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**Master Degree in Cognitive Neuroscience and Clinical
Neuropsychology**

Final dissertation

**An fNIRS investigation of the perception of non-adjacent linguistic
regularities across development**

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1. Introduction

Infants manage to acquire their native language in a few years, without any prompt needed. Language acquisition starts during the intrauterine period, when fetuses are first exposed to speech (Gervain, 2022). Indeed, newborns already have sophisticated language abilities. They can extract linguistic regularities from speech and generalize it to novel stimuli (Gervain et al., 2008). This ability is called rule learning, and infants can apply it across different domains, although the most robust evidence comes from language acquisition (Rabagliati et al., 2019).

While research in the last decades has made considerable advances in better understanding young learners' rule learning abilities (for a review, see Rabagliati et al., 2019), the nature of the ability is still not fully understood, especially very early in life. The study presented in this thesis aims to investigate some of the features of linguistic rule learning. Using functional near-infrared spectroscopy (fNIRS), a brain imaging technique measuring the hemodynamic response, Gervain et al. (2008) found that newborns (3-day-old infants right after birth) show significantly different brain responses to trisyllabic nonsense words in which the last two syllables are identical, i.e. words having an ABB structure (e.g. “mubaba”, “penana”) and ABC control words, i.e., words with three different syllables (e.g. “mubage”, “penaku”), but do not respond differently to ABA and ABC words. Their results suggest that newborns are able to distinguish grammatical rules from unstructured, random words only when the rule includes an adjacent identity-relation, like in the case of ABB or AAB, but not a grammar based on non-adjacent identity, like ABA, from unstructured words, like ABC.

Behavioral studies show that 7-month-old infants are able to distinguish ABA words from ABC words (Gervain & Werker, 2013). Thus, it seems that rule learning in newborns is constrained by the presence of adjacent repetitions, while infants of 7 months of age can learn more complex grammars. As suggested by de la Cruz-Pavía and Gervain (2021), newborns might hold only the concept of sameness or identity, while infants from 6 months onwards might hold both the concepts of sameness/identity and diversity. Developmentally, this timing coincides with the age

at which infants start learning the first word forms (Bergelson & Swingley 2012), so the ability to represent sequences of diverse syllables may be particularly relevant at this developmental stage.

Currently, the neural correlates of infants' ability to represent diversity in linguistic stimuli is unexplored. Consequently, we decided to test a sample of 6-month-old infants, as well as an adult group, in order to assess the developmental trajectory of this ability and identify its neural correlates. We presented participants with ABA vs ABC sequences in a block-design paradigm similar to Gervain et al. (2008), and we recorded the brain responses with fNIRS. Our objective was to evaluate whether 6-month-old infants can encode syllabic relations based on diversity and non-adjacent repetitions. Adults, who can easily distinguish these structures behaviorally and have been exposed to a rich linguistic environment, served to establish the mature state of the ability.

2. Early language acquisition

Infants are capable of learning languages without any formal instruction. Several theories have been proposed to account for the putative processes underlying infants' linguistic capabilities. These models typically belong to either the nativist or the empiricist theoretical framework. The nativist approach highlights the role of genetically endowed factors, while experience and domain-general, non-language-specific learning mechanisms are pivotal for the empiricist approach.

Specifically, the nativist theoretical approach argues that language acquisition is supported by a system of innate structured linguistic knowledge (Chomsky, 1975), that is species-specific and specific to the language domain. In this case, the environment serves as a trigger, rather than a tutor, for the infant (Gervain & Mehler, 2010). This innate knowledge is often referred to as Universal Grammar (Chomsky, 1975), and capitalizes on the presence of universal features shared across languages. These features, thus, would be encoded as innate principles and would be part of the human biological endowment (Gervain & Mehler, 2010).

By contrast, the empiricist theoretical approach posits that language acquisition is supported by classical, domain-general learning mechanisms, some of which may even be shared with different species (Elman 1996, Tomasello 2000). In this case, language acquisition is believed to be fully supported by the environment, and the ability to extract abstract patterns is developed over time, but may not be present at birth.

Recent work, however, focused on building bridges between the “nature” and “nurture” factors. The genetic makeup of the individual interacts with experiential factors and both aspects are fundamental in the process of language acquisition. Brain imaging studies, along with epigenetic studies (Werker and Hensch 2015), support a view in which experience and neurobiology act synergistically. For instance, newborns show sensitivity to some features of speech (for a review, Gervain 2022). These features drive learning, and in turn, learning and exposure to language(s) shape the infant brain. Such a circular process has been proposed in the native language neural

commitment hypothesis (Kuhl, 2004). According to this hypothesis, exposure modulates the linguistic neural network. Newborns, who are first “universal listeners”, become attuned to their native language(s) and lose the ability to discriminate non-native speech features, and this developmental change is reflected by the change in the hierarchical organization of the neural network dedicated to language and speech processing.

Studying preverbal infants, particularly newborns, can shed light on the processes that support language acquisition before these are shaped by the environment. Researchers employed tasks, stimuli, and structures that allow them to investigate whether infants hold the concepts of sameness/identity and difference/diversity within the linguistic domain (de la Cruz-Pavía & Gervain, 2021). The first study to show that infants can learn abstract linguistic rules based on identity was Marcus et al.’s work in 1999 (Marcus et al., 1999). During familiarization, 7-month-old infants heard a 2-minute speech sample in an artificial grammar. The speech contained trisyllabic words, which followed an identity-based rule (e.g., ABA: *wa ti wa*), where two syllables were identical. Infants were divided into two groups: one of them heard words with an ABA structure (e.g., *wo fe wo*), while the other heard words with an ABB structure (e.g., *wo fe fe*). During the test phase, infants were presented with sentences that either contained the familiarized structure or the unfamiliar structure. Results indicated that infants looked longer to the unfamiliar structure, suggesting that they learned the familiar rule and they could generalize the learned grammar to novel stimuli, distinguishing them from unfamiliar ones. This learning mechanism is known as abstract rule learning, algebraic learning, or pattern extraction. Although this mechanism seems to be employed by infants in many cognitive domains, research results are robust only within the linguistic domain (Rabagliati et al., 2019).

Even newborns (Gervain et al., 2008; Gervain et al., 2012) show sensitivity to regularities based on identity and repetitions. Newborns exposed to an artificial grammar successfully extracted an identity-based rule, and they could discriminate between words with an ABB structure (e.g., *mu ba ba*) and random control words (ABC: e.g. *mu ba ge*). These findings suggest that newborns can represent identity and

detect the sequential position of syllables (Gervain et al., 2012). However, newborns were only able to learn the underlying grammar when the identical syllables were adjacent but failed to discriminate non-adjacent repetitions, i.e., ABA structures (e.g., *ba mu ba*) from ABC words (Gervain et al., 2008). As suggested by Endress and colleagues (2009), detecting adjacent repetitions might be an auditory bias, which functions as a perceptual primitive. According to their review, adjacent repetitions constitute a special, perceptually salient relation that is easier to learn for newborns than non-adjacent structures, where basic perceptual mechanisms do not facilitate learning.

Marcus and colleagues' study (1999) compared grammars with adjacent repetitions and grammars with non-adjacent ones and could thus not determine whether the discrimination between them was based purely on the presence of the adjacent repetition or both grammars were learned, as pointed out by Gervain and colleagues (2008). To evaluate whether infants are sensitive to non-adjacent repetitions, they should be tested with a paradigm that compares a non-adjacent repetition grammar against random control words, i.e., ABA vs. ABC.

Furthermore and relatedly, we do not know whether infants can detect differences, i.e., encode the structure of the random controls as a sequence of non-identical syllables (de la Cruz-Pavía & Gervain, 2021) or whether they only encode the structures containing repetitions. Whether rule learning abilities change during development is also unknown, although the fact that newborns cannot distinguish non-adjacent repetitions from random controls (Gervain et al., 2008) as measured by fNIRS, but behaviorally 7-month-olds can (Gervain & Werker, 2012) suggests that this ability may undergo change. The current study intends to answer some of these open questions.

2.1 Neural correlates of early language acquisition

To address these questions, we used functional near-infrared spectroscopy (fNIRS). fNIRS is a non-invasive neuroimaging technique. It is an optical technique that uses red and near-infrared light (650-900 nm) to monitor the metabolic activity of the brain.

Specifically, fNIRS detects changes in the local concentration of oxygenated (HbO) and deoxygenated (HbR) hemoglobin (Lloyd-Fox et al., 2010). These changes are indirect markers of brain activity, as the oxygen level of a given brain area is regulated by the neurovascular coupling principle (Brigadoi & Cooper, 2017). When an individual is performing a task, the brain areas involved consume oxygen, and the vascular system supplies those areas with abundant oxygenated hemoglobin in order to support brain activity.

fNIRS is lightweight, silent, and more robust to motion artifacts than other neuroimaging techniques. Because of these qualities, fNIRS has been applied to populations that are difficult to test with other techniques, such as infants (Hyde et al., 2010). Nonetheless, this technique has limitations. For instance, it can detect only cortical activity, as given the optical properties of the head tissues, the penetration of light is limited to the cortex, and it has poor spatial resolution compared to other metabolic techniques (Lloyd-Fox et al., 2010). Additionally, the fNIRS signal is sensitive to hair, skull thickness, and extracerebral dynamics (Brigadoi & Cooper, 2017). As some of these factors play a lesser role in infants than in adults, fNIRS is very commonly used to image the infant brain.

One of its most prominent areas of application in developmental cognitive neuroscience is the area of speech and language processing. Studies suggest that the infant brain shows a functional organization for language processing that is analogous to the one found in the adult brain (Gervain & Mehler, 2010). Nonetheless, the infant brain undergoes changes, with structures that become increasingly specialized in processing familiar, i.e., native, linguistic contrasts, supporting perceptual attunement to the native language (Kuhl et al., 2008).

The neural mechanisms underlying repetition-based regularities have been explored since birth. In newborns, repetition-based words activate left temporal areas, which are involved in auditory processing, as well as left frontal areas, involved in higher-level learning and memory (Gervain et al., 2008). The same authors also showed that in newborns the brain response to repetitions increases over time, contrary to the brain response to random sequences, indicating that repeated exposure enhances

pattern detection. These findings are coherent with fMRI studies with infants (Dehaene-Lambertz et al., 2002), which also highlight an early left-hemisphere specialization for native speech, with a hierarchical organization: speech is first processed by the primary auditory cortex, then the superior temporal gyrus and finally the inferior frontal area (Dehaene-Lambertz et al., 2008).

Recent fNIRS studies suggest that by 6 months of age, the infant brain can also process diversity-based structures in speech (de la Cruz-Pavía & Gervain, in press), suggesting a developmental shift. Processing diversity, i.e., the non-identity of syllables, might be computationally too demanding for the newborn brain (de la Cruz-Pavía & Gervain, 2021), explaining why newborn infants do not distinguish between non-adjacent repetitions, i.e., ABA, and the diversity-based ABC structures (Gervain et al., 2008).

Our study asks whether the emerging ability of 6-month-olds to detect diversity-based structures and their increasing memory and other cognitive capacities also make them able to distinguish these structures from non-adjacent repetitions, i.e., ABA vs. ABC. If infants represent identity and diversity only locally, i.e., only between adjacent syllables, then ABA and ABC structures do not differ, as adjacent syllables are always different in both structures. If, however, they are also able to encode identity and diversity in the entire sequence, then they should notice the repetition of the A syllable in the non-adjacent repetition sequence. The aim of the current study is, therefore, to test how 6-month-old infants process ABA and ABC structures. As the processing of repetition-based regularities have never been investigated with adults, we also tested an adult sample to investigate the brain mechanisms underlying the mature ability.

To summarize, the journey of language acquisition begins in intrauterine life, with exposure to speech (Gervain, 2022). Thus, speech perception is the foundation of

language acquisition. Newborns can extract structurally relevant information from speech, such as identity and position of syllables (Gervain et al., 2008). These two pieces of information, taken together, allow for regularity detection, such as repetitions. Existing studies (Gervain & Werker, 2013) support the hypothesis of a developmental shift in this ability. While newborns do not show heightened brain activation to random control sequences and cannot distinguish them from non-adjacent repetitions, by 6 months of age, infants show the ability to detect diversity in linguistic sequences. Here, we ask whether the infant brain can encode diversity-based structures, as well as identity-based ones in entire sequences and use this ability to discriminate random sequences from non-adjacent repetition-based ones. The ability to detect differences could be pivotal for language acquisition, as most linguistic units such as words are sequences that are highly variable and consist of diverse syllables (de la Cruz-Pavía & Gervain, in press).

3. The study

The current study aims to assess whether infants, as well as adults, encode the nature of syllables in a sequence (in terms of identity/diversity) only locally, comparing only adjacent syllables or also more globally, taking the entire sequence into account. Additionally, the adult sample will help define the mature state of pattern extraction from diversity-based sequences. Using an experimental design similar to those in previous studies (e.g. Gervain et al., 2008, de la Cruz-Pavía & Gervain, in press), we, therefore, compared infants' and adults' brain responses to ABA and ABC structures using fNIRS in order to assess whether the relations among the syllables are encoded only locally, i.e., between adjacent syllables, or globally, i.e., the three syllables of the word are computed simultaneously.

3.1 Methodology

3.1.1 Participants

The study included two groups of participants. The first group comprised 63 adults (mean age: 23.60 years, SD 3.33 years, range: 19-36 years; 32 males). The second group comprised 12 infants. Additionally, 60 more infants were tested by Gaia Lucarini and were included in the following analyses. Thus, the final infant group comprises 72 infants (mean age: 206.72 days, SD = 36.30 days, range: 152-297; 35 males). All participants were healthy and did not present any linguistic or hearing impairments. Within the infant group, all participants had normal birth weight (mean: 3.19 kg), gestational age (mean: 39 weeks), and a normal APGAR score at birth. The ethics committee of the University of Padova approved all the experimental procedures. Participants who did not complete the procedure due to fussiness or crying or had insufficient number of valid blocks due to motion artifacts were not included in the final analysis. All rejection was done in batch, prior to statistical analysis in order to avoid biasing the final results. A group of 26 infants was selected and underwent final analyses.

3.1.2 Materials

Participants were exposed to a speech sample in an artificial grammar that comprised trisyllabic words with an ABA or an ABC structure. In the first case, words contained a non-adjacent repetition, i.e., the first and third syllables were identical, while in the second case, all the syllables were different. ABC words are used in this study as random control words. Both types of words were created from the same syllabic pool that was also employed in previous studies (Gervain et al., 2008; Gervain et al., 2012). The syllabic repertoire contained 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, and each pair contained two syllables with the same consonant (e.g., “ba”, “bi”) or two consonants from the same class (for ex., nasal; “mu”, “na”), but a different vowel. For the ABA grammar, one member of a syllable pair was assigned to the X group, and the other to the Y group. X and Y syllables were presented with equal frequency in each sequential position. ABA sequences were created by mapping all X syllables to A and all Y syllables to the B position and vice versa with the following constraints. To maximize discriminability, the X and Y syllables within a sequence could not have the same vowel and could not belong to the same syllable pair. As a result, 140 distinct sequences were created. The ABC words were then created by shuffling the third syllable from the ABA words within a block. Thus, between the two grammars, the overall frequency of the syllables, the frequency of each syllable, and all the phonological and prosodic features were matched.

Syllables were synthesized using the MBROLA diphone database, fr4 French female voice. The syllables had a monotonous pitch of 200 Hz and lasted 270 ms, of which consonants took up 120 ms and vowels 150 ms. These characteristics were the same as in previous studies (Gervain et al., 2008, 2012 etc.).

Words were assigned to blocks representing a given condition, each block containing 6 words, that were separated by a jittered pause that lasted at least 0.5 ms and at most 1.5 seconds. Every block lasted about 11 seconds. There were 7 blocks per condition for a total of 14 blocks. The pauses between blocks were also jittered and

could vary between 20 to 25 seconds. The pause interval between blocks varied to prevent phase-locked brain responses. Within the 14 blocks presented, the same grammar could not occur for more than two consecutive blocks, yielding an interleaved block design. Block order was pseudorandomized and counterbalanced across participants.

3.1.3 Data acquisition

fNIRS data was acquired using a NIRx NIRSport 2 NIRS machine (source–detector separation, 3 cm; two continuous wavelengths of 695 nm and 830 nm) in a dimly lit room at the Baby Lab of the University of Padua. The NIRS machine used light intensity of 0.30–0.35 mW.



Figure 3. One of the infant participants of the study.

Infants were placed on the lap of a parent, who was sitting on a chair at approx. 80 cm from a computer monitor. Two speakers were placed laterally to the computer monitor. On the screen, a cartoon video was shown to keep infants attentive and engaged in the study. The acoustic stimuli were administered through the two speakers, at 60-65 dB. The parent was naïve to the experimental hypotheses and was instructed to not interact with the infant during the run.

Adult participants sat directly on the chair and underwent the same procedure.

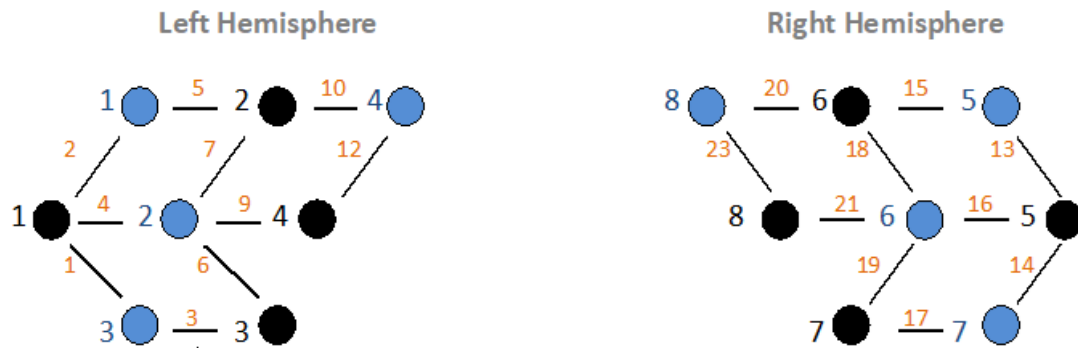


Figure 1. The fNIRS array for the infant group. Detectors are blue, sources are black, and the channel number is orange. Channel numbering is not continuous to match numbering conventions used in previous studies (Gervain et al., 2008, 2012; de la Cruz-Pavà & Gervain, in press) with a larger channel array.

The fNIRS array consisted of 10 channels for each hemisphere for the infant group (Figure 1) for a total of 20 channels.

For the adult group, one source in the right hemisphere, known to be less involved in language processing, was coupled with short channel detectors, i.e., detectors placed 8 mm away from the source as opposed to 3 cm for regular channels, to be used for correction for physiological contamination. This resulted in 10 LH and 8 RH channels for adults. The layout was thus as shown in Figure 2.

For both groups, the tragus, the vertex, and the ears were utilized as surface landmarks for cap placement. This configuration allowed us to probe the temporal, parietal and frontal brain areas bilaterally, known to constitute the language network (Friederici, 2005). For exact brain localization of the layout used here, see Abboub et al. (2016). The coverage was larger in infants than in adults due to the obvious differences in head size in the two populations.

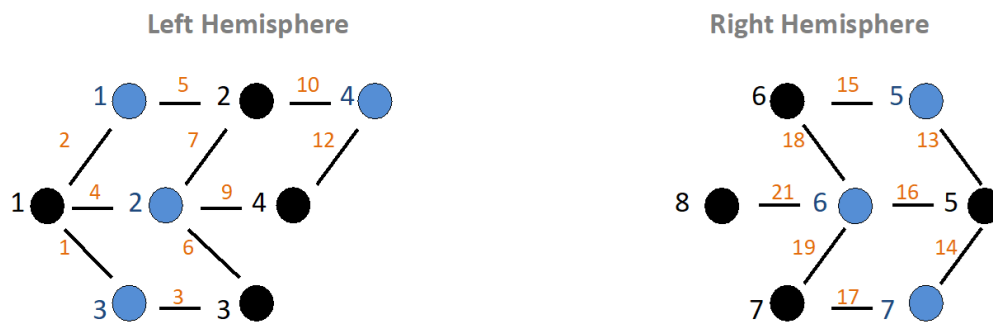


Figure 2. The fNIRS array for the adult group. Sources are black, detectors are blue, and the channel number is orange.

Participants were tested in a dimly lit, silent cubicle, while the experimenter was placed outside the cubicle and controlled stimulus presentation and NIRS data acquisition. Infant participants were monitored through a camera during the experiment in order to control for any sign of distress.

3.1.4 Data processing and analysis

Data analysis focused on the concentrations of HbO and HbR. These were computed by the absorption of light registered by the fNIRS machine. Data underwent bandpass-filtering between 0.01 and 0.7 Hz, as in previous studies. To remove movement artifacts from the signal, block-channel pairs where artifacts occurred were automatically rejected. Artifacts were defined as changes in Hb concentrations above $0.1 \text{ mmol} \cdot \text{mm}$ over 0.2sec, as in previous studies. A baseline was linearly fitted between two 5-second periods, one before the onset of the block and the other one 15 seconds after the end of the block.

The statistical analysis consisted of performing cluster-based permutation tests (Maris & Oostenveld, 2007) comparing (i) the two conditions, (ii) the non-adjacent repetition (ABA) condition to baseline and (iii) the diversity-based control condition (ABC) to baseline, as in previous studies.

3.2 Results

3.2.1 Adults

Although data collection in the adult group has been completed, the analysis could not be fully carried out. We created a pipeline for short-channel analysis based on the literature (Saager & Berger 2005; Scholkmann et al., 2014). However, short-channel correction algorithms assume that data in the short channels is of good quality and the correction procedure will thus improve overall data quality and eliminate physiological and possibly other sources of noise. By contrast, short channel data was particularly noisy in our dataset, possibly due to the location of the short channels over areas of the scalp where head curvature is strong and thus the coupling of the optodes to the scalp source is easily compromised. This led to after-correction results that were noisier than pre-correction data, which was hard to interpret.

As there are no standardized procedures for short-channel correction in the literature and discussion about the most suitable methods is still open, further work will be necessary to find the optimal correction method for the adult dataset.

3.2.2 Infants

Figure 4 shows the oxyhemoglobin and deoxyhemoglobin concentrations of the infant group, averaged for each condition across blocks.

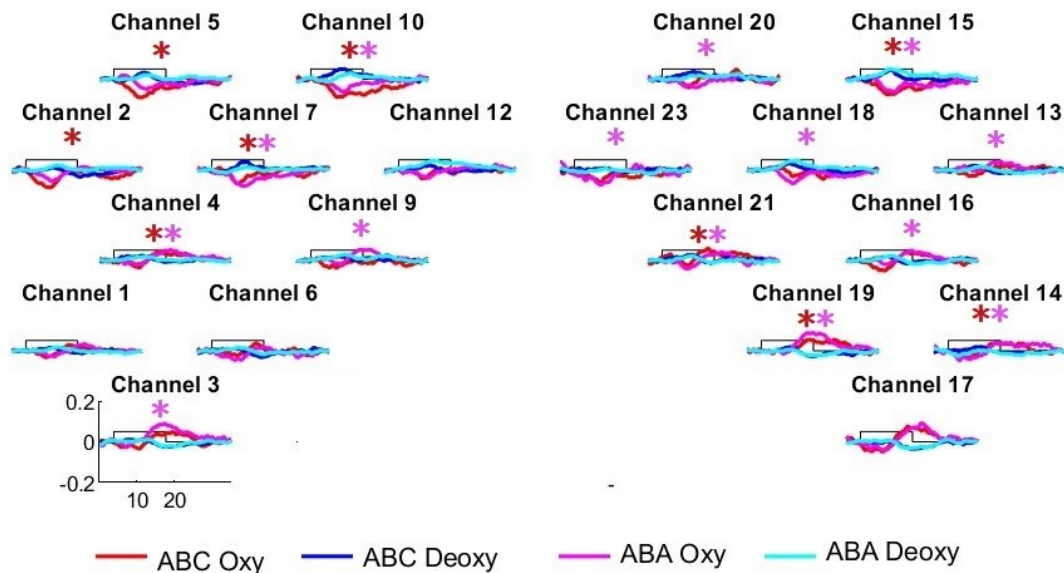


Figure 4. Average hemodynamic responses across blocks for the infant group. Channels 1 to 12 are placed on the left hemisphere, while channels 13 to 24 are placed on the right hemisphere. Channel locations are as shown in Figure 1. The x-axis shows time in seconds, while the y-axis represents concentration in $\text{mmol}\cdot\text{mm}$. Magenta and cyan lines display the metabolic responses to the ABA condition- the magenta line represents the oxyhemoglobin and the cyan line depicts the deoxyhemoglobin, respectively. The red and blue lines are associated with the ABC condition; red indicates the oxyhemoglobin response, and blue the deoxyhemoglobin. Channels that exhibited an activation significantly different from the baseline are marked with an asterisk, and the color indicates the condition in which the difference was observed.

We applied a cluster-based permutation analysis based on oxyhemoglobin concentration changes and compared the two conditions to the baseline and to each other. This analysis defines spatially adjacent channels which exhibits a significant

activation in temporally adjacent samples (de la Cruz-Pavía & Gervain, in press). In this way, the regions and time windows of interest are designed in a data-driven manner and the multiple comparison problem can be avoided. We used paired-sample t-tests with a significance threshold of $t=2.06$ and ran 1000 permutations under the null hypothesis.

ABA vs. baseline. Two clusters, one in each hemisphere, showed a more negative, i.e., inverted response to ABA sequences than to baseline (all clusters: $p < 0.001$). In the LH the cluster involved channels 7 and 10, in the RH channels 15, 18, 20 and 23. These largely analogous channels in the two hemispheres covered the bilateral frontal / fronto-parietal areas. Additionally, two clusters, one in each hemisphere, showed an increased, canonical response to ABA sequences (all clusters: $p < 0.001$): channels 3, 4 and 9 in the LH and channels 13, 14, 16, 19, and 21 in the RH. These channels covered the bilateral temporal / fronto-temporal areas.

ABC vs. baseline. A fronto-parietal cluster in the LH including channels 2, 5, 7, and 10 showed a significantly more negative activation to ABC sequences ($p < 0.001$) compared to the baseline. A similar cluster in the RH involved channel 15. Additionally, two clusters, one in each hemisphere, showed an increased, canonical response to ABC sequences (all clusters: $p < 0.001$): channel 4 in the LH and channels 14, 19, and 21 in the RH. These channels covered the bilateral temporal areas.

ABA vs. ABC. The permutation analysis yielded no significant difference between the two conditions.

4. Discussion

In this study, we wanted to investigate how 6-month-old infants encode a sequence of syllables and define the developmental trajectory of such ability. The ability to extract identity-based structures from linguistic stimuli has been studied for several decades now, beginning with the work of Marcus et al. (1999). Even newborns exhibit this ability (Gervain et al., 2008), but they fail to distinguish between a random sequence, such as ABC, and a non-adjacent structure, i.e., ABA (Gervain et al., 2012). Adjacent repetitions might be extracted relying on a particular bias that is more readily perceivable (Endress et al., 2009), or it may be the case that the computation of diversity-based or non-adjacent repetitions might be too demanding for the newborn brain (de la Cruz-Pavía and Gervain, 2021). Although there is an abundance of words in infant-directed speech that follows an adjacent-repetition structure (e.g., *bebé*, “baby” in French, *mamma*, “mom” in Italian, *daddy* in English), infants cannot rely solely on adjacent repetitions to build their vocabulary, as most linguistic units are highly variable (de la Cruz-Pavía and Gervain, in press). Based on previous behavioral findings (Gervain & Werker, 2013), infants at 7 months of age are able to distinguish between non-adjacent ABA structures and random ABC words. Thus, it seems that there might be a developmental shift, and the ability to discriminate between non-adjacent repetitions (ABA) and diversity-based (ABC) grammars emerges around this age, as also supported by neuroimaging studies, such as de la Cruz-Pavía and Gervain (in press).

To test our hypothesis, we presented to a sample of 6-month-old infants a speech stream that was characterized by trisyllabic words- they could either follow an ABA or an ABC structure- and recorded brain activity with fNIRS. No significant difference between the brain responses to the ABA and the ABC sequence was found. As we know from behavioral studies (Gervain & Werker, 2013), infants at 7 months of age can discriminate between these two types of structure. Additionally, the brain response to ABC seems to increase at 6 months (de la Cruz-Pavía & Gervain, in press). The most likely interpretation of our findings is thus not necessarily that 6-month-olds cannot discriminate these structures, but that the metabolic cost to process the two

grammars is similar, and this lead to non-significant differences between the two grammars.

This interpretation is reinforced by the activations to each condition as compared to baseline. Indeed, both grammars yielded heightened activation in several brain areas, i.e an actual neural response to both grammars, and they showed an overall quite similar pattern. Specifically, both grammars activated similar clusters, with a canonical response in the bilateral temporal / fronto-temporal areas, and an inverted response in the frontal areas. The former may be explained by the auditory responses triggered by the stimuli, closely matching all previous repetition-based rule learning studies using NIRS (Gervain et al. 2008, 2012; see Gemignani et al. 2023 for a meta-analysis of all existing studies). The inverted response, not uncommon in infants, but more challenging to interpret (Issard & Gervain 2018), may be attributable to habituation due to the repeated exposure to the stimuli in particular in the frontal areas, responsible for higher-order processing and sequence learning (Dehaene-Lambertz et al. 2008). While most NIRS studies testing repetition-based regularities do not usually find such an inverted response in the frontal areas, at least one study did observe a similar response (Bouchon et al., 2015), which the authors indeed attributed to habituation.

Despite the overall similarity of the responses, the clusters elicited by the ABC condition were smaller compared to the ones in response to the ABA condition, in particular in the RH, hinting to a potential discrimination of the two grammars. Future studies will be needed to better test this interpretation. In particular, future studies may use the alternating/non-alternating design, such as the one employed by Gervain et al. (2012), known to be a more stringent test of discrimination than the simple block design employed here. In an alternating/non-alternating design, half of the blocks contain a single structure (in our design, either ABA or ABC grammars), while in the other half the two grammars are alternated within-block. In this way, one could investigate in a more sophisticated manner the discrimination ability of infants. It would also be important to include the adult population in this line of research. Adults have been exposed to a rich and complex linguistic environment and can help identify

the mature state of the neural network underlying this ability. Thus, including adults would be crucial to define the developmental trajectory of grammar acquisition.

5. Conclusion

The purpose of this study was to identify one of the processes at the foundations of language acquisition. Language acquisition begins with speech processing (Gervain, 2022). Newborns show sensitivity to some features of the speech, such as syllabic repetition. Sensitivity to repetitions is constrained by adjacency in newborns (Gervain et al., 2012), while infants at 7-months of age show behavioral discrimination between non-adjacent and diversity-based structures, i.e., ABA vs ABC (Gervain & Werker, 2013).

Our results imply that both grammars activated clusters usually associated with language processing. However, there was no significant difference in the brain response between the two conditions. Based on the literature, our interpretation is that, at this age, the metabolic costs to process the two sequences are similar. This hypothesis should be corroborated by future studies that investigate the same population with an alternating / non-alternating paradigm. Additional investigation would also disentangle whether the discrimination between the identity-based structure and the diversity-based one occurred due to local (only adjacent syllables are compared) or global (all the syllables are compared to each other) computation. Taken together with de la Cruz-Pavía and Gervain (in press) findings, i.e., 6-month-old infants hold both the concepts of sameness and diversity, we can evaluate a developmental trajectory of grammar acquisition, in which infants become able to manage more complex structures as they grow.

Although the results are preliminary, we were able to contribute to the grammar acquisition research with a new hypothesis about the underlying network architecture and its development, which is still mostly unknown.

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