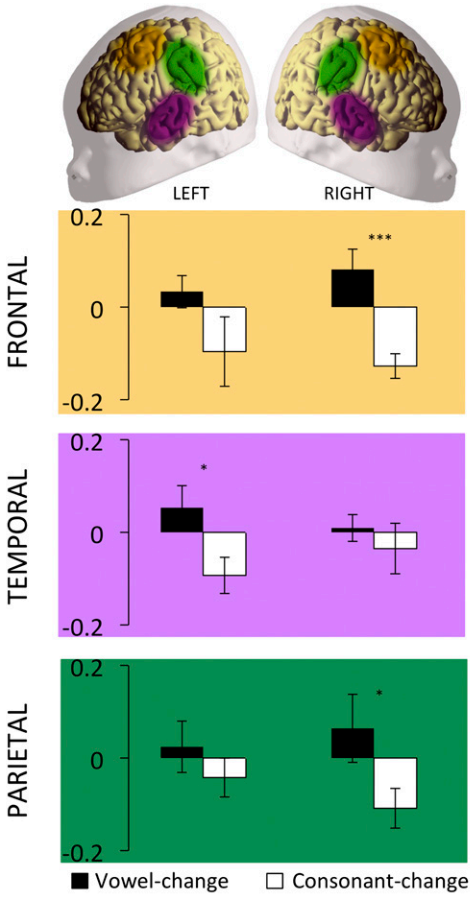

Fig. 3. Oxyhemoglobin concentration changes from the last block of familiarization to the first block of the test phase. Channels located in the right frontal, left temporal, and right parietal areas showed a decrement in oxyhemoglobin when participants heard a test word that shared the same vocalic-tier of the familiarization word but had different consonantal-tier (white bar). In contrast, there was an increment in the concentration of oxyhemoglobin from the familiarization to the test when neonates heard a word containing the same consonantal content of the familiarization word but novel vowels (black bar). Colored ellipses on the schematic neonate brain indicate the localization of the channels included in the ROI. Error bars indicate SEM (*t* test, $***P < 0.0001$; $*P < 0.05$).

vowel distinctions (14, 61, 62), thus both kinds of information could potentially support neonates' recognition of familiar sounds.

These data also suggest that the consonantal bias for word learning and word processing emerges during the first year of life. Newborns encode the properties of vowels, whereas by the end of the first year, infants start making use of consonants to establish phonological representations of words (23). Although this intriguing developmental change requires further study, it is conceivable that factors, such as the statistical properties of the environmental language (63, 64), maturation of areas of the brain implicated in language processing (40, 41), as well as the emergence of native consonantal categories (23), contribute to this transition.

Nespor et al. (65) proposed that vowels and consonants play different roles in speech processing and language acquisition. These authors suggest that consonants are more important for lexical processes, whereas vowels are the main carriers of prosodic and structural properties. The authors also suggest that very young infants engage in discovering the structure of the utterances of their native language before they begin to compile the lexicon. In light of Nespor et al.'s proposal, our data might suggest that, rather than fully encoding words from the speech input, newborns may be focusing more on the extraction of structural properties cued by vowels (34, 66). This focus might be an advantage for young infants, given that despite their immature cognitive systems they seem to learn language more readily than adults. Thus, disregarding changes in consonantal information might in fact facilitate the very first steps of language acquisition (29).

To summarize, the present results reveal some properties of the initial state of humans' auditory memory, the brain areas that support it, and the information that newborns retain from the speech signal. The data show that at birth there are basic memory systems capable of storing speech information for several minutes. Moreover, these systems involve right frontal brain areas, which are also recruited during information retrieval in adults. Additionally, our results provide evidence that newborn's discrimination capacities reported in previous studies do not necessarily translate into a detailed memorization of all of the segments of a CVCV word; newborns memorize mainly the information of vowels: the segments that carry most of the energy within words. After Eimas et al. showed that very young infants discriminate CV syllables (9, 10), most developmental psychologists assumed that in the first months of life infants retain vowels and consonants equally well. In our investigations of the memory of the sounds of words, we found an important asymmetry between the two categories of segments, opening new perspectives on phonological development and language acquisition.

Materials and Methods

Participants. Forty-four healthy full-term neonates (17 males and 27 females; mean age 2.5 d; range 1–4 d; birth weights 2,764–4,302 g) participated in the study. Seven additional neonates were tested but excluded from the analysis either because their head movements produced large motion artifacts ($n = 2$), because they cried before the end of the experiment ($n = 4$), or because of experimental error ($n = 1$). Selection criteria included gestational age between 38 and 42 wk, Apgar scores ≥ 8 in the first and fifth minutes, diameter of head ≥ 33.5 cm, absence of cephalohematoma, and intact hearing. Neonates were recruited from the newborn nursery at the Hospital in Udine, Italy. All parents provided informed consent for the experiment. The Ethics Committee of the International School for Advanced Studies approved the study.

Stimuli. Two CVCV words (*/mimi/* and */lili/*) were used during the familiarization (see next section); the test words (*/sisi/, /mama/; /titi/, /lala/*), were chosen because they have consonants and vowels that differ from those of the familiarization words in the maximum number of phonetic features (maximum vocalic distance possible in Italian is three features from */i/* to */a/*; maximum consonantal distance possible in Italian is four features, from */m/* to */s/* and from */l/* to */t/*) (Fig. S2). None of the words have meaning in Italian, the language spoken by the parents of the infants. A female speaker recorded all stimuli. Each word carried stress on the first syllable and was edited to 70 dB mean intensity and 700-ms duration.

Data Acquisition. Hemodynamic responses of the neonates' brain were measured with fNIRS (ETG-4000, Hitachi). This machine allows simultaneous recording from 24 channels. The separation between emitters and detectors was 3 cm, the sampling rate 10 Hz, and the total laser power 0.75 mW. Two probes holding the fibers were placed on the neonate's head (one probe on the left and one on the right hemisphere) using skull landmarks. Although individual variation cannot be excluded, placement maximizes the likelihood of monitoring the temporal, parietal, and frontal areas.

Procedure. A medical doctor assisted the participants inside a dimly lit sound-attenuated booth where the experiment was run. Neonates were tested while lying in their cribs either in a state of quiet rest or sleeping. Sound stimuli were presented via two loudspeakers. A Mac power PC G5 operated the fNIRS machine and presented the auditory stimuli using the software PsyScope X (http://psy.ck.sissa.it/). An infrared video-camera was used to monitor infants' behavior.

We implemented a block design to assess memory for words in neonates, as described in previous studies (3, 7). The design consisted of a familiarization phase of 10 blocks, a silent interval, and a test phase of 5 blocks (Fig. 1*B*). Each block lasted 10 s and contained six identical words separated by pauses of randomized length (0.5 s or 1.5 s). Blocks were spaced at time intervals of varying duration (25 s or 35 s). The experiment lasted about 11 min (6-min familiarization phase, 2-min silent interval, 3-min test phase).

Two words were used during the familiarization phase; half of the participants heard one word (e.g., */mimi/*), and half heard the other word (e.g., */lili/*). In the test phase, half of the newborns heard a word that preserved the consonants of the familiar word but had a different vocalic content (vowel-change group), whereas the other half heard a word that changed the consonants, but preserved the vowels of the familiar word (consonant-change group). For example, if the familiarization word was */mimi/*, the test words were */mama/* for the vowel-change group and */sisi/* for the consonant-change group. Similarly, if the familiarization word was */lili/*, the test words were */lala/* for the vowel-change group and */titi/* for the consonant-change group.

Data Processing and Analysis. The signal was band-pass filtered between 0.02 and 1.00 Hz. Single channels from specific blocks were eliminated if the light absorption was less than 1% of the total light emitted or if there were movement artifacts (changes in the signal greater than 0.1 mmol·mm in an interval of 0.2 s). Blocks with more than 12 rejected channels were excluded. Participants were included in the analysis only if the amount of data rejected was less than 30%.

A baseline was linearly fitted between the mean of the 5 s preceding the onset of the block and the mean of the 5 s between the 15th second and the 20th second after the offset of the sound. The mean signal over the 9 s following the end of the auditory stimulation was used to carry out the statistical analysis. This analysis period corresponds to the time window in which the maximum amplitudes of the hemodynamic responses are expected based on previous studies (e.g., refs. 55, 67, and 68). Oxyhemoglobin concentrations of six ROIs were used for the data analysis (Fig. 1*A*). The channels included in the ROIs were chosen on the basis of previous studies on newborns' memory and speech processing using fNIRS (3, 5).

To assess whether the two conditions differed in the test, we computed the maximum difference between the mean activation for each condition. That is, for each block $b = 1,2,\ldots$, we calculated

$$\mathrm{Diff}(b) = \max_{c=1,\ldots,24}\left|\overline{A}_1(b,c) - \overline{A}_2(b,c)\right| \qquad [1]$$

where $\overline{A}_j(b,c)$ is the activation in block b and channel c, averaged among all neonates assigned to condition j (consonant-change/vowel-change). When analyzing the familiarization phase as a whole, we further computed Diff (fam) as the maximum of Diff(b) for all blocks $b = 1,2,\ldots,10$. Because the distribution was not Gaussian, we evaluated significance using nonparametric methods. Specifically we used an approximate permutation test (69) by randomly assigning a group label (i.e., "consonant-change" or "vowel-Change" group) to each infant. A permutation test was run for each ROI. The number of reassignments was 10,000 for each permutation test.

ACKNOWLEDGMENTS. We thank the staff at the Neonatology and Obstetrics Departments, Udine Hospital, for valuable assistance on the recruitment of neonates and thank the parents of the newborns for their participation. We also thank Amy Skerry for comments on a previous version of the manuscript; and Marijana Sjekloca, Francesca Gandolfo, and Alessio Isaja for their administrative and technical support. The research leading to the present results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013)/European Research Council Grant 269502 ("Processing Activates Specific Constraints for Language Acquisition") (to J.M.) and partially from the Consejo Nacional de Investigaciones Científicas y Tecnológicas and Ministerio de Ciencia y Tecnología of Costa Rica (to S.B.-V.).

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