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Brain regions and functional interactions supporting early word recognition in the face of input variability

Silvia Benavides-Varela[a,b,1], Roma Siugzdaite[c,d], David Maximiliano Gómez[e,f], Francesco Macagno[g], Luigi Cattarossi[g], and Jacques Mehler[h]

[a]Department of Developmental Psychology and Socialization, University of Padova, 35131 Padova, Italy; [b]Neuropsychology Unit, Fondazione Ospedale San Camillo Istituto di Ricovero e Cura a Carattere Scientifico, 30126 Venice, Italy; [c]Data Analysis Department, Faculty of Psychological and Educational Sciences, Ghent University, 9000 Ghent, Belgium; [d]Experimental Psychology Department, Faculty of Psychological and Educational Sciences, Ghent University, 9000 Ghent, Belgium; [e]Centro de Investigación Avanzada en Educación, Universidad de Chile, 8330014 Santiago, Chile; [f]Instituto de Ciencias de la Educación, Universidad de O'Higgins, 2841959 Rancagua, Chile; [g]Patologia Neonatale, Santa Maria della Misericordia Hospital, 33100 Udine, Italy; and [h]Language Cognition and Development Laboratory, International School for Advanced Studies, 34136 Trieste, Italy

Perception and cognition in infants have been traditionally investigated using habituation paradigms, assuming that babies' memories in laboratory contexts are best constructed after numerous repetitions of the very same stimulus in the absence of interference. A crucial, yet open, question regards how babies deal with stimuli experienced in a fashion similar to everyday learning situations—namely, in the presence of interfering stimuli. To address this question, we used functional near-infrared spectroscopy to test 40 healthy newborns on their ability to encode words presented in concomitance with other words. The results evidenced a habituation-like hemodynamic response during encoding in the left-frontal region, which was associated with a progressive decrement of the functional connections between this region and the left-temporal, right-temporal, and right-parietal regions. In a recognition test phase, a characteristic neural signature of recognition recruited first the right-frontal region and subsequently the right-parietal ones. Connections originating from the right-temporal regions to these areas emerged when newborns listened to the familiar word in the test phase. These findings suggest a neural specialization at birth characterized by the lateralization of memory functions: the interplay between temporal and left-frontal regions during encoding and between temporo-parietal and right-frontal regions during recognition of speech sounds. Most critically, the results show that newborns are capable of retaining the sound of specific words despite hearing other stimuli during encoding. Thus, habituation designs that include various items may be as effective for studying early memory as repeated presentation of a single word.

newborns | language | habituation | memory | fNIRS effective connectivity

Habituation, namely the decreased response to repeated presentations of stimuli, has been widely used to investigate infant cognition. Both behavioral (1) and neuroimaging (2, 3) habituation paradigms are regularly implemented for assessing a wide range of mental processes including categorization, object representation, and memory in very young babies. Despite this long tradition, it remains elusive the extent to which the results of habituation studies (which often consist of massive repetition of a single stimulus) can inform our understanding of memory functions in everyday-like situations—that is, in the presence of various stimuli.

Developmental studies in the language domain have uncovered basic perceptual (4–6), discrimination (7, 8), and mnemonic capacities (9–14) in newborns and fetuses, supporting the hypothesis that memories for sounds begin to be established very early in life. However, infants' memory for specific words seems to be highly vulnerable to interference. Newborns are capable of remembering a single word that they have heard in a classic habituation paradigm (i.e., consecutive/massed repetitions) and after a silent pause but readily forget the word if interfering words are introduced in the interval before testing (10). Whether these findings reflect memory constraints that allow newborns to remember specific words only if

presented in isolation is an open yet crucial question whose answer will contribute to better characterizing the initial state of human memory and will advance our understanding of the foundations of learning and language acquisition in infancy.

Here, we used a modified habituation paradigm that incorporated various words to examine a counterintuitive hypothesis: Newborns may remember specific words even in the presence of other—potentially distracting—words but may be better able to do so when the different words are presented in an interleaved fashion during habituation than when a word is presented alone during habituation and the "distracting" word appears afterward. In other words, additional words may not cancel or weaken infants' recognition of the most frequently presented word in habituation paradigms, as long as the former are distributed during the encoding stage.

This hypothesis finds support on at least two pieces of evidence. First, there is a phenomenon robustly and consistently observed in adults known as the spacing effect. This refers to the observation that repeated presentations of a stimulus induce better recollection if intervening stimuli occur between the various presentations (i.e., spaced condition) compared with a situation in which no intervening stimuli occur between the repetitions (i.e., massed condition) (15–20). Because the spacing effect has been observed in adults even during incidental learning—when participants are not intentionally memorizing or paying attention to the stimuli (21, 22)—it is likely that this effect influences the functioning of infants' memory as well.

The second source of information that supports our hypothesis derives from studies showing that specific word-sound representations in infants and toddlers become more robust, generalizable,

Significance

Since birth, infants begin to learn a myriad of sounds. Yet our knowledge of their abilities to remember specific sounds is primarily based on habituation studies that presented them with massive repetitions of single sounds. The present work opens vistas on the study of language acquisition and memory development by suggesting that the presence of various sounds during encoding does not impair recognition in newborns. Results also indicate that a coordinated interplay between temporal and frontal regions of the brain supports newborns' ability to memorize specific words in this—previously thought—disruptive context.
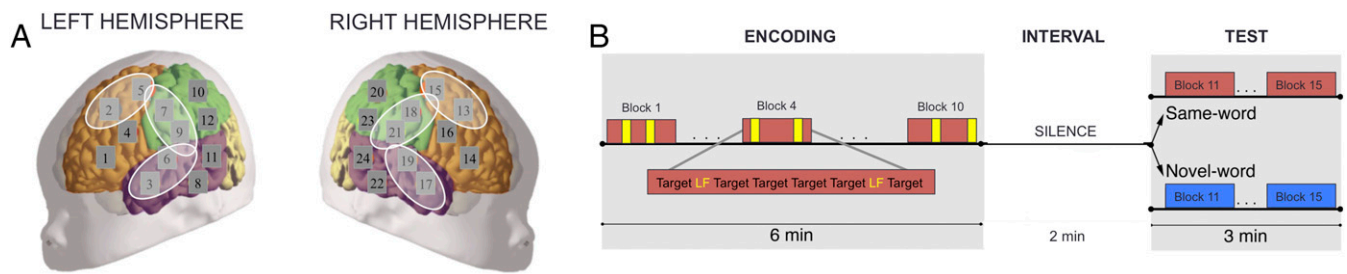
Fig. 1. (*A*) Location of channels (gray squares) and ROIs (white ellipses) on a schematic neonate brain; see also Fig. S1 depicting a projection of the probes to a label map of a MRI neonate template and the *SI Materials and Methods* for a detailed description of the cortical regions underlying the channels. (*B*) Experimental design. Each rectangle represents a block consisting of a series words separated by short pauses of 0.5 or 1.5 s. During the encoding phase, all neonates heard 10 blocks composed of 6 repetitions of the target word and 2 repetitions of a potentially distracting word (low-frequency word, LF). In the test, half of the neonates heard the target word and the other half heard a completely novel word. A 2-min silent interval separated the encoding and test phases.

and phonologically precise with increased input variability and conversely that low variability during encoding appears to degrade later word recognition (23–25). In a related line of research, studies on statistical learning further show that 8-mo-old infants successfully use statistical cues to segment words in conditions of high acoustic variation, whereas low acoustic variation hinders infants' efficiency in segmenting words from continuous speech (26). A similar advantage provided by input variability has been reported in an artificial language study, where increasing variability between adjacent elements led to better detection of nonadjacent dependencies, both in 14-mo-old infants and adults (27). Altogether, these studies endorse our initial hypothesis that input variability during encoding should at the very least not interfere with the recognition of the words and, if anything, might rather favor a more stable representation of these words.

The structure of the present experiment consisted of an encoding phase that incorporated various items followed by a silent retention interval of 2 min and a test phase. During the encoding phase, neonates were presented with 10 blocks containing 8 sounds each. These sounds were either a high-frequency word (hereafter the target) presented six times or a low-frequency word presented two times (Fig. 1*B*). The low-frequency word plays an analog role to that of interfering stimuli in previous studies. The total number of instances of the target and low-frequency words was the same as in previous studies (experiment 3 in ref. 10). Unlike previous work, however, the low-frequency word was randomly distributed in the blocks during the encoding phase rather than being presented after mass repetition of the target word and before testing. We expected newborns' brain activity to exhibit a recognition response to the

target despite the presence of the potentially distracting low-frequency word during the encoding phase. During the test phase, brain hemodynamic responses to the target word (same-word group) and a completely novel word sound (novel-word group) were assessed in six regions of interest (ROIs).

We examined brain local hemodynamic activity in frontal, parietal, and temporal cortical regions as well as functional interactions among these regions during the encoding and recognition phases. Each of these areas appears to support relatively specialized functions in newborns. Temporal areas are mainly involved in perception of the speech signal, with those in the left hemisphere dedicated to the processing of fast phonemic transitions and those in the right one to the processing of the slow acoustic modulations associated with prosody (28). Frontal and parietal regions are believed to sustain important domain-general functions from early infancy (29). Frontal regions are functionally involved in memory tasks (11, 30, 31), novelty and invariance detection (32, 33), and attentional orienting (33–35). Parietal regions have connections with the frontal regions and have also been associated with mnemonic (36, 37), attentional (38), and verbal working memory processes in adults (39, 40).

We evaluated the coordinated interactions among these cortical regions during the elaboration of verbal memories in newborns using Structural Equations Modeling (SEM). Previous studies have shown that frontal and temporal regions of the language network appear anatomically connected already in the first postnatal weeks (41–43). Moreover, these regions show time-lagged cross-correlations in response to passive listening to speech stimuli (44) and exhibit phase synchronization particularly in the left hemisphere (45). Our study aimed to provide a
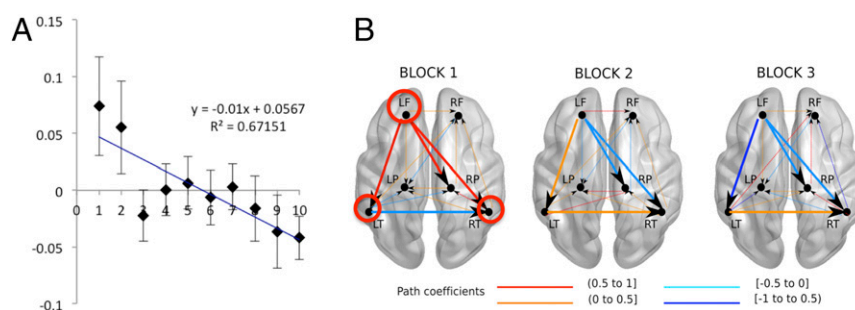

Fig. 2. (*A*) Time course of the relative OxyHb changes in the LF area averaged across subjects. The plot depicts mean concentration changes in the encoding phase. The *x* axis shows block numbers. The *y* axis shows the changes in concentration of OxyHb in mmol•mm. Error bars indicate standard error of the mean. (*B*) Effective connections observed among the bilateral frontal (LF, RF), temporal (LT, RT), and parietal (LP, RP) areas during the habituation response in the first three blocks of the encoding phase. The evaluation of different models with AMOS showed good data fit in all of the blocks. Block 1, χ^2 (df = 2) =1.377, P = 0.502; block 2, χ^2 (df = 3) = 4.03, P = 0.258; block 3, χ^2 (df = 3) = 1.195, P = 0.754. Wider lines highlight the progressive weakening of the functional connections of the LF region and the strengthening of the connections between the temporal regions. Red circles highlight the regions with noteworthy connections. Fig. S2 depicts the hypothetical starting model.

characterization of the spatiotemporal dynamics within this network during memory assessments by exploring the different configurations as a function of the familiarity of a given speech stimulus—namely, when the system processes a word that is familiar to the newborn versus a totally novel word.

Results

Encoding Phase. As expected, there were no significant differences in this phase between the hemodynamic activity associated with the same-word and novel-word groups (permutation test, $P = 0.49$). Hence, data from all participants were pooled together for the analysis. A robust linear regression computed over the 10 encoding blocks showed a significant reduction of oxyhemoglobin (OxyHb) in the left-frontal (LF) ROI [$R^2 = 0.671$; $y = -0.01x$ ($P = 0.002$) + 0.06 ($P = 0.018$, Bonferroni-corrected)]. This reduction was most evident in the first three blocks of the encoding phase (Fig. 2A). Computing regressions separately for each participant in this ROI yielded results consistent with the group analysis: The slope values across participants were altogether significantly lower than zero [mean slope = -0.01; $t(39) = -2.22$, $P = 0.03$]. No other ROI showed significant changes in OxyHb responses during encoding.

A comparative analysis of effective connectivity across blocks in the encoding phase (where each combination of brain regions and connections among them represents the best fit model for each block) evidenced two systematic changes associated with the habituation effect observed in the first three blocks of the encoding phase (Fig. 2B): (i) weakening of the functional connections from the LF to the left-temporal (LT) (path coefficients block 1, 0.880; block 2, 0.433; block 3, -0.683), right-temporal (RT) (path coefficients block 1, 0.908; block 2, 0; block 3, -0.475), and right-parietal (RP) ROIs (path coefficients block 1, 0.562; block 2, -0.062; block 3, 0) and (ii) strengthening of connections between both temporal ROIs (path coefficients block 1, 0; block 2, 0.238; block 3, 0.476). These differences were confirmed statistically: Whereas connections from LF were weaker in block 1 compared with block 3 (LF to LT $\Delta = 1.756$, $P = 0.001$; LF to RT $\Delta = 1.717$, $P = 0.001$; LF to RP $\Delta = 0.391$, $P = 0.001$) and block 2 compared with block 3 (LF to LT $\Delta = 0.271$, $P = 0.001$; LF to RT $\Delta = 1.467$, $P = 0.001$; LF to RP $\Delta = -0.007$, $P = 0.884$), the interhemispheric connections between temporal regions were stronger (block 1 vs. block 3 $\Delta = -0.424$, $P = 0.001$; block 2 vs. block 3 $\Delta = 0.17$, $P = 0.002$).

Test Phase. A robust linear regression, comparable to the one carried out in the encoding phase, consistently showed a significant reduction of OxyHb in the LF ROI in the test phase [$R^2 = 0.876$; $y = -0.01x$ ($P = 0.02$) + 0.004 ($P = 0.58$)] (Fig. 3A, *Top Left*). Permutation tests performed over each ROI showed significant differences between groups (same word vs. novel word) in the right-frontal (RF) region in the first block of the test phase ($P = 0.006$, Bonferroni-corrected) (Fig. 3A, *Top Right*). In agreement with previous studies reporting a differential response with similar
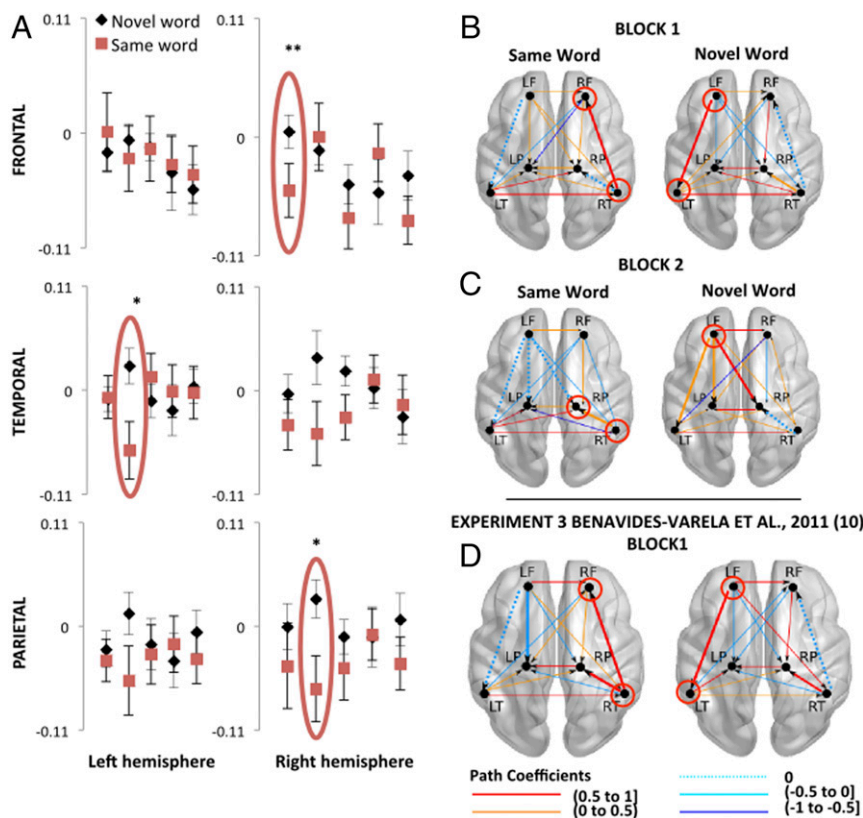

Fig. 3. (A) Relative OxyHb changes measured in six ROIs during the 5 blocks comprising the test phase. The y axes show concentrations of OxyHb in mmol·mm. Red ellipses indicate the blocks in which significant differences between groups were found. Fig. S3 shows the hemodynamic curves of the same-word and novel-word groups in the RF area during the first block of the test phase. In all graphs, error bars indicate standard error of the mean (permutation test, *$P < 0.01$; **$P < 0.001$). (B–D) Functional connections observed during the first (B) and second block (C) of the recognition test in the current study and the first block (D) of the recognition test in Benavides-Varela et al., 2011 (10), experiment 3. The models appropriately fit the data: block 1 same-word group, χ^2 (df = 4) = 5.011, $P = 0.286$; novel-word group, χ^2 (df = 2) = 2.692; $P = 0.260$; block 2 same-word group, χ^2 (df = 4) = 5.694; $P = 0.223$; novel-word group, χ^2 (df = 1) = 1.697; $P = 0.193$; previous study: block 1 same-word group, χ^2 (df = 1) = 1.109, $P = 0.292$; novel-word group, χ^2 (df = 1) = 0.074, $P = 0.786$. Dotted lines depict connections that were absent in a given block-group model; solid lines highlight the corresponding connections between each pair of areas in the other group. Red circles highlight the regions with noteworthy connections. Fig. S2 depicts the hypothetical starting model.

functional near-infrared spectroscopy (fNIRS) paradigms (10, 11), we found that neonates in the novel-word group displayed greater hemodynamic responses than neonates in the same-word group. Furthermore, model comparisons within the connectivity analysis evidenced distinct functional configurations in the same-word versus the novel-word groups (χ^2 = 1,365.39, df = 14, P < 0.0001); all but two pathways [LF to RP (Δ = 0.051, P = 0.390); LT to left-parietal (LP) (Δ = –0.123, P = 0.354)] differed between groups (all Ps < 0.005). Moreover, connections from the RT to the RF (the region showing hemodynamic differences between groups) were present only in the same-word (path coefficient, 0.53) but not in the novel-word group. The response in the novel-word group was characterized, like the encoding phase, by strong connections from the LF to the LT areas (path coefficient, 0.50) and from the RT to the RP areas (path coefficient, 0.38). These connections were absent in the same-word group (Fig. 3B).

The hemodynamic analysis also showed differences between groups in the second block of the test phase in the RP region (permutation tests, P = 0.001; Bonferroni-corrected, P = 0.012) and a statistical tendency in the LT ROI (P = 0.01; Bonferroni-corrected, P = 0.12). Consistently with the pattern observed in the RF region and in previous memory studies in newborns (10, 11), the response of the novel-word group was greater than the response of the same-word group.

The connectivity analysis also showed distinct functional configurations in the same-word and the novel-word groups (all pathways differed between groups, χ^2 = 1,365.39, df = 14, P < 0.0001). Similar to what was observed in the first block, the region showing significant hemodynamic differences between groups (RP) showed effective connections with the RT region in the same-word group only (path coefficient, 0.53). Moreover, critical connections from the LF region were observed in the novel-word group only: LF–LT path coefficient, 0.416; LF–LP path coefficient, 0.067; LF–RP path coefficient, 0.738 (Fig. 3C).

To further specify the functional connections that distinguish the newborns' brain responses in the recognition test, we implemented the same connectivity analysis on a previous dataset (experiment 3 in ref. 10). (We contrasted the results of the test phase where the quantity and quality of information is equivalent and thus comparable across studies.) Because this appears to be one of the earliest implementations of the SEM approach to fNIRS data, this analysis allowed us to additionally validate such implementation. In line with the results of the current study, there was a strong coupling between the LF and LT areas (path coefficient, 0.62) and the RT and the RP areas (path coefficient, 0.57) but no connection between the RT and the RF areas (path coefficient, 0) associated with the presentation of novel sounds (Fig. 3D). The critical connections—in the left hemisphere—were significantly stronger in the previous dataset than in the current one (LF to LT Δ = 0.281, P = 0.001; RT to RP Δ = 0.16, P = 0.058). Furthermore, like in the current study, we observed strong connections from the RT to the RF areas (path coefficient, 0.73) and no connections from the LF to the LT areas (path coefficient, 0) in the same-word group. Again, the critical connections—in the right hemisphere—were significantly stronger in the previous dataset than in the current one (RT to RF Δ = –0.132, P = 0.035). A strong connection from the RT to the RP areas (path coefficient, 0.84) was present in the same-word group of the previous study but not in the present one.

Discussion

In habituation-based studies, newborns are able to retain the sounds of specific words for some minutes only if no interfering speech information is presented after the habituation phase and before the test (10). This suggests a strong limitation of the newborns' verbal memory that might constrain the acquisition of specific sounds from the surrounding language. As opposed to what could have been expected from those previous studies, the present work reports a characteristic recognition response to a familiar word that was presented to newborns in concomitance with other words. Differently from previous works, the various words were presented during—rather than after—habituation. The results corroborated our hypothesis that, in newborns, word-sound representations become more robust with increased input variability and also that, similar to adults (15–22), newborns' word memories seem to benefit from spaced rather than massive repetitions of a single sound.

The differential brain activations between the same-word group and the novel-word group in the recognition test (firstly and most strongly in RF areas) closely resemble those observed in previous studies addressing word memory in newborns (10, 11). It is hard to disentangle, from these findings, whether the RF region is implicated in recognizing "novel features" (thus the increment of the OxyHb in the novel-word group) or "familiar features" (reflected in the decrement of the OxyHb in the same-word group). [Some studies, particularly with infants and newborns, have reported decrements of OxyHb in response to various experimental stimuli (see ref. 46 for a review).] The connectivity measure contributes information to clarify this issue by showing a strong coupling of the RF region in the same-word group but not the novel-word one. This suggests that the RF region is strongly implicated in the network supporting the recognition of familiar sounds. The connectivity profile in the same-word group was additionally characterized by the presence of strong effective connections between the RT regions and the regions showing significant hemodynamic differences (RF in the first block; RP in the second block). These connections were, by contrast, absent in the novel-word group. This pattern indicates a fundamental role of the RT region [known to process the slow information associated with speech prosody (28, 47) and the prosodic information carried by vowels in single words (11)] as a hub modulating the recognition response. Altogether, this pattern reflects a precocious functional specialization of a network including the temporal to the parietal and frontal connections in the right hemisphere [associated with retrieval in adults (37, 48–51)] supporting the recognition of particular features of word sounds at birth.

Our results also suggest the involvement of different brain regions on different memory stages (Fig. 4). In particular, although the recognition response included mainly the regions of the right hemisphere described above, encoding recruited predominantly the LF region, as evidenced by the habituation-like function in this region in the first three blocks of the encoding phase (Fig. 2). This localization of the habituation response is consistent with a previous study examining the time evolution of auditory habituation in 3-mo-old infants (33) and learning in newborns (32, 52). These results are also compatible with studies showing the involvement of the LF cortex while adults retrieve previously learned information and simultaneously encode novel aspects of the retrieved information (49–51). This appears highly congruent with the structure of our paradigm that intermixed various sounds during encoding. Such alternation enables the system to contrast the various words several times, highlighting the distinctive aspects of each of them. This should contribute, in turn, to a more accurate representation of these sounds.

The reduction of functional connections from and to the LF region in concomitance with the habituation response further indicates that encoding information at birth is selectively modulated by left-lateralized fronto-temporal and fronto-parietal interactions. The former are likely contingent upon the nature of the stimuli presented to infants (language in the case of our study), whereas the latter might reflect the activation of attentional networks involved in monitoring the invariance or salience of the surrounding stimuli (33, 53). Noticeably, the results of both the connectivity and the hemodynamic activation patterns in the LF region during familiarization (i.e., significant decrement of oxyHb across blocks) are coherent with those observed for the novel words in the test phase.

Even though the models obtained with the SEM approach do not disentangle coactivation of areas in response to a given stimulus from effective connectivity (i.e., directional coupling), the fact that specific connections differentiate the presentation
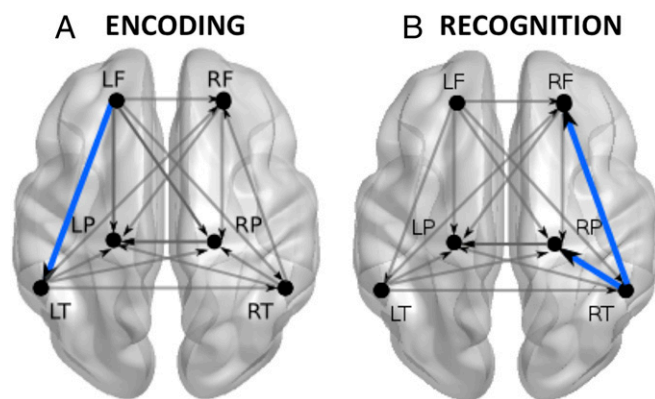
Fig. 4. Verbal memory network at birth and its interactions, mainly characterized by (A) the interplay between temporal and LF regions during encoding and (B) the interaction between temporal, parietal, and RF regions during recognition of words. Blue lines depict the most significant connections characterizing the two memory stages.

of novel and familiar words suggests that the areas do not simply coactivate in response to speech in newborns but rather interact with each other differently depending on the context.

The results of the connectivity analysis of a previous dataset (experiment 3 in ref. 10) served to document the reliability of the identified connections. In particular, the analysis confirmed that LF–LT connections in the test phase distinguish the exposure to novel sounds even when interfering words appear before testing. The main connection distinguishing the presentation of familiar sounds in the test phase (RT–RF) was also observed in this dataset. These critical connections were significantly stronger in the previous experiment (where interfering sounds presented before the test hindered the differential hemodynamic responses in the test phase) than in the current one (where differential hemodynamic responses between the novel- and same-word groups were observed). Taken together, these findings suggest, on the one hand, that specific connectivity profiles—that is, presence/absence of specific connections—might be informative for generally identifying distinctive memory states: encoding new sounds versus recognition of familiar sounds across studies. On the other hand, the statistical differences suggest a closer link with the results obtained in the traditional hemodynamic activation analysis indicating that the strength of the effective connections might be mostly related to the difficulty of the learning context or increasing cognitive load, as already proposed in the adult literature (54, 55).

To summarize, the present results provide evidence for a functional verbal memory network at birth, mainly characterized by the interplay between temporal and LF regions during encoding and between temporo-parietal and right-frontal regions during recognition of words (Fig. 4). This coordinated activity supports the first and most fundamental stages of verbal learning, enabling human infants to retain the sound of specific words even in the presence of other heterogeneous stimuli.

Although one could believe that encoding and recognition responses rely on similar brain structures, the precocious indication of hemispheric specialization reported here is far from unprecedented. There is a wealth of adult studies showing the consistent involvement of the left prefrontal cortex at encoding as well as activation of the right prefrontal cortex during memory retrieval in a variety of psychological paradigms and test modalities (37, 48–51, 56, 57). The results of the current study suggest that this widely reported encoding–retrieval lateralization pattern between frontal cortices might be rooted very early in development and that this elementary organization might be easily observable in habituation paradigms with variable exposure.

Since the first studies of habituation in infants showing that very young babies memorize a single stimulus after many repetitions (58, 59), it was assumed that presenting various stimuli was detrimental to recognition. Our investigation opens up perspectives on the study of language acquisition and memory development by showing that newborns are able to recognize specific words they heard before even when other words are also presented during the encoding phase.

Materials and Methods

Participants. Forty healthy full-term newborns (14 males; mean age, 2.7 d; range, 2–5 d) participated in the study. Five additional neonates were tested but not included in the analyses because they failed to complete the experiment due to fussiness. Selection criteria included gestational age between 38 and 42 wk, Apgar scores ≥ 8 in the first and fifth minutes, absence of cephalohematoma, and intact hearing. Moreover, to maximize the likelihood of monitoring the same areas of the brain across different infants, we recruited only babies whose head diameter falls within the 33.5–36.0 cm range (see also ref. 12). Neonates were recruited from the newborn nursery at the Azienda Ospedaliera Universitaria Santa Maria della Misericordia in Udine, Italy between September 2009 and November 2010. All parents gave informed consent for the experiment. The Ethics Committee of the International School for Advanced Studies approved the study.

Stimuli. Three pseudowords were used in the study (/mita/ /pelu/ /noke/). A female speaker recorded each word in isolation. The words carried stress on the first syllable and were edited to have a mean intensity of 70 dB and a duration of 700 ms. None of the pseudowords have meaning in Italian, the language spoken by the parents of the infants.

Procedure. The experiment was run inside a dimly lit sound-attenuated booth. Neonates were tested while lying in their cribs either in a state of quiet rest or sleeping. A medical doctor, who was blind to the purpose of the study, assisted the participants during the experiment and contributed to reducing babies' head movements. 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 (psy.ck.sissa.it/). An infrared video camera was used to monitor infants' behavior and to ensure the correct and stable placement of the probes throughout the experiment.

We implemented a modified version of previous experimental designs to assess memory for words in neonates (10–12), consisting of an encoding phase, a 2-min silent interval, and a test phase (Fig. 1B). In the encoding phase, 10 blocks contained eight words each: six repetitions of a target word (mita for half of the participants and pelu for the other half) and two repetitions of another word (noke). Target and intervening words were presented in random order within blocks. In the test phase, participants heard five blocks containing eight repetitions of a given word: Half of the participants heard again the target word (same-word group), and half heard a completely novel one (novel-word group). All words were 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 30 s) to avoid synchronization between stimuli occurrences and spontaneous oscillations.

Information about data acquisition, data processing, and probe placement can be found in *SI Materials and Methods*.

Hemodynamic Response Analysis. The hemodynamic changes over the encoding phase were assessed by means of robust linear regressions. Regressions were computed both at the group and the individual level. As a means to evaluate the robustness of the results across subjects, slope values for each individual were pooled together and compared against zero with one-sample t tests. To assess whether the same-word and novel-word groups differed in the test, we computed the maximum difference between the mean activation for each condition, as described in previous works (10–12). We evaluated significance using approximate permutation tests (60) by randomly assigning a group label (i.e., "same word" or "novel word") to each infant. A permutation test was run for each ROI, each of them using 10,000 reassignments. Bonferroni correction for multiple comparisons was applied, when appropriate, across six ROIs × 1 (for the first block) or two test blocks. For additional details, see previously published work (10).

Directional Brain Network Analysis Using SEM. Effective connectivity analysis was performed with SEM using the AMOS software. We followed the standard procedure to study neural systems connectivity modeling (61), recently implemented in fMRI (that provides comparable neural signals to those measured with fNIRS) (62–64). This approach included the following steps (described in detail in *SI Materials and Methods*): specification of the

theoretical/hypothesized anatomical model, generation of the covariance matrices and structural equations, goodness of fit evaluation, and comparison between models.

Individual models in the test phase were first fitted and then compared using the "stacked model" approach (61). The stacked model implies that when two conditions are compared, they are simultaneously fit to the same model, with the null hypothesis that there are no differences between conditions. In addition, to test for differences in pathways between models, we used bootstrapping with 2,000 samples to estimate 90% bias-corrected confidence intervals. No correction for multiple comparisons is needed for this analysis because the significance of all paths is evaluated at once in model comparisons.

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