



# The neonate brain's sensitivity to repetition-based structure: Specific to speech?

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## Abstract

Newborns are able to extract and learn repetition-based regularities from the speech input, that is, they show greater brain activation in the bilateral temporal and left inferior frontal regions to trisyllabic pseudowords of the form AAB (e.g., “babamu”) than to random ABC sequences (e.g., “bamuge”). Whether this ability is specific to speech or also applies to other auditory stimuli remains unexplored. To investigate this, we tested whether newborns are sensitive to regularities in musical tones. Neonates listened to AAB and ABC tones sequences, while their brain activity was recorded using functional Near-Infrared Spectroscopy (fNIRS). The paradigm, the frequency of occurrence and the distribution of the tones were identical to those of the syllables used in previous studies with speech. We observed a greater inverted (negative) hemodynamic response to AAB than to ABC sequences in the bilateral temporal and fronto-parietal areas. This inverted response was caused by a decrease in response amplitude, attributed to habituation, over the course of the experiment in the left fronto-temporal region for the ABC condition and in the right fronto-temporal region for both conditions. These findings show that newborns' ability to discriminate AAB from ABC sequences is not specific to speech. However, the neural response to musical tones and spoken language is markedly different. Tones gave rise to habituation, whereas speech was shown to trigger increasing responses over the time course of the study. Relatedly, the repetition regularity gave rise to an inverted hemodynamic response when carried by tones, while it was canonical for speech. Thus, newborns' ability to detect repetition is not speech-specific, but it engages distinct brain mechanisms for speech and music.

## KEYWORDS

fNIRS, language acquisition, newborns, speech perception

## RESEARCH HIGHLIGHTS

- The ability of newborns' to detect repetition-based regularities is not specific to speech, but also extends to other auditory modalities.
- The brain mechanisms underlying speech and music processing are markedly different.

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## 1 | INTRODUCTION

At birth, newborns already show remarkable speech perception abilities. They recognize and prefer speech over similarly complex sine wave analogs (Vouloumanos & Werker, 2004), prefer their mother's voice compared to unfamiliar female voices (DeCasper & Fifer, 1980; Moon, 2017) and are able to discriminate their native language from an unfamiliar language (Mehler et al., 1988; Moon et al., 1993). These sophisticated speech perception abilities pave the way for the discovery of their native language.

One of these early abilities is newborns' capacity to detect and learn structural regularities, in particular repetition- or reduplication-based structures, from the speech input (for an exhaustive review, see de la Cruz-Pavía & Gervain, 2021). When neonates listen to repetition-based sequences of syllables of the form AAB (e.g., "babamu") and random sequences of the form ABC (e.g., "bamuge"), they show greater hemodynamic responses to the AAB sequences in the bilateral temporal and left inferior frontal regions (including Broca's area) (Gervain et al., 2012) than to the random ABC sequences. This pattern of responses suggests that newborns can discriminate and differently process repetition-based and random, diversity-based structures. Newborns respond similarly to repetitions in sequence-final positions (ABB, e.g., "mubaba"; Gervain et al., 2008).

What is the nature of the mechanism that allows newborns to represent such structures? The empirical results suggest that two different mechanisms may be at work (Gervain et al., 2008; de la Cruz-Pavía & Gervain, 2021). Greater brain responses to the repetition-based than to the diversity-based structures have been observed in the left frontal areas from the beginning of the experiment (Gervain et al., 2008), suggesting an immediate and automatic recognition of repetition (Endress et al., 2009). Additionally, the differential response increased over the time course of the study, suggesting a possible mechanism responsible for the extraction of the abstract underlying reduplication regularity that is common across all ABB sequences. Indeed, as all sequences were unique, never repeated during the study and were made up of a relatively large inventory of different syllables, the only commonality across them was the underlying, abstract ABB structure. Thus, continued increase in response to ABB sequences over the course of the study can only be attributed to the extraction of this common underlying pattern across them. This interpretation is supported by the left frontal location of the effect (Gervain et al., 2008).

Newborns thus show basic abilities to learn structural regularities in speech. Is this sensitivity to repetition-based structures specific to language? In the visual domain, it has been shown that 3–4 month-old (Ferguson et al., 2018) and 7-month-old (Saffran et al., 2007) infants can discriminate ABB and ABA patterns behaviorally when presented with pictures of animals. In the auditory domain, Dawson and Gerken (2009) demonstrated that 4-month-old infants can learn repetition-based regularities carried by musical chords and tones. These results suggest that the ability to extract repetition-based regularities is not restricted to speech in infants older than newborns at the behavioral level. However, the question remains whether this is also the case for newborns.

Is this ability specific to speech at birth? Or can newborns also discriminate repetition-based sequences from diversity-based ones when those are implemented with musical tones, that is, non-linguistic auditory stimuli? If so, are the underlying brain mechanisms similar or do they differ between linguistic and non-linguistic auditory stimuli? Specifically, is there a domain-general mechanism allowing the extraction of repetition from both linguistic and non-linguistic stimuli, or does the extraction of repetition rely on different mechanisms in the linguistic and non-linguistic domains? To address these questions, we tested whether newborns are sensitive to repetition-based regularities when those are implemented with musical tones. We followed the same experimental design as Gervain et al. (2008, 2012), comparing infants' responses to blocks of AAB and ABC sequences, except that syllables were replaced by tones. Newborns' brain activity was recorded using functional Near-Infrared Spectroscopy (fNIRS), as in the previous studies.

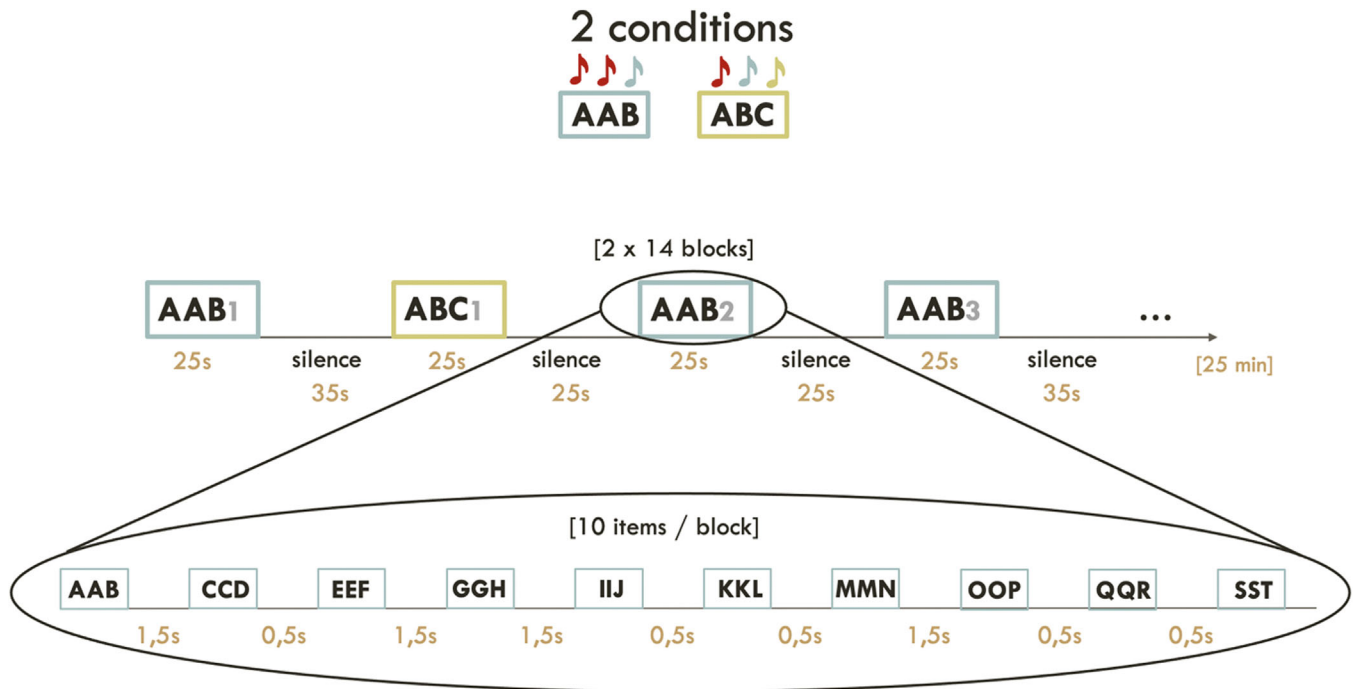
Differential responses to AAB versus ABC sequences indicate newborns' ability to discriminate repetition-based sequences from diversity-based ones. As an advantage of using a brain imaging technique, we can go beyond this binary response to test not only the presence or absence of discrimination, but also whether the mechanisms underlying the processing of these sequences in speech and in non-speech stimuli are shared or different. It may be the case that while newborns can discriminate AAB and ABC sequences both in speech and tones, they process the two types of stimuli differently.

Previous results suggest that stimulus complexity and variability play a role in the observed responses. Indeed, Bouchon et al. (2015) replicated Gervain et al.'s (2012) study, but used a much smaller phoneme and syllable repertoire. With such reduced stimulus variability, the authors still found greater activation in response to the ABB than to ABC sequences. But while, in Gervain et al.'s (2012) study, responses to ABB sequences increased over time, in Bouchon et al.'s (2015) experiment, responses to the ABB structure remained stable over the course of the study, whereas responses to ABC increased. These results offer two critical lessons. First, they suggest that the variability and the complexity of the stimuli play a role in the temporal dynamics of the response patterns found, as neural responses show different degrees of habituation to the repeated presentation of stimuli as a function of stimulus complexity. Second, these results demonstrate that the temporal dynamics of neural responses can provide relevant insights into the neural mechanisms that support the detection of repetition. Accordingly, in the present study, we both compare the time-averaged responses and explore the temporal dynamics of infants' responses to ABB and ABC sequences in tones.

## 2 | MATERIALS AND METHODS

### 2.1 | Participants

Thirty-two healthy, full-term newborns (Apgar score  $\geq 8$ ) participated in the study. Of these, data from 23 newborns (mean age: 1.18 days, range: 0–3 days; 12 females) were kept for the final analyses. Nine



**FIGURE 1** Design of the study. The upper boxcar shows the timescale of the entire experiment; the lower boxcar illustrates the organization of a block.

infants were excluded for crying and fussiness ( $n = 6$ ), parental intervention ( $n = 1$ ), or poor data quality ( $n = 2$ ). Rejection for data quality was performed in batch prior to statistical analysis. According to parental report, the infants did not receive greater than average prenatal exposure to music (specifically, mothers reported listening to music only occasionally), and the parents were not musicians. The infants' parents or legal guardians provided written informed consent prior to participation. The study was approved by the ethics boards of the University of British Columbia and BC Women's Hospital.

## 2.2 | Stimuli

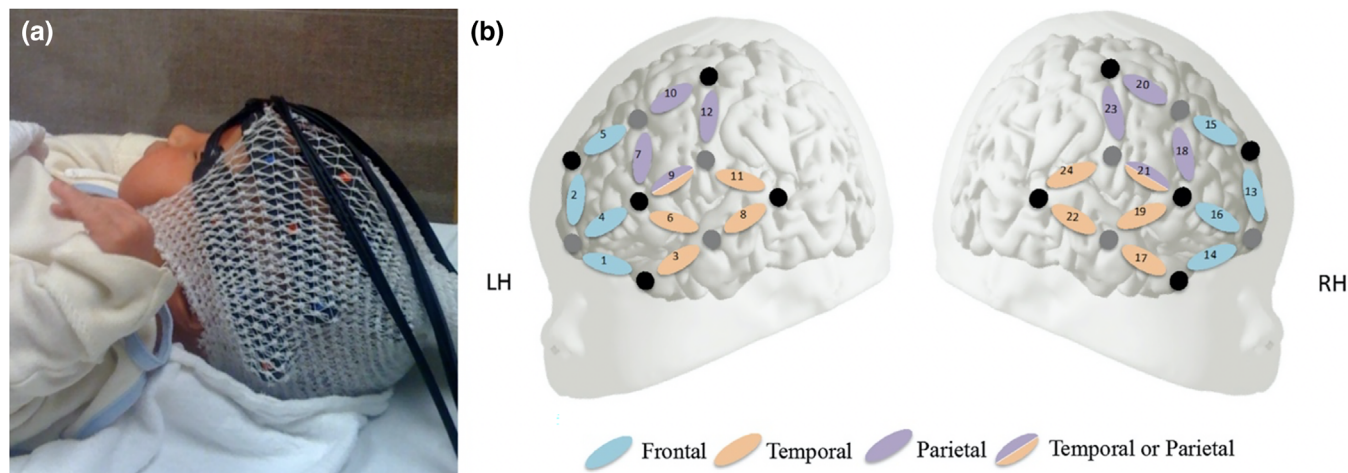
Two artificial grammars were used in the study: AAB and ABC (Figure 1). The AAB grammar generated sequences of three musical tones, whereby the first and second tones were identical, whereas the ABC grammar generated sequences with three different tones. The sequences were identical to those used in Gervain et al. (2012) except that they were implemented with musical tones rather than syllables. Each syllable of the original AAB and ABC sequences in Gervain et al. (2012) was mapped onto a piano tone for a total of 20 tones corresponding to the 20 syllables used in the Gervain et al. (2012) study. The tone repertoire included C, D, E, F, G, A, B, c, d, e, f, g, a, b, c', d', e', f', g', a' (reported here using ABC notation <https://abcnotation.com>, C denotes middle C). Thus, the distribution and frequency of occurrence of syllables and tones were fully matched between the two studies. Furthermore, the AAB tone grammar was matched to the ABC tone grammar on (1) the overall frequency of each tone, (2) the frequency of each tone in each sequential position, and (3) all acoustic

characteristics. Additionally, the distribution of transitional probabilities (TPs) between adjacent tones was equated by keeping the TPs as high between certain designated AB tone pairs, as they were between the repeated AA tones. Furthermore, when mapping the syllables to tones, the choice of tones was optimized so as to avoid dissonant tone sequences. Tones were generated using the flabc software (<https://flabc.software.informer.com>) with the acoustic grand piano as the MIDI instrument. Tones lasted 510 ms (i.e., the default quarter note setting in flabc), sequences thus lasted 1530 ms.

The design of the study (Figure 1) was identical to the one used in Gervain et al. (2012). Thus, the sequences were presented in simple blocks consisting of 10 tone sequences from a given condition (AAB or ABC) for a total of 14 blocks per condition. All 140 tone sequences for a condition were unique. No sequence was ever repeated. Within blocks, sequences were separated by pauses of varying duration (0.5–1.5 s), yielding blocks of approx. 25 s (Figure 1). Blocks were also spaced by silence periods of varying duration (25–35 s) to avoid inducing phase-locked brain responses. The 28 blocks were presented in an interleaved fashion. The order of blocks was pseudorandomized and counterbalanced across participants. At most two consecutive blocks of the same condition were allowed.

## 2.3 | Procedure

We used the same procedure as in Gervain et al. (2012). Infants were tested with a HITACHI ETG-4000 NIRS machine (source detector separation: 3 cm; two continuous wavelengths of 695 and 830 nm) in a dimly lit, sound-attenuated room at BC Women's Hospital, lying in their



**FIGURE 2** The position of the NIRS headgear. (a) A study participant with the headgear. (b) Configuration of light sources and detectors as well as NIRS measurement channels used in the study overlaid on a schematic newborn brain. Grey circles indicate detectors, while black circles indicate sources. Localization analysis was conducted as described in Abboub et al. (2016), localization figure adapted from Abboub et al. (2016).

cribs throughout the test session. At least one parent was present at all times. Babies were tested while asleep. The NIRS optical probes were placed on infants' heads bilaterally (12 channels per hemisphere; Figure 2) using the tragus, the vertex, and the ears as surface landmarks (Gervain et al., 2008; Peña et al., 2003). Sound stimuli were administered at an intensity of 60 dB/SPL through two loudspeakers positioned at a distance of 1.5 m from the babies' heads, at an angle of 30°, and elevated to the same height as the infants' cribs. A portable Macintosh computer played the stimuli and operated the NIRS machine, running the PsyScope experimental software (<http://psy.ck.sissa.it>). The NIRS machine used 0.7 mW laser power.

## 2.4 | Data processing and statistical analysis

Changes in the concentration of oxygenated hemoglobin (oxyHb) and deoxygenated hemoglobin (deoxyHb) were calculated from the absorption of near-infrared light as metabolic indicators of neural activity. Data were band-pass filtered between 0.01 and 0.5 Hz. Movement artifacts, defined as concentration changes larger than 0.1 mmol  $\times$  mm over 0.2 ms, were removed by rejecting block-channel pairs where 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 40 s after the onset of the block (25 s of stimulation plus 15 s of resting period). To further ensure appropriate data quality, we then performed a manual rejection of the remaining artifacts. Newborns were included in the analysis if at least 40% of their data was found valid after pre-processing.

Statistical analyses were carried out over the concentration changes of oxyHb and deoxyHb. First, we conducted a cluster-based permutation analysis (Maris & Oostenveld, 2007) in order to identify clusters of channels in which a significant difference in concentration changes between the two conditions were found. This analysis can define regions of interest (ROIs) and time windows of interest in a

non-arbitrary and data-driven manner, while safeguarding against multiple comparisons (Abboub et al., 2016; Benavides-Varela & Gervain, 2017; Mahmoudzadeh et al., 2013). The definition of spatial clusters was anatomically constrained, as determined by a localization analysis (Abboub et al., 2016; Figure 2b). One thousand permutations were conducted under the null hypothesis, for both oxyHb and deoxyHb.

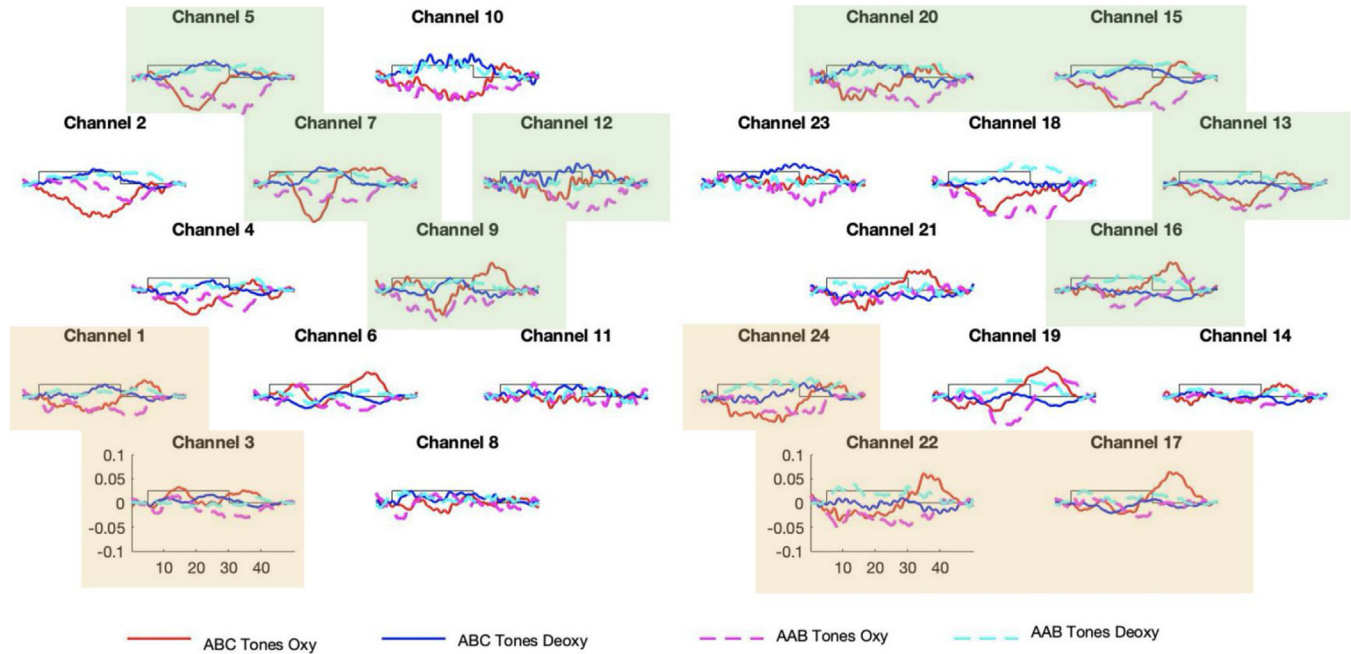
We then performed a linear mixed effects model over concentration changes in the clusters and time windows identified by the permutation analysis, with Participants as a random factor and Condition (AAB/ABC), ROI (Left Temporal cluster/Left Fronto-Parietal cluster/Right Temporal cluster/Right Fronto-Parietal cluster) and Time Course (Blocks 1–14) as fixed factors in order to assess differences across conditions in a temporally dynamical fashion. We tested all the possible models. Model selection was based on the Akaike Information Criterion (AIC) (Claeskens & Hjort, 2008).

Furthermore, to directly compare newborns' responses to the regularities in tones and speech, we normalized the NIRS data to allow for between-subject comparisons (Berent et al., 2021; Otsuka et al., 2007) and conducted an ANOVA with Type of Stimulus (Tones/Syllables) as a between-subjects factor and Regions of Interest (ROI; frontal/temporal), Hemisphere (Left Hemisphere, LH/Right Hemisphere, RH) and Condition (Repetition/Non-Repetition) as within-subjects factors.

## 3 | RESULTS

### 3.1 | Discrimination of AAB and ABC structures with tones

*OxyHb.* The grand average results for oxyHb and deoxyHb concentration changes are presented in Figure 3. The cluster-based permutation analysis revealed a fronto-temporal and a fronto-parietal cluster in each hemisphere in which brain activity significantly differed between



**FIGURE 3** The grand average hemodynamic response. Channels are plotted following the probe placement displayed in Figure 2. The x-axis represents time in seconds; the y axis shows the concentration in mmol x mm. The rectangle along the x-axis indicates the time of stimulation. OxyHb and deoxyHb concentration changes in response to the ABC condition are shown in red and blue, respectively (continuous line). OxyHb and deoxyHb concentration changes in response to the AAB condition are shown in magenta and cyan, respectively (dashed line). The four significant clusters revealed by the cluster-based permutation analysis over oxyHb concentrations are overshadowed.

the AAB and the ABC conditions (Figure 3). In the left hemisphere (LH), the fronto-temporal cluster included channels 1 and 3 ( $p = 0.002$ ), the fronto-parietal cluster channels 5, 7, 9, and 12 ( $p < 0.001$ ). In the RH, the fronto-temporal cluster included channels 17, 22, and 24 ( $p < 0.001$ ), while the fronto-parietal cluster included channels 13, 15, 16, and 20 ( $p < 0.001$ ).

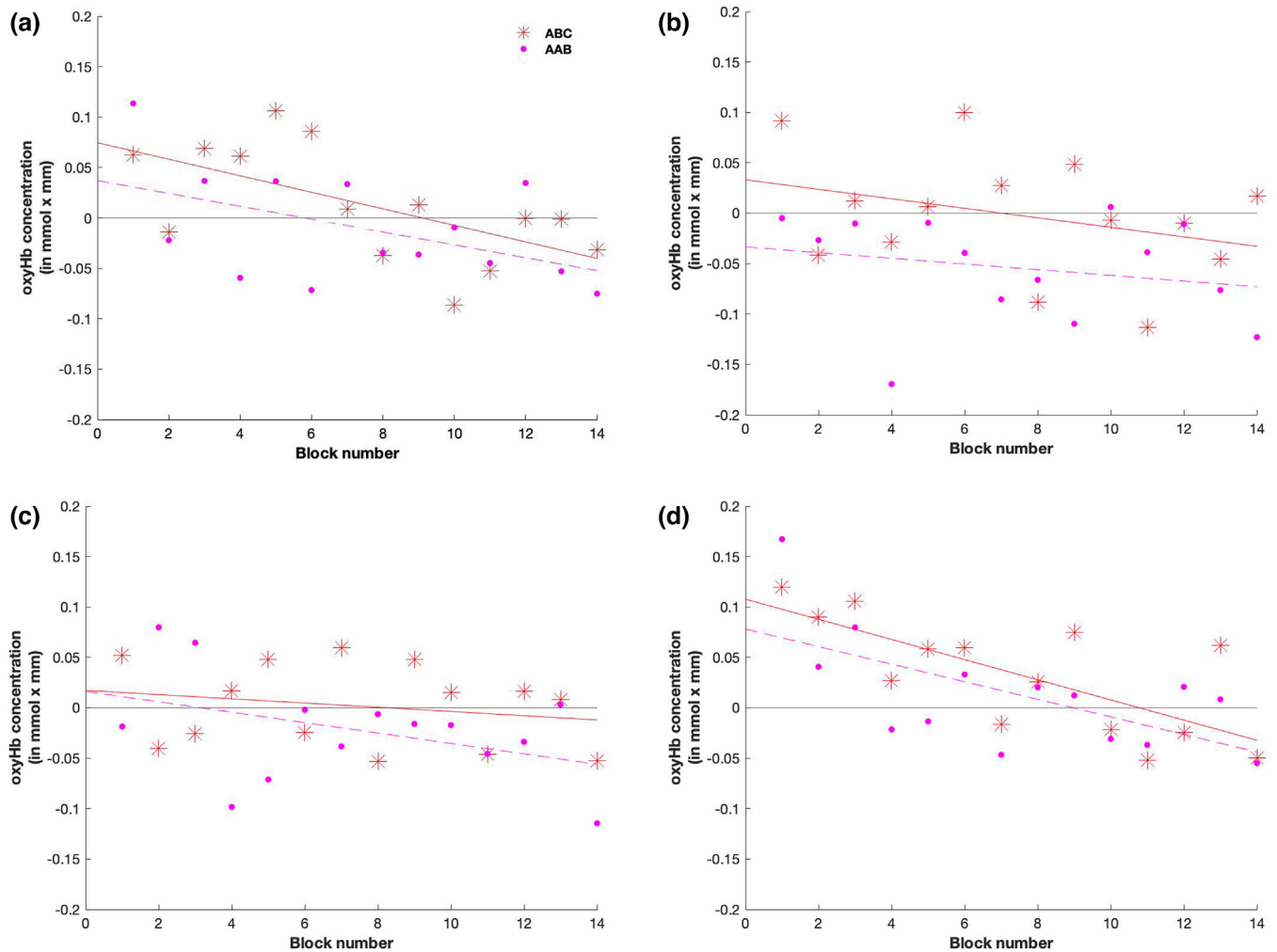
**DeoxyHb.** The cluster-based permutation analysis over the concentration changes of deoxyHb revealed that brain activity significantly differed between the AAB and ABC conditions in channel 12 in the left parietal region ( $p < 0.001$ ), in channel 23 in the right parietal region ( $p < 0.001$ ), in channels 15 and 18 in the left fronto-parietal region ( $p < 0.001$ ), and in channels 14, 16, 17, 19, and 22 in the right fronto-temporal region ( $p < 0.001$ ). The results obtained for deoxyHb were thus largely congruent with those found for oxyHb.

The best fitting linear mixed effects model carried out on oxygenated hemoglobin concentration changes was the one with Time Course and Condition as fixed factors. This model revealed a significant main effect of Time Course ( $p < 0.001$ ) as well as a significant main effect of Condition ( $p < 0.001$ ). The main effect of Condition was due to a larger, that is, more negative, inverted response to the AAB than to the ABC sequences. The best fitting linear mixed effects model when considering deoxygenated hemoglobin concentration changes was the one with Condition as a fixed factor. This model highlighted a significant main effect of Condition ( $p = 0.015$ ). This pattern of results confirms that newborns can discriminate repetition-based sequences of musical tones from random ones. Additionally, as the main effect of Time Course indicates, responses changed significantly over the time course

of the study. This was due to a general decrease in response amplitude over time for both conditions (Figure 4) reflecting neural habituation. As post hoc analyses to explore this main effect, we ran correlations between Time Course and Concentrations in each ROI. The correlation was significant in the left fronto-temporal cluster (channels 1 and 3) for the ABC condition ( $r = -0.605$ ,  $p = 0.022$ ) and in the right fronto-temporal cluster (channels 17, 22, and 24) for the ABC condition ( $r = -0.728$ ,  $p = 0.003$ ) as well as for the AAB condition ( $r = -0.626$ ,  $p = 0.017$ ).

### 3.2 | Comparing tones and speech

To compare newborns' brain responses to the regularities implemented by tones and by speech, we conducted a direct statistical comparison on normalized oxyhemoglobin concentration changes in the significant clusters and time windows obtained through the permutation tests in the two studies. For the tones study, we used the cluster of channels reported above (Figure 3), that is, channels 1 and 3 for the left temporal region, channels 5, 7, 9, and 12 for the left frontal region, channels 17, 22, and 24 for the right temporal region and channels 13, 15, 16, and 20 for the right frontal region. For the speech study (Gervain et al., 2012), we performed the same cluster-based permutation analysis as for the tones study to identify significant clusters. This analysis yielded a left temporal cluster composed of channels 3 and 6, a left frontal cluster composed of channels 4 and 9, a right temporal cluster including channels 16 and 19 and a right frontal cluster including channel 20.



**FIGURE 4** Changes in the concentration of oxygenated hemoglobin over the time course of the study for each block in the four clusters: (a) left fronto-temporal cluster comprising channels 1 and 3, (b) left fronto-parietal cluster comprising channels 5, 7, 9, and 12, (c) right fronto-parietal cluster comprising channels 13, 15, 16, and 20, (d) right fronto-temporal cluster comprising channels 17, 22, and 24.

We then performed an ANOVA over oxyHb concentration changes with Type of Stimulus (Tones/Syllables) as a between-subjects factor and Region of Interest (ROI; Temporal/Frontal), Hemisphere (LH/RH) and Condition (Repetition/Non-Repetition) as within-subjects factors. The main effect of Type of Stimulus was significant ( $F(1,32) = 5.905$ ,  $p = 0.021$ ), as speech triggered a larger, positive, response ( $M = 0.0176$  mmol  $\times$  mm), while tones triggered a negative, inverted response ( $M = -0.0056$  mmol  $\times$  mm). The interaction Condition  $\times$  Type of Stimulus was also significant ( $F(1,32) = 9.071$ ,  $p = 0.005$ ). Post hoc comparisons revealed that this was due to significantly more negative responses to repetitions ( $M = -0.0204$  mmol  $\times$  mm) than to non-repetitions ( $M = 0.0092$  mmol  $\times$  mm) for tones, as well as to greater, positive response for speech ( $M = 0.0264$  mmol  $\times$  mm) as compared to negative, inverted response for the tones ( $M = -0.0204$  mmol  $\times$  mm). The main effect of ROI was also marginally significant ( $F(1,32) = 3.861$ ,  $p = 0.058$ ), due to larger brain responses in the temporal ( $M = 0.0112$  mmol  $\times$  mm) than in the frontal ROIs overall ( $M = 0.0009$  mmol  $\times$  mm). The other factors and interactions were not significant.

## 4 | DISCUSSION

We conducted an fNIRS study to investigate whether newborns can detect and learn a repetition-based regularity presented with tones, as they do with syllables. Newborns show greater brain activations in response to trisyllabic pseudo-words containing an initial (e.g., “babamu”) or a final repetition (e.g., “mubaba”) compared to trisyllabic random pseudowords (e.g., “mubage”) (Gervain et al., 2008, 2012). By mapping each syllable onto a unique tone, we wanted to test whether this precocious ability was specific to speech or extended to other auditory stimuli. Results show significantly different patterns of brain activation between the repetition and the non-repetition conditions in bilateral temporal and fronto-parietal areas. This is due to larger inverted (negative) responses to the AAB sequences than the ABC sequences. Thus, our findings suggest that newborns’ ability to detect repetition is not specific to speech, it also applies to musical tones.

This study, while based on a relatively small group of babies, can be considered within the larger framework of NIRS studies investigating young infants’ abilities to extract repetition-based regularities

from language and other stimuli. To statistically assess the robustness and replicability of these results and to identify moderating factors that may impact the effects, we have recently conducted a meta-analysis of all published and unpublished NIRS studies within this paradigm (Gemignani et al., 2023), and found a consistent, replicable, low-to-medium sized effect for repetition-based rule learning in newborns from speech stimuli with a sample size of 355 newborns from 23 studies. This meta-analysis thus confirms the robustness of the repetition-based rule-learning effect and provides converging evidence with the current results.

However, the patterns of brain activation we observed to tones differed from that observed with spoken stimuli. The first difference is in the localization of the responses, as suggested by the distribution of the significant clusters. Repetitions in syllables trigger greater differential activation in the temporal and frontal areas bilaterally, but with a greater involvement of the left hemisphere (Gervain et al., 2008, 2012). By contrast, brain responses to the tone sequences were not left lateralized, but rather symmetrical between the two hemispheres. Larger activation in the left hemisphere in response to linguistic regularities is consistent with the general left hemispheric specialization of the brain for language, which is well documented in adults (Zatorre & Belin, 2001; Hickok & Poeppel, 2007) as well as in infants (Dehaene-Lambertz et al., 2002; Peña et al., 2003; Minagawa-Kawai et al., 2011). By contrast, music has often been observed to activate the right hemisphere (Peretz & Zatorre, 2005). Whether our stimuli may be considered truly musical is an open question, as the assignment of tones to structure was determined randomly, but they were made up of piano tones, which was sufficient to trigger a non-left-lateralized response.

A second difference between the responses to regularities implemented with speech and tones lies in the nature of the hemodynamic response, as shown qualitatively, by the shape of the hemodynamic responses, and quantitatively, by the direct statistical comparison of the two studies. For syllables, newborns showed canonical (positive) responses, while in our study, responses were inverted (negative). How to best interpret inverted hemodynamic responses in infants is still under debate (Issard & Gervain, 2018). Such responses have been related to a number of physiological factors, such as the immaturity of infants' vasculature, brain and the neurovascular coupling, but also to experimental factors, such as deactivation due to experimental design, ill-formed, unusual or degraded stimuli, and so on. In the current study, it is the result of a third difference between the responses to speech and tone stimuli, namely their temporal dynamics. Specifically, responses to syllables and tones differ when we look at them over time. In Gervain et al. (2008), the results show a greater activation for the ABB sequences from the beginning of the experiment, which further increased over the time course of the study. By contrast, in our study, responses to the tone sequences decreased over time, resulting in inverted responses after the first few blocks. This kind of deactivation over repeated stimulus presentation corresponds to a classical habituation effect.

Why did tone sequences trigger habituation, but syllables did not? The literature on infants' neural responses to repetition-based regularities offers two possible, not necessarily mutually exclusive

explanations. First, Bouchon et al. (2015) replicated Gervain et al.'s (2008) study, but drastically reduced the variability of the speech stimuli, decreasing the number of trisyllabic sequences from 280 to 24 and increasing the frequency of occurrence of each item from 1 to 6. Contrary to the gradually increasing response to repetition sequences found in Gervain et al. (2008), that is, a "repetition-enhancement" effect, Bouchon et al. (2015) observed a stable response over time. This suggests that, similarly to adults (Henson & Rugg, 2003), the habituation of infant brain to the stimuli depends on their variability/complexity. In our study, we have found decreasing activation over the time course of the study, often termed "repetition-suppression" in the fMRI literature (Henson & Rugg, 2003). Despite the that our study perfectly match the frequency of occurrence and distribution of the tones and syllables (as our tone stimuli were constructed by replacing each syllable of Gervain et al.'s (2008) with one tone), linguistic syllables are still inherently more complex than tones at the acoustic level. This lower acoustic complexity is one possible factor that may have contributed to the habituation effect and thus the inverted hemodynamic responses we observed, just as lower variability in frequency of occurrence did so in Bouchon et al. (2015). This interpretation is empirically supported by the fact that while for speech stimuli, the repetition-based regularities differentially triggered enhancement over the course of the study, for tones, both the repetition- and the diversity-based sequences gave rise to a habituation response. In other words, the deactivation was common to all tone stimuli irrespective of structure, suggesting that it is related to their general acoustics.

A second, and possibly related explanation is that linguistic stimuli, as identified acoustically by their characteristic features and complexity, may preferentially trigger the extraction of rule-learning mechanisms that are distinct from those triggered by tones. In a recent study, Berent et al. (2021) asked whether infants' ability to extract repetition-based regularities from language input is restricted to the spoken modality, or if it also extends to the visual modality. They thus contrasted sign-naïve infants' brain responses to repetition-based regularities carried by linguistic signs (novel syllables in American Sign Language) as well as to matched non-linguistic visual control stimuli. While infants were able to extract the repetition-based regularity from both types of stimuli, they showed opposite patterns of activations. In the signs condition, a greater activation was found for the repetition sequences than for the random ones, while the random sequences elicited greater activation than repetitions in the visual controls. Even more importantly, infants' brain responses to repetitions implemented with signs were very similar to those found for speech in Gervain et al. (2008, 2012). Despite the highly different sensory characteristics of speech and sign, repetition-based regularities elicited similar brain responses. Berent et al. (2021) interpreted these findings as a double dissociation between the sensory modality of stimuli (auditory or visual) and their linguistic status (linguistic or non-linguistic). Linguistic stimuli trigger similar brain responses, irrespective of their sensory properties, while non-linguistic stimuli yield a different response pattern despite perceptual similarities.

Our results are in line with this double dissociation hypothesis: despite being in the same perceptual modality as speech, tones trigger

different brain responses. Taken together, our results and those of Berent et al. (2021) show that repetition-based regularities are detected by infants in both linguistic and non-linguistic stimuli, but they engage different processing mechanisms. The dynamically increasing canonical hemodynamic response observed for linguistic stimuli suggests that the infant brain extracts the underlying structural regularity, that is, reduplication, for these stimuli, but no such rule extraction takes place for tones or other non-linguistic stimuli, as indicated by the strong habituation, that is, increasing deactivation we observed.

## 5 | CONCLUSION

A large body of evidence suggests that the human brain is equipped with sophisticated abilities to efficiently process and organize perceptual input already from birth. Our study contributes to the exploration of these abilities. In an fNIRS study, we asked whether newborns could extract a repetition-based regularity from non-linguistic auditory stimuli, that is, piano tones, like they do from speech. Our results show that newborns' ability to extract a repetition rule is not specific to language as we found differential brain responses to repetition- versus diversity-based sequences when those were carried by tones. However, the brain signatures of this response are different from those observed for structurally identical speech stimuli. We thus conclude that the detection of repetition is present for both linguistic and non-linguistic stimuli, but the underlying neural mechanisms differ.

## ACKNOWLEDGMENTS

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## CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the authors upon reasonable request.

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