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The neonate brain detects speech structure

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What are the origins of the efficient language learning abilities that allow humans to acquire their mother tongue in just a few years very early in life? Although previous studies have identified different mechanisms underlying the acquisition of auditory and speech patterns in older infants and adults, the earliest sensitivities remain unexplored. To address this issue, we investigated the ability of newborns to learn simple repetition-based structures in two optical brain-imaging experiments. In the first experiment, 22 neonates listened to syllable sequences containing immediate repetitions (ABB; e.g., ''mubaba,'' ''penana''), intermixed with random control sequences (ABC; e.g., ''mubage,'' ''penaku''). We found increased responses to the repetition sequences in the temporal and left frontal areas, indicating that the newborn brain differentiated the two patterns. The repetition sequences evoked greater activation than the random sequences during the first few trials, suggesting the presence of an automatic perceptual mechanism to detect repetitions. In addition, over the subsequent trials, activation increased further in response to the repetition sequences but not in response to the random sequences, indicating that recognition of the ABB pattern was enhanced by repeated exposure. In the second experiment, in which nonadjacent repetitions (ABA; e.g., ''bamuba,'' ''napena'') were contrasted with the same random controls, no discrimination was observed. These findings suggest that newborns are sensitive to certain input configurations in the auditory domain, a perceptual ability that might facilitate later language development.

language acquisition | newborns | optical imaging | perceptual primitives | speech perception

A fascinating aspect of language acquisition is infants' ability to go beyond the input that they receive by generalizing structural regularities onto sentences that they have not heard before (1). This accomplishment suggests that infants have efficient perceptual, processing, and learning abilities. But although we know that hearing newborns and very young infants are tuned to the phonological and melodic aspects of spoken language (2–5), our understanding of how they detect and represent structural regularities remains limited.

Previous studies investigating the acquisition of structure have focused mostly on older infants (6–8) and adults (9–11), revealing several different mechanisms underlying the acquisition of language structure, such as symbolic rule extraction and perceptual biases. Rule extraction usually is defined as a computation that uses abstract, symbolic representations and operations over variables that are independent of the actual tokens that implement them (1). Research focusing on how adults (9, 10) and infants (6, 8) learn artificial grammar has shown that after a brief exposure to strings generated by a set of underlying rules, both populations are able to generalize the structural regularities to novel instances; for example, 7-month-old infants were able to discriminate grammars conforming to an ABB rule (e.g., "wo fe fe") from grammars following an AAB rule (e.g., "wo wo fe") or an ABA rule (e.g., "wo fe wo"), after only 2 min of exposure and when tested on previously unheard sequences (8). The authors of that study interpreted these results to indicate that infants are able to represent and compute identity symbolically, as an operation over variables (8).

In contrast, perceptual biases are automatic processing mechanisms inherent to the perceptual system, which are sensitive to specific salient Gestalt-like configurations in the input (12, 13). The existence of several such mechanisms has been established in vision (e.g., the famous Kanizsa triangles) (14, 15), but these mechanisms have received relatively less attention in auditory processing. Recently, however, it has been shown that repetitions constitute precisely such an automatically detected auditory bias (13). When exposed to tone sequences containing a repetition, adults readily generalized the regularity to novel sequences, but they failed to learn and generalize ordinal relations between tones ("higher than" or "lower than"). The investigators argued that such a perceptual bias, and not abstract rule learning, may explain participants' success in a number of artificial grammar learning tasks, namely those that include reiterating rules in their grammar, resulting in adjacent repetitions of the same lexical item (6, 8, 9). For instance, the artificial grammar in Reber's classic experiment (9) allows some items (Reber used consonants) to reiterate, producing sequences like "MTTVT." Participants successfully learned the grammar and were able to generalize it when the test sequences were implemented using new consonants that did not occur during familiarization (10). Subsequent research revealed that this generalization performance depended crucially on the presence of repetitions in the consonant strings, however. Indeed, when repetition was not allowed, participants failed to generalize to novel consonants (16–18).

Experiment 1. Investigating the developmental trajectories of these mechanisms might allow us to better understand the roles that these mechanisms play in language acquisition. Therefore, in two brain imaging experiments using near-infrared spectroscopy (NIRS; also known as optical topography) (4, 19), we explored the origins of these mechanisms, finding evidence that newborns are able to detect simple structures in speech, provided that these structures conform to salient perceptual configurations, such as immediate repetitions.

In experiment 1, we tested 22 neonates, comparing a repetition-based ABB artificial grammar (e.g., "mubaba," "talulu," "penana") and an unstructured ABC control grammar (e.g., "mubage," "talupi," "penaku") that was matched to ABB in all nonstructural properties: syllabic repertoire; frequency of the A, B, and C syllables; phonologic characteristics; flat prosody; and transitional probabilities between syllables. Sample sound files are available in the supporting information (SI). The trisyllabic sequences were separated by pauses (i.e., the input stream was segmented); the transition probabilities (7) between consecutive syllables were equated between the two grammars, and all of the sequences differed from one another. Thus, statistical learning mechanisms

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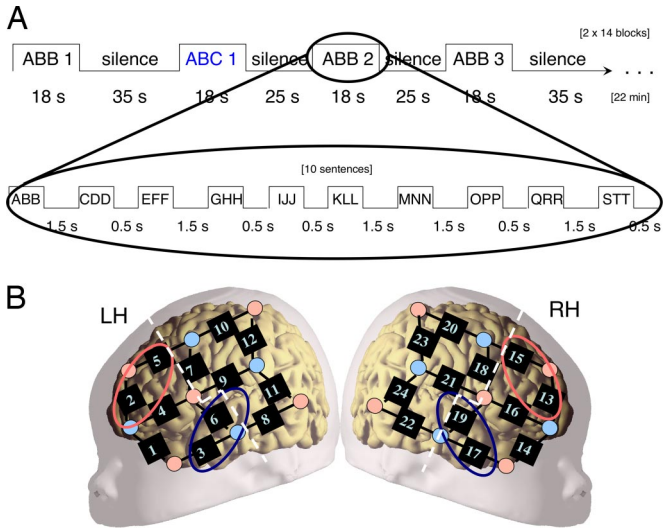

Fig. 1. Details of the procedure used in experiments 1 and 2. (*A*) The experiments' design. The upper boxcar shows how the consecutive stimulation blocks unfold. The lower boxcar indicates the sequence of sentence types within a block. (*B*) The placement of the probes overlaid on a schematic neonate brain. Although individual variation cannot be excluded, this placement ensured recording from perisylvian and anterior brain regions. The dashed white lines separate anterior and posterior ROIs. The red ellipses indicate the channels included in the frontal area of interest (LH: channels 2 and 5; RH: channels 13 and 15). The blue ellipses indicate channels included in the temporal area of interest (LH: channels 3 and 6; RH: channels 17 and 19).

(7) cannot play a role in differentiating or learning the two grammars.

Neonates listened to the ABB and ABC grammars, presented in interleaved blocks (14 blocks per grammar), separated by pauses of varying duration to avoid inducing phase-locked brain activity. Each block contained 10 different trisyllabic sequences of either the ABB or the ABC grammar and lasted 18 s (Fig. 1*A*). The optical probe was placed on the neonate's head, as shown in Fig. 1*B*. The tragus and the vertex were used as surface landmarks, to maximize the likelihood of recording from the perisylvian and the anterior areas of the cortex.

The NIRS machine measured the scattering and absorption of near-infrared light, from which the changes in concentration of oxygenated hemoglobin (oxyHb) and deoxygenated hemoglobin (deoxyHb) were calculated as indicators of neural activity. After bandpass filtering and artifact removal, we averaged the oxyHb and deoxyHb concentrations across all blocks for each grammar over the 18-s time window of stimulation. In an initial analysis, we compared the activations obtained for the ABB and the ABC grammars in each channel, plotting a *t*-map of the differential activation (20, 21). In a second analysis, we grouped the 24 channels according to hemisphere (left hemisphere [LH] vs. right hemisphere [RH]) and region of interest (ROI; anterior vs. posterior regions), comparing activations for the two grammars in these broadly defined brain areas (Fig. 1*B*). These ROIs were chosen such that the anterior ROI contained the channels in which any stimulus-related activation might reasonably be predicted to occur, whereas the posterior ROI, where little activation was expected, could serve as a baseline for comparison. In a third analysis, targeting auditory and language processing more specifically, we evaluated the responses in the temporal areas (defined as channels 3 and 6 in the LH and channels 17 and 19 in the RH; Fig. 1*B*), known to be responsible for auditory processing in infants (4, 22, 23), and the frontal areas (defined as channels 2 and 5 in the LH and channels 13 and 15 in the RH; Fig. 1*B*), involved in the computation of structure and higher-order representations in infants and adults (22–25). We concentrated on these two areas given previous results on speech and auditory processing in infants and the spatial resolution of NIRS; however, this is not to deny the possibility that a more complex neural network might be responsible for both auditory processing and higher-order structural computations in infants, as has been suggested by some adult studies (26–28).

The resulting grand average of all 22 neonates is shown in Fig. 2. In the initial analysis, we compared the oxyHb changes evoked by ABB and ABC patterns in each channel using a paired *t* test. The resulting *t*-map is shown in Fig. 3*A*. We obtained significantly greater activation for the ABB pattern in channels 5, 6 ($P < 0.05$), 4 ($P < 0.01$), and 3 ($P < 0.001$) in the LH and in channels 20 ($P < 0.05$) and 19 ($P < 0.01$) in the RH (*P* values are uncorrected). These results indicate that ABB and ABC are distinguished in most channels of the temporal (i.e., auditory) areas (channels 3, 6, 19, and possibly 4) and in some channels of the frontal areas (channel 5 and possibly channel 20). The results also show a much stronger involvement of the LH in distinguishing the two patterns, with four channels exhibiting a significant differential activation, compared with only two such channels in the RH. A similar analysis for deoxyHb yielded no significant differences between ABB and

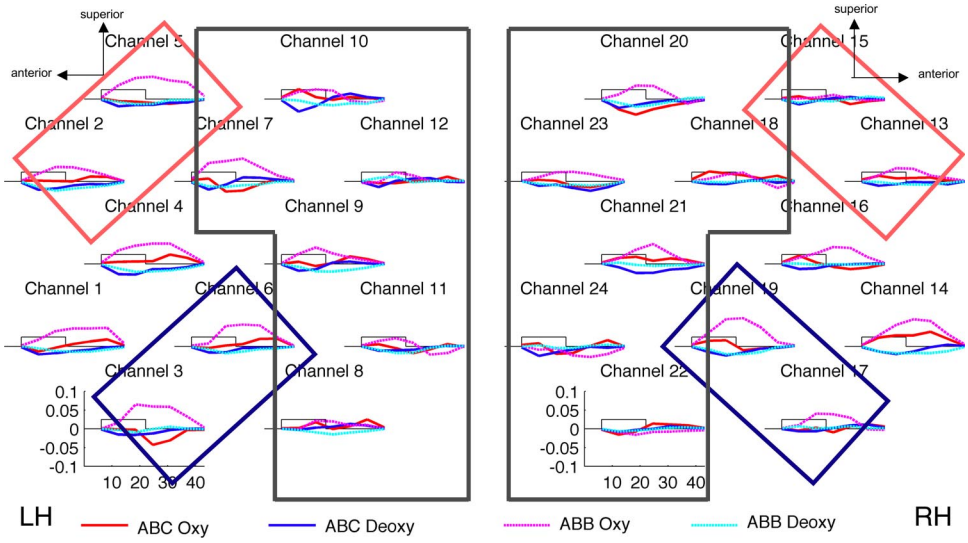

Fig. 2. The grand average results of experiment 1. Channels are plotted following the same placement as in Fig. 1*B*. The *x*-axis represents time in seconds; the *y*-axis shows concentration in mmol·mm. The rectangle along the *x*-axis indicates time of stimulation. The continuous red and blue lines in the graphs represent oxyHb and deoxyHb concentrations, respectively, in response to the ABC grammar. The dashed magenta and cyan lines represent oxyHb and deoxyHb concentrations, respectively, in response to the ABB grammar.

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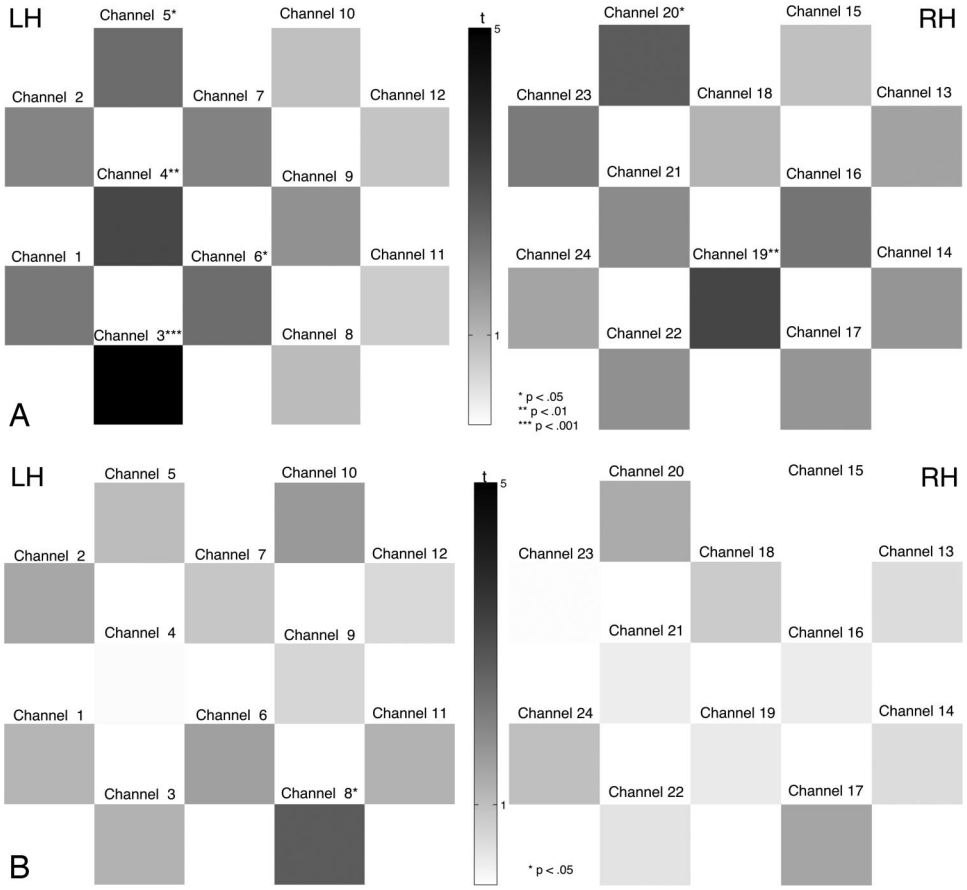

Fig. 3. Statistical maps (*t*-maps) comparing the responses to the repetition and control grammars in experiment 1 (*A*) and experiment 2 (*B*). Channels are plotted following the same placement as in Fig. 1*B*. The *t*-values for each channel are color-coded as indicated on the color bar. Significance levels are indicated for each channel (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$).

ABC. This result is consistent with previous studies (4, 19, 21) suggesting that oxyHb is a much more sensitive measure than deoxyHb.

In the second analysis, we performed a repeated-measures analysis of variance (ANOVA) with the factors Grammar (ABB/ABC), Hemisphere (left/right), and ROI (anterior/posterior), using oxyHb as the dependent measure. We obtained a main effect of Grammar [F (1, 21) = 4.818; P = 0.040] because of a greater overall activation for ABB than for ABC. The main effect of ROI [F (1, 21) = 11.001, P = 0.003] also was significant, with the anterior regions being more activated than the posterior regions. In addition, a significant interaction between Grammar and Hemisphere was seen [F (1, 21) = 5.275; P = 0.033; Scheffé's post hoc test for relevant pairwise comparisons: ABB LH > ABC LH, $P < 0.0001$; ABB RH > ABC RH, P = 0.001; ABB LH > ABB RH, P = 0.017; ABC LH ≈ ABC RH, P = 0.519], indicating greater activation for the ABB grammar in the LH. A similar ANOVA with the factors Grammar (ABC/ABB) × Hemisphere (left/right) × ROI (anterior/posterior) was conducted for deoxyHb and yielded no significant results, although the interaction Hemisphere × ROI showed a trend toward significance [F (1, 21) = 3.561; P = 0.073]. These results suggest that the neonate brain can distinguish ABB from ABC. As expected, the anterior regions responded more readily to linguistic stimulation than the posterior regions. The observed LH superiority is consistent with the lateralization of language in most adults (29) and infants (4, 23).

To further examine areas of the brain associated with auditory and language-related processing, we compared temporal and frontal areas in a second ANOVA with the factors Grammar (ABB/ABC), Hemisphere (left/right), and Area (frontal/temporal), using oxyHb concentrations as the dependent measure. We obtained a significant main effect of Grammar [F (1, 19) = 5.516, P = 0.030][‖], as before, due to a larger activation for the ABB grammar overall. No other main effect was significant. Also significant were the interactions Grammar × Area [F (1, 19) = 6.321; P = 0.021; Scheffé's post hoc test for relevant pairwise comparisons: ABB temporal > ABC temporal, $P < 0.0001$; ABB frontal > ABC frontal, P = 0.016; ABB temporal > ABB frontal, P = 0.036; ABC temporal ≈ ABC frontal, P = 0.207) and Hemisphere × Area [F (1, 19) = 6.603; P = 0.019; Scheffé's post hoc test for relevant pairwise comparisons: LH temporal ≈ RH temporal, P = 0.121; LH frontal > RH frontal, P = 0.050; LH temporal ≈ LH frontal, P = 0.290; RH temporal > RH frontal, P = 0.019]. The interaction Grammar × Hemisphere demonstrated a trend toward significance [F (1, 19) = 3.094; P = 0.095]. A similar ANOVA for deoxyHb yielded no significant results. The foregoing results again indicate that the newborn brain can distinguish ABB from ABC. More specifically, both grammars activated the temporal auditory areas, as would be expected given that the stimuli are speech sounds; however, the repetition grammar evoked a much stronger response in the auditory areas, indicating that the discrimination between the two grammars is perceptually based and occurs early in processing. We also observed a greater response to the ABB grammar in the frontal areas, suggesting that the discrimination is preserved during the later stages of processing, possibly due to the formation of a memory trace. This is consistent with previous findings showing that activation in the left frontal areas may be related to the later stages of (artificial) grammar learning or memory processes in adults (22, 24) and older infants (25).

[‖]Two infants did not have a sufficient number of nonrejected trials in at least one of the areas of interest and thus were not included in the analysis.

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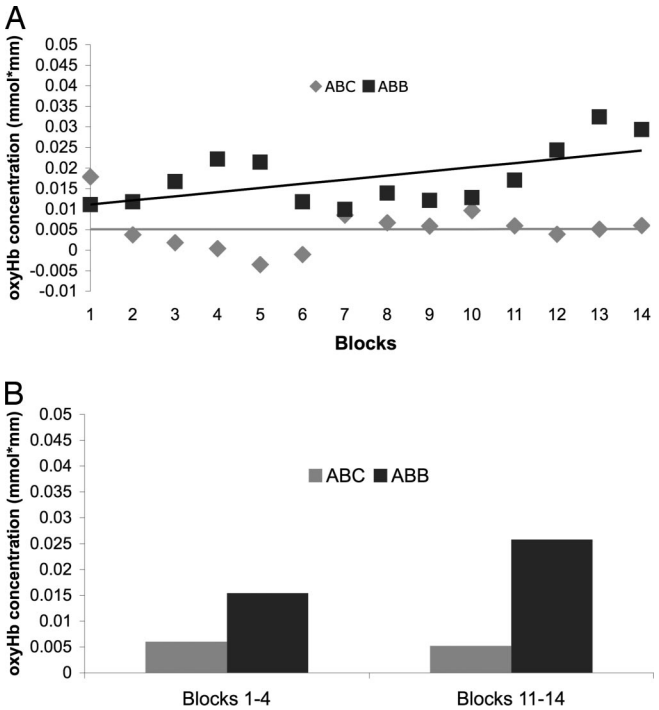

Fig. 4. The time course of the responses in experiment 1. (*A*) The linear regression lines of the oxyHb concentrations fitted on the data points provided by the 14 consecutive blocks for the two grammars. The light-gray line represents ABC; the dark-gray line, ABB. The r^2 values are $r^2 = 0.00002$ for ABC and $r^2 = 0.3427$ for ABB. (*B*) The bars indicate the average oxyHb concentration in the left frontal area (channels 2 and 5) for the first and the last four blocks for the two grammars. The *y* axis shows the average totalHb concentration in mmol·mm. The light-gray bars represent ABC; the dark-gray bars, ABB.

We also analyzed the temporal evolution of responses during the course of the experiment, assuming that the effects of an automatic perceptual detection mechanism, if any, should be immediately observable. Fig. 4*A* illustrates the changes in oxyHb concentration in the left anterior ROI over the 14 consecutive blocks of the experiment for the two grammars, as well as the linear regression line fitted on the learning curve. As indicated by the r^2 values ($r^2 = 0.00002$ for ABC and $r^2 = 0.3427$ for ABB), a considerable increase occurred only for the ABB grammar. For statistical purposes, we compared the beginning and the end of the experiment, defined as the first and the last four blocks per grammar. Fig. 4*B* illustrates the averages of the oxyHb concentrations in the two time periods for the two grammars. In an ANOVA with the factors Grammar (ABC/ABB) × Time (beginning/end), we obtained a significant main effect of Grammar [F (1, 21) = 7.174; $P = 0.015$], as before, because the response to the ABB grammar was greater than the response to the ABC throughout the experiment, confirming the neonate brain's ability to discriminate between the two grammars. The main effect of Time was not significant. Importantly, a significant interaction between Grammar and Time [F (1, 21) = 6.136; $P = 0.023$] was seen. This was because although the response to ABC tended not to change throughout the experiment, ABB elicited increasing activation over time. These results indicate that the ABB and ABC patterns were discriminated from the start of the experiment, consistent with the hypothesis that repetitions might be detected by an automatic perceptual mechanism. The increasing response for ABB but not for ABC throughout the experiment suggests that repeated exposure to different tokens of a previously detected Gestalt-like configuration may prime its subsequent recognition. Given its left frontal location, we might assume that this enhanced response involves some memory process, such as the formation of a memory trace.

Experiment 2. To explore the scope of the observed perceptual repetition detector mechanism, we investigated whether it was sensitive to another type of repetition-based configuration. Because nonadjacent relations play an important role in language structure (30), in experiment 2 we measured the brain responses of another 22 neonates to an ABA grammar containing nonadjacent repetitions ("bamuba," "lutalu," "napena"), comparing it with the same ABC control as before. We used the same procedure, probe placement, and analysis as in experiment 1.

The grand average results are shown in Fig. 5. The channelwise comparisons (Fig. 3*B*) reveal that except for channel 8 ($P < 0.05$, uncorrected), where a significantly greater activation was observed for ABC than for ABA, no discrimination between the two grammars was obtained using change in oxyHb concentration as a dependent measure. A similar lack of discrimination was observed using deoxyHb.

ANOVA with the factors Grammar (ABA/ABC), Hemisphere (LH/RH), and ROI (anterior/posterior) revealed no significant

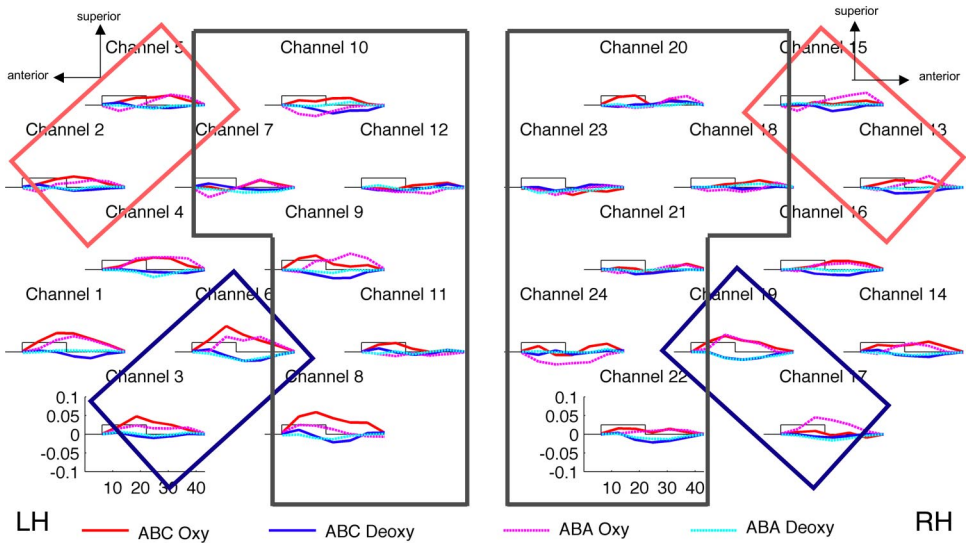

Fig. 5. The grand average results of experiment 2. All graphical conventions are the same as those in Fig. 2.

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effect of Grammar or Hemisphere, but the effect of ROI was significant [F (1, 21) = 11.470; P = 0.003], due to greater activation in the anterior ROI than in the posterior ROI. No interactions were significant. A similar ANOVA using deoxyHb concentrations revealed no significant main effects or interactions. These results indicate that the neonate brain treats a grammar containing nonadjacent repetitions no differently than a random grammar. The significantly greater activation in the anterior ROI indicates that the lack of discrimination was due not to newborns' failure to perceive the stimuli, but rather to their inability to detect the differences in structure.

To further evaluate auditory and language-related processing, we ran an ANOVA with the factors Grammar (ABA/ABC), Hemisphere (LH/RH), and Area (frontal/temporal), using oxyHb concentrations as the dependent measure, as in experiment 1. We obtained a significant effect of Area [F (1, 21) = 9.506; P = 0.006] due to greater activation in the temporal areas compared with the frontal areas. No other main effects or interactions were significant. A similar ANOVA for deoxyHb concentrations yielded no significant main effects or interactions. These results again indicate that the two grammars are processed in a similar fashion, eliciting similar auditory responses. Evaluation of the time course of the responses in an ANOVA with the factors Grammar (ABA/ABC) and Time (beginning/end) revealed no main effects or interactions.

Experiments 1 and 2 were conducted using the same experimental parameters and the same Hitachi ETG-4000 NIRS machine. However, due to hardware and software updates performed on the machine, a laser power of 0.30–35 mW was used in experiment 1, compared with 0.75 mW in experiment 2. Given the doubled laser power, the signal obtained in experiment 2 was considerably greater than that in experiment 1. This precludes a direct statistical comparison of the data from the two experiments, and also explains why the ABC control condition gave rise to a much greater response in experiment 2.

General Discussion. Taken together, our findings demonstrate that on its first encounters with language, the neonate brain is able to detect certain structural regularities present in the input. The discovery of such early sensitivities, operational from the first days of life, opens up new ways of exploring speech perception even in very young infants. Although our findings cannot definitively determine the exact nature of the underlying mechanisms, they allow us to evaluate certain possibilities.

First, as discussed before, Marcus *et al.* (8) invoked abstract rule-learning mechanisms to account for 7-month-olds' successful discrimination and generalization of trisyllabic repetition-based grammars. Because they compared different repetition grammars to one another (e.g., ABB vs. ABA), it cannot be determined whether the infants' success was due to discrimination of the adjacent repetition grammar alone (which is sufficient to succeed in ABB versus ABA) or whether both grammars were learned. Consequently, whether 7-month-olds would succeed on the comparisons that we used, that is, repetition grammars against random controls (ABB vs. ABC and ABA vs. ABC), remains an open question. Importantly, however, newborns succeeded only in the former case (i.e., they were able to detect adjacent repetitions) and failed in the latter case (i.e., on nonadjacent repetitions). This pattern of results can be explained only in terms of abstract rule learning if additional assumptions are made about why distant occurrences of the same variable differ from immediate ones. In the absence of such principled constraints, our findings are difficult to explain by an abstract rule-learning mechanism.

A second possibility, then, is that the auditory system, similar to vision, may rely on automatic processing mechanisms that are sensitive to certain input configurations. The discriminative response to the ABB grammar observed in experiment 1 suggests that newborns may have a perceptual repetition detector, similar to that in adults (13). This hypothesis is supported by both the location and the time course of the discriminative response, which was observed in both the perceptual (i.e., temporal) and more frontal areas and emerged immediately in the first trials. Therefore, we propose that a perceptual repetition detector mechanism accounts for the newborns' pattern discrimination abilities observed in the current study. This proposal raises a number of questions and implications.

First, our experiments yielded an enhanced discriminative response to repetition patterns, whereas previous sequence learning studies often found suppressed neural activation for repeating stimuli (31, 32). Because those earlier studies used mostly single-cell recordings (31) and electrophysiologic measures (32), whose relation to metabolic correlates of neural activity is not fully understood, how their results relate to our findings is not clear. In contrast, other studies that used metabolic measures (e.g., functional magnetic resonance imaging) found both suppressing and enhancing effects in response to repeating stimuli. In fact, enhancing effects were observed when unknown/unfamiliar or highly complex stimuli were used (33). Because the trisyllabic repetition patterns that we used were arguably novel and complex for newborn infants, our findings are consistent with previously reported results.

Second, the question arises as to the level of processing that the infants used to detect syllable repetitions. Did they rely on acoustic similarity or phonemic identity? Whereas in the current study, we used synthesized speech (wherein the repeated syllables were acoustically highly similar, although not identical), future studies using natural speech tokens in the same paradigm will be able to address the question of whether (and if so, how) infants may normalize speech. Indeed, manipulating the physical similarity between the repeated items while keeping them within the same category (e.g., two different tokens of the same syllable pronounced by the same speaker, then pronounced by two different speakers) may provide important information about how newborn infants perceive and represent speech.

Third, although the repetition-sensitive response was observed in our study using speech stimuli, our proposed perceptual repetition detector mechanism may be more general, applying to nonlinguistic auditory stimuli as well. The currently available evidence is not conclusive in this regard. Whereas adults are able to learn repetition-based grammars implemented with piano tones rather than syllables (13), infants demonstrate mixed performance with nonlinguistic auditory stimuli. They are able to generalize repetition-based regularities from syllables to tones, animal sounds, and timbre but fail when tones, animal sounds, and timbre are used alone (34). Further research is needed to clarify whether newborns are able to detect repetitions when implemented with nonlinguistic auditory input. Whether the mechanism is even more general, extending to other domains of perception, also remains an open question. Recent evidence suggests that 7-month-olds can detect and learn ABB and ABA patterns when the stimuli are pictures of dogs and cats (35). Whether or not they do so by using a visual repetition detector awaits clarification.

Fourth, we might ask what role such a repetition detector plays in infant speech perception and language acquisition. For instance, infants' sensitivity to repetitions may be related to the observation that infant-directed speech abounds in identical and immediate repetitions of words and phrases (36). Similarly, typical "child words" in different languages often contain full or partial reduplications [e.g., *baby*, *daddy* in English; *bébé* (baby), *dodo* (sleep) in French; *baba* (baby), *tata* (grandpa) in Hungarian; *papà* (daddy) in Italian]. These also are very often a child's first words. Thus, the perceptual saliency of these words might help infants discover and learn the first entries in their lexicons.

Conclusion

From a theoretical perspective, our findings imply that the role of the perceptual system in acquisition of the structural regularities of speech may be more important than previously believed. From a neurodevelopmental standpoint, our findings converge with previ-

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ous studies (4, 23, 25) arguing that the newborn brain is not undifferentiated, but rather has at least some of the functional specializations characteristic of the mature brain.

Materials and Methods

Materials. In experiment 1, the ABB and ABC grammars generated trisyllabic ''sentences.'' In ABB, the second and third syllables were identical, whereas in ABC, all syllables were different. Both grammars used the same syllabic repertoire, containing 20 consonant–vowel syllables (''ba,'' ''bi,'' ''du,'' ''ge,'' ''pe,'' ''pi,'' ''ta,'' ''to,'' ''ko,'' ''ku,'' ''lo,'' ''lu,'' ''mu,'' ''na,'' ''fi,'' ''fe,'' ''sha,'' ''sho,'' ''ze,'' and ''zi''). The syllables were organized into syllable pairs. A syllable pair was defined as two syllables containing the same consonant but a different vowel (e.g., ''ba''–''bi'') or at least consonants from the same class (e.g., nasal) and a different vowel (e.g., ''mu''–''na'').

The material was constructed as follows. For the ABB grammar, half of the syllables were designated A syllables, and the other half were designated B syllables. The two categories were established such that one member of a syllable pair was assigned to category A and the other was assigned to category B. In half of the blocks, A syllables were used as the initial unrepeated syllable, with B syllables providing the repeated second and third syllables. This was reversed in the other half of the blocks. Thus, each syllable appeared in each sentential position with equal frequency. In addition, each block used different pairings of the A and B syllables. To maximize discriminability, two constraints were applied when pairing up A and B syllables: The two syllables could not contain the same vowel, and they could not come from the same syllable pair. This resulted in 7 possible sentence combinations for each initial syllable, yielding 140 sentences. Thus, the 14 blocks exhausted all possible combinations without requiring repetition of sentences. The ABC sentences were derived from the ABB sentences by shuffling around the repeated third syllables of the sentences within a block.

Sentences were synthesized using the fr4 French female voice of the MBROLA diphone database. Syllables were 270 ms long (consonant, 120 ms; vowel, 150 ms) and had a monotonous pitch of 200 Hz (see the sound files for examples).

As a consequence of the design, the two grammars were identical for the overall frequency of all syllables, for the frequency of each syllable in each sentential position, and for all phonological and prosodic characteristics. In addition, the distribution of transitional probabilities also was equated by keeping the transition probabilities between certain designated BC syllables as high as those between the repeated syllables.

Within blocks, sentences were separated by pauses of varying length (0.5–1.5 s), yielding blocks of about 18 s (Fig. 1). Blocks also were spaced at time intervals of varying duration (25–35 s) to avoid inducing phase-locked brain responses. The 28 blocks were presented in an interleaved fashion in such a way as to disallow more than two consecutive blocks of the same type. The order of the blocks was pseudorandomized and counterbalanced across subjects.

In experiment 2, the ABA grammar was derived from the ABB grammar by moving the first repeated syllable into the initial sentential position. All other parameters were kept identical. The ABC grammar was identical to that used in experiment 1.

Subjects. Twenty-two healthy, full-term neonates (12 females; mean age, 3.14 days; range, 1–6 days; Apgar score ≥ 8) born to Italian-speaking families participated in experiment 1. Another group of 22 healthy, full term neonates (12 females; mean age, 2.86 days; range, 2–5 days; Apgar score ≥ 8) born to Italian-speaking families participated in experiment 2. All parents gave informed consent before the experiment. The study design was approved by the Ethics Committee of the Azienda Ospedaliera Universitaria di Udine, where the experiments were conducted.

Procedure. In both experiments, infants were tested with a Hitachi ETG-4000 NIRS machine (source–detector separation, 3 cm; two continuous wavelengths of 695 nm and 830 nm) in a dimly lit sound-attenuated booth in their hospital environment, lying in their cribs throughout the 22- to 25-min testing session, assisted by a nurse and an experimenter. Parents could choose to attend the session. Testing was done with the infants in a state of quiet rest or sleep.

Sound stimuli were administered through two loudspeakers positioned at a distance of 1.5 m from the infant's head, at an angle of 30°, elevated to the same height as the crib. A Macintosh PowerPC G5 computer played the stimuli and operated the NIRS machine. Both the NIRS machine and the computer were placed outside the experimental booth. Infants were videotaped during the experiment. (Tapes are available on request.) The NIRS machine used a laser power of 0.30–0.35 mW in experiment 1 and 0.75 mW in experiment 2.

Data Processing and Analysis. OxyHb and deoxyHb concentrations were used in the data analysis. They were calculated from the absorption of light recorded by the NIRS machine. To eliminate high-frequency noises (e.g., heartbeat) and overall trends, the data were bandpass-filtered between 0.01 and 0.7 Hz. Movement artifacts, defined as concentration changes > 0.1 mmol·mm over 0.2 ms for 0.30–0.35 mW laser power and concentration changes > 0.15 mmol·mm over 0.1 msec for 0.75 mW laser power, were removed by rejecting block-channel pairs in which artifacts occurred. For the nonrejected blocks, a baseline was linearly fitted between the means of the 5 s preceding the onset of the block and the 5 s starting 18 s after onset of the block.

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