1 **From computing transition probabilities to word recognition in** 2 **sleeping neonates, a two-step neural tale**

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8 **Keywords**

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10 **Abstract**

11 Extracting statistical regularities from the environment is a primary learning mechanism,
12 which might support language acquisition. While it is known that infants are sensitive to
13 transition probabilities between syllables in continuous speech, the format of the encoded
14 representation remains unknown. Here we used electrophysiology to investigate how 31
15 full-term neonates process an artificial language build by the random concatenation of four
16 pseudo-words and which information they retain. We used neural entrainment as a marker
17 of the regularities the brain is tracking in the stream during learning. Then, we compared
18 the evoked-related potentials (ERP) to different triplets to further explore the format of the
19 information kept in memory. After only two minutes of familiarization with the artificial
20 language, we observed significant neural entrainment at the word rate over left temporal
21 electrodes compared to a random stream, demonstrating that sleeping neonates
22 automatically and rapidly extracted the word pattern. ERPs significantly differed between
23 triplets starting or not with the correct first syllable in the test phase, but no difference was
24 associated with later violations in transition probabilities, revealing a change in the
25 representation format between segmentation and memory processes. If the transition
26 probabilities were used to segment the stream, the retained representation relied on
27 syllables' ordinal position, but still without a complete representation of the words at this
28 age. Our results revealed a two-step learning strategy, probably involving different brain
29 regions.

1. Introduction

From before birth, infants demonstrate learning capacities. During the last weeks of gestation, they learned some prosodic features of their native language (Mehler et al., 1988) and their mother's voice (DeCasper & Fifer, 1980), as the taste of the amniotic liquid (Marlier et al., 1998), and rapidly learn to recognize their mother's face after birth (Bushneil et al., 1989). Neonates also quickly adapt to repeated sensory information. For example, after a few minutes of familiarization with a word, they notice when it changed (Benavides-Varela et al., 2012; Benavides-Varela & Mehler, 2011), and similar short-term memories have been described for previously seen faces (Pascalis et al., 1995, p. 994). Despite these undeniable learning and memory capacities, very little is known about the underlying mechanisms, the information neonates are sensitive to, and the format of the representation in which information is memorized.

Here we focused on a primary yet indispensable fast learning mechanism: statistical learning. Statistical learning refers to the capacity to detect regularities in the input. Abundant literature (Saffran & Kirkham, 2018) shows that this mechanism is common across domains (visual, auditory) (Bulf et al., 2011; Fiser & Aslin, 2002; Kirkham et al., 2002; Saffran et al., 1996, 1999), species (primates, rodents) (Hauser et al., 2001; Toro & Trobalón, 2005), and extends to different levels of stimulus/scene complexity. Concerning language acquisition, statistical learning has been proposed as a critical mechanism to explain how infants might discover linguistic regularities. For example, it might serve to identify word candidates based on frequently co-occurring syllables (Saffran et al., 1996), to discover phonotactic and acoustic patterns (Friederici et al., 2007; Jusczyk et al., 1999), and to detect morphological and syntactic regularities (Shi et al., 1999).

Experimental evidence supporting the role of statistical learning in language acquisition has been mainly obtained in word segmentation tasks from an artificial speech stream in which acoustic cues have been removed. In a seminal study (Saffran et al., 1996, p. 996), 8-month-old infants were first exposed to 3 minutes of an artificial speech (thereafter called Structured stream) constituted by four randomly concatenated tri-syllabic pseudo-words, with the drops of transition probabilities (TPs) between syllables as the only cue to word

1 boundaries. Within a pseudo-word, the first two syllables predict the following syllable
2 (TP equal to 1), while the last syllable could be followed by any other pseudo-words (TP
3 equal to 1/3). When test triplets were then played in isolation, infants' looking pattern
4 differed between the pseudo-words (i.e., Words: both TPs in the triplet equal 1) and triplets
5 straddling a TP drop (i.e., Part-words: one TP equal 1 and the other equal 1/3). This result,
6 uncovered that infants are sensitive to the statistical relations between syllables, yet, it
7 remains unknown what they exactly learn.

8 It is commonly assumed that infants segment the stream into words that are memorized
9 and subsequently recognized when presented in isolation. However, two other hypotheses
10 can also explain the results. Infants may compute the transitional probabilities matrix
11 between all syllables through synaptic plasticity and Hebbian learning (Endress & Johnson,
12 2021) without segmenting the stream (Benjamin et al., in prep.). The different association
13 strength between syllables in Words and Part-Words could support the difference between
14 these conditions. Alternatively, infants may segment the stream using the drop of
15 transitional probabilities at the end of the Words but only memorize the syllable following
16 the drop. Indeed, because this syllable being less predictable during the stream, it might
17 induce surprise, a powerful learning factor for infants (Stahl & Feigenson, 2015). The three
18 hypotheses are not dissociable in the existing studies since they all result in differential
19 responses to Words and Part-words. Nevertheless, each explanation relies on different
20 mechanisms in terms of computational complexity and neural bases.

21 A crucial difference between encoding the TPs matrix and segmenting the stream into
22 Words is that memory constraints for sequence encoding may enter into play. When
23 encoding a sequence of items, each item is associated with the close items (i.e., TPs) and
24 its ordinal position within the sequence (Henson, 1998). Indeed, Dehaene et al. (Dehaene
25 et al., 2015) proposed a taxonomy of five levels along which a sequence can be encoded:
26 from (1) TPs between elements, passing by (2) chunking (grouping of elements in a unit),
27 and (3) ordinal knowledge (the elements have an ordered position in the unit), until more
28 abstract encoding based on (4) rules and (5) nested structures. In a very recent study in
29 adult patients with implanted electrodes who listened to a structured stream containing
30 Words, the first stages of this taxonomy were explored using representational similarity

analyses. The authors reported a complex picture in which different brain regions hosted different representations (Henin et al., 2021). Some electrodes, located in the superior temporal gyrus and the pars opercularis and motor cortex, were responding to TPs encoding. Others, located in the inferior frontal gyrus, anterior temporal lobe, and posterior superior temporal sulcus, were sensitive to ordinal position (first vs. second vs. third syllable). Finally, in the hippocampus, electrodes were sensitive to Words (chunks). Given the complex maturational calendar of the different brain structures, particularly the slow maturation of the hippocampus (Lavenex & Banta Lavenex, 2013) and frontal areas (Lebenberg et al., 2019), the generalization of these results to young infants might be inadequate. Furthermore, attention is notably limited at a young age, especially in neonates who sleep most of the time. Thus, we may wonder whether passive exposure might be sufficient or whether some of these computations, such as representing syllables' ordinal position and active prediction of the next item, might not be observed during sleep. In other words, our goal was to study which levels of this taxonomy newborns possess to support language acquisition.

Three previous studies have shown that neonates are at least sensitive to the first level, TPs encoding. During a long familiarization with an artificial stream of syllables (15 mn) (Teinonen et al., 2009) and of tones (9 mn) (Kudo et al., 2011), a different event-related responses emerged to the first syllables/tones of the Words. However, this result may reflect either the response to a local prediction error (i.e., TPs), or to changes in the syllable frequencies as the medial and last syllable were repeated from time to time, or to truly individual triplets. A third study using Near-Infrared Spectroscopy (NIRS) showed a differential BOLD response to Words and Part-words following a 3.5 minutes familiarization with the structure stream (Fló et al., 2019). While adding that neonates can remember the extracted information for a few minutes, it leaves pending the information they retained that triggered the differential response. We, therefore, propose here to further investigate the study of statistical learning in neonates using high-density EEG (128 electrodes) in a paradigm based on three minutes of exposure to a structured stream, followed by the presentation of isolated triplets in a test phase (Fig 1). Our goal was double, first to target learning cues during the stream exposure thanks to neural entrainment, and

1 second to characterize the format of the learned representation by presenting four different
2 types of triplets in isolation.

3 Thanks to its temporal sensitivity, EEG allows monitoring learning, even in non-
4 participating subjects, such as sleeping neonates. In particular, in this paradigm, where
5 syllables have a fixed duration, the auditory response induced by the regular presentation
6 can be captured as entrainment at the frequency of stimulation ($f=1/\text{syllable duration}$).
7 Crucially, this steady-state response is not limited to low-level features like syllable onset
8 but can reflect any regular pattern the brain is tracking. Thus, if the listener detects the 3-
9 syllabic pattern embedded in the stream, entrainment should also be observed at the triplet
10 frequency (1/3 of the syllabic rate) (Batterink & Choi, 2021; Benjamin et al., 2021; Buiatti
11 et al., 2009; Kabdebon et al., 2015). Here we quantified the entrained neural responses at
12 the syllabic and Word rates measuring an enhanced Power and Inter Trial Coherence (ITC)
13 during the presentation of the Structured stream, a Random stream (random concatenation
14 of the syllables), and Resting-state (i.e., no stimulation). We expected a similar entrainment
15 at the syllabic rate for both streams relative to resting-state, but an increased activity at the
16 word rate during the Structured stream.

17 However, neural entrainment at the word frequency can result from two different
18 processes, similarly to differential ERPs to syllables during the stream (Kudo et al., 2011;
19 Teinonen et al., 2009). Either the neonates have detected a drop in TPs, or they recognize
20 the triplets re-occurrence. To test what they learned and memorized, we compared the
21 ERPs to isolated triplets in a post-learning phase (Fig 1B). We build four types of triplets
22 to disentangle different hypotheses on the encoding format of the memorized pattern. We
23 contrasted: (1) triplets respecting, or not, TPs between syllables, and (2) triplets violating,
24 or not, the ordinal position of the first syllable. Therefore, we presented the classical
25 conditions: Words ($A_i B_i C_i$) corresponding to the pseudo-words present in the stream, and
26 Part-words ($B_i C_i A_k$) corresponding to triplets straddling a TP drop. Note that Part-words
27 also have an incorrect first syllable. To these common conditions, we added two other
28 conditions: Edge-words and Non-words. Edge-words ($A_i B_i C_k$) were triplets in which the
29 last syllable between two Words was exchanged; thus, they retained the ordinal position of
30 the syllables, but they were never presented in the stream (last TP equaled zero). Non-

1 words ($B_iC_iA_i$) were triplets in which the first syllable appeared in the last position; thus,
 2 all syllables belonged to the same Word, but the ordinal position was incorrect, and the
 3 triplet was never heard (last TP equaled zero).

4
 5 **Figure 1. (A)** Experimental protocol. A long Structured stream (180 s) was followed by 8 test short
 6 familiarizations (30 s) and test blocks, where 16 triplets were presented in isolation (ISI 2-2.5 s).
 7 Resting state and a Random stream were sandwiching the entire experiment to control for the effect
 8 of time, and notably infant vigilance, on the EEG recordings. **(B)** Possible types of test words. Test
 9 words could have violations in the TPs between the second and third syllables, in the ordinal
 10 position of the syllables, or both.

11 If neonates segment the stream and encode ordinal information or at least the first syllable
 12 of a word, we expected an early differential response between ABx (Words and Edge-
 13 Words) and BCx triplets (Part-Word and Non-Words). Note that any difference before the
 14 third syllable can only be due to the encoding of the first syllable — A_iB_i and B_iC_i had both
 15 TPs equal to one. By contrast, if the response to the isolated triplets only depends on the
 16 adherence to the statistical structure of the Structured stream, the ERPs between never
 17 heard triplets (Edge-words and Non-words) and those present in the stream (Words and
 18 Part-words) should differ from the third syllable. For the sake of completeness, we also
 19 considered that memory encoding following segmentation might be sensitive to the
 20 temporal proximity of the elements belonging to the same chunk as a community structure,
 21 predicting that Non-Words ($B_iC_iA_i$) are closer to Words ($A_iB_iC_i$) than Part-Words ($B_iC_iA_k$).

22 Additionally, we tested 32 adult participants in a behavioral online experiment analog to
 23 the infant task. After familiarization with the structured stream, participants had to rate
 24 their familiarity with the test triplets. Because the stimuli (duration of the Structured

streams and number of tests words) were the same as in the neonates' study, this experiment provides a reference point of what mature and expert participants encode and memorize.

To summarize, simple TP learning should result in a difference between triplets present or not in the stream (Words+Part-words vs. Edge-words+Non-words). Segmentation should be revealed by neural entrainment at the word rate during the Structured stream and a difference between ABx and BCx sequences. The granularity of the encoding can be further investigated by comparing Words vs. Edge-Words and Non-words vs. Part-Words.

2. Materials and Methods

2.1. Participants

Participants were healthy-full-term neonates, with normal pregnancy and birth (GA > 38 weeks, Apgar scores $\geq 7/8$ in the 1/5 minute, birthweight > 2.5 Kg, cranial perimeter ≥ 33.0 cm), tested at the Port Royal Maternity (AP-HP), in Paris, France. Parents provided informed consent. 31 participants who provided enough data without motion artifacts were included (10 females; 1 to 4 days old; mean GA: 40.2 weeks; mean weight: 3475 g). Seven other infants were excluded from the analysis (3 due to excessive hair or cradle cap, 2 due to excessive motion artifacts, and 2 because the parents decided to interrupt the experiment).

2.2. Stimuli

The stimuli were synthesized using the fr4 French female voice of the MBROLA diphone database (Dutoit et al., 1996). Syllables had a consonant-vowel structure. Each phone had a duration of 125 ms and a constant pitch of 200 Hz. The streams were continuous with co-articulation and no pauses, and they were ramped up and down during the first and last 5 s to avoid the start and end might serve as perceptual anchors. The structured streams consisted of a semi-random concatenation of the four tri-syllabic pseudo-words. Pseudo-words were concatenated with the only restrictions that the same word could not appear twice in a row, and the same two words could not repeatedly alternate more than two times (i.e., the sequence $W_k W_j W_k W_j$, where W_k and W_j are two words, was forbidden). The learning stream lasted 180 seconds, each word appearing 60 times and each of the 12

possible part-words 18 to 21 times; the average TPs between words was 0.332 (SD = 0.017, range 0.310 to 0.361). The eight short structured streams lasted 30 seconds each, each word appearing 80 (8x10) times and each of the 12 possible part-words between 24 and 28 times; the average transitional probability between words was 0.325 (SD = 0.012, range 0.308 to 0.345). The pseudo-words were created to avoid that specific phonetic features could help to segment the stream. Additionally, three different structured streams (lists A, B, and C, corresponding to three sets of pseudo-words) were used by modifying how the syllables were combined to form the Words (Table 1). Participants were randomly assigned and balanced between lists.

Table 1. Triplets for each condition (Words, Edge-words, Part-words, and Non-words) used for each of the three lists.

List	A _i B _j C _i	A _i B _j C _k	B _i C _i A _k	B _i C _i A _i
A	dinapo	dinava	napolu	napodi
	lutiva	lutimi	tivafo	tivalu
	fobumi	fobugu	bumisa	bumifo
	sazogu	sazopo	zogudi	zogusa
B	napolu	napofo	poluti	poluna
	tivafo	tivasa	vafobu	vafoti
	bumisa	bumidi	misazo	misabu
	zogudi	zogulu	gudina	gudizo
C	poluti	polubu	lutiva	lutipo
	vafobu	vafozo	fobumi	fobuma
	misazo	misana	sazogu	sazomi
	gudina	guditi	dinapo	dinagu

The random were built a semi-random concatenation of the same 12 syllables, with the only restriction that the same syllable could not appear twice in a row and that two syllables could not alternate more than two times (i.e., the sequence $S_k S_j S_k S_j$, where S_k and S_j are two syllables, was forbidden). Streams lasted 120 seconds each, and each syllable appeared 480 times in each of them.

Test words were tri-syllabic triplets presented in isolation.

2.3. Procedure and data acquisition

1 Scalp electrophysiological activity was recorded using a 128-electrode net (Electrical
2 Geodesics, Inc.) referred to the vertex with a sampling frequency of 250 Hz. Neonates were
3 tested in a soundproof booth while sleeping or during quiet rest. The study involved: (1)
4 60 s of resting-state; (2) 120 s of a random stream; (3) 180 s of a structured stream (4) 8
5 series of a 30 s of structured streams followed by 16 test sequences (ISI 2-2.5s); (5) 120 s
6 of a random stream; (6) 60 s of resting state. The random streams and resting-state were
7 presented before and after the learning and test parts to avoid sensing entrainment
8 differences due to time in the experiment (i.e., a change in the vigilance state).

9 **2.4. Data pre-processing**

10 Data were band-pass filter 0.1-40 Hz and pre-processed using custom MATLAB scripts
11 based on the EEGLAB toolbox 2021.0 (Delorme & Makeig, 2004), according to the
12 APICE pre-processing pipeline (Fló et al., 2021). The following steps were applied: (1)
13 Data was band-pass filter 0.1-40 Hz. (2) Artifacts were identified based on voltage
14 amplitude, variance, first derivative, and running average using adaptive thresholds. (3)
15 Time samples were defined as artifacts if more than 30% of the channels presented
16 artifacts. (4) Electrodes were spatially interpolated using spherical splines for samples that
17 were not marked as bad.

18 **2.5. Neural entrainment**

19 The pre-processed data were resampled to 300 Hz to achieve an integer number of samples
20 per triplet (225 samples in 0.75 s) and further high-pass filtered at 0.2 Hz. Then, data was
21 segmented from the beginning of each phase into 0.75 s long segments. Segments
22 containing samples with artifacts were rejected. On average we retained 74 % of the data
23 during Resting (SD 17, range [31, 100]), 84 % of the data during the Random (SD, 11, [47,
24 100]), and 87 % of the data during the Structured (SD 7, range [71, 100]). Subjects who
25 did not provide at least 6 segments per condition were not included.

26 Neural entrainment per condition. The 0.75 s epochs belonging to the same condition were
27 reshaped into non-overlapping epochs of 7.5 s (10 triplets, 30 syllables), retaining the
28 chronological order; thus, the timing of the steady state response. Data were referenced

average and normalized by dividing by the standard deviation within an epoch. DSS, a technique based on spatial filters designed to remove stimulus-unrelated activity (de Cheveigné & Simon, 2008), was applied, and the first 30 components of the first PCA and the first 6 of the DSS filter were retained (the pattern of results did not differ if DSS was not used). Then, data were converted to the frequency domain using the Fast Fourier Transform (FFT) algorithm, and the power and ITC were estimated for each electrode during each condition (Resting-state, Random, Structured). Then, the SNR relative to the twelve adjacent frequency bins (six of each side corresponding to 0.8 Hz) was estimated. The power was computed as the power spectrum of the average response across trials. Then, the noise level was estimated at each frequency by assuming a power-law fit on the adjacent frequency bins $\log(P_{estimate}(f)) = a + b * \log(f)$. The SNR for the power was $SNR(f) = (\log(P(f)) - \text{mean}(P_{noise}(f))) / \text{std}(P_{noise}(f))$, where $P_{noise}(f) = \log(P_{estimate}(f)) - \log(P)$. The ITC was computed as $ITC(f) = \frac{1}{N} |\sum_{i=1}^N e^{i\varphi(f,i)}|$, where N is the number of trials and $\varphi(f,i)$ is the phase at frequency f and trial i . The ITC ranges from 0 to 1 (i.e., completely desynchronized activity to perfectly phased locked activity). The SNR was also estimated using the twelve adjacent frequency bins (six of each side corresponding to 0.8 Hz) as $SNR(f) = (ITC(f) - \text{mean}(ITC_{noise}(f))) / \text{std}(ITC_{noise}(f))$, where $ITC_{noise}(f)$ is the ITC over the adjacent frequency bins.

For statistical analysis, the SNR was compared at the syllabic rate (4 Hz) and word rate (1.33 Hz) against zero (null hypothesis) using a one-tail t-test. P-values were corrected across electrodes by FDR.

Neural entrainment time course. The 0.75 s epochs were concatenated chronologically (1 minute of RS, 2 minutes of Random, 3 minutes of long Structured stream, 4 minutes of short Structure blocks, 2 minutes of Random, and 1 minute of RS). The same analysis than above was performed in sliding time windows of 2 minutes with a 1.5 s step.

2.6. ERPs to test words

The pre-processed data were filtered between 0.5 and 20 Hz, epoched between [-1.50, 3.25] s from the onset of the triplets. Epochs containing samples identified as artifacts were rejected. On average we retained 24.8 trials for the Word condition (SD 3.6, range [17,

31]), 24.5 for the Edge-word condition (SD 3.6, range [16, 30]), 24.7 for the Part-word condition (SD 4.0, range [16, 30]), and 24.5 for the Non-word condition (SD 4.0, range [14, 30]). Subjects who did not provide at least 12 trials per condition were excluded. Data were reference averaged, normalized by dividing by its standard deviation, and baseline corrected by subtracting the average over the interval between 2.25 s from the onset of the previous word and the corresponding word. Trials were averaged by condition, and two contrasts were studied: (1) *ABx* (Words and Edge-words) vs. *BCx* (Part-words and Non-words) triplets; (2) triplets with heard transitions (Words and Part-words) vs. un-heard transitions (Edge-words and Non-words). The responses were compared using non-parametric cluster-based permutation analysis (Oostenveld et al., 2011) in two time windows: (1) [0, 0.5] s to detect early effects only attributable to the encoding of the first syllable, and (2) [0.5, 2.75] s to detect effects related to a TPs violation or the triplets' offset. A t-statistic with an alpha threshold of 0.05 was used for clustering; neighbor electrodes had a maximum distance of 3 cm (4.2 neighbors per channel on average); clusters had a minimum size of two, and 5,000 permutations were run to estimate the significance level. The quantification of the effect along test blocks was performed by computing the average difference between *ABx* and *BCx* conditions over the clusters. Data points were included for subjects and blocks when at least 3 out of 8 trials in both conditions were included.

2.7. Adult behavioral experiment

33 French speaking adults were tested in an online experiment analogous to the infant study through the Prolific platform and received monetary compensation for their participation. The same stimuli as in the infant experiment were used. Participants first heard 3 minutes of familiarization with the Structured stream. Then, they completed eight sessions of re-familiarization and testing. Each re-familiarization lasted 30 s, and in each test session, all 16 possible test words were presented. Subjects were said they should try to identify the words from an invented language. During the test phase, subjects had to report after each test word their familiarity with it. Subjects responded by using the cursor to click on the screen on a scale from 1 to 6. One participant was excluded because (s)he always responded with a score of 1 or 2. Subjects were randomly assigned to one of the three lists.

Figure 2. Neural entrainment during Resting-state, Random streams, and Structured streams. **(A)** SNR for the power. In light gray, the entrainment for all electrodes. In red, the mean over the electrodes showing significant entrainment ($p < 0.05$, one-sided t-test, FDR corrected) at the syllabic rate (4 Hz). In blue, the mean over the electrodes showing significant entrainment ($p < 0.05$, one-sided t-test, FDR corrected) at the word rate (1.33 Hz). The topographies represent the entrainment in the electrodes space at the word rate (1.33 Hz) and at the syllabic rate (4 Hz). Asterisks indicate the electrodes showing enhanced neural activity (cross: $p < 0.05$, one-sided t-test, FDR corrected; dot: $p < 0.05$, one-sided t-test, without FDR correction). **(B)** Same based on ITC.

3. Results

3.1. Neural markers of learning in neonates: familiarization phase

During Resting-state, as expected, no entrainment was seen either at the syllabic (4 Hz) or word (1.33 Hz) rates. As expected, for Random streams, we observed enhanced activity

at the syllabic rate for many central-frontal and posterior electrodes ($p < 0.05$, FDR corrected) and no enhanced activity at the word rate. During the Structured streams, we observed a similar enhanced oscillatory activity at the syllabic rate and significant neural entrainment at the word rate mainly over left temporal electrodes ($p < 0.05$, FDR corrected) (Figure 2).

By comparing the entrainment with a 1-way-ANOVA with condition as within-subjects factor (Fig. 3 A and B), similar results were obtained for power and ITC. A main effect of condition was observed at the syllabic rate (power: $F(2,58) = 21.8$, $p = 8.6 \times 10^{-8}$, ITC: $F(2,58) = 21.8$, $p = 8.7 \times 10^{-8}$, driven by a lower power/ITC during Resting than Random (power: $p = 0.0021$, ITC: $p = 0.0085$) and Structured ($p = 8.4 \times 10^{-9}$, ITC: $p = 7.5 \times 10^{-9}$), and lower power/ITC during Random than Structured (power: $p = 0.0075$, ITC: $p = 0.0017$). At word rate there was a main effect of condition (power: $F(2,58) = 10.7$, $p = 0.00018$, ITC: $F(2,58) = 8.2$, $p = 0.000706$), due to a higher power/ITC during Structured than Resting (power: $p = 2.9 \times 10^{-5}$, ITC: $p = 0.00038$) and Random (power: $p = 0.0052$, ITC: $p = 0.013$). All p-values were Bonferroni corrected for multiple comparisons.

To quantify learning through the experiment, we measured entrainment at the syllabic and word rate in sliding time windows of 2 minutes with a 1.5 s step by concatenating the data from all conditions. Notice that because the integration window is two minutes long, the entrainment during the first minute of random, for example includes, data from the structured stream. Results show an increase in Power and ITC at the word rate at around 2 minutes from the beginning of the structured stream (Figure 3 C and D).

3.2. Encoding format in neonates: Post-learning phase

We first looked for ERPs components related to ordinal position violations by comparing ABx (Words and Edge-words) vs. BCx triplets (Part-words and Non-words). A non-parametric cluster-based permutation analysis (Oostenveld et al., 2011) revealed a significant early difference before 500 ms in a positive frontal cluster ($p = 0.0152$, time window [0, 388] ms) and in a left-posterior negative cluster ($p = 0.0324$, time window [0, 308] ms), (Fig. 4 A, B). Given the time window, this effect can only be related to the encoding of the first syllable (i.e., ordinal encoding). A second difference was also

1 observed after the offset of the triplet, in a frontal-left positive cluster ($p = 0.0142$, time
2 window [788, 1600] ms), and even a third one later in a frontal cluster ($p = 0.002$, time
3 window [1684, 2628] ms) (Fig. 4 C, D).

4
5 **Figure 3. (A)** SNR for the power at the Syllabic and Word rate during the three conditions. Asterisks
6 represent Bonferroni corrected p-values. **(B)** Same as A based on ITC. **(C)** Time course of
7 entertainment based on power computed on 120 s time windows. Error bars represent standard
8 errors. The red line on the top indicates when the power at the Syllabic rate (4 Hz) was bigger than
9 the null hypothesis 0 ($p < 0.05$, one-sided t-test, corrected by FDR). The blue line on the bottom
10 indicates when the power at the Word rate (1.33 Hz) was bigger than the null hypothesis 0 ($p <$
11 0.05 , one-sided t-test, corrected by FDR). **(D)** Same as C based on ITC.

12 We then looked for ERPs components related to TPs violations by comparing heard triplets
13 (Words and Part-words) vs. non-heard triplets (Edge-words and Non-words), but we found

1 no significant difference ($p > 0.1$). No significant differences were detected in the
2 comparisons Words vs. Edge-words, and Part-words vs. Non-words ($p > 0.1$).

3 To ensure that ordinal encoding was present from the beginning of the test phase and was
4 not triggered by hearing isolated triplets, we computed the effect throughout the eight test
5 blocks. Despite fluctuations likely due to the small number of trials, the effect was present
6 from the earliest test blocks (Fig. 4E), suggesting that the encoding of the first syllable in
7 Words had emerged while infants were listening to continuous speech.

8
9 **Figure 4.** Responses to triplets in isolation. **(A)** Grand-average response to ABx and BCx triplets
10 over the early frontal positive cluster ($p = 0.0152$) obtained from the cluster-based permutation
11 analysis. The thick lines correspond to ABx (gray line) and BCx (orange line) conditions and the

1 thin lines to the sub-conditions (Words and Edge-Words vs. Part-words and Non-words). Shaded
2 areas correspond to the standard error across neonates. The time zero corresponds to the onset
3 of the test word. The topography shows the difference $ABx-BCx$ during the time window where
4 significant differences were observed (gray line under the plot). **(B)** Same as A, but for the early
5 negative cluster over left-temporal posterior electrodes ($p = 0.0324$). **(C)** Same as A, but for a late
6 positive cluster over frontal-left electrodes ($p = 0.0142$). **(D)** Same as A, but for a later positive
7 cluster over frontal electrodes ($p = 0.0020$). **(E)** Time progression of the ERP early effects (A, and
8 B) over the 8 test blocks. **(F)** Time progression of the average of the two late ERP effects (C, and
9 D) over the 8 test blocks.

10 **3.3. Encoding format in adults**

11 Adults rated on a scale their familiarity with the triplets after familiarization with identical
12 streams as neonates (Fig. 5). Results from a linear mixed model using the scoring as
13 dependent variable, the triplet condition as predictor, and subjects as a random factor
14 ($Scoring \sim Cnd + 1 / Sbj$) showed a main effect of condition ($F(3,3721) = 79.72$, $p <$
15 2.2×10^{-16}). A post hoc Tukey test revealed that the Words score was higher than each of
16 the other conditions ($ps < 0.0001$) whereas the Non-words was the lowest, significantly
17 inferior to Part-words ($p < 0.0001$), and to Edge-words ($p = 0.0045$).

18 **4. Discussion**

19 Here, we used a classical speech segmentation task (Saffran et al., 1996) to investigate
20 statistical learning in neonates. While previous studies have shown that infants are sensitive
21 to statistical regularities in speech since birth (Fló et al., 2019; Kudo et al., 2011; Teinonen
22 et al., 2009), it was still unknown what information they tracked and memorized. First, our
23 study revealed that sleeping neonates responded rapidly (within 2 minutes) to the tri-
24 syllabic pattern. Second, when isolated triplets were presented, a differential response was
25 observed from the first syllable, revealing that they expected triplets to start with a specific
26 set of syllables. Third, TP violation did not modulate ERP to triplets. This result indicates
27 a memory representation that no longer depended on TPs, despite TP were used to segment
28 the stream, suggesting a switch to a different format. Finally, these results reveal the
29 accuracy of consonant encoding in newborns that allow them to keep the relationship
30 between 12 syllables and memorize a set of 4 first syllables despite common vowels at

different ordinal word positions. This observation is not trivial given the common assumption that infants are initially limited to the most stable units, such as vowels. For example, Benavides et al. (Benavides-Varela et al., 2012) reported a larger novelty response when changing the vowels of a bi-syllabic word (e.g., *lili* to *lala*) compared to a change of consonants (e.g., *lili* to *titi*). However, a recent EEG study showed that phonetic features were at the basis of speech perception in 3-month-old pre-babbling infants, opening the possibility of an innate code based on phonetic features for all phonemes, vowels, and consonants (Gennari et al., 2021).

9

10 **Figure 5.** Results for the adults' behavioral experiment. The distribution of the scores for all trials
11 and participants are represented per condition.

12 **4.1. Learning based on TPs**

13 The significant increase in power and ITC to word rate in the Structured stream
14 demonstrated that TP computations lead to stream structuring. Learning occurred within 2
15 min of familiarization. This rapid learning is consistent with the length of the stream
16 previously used in behavioral experiments in 8-month-old infants (Saffran et al., 1996) and
17 EEG experiments in adults and 6-month-old infants (Batterink & Choi, 2021; Benjamin et
18 al., 2021). The concordance of learning rate across ages indicates that statistical learning
19 abilities do not improve markedly with age, a remarkable observation given the significant

1 maturational changes in auditory/linguistic regions and hippocampus during the first years
2 of life (Adibpour et al., 2020; Leroy et al., 2011).

3 We did not characterize the neonates' sleep stages. However, their general behavior during
4 the recording session (eyes closed, hypotonia), the duration of the experiment, and the lack
5 of task and reward, combined with the short awake periods outside of feeding in the days
6 after birth, certainly did not favor an attentive and focused listening of the auditory input.
7 Neonates' success in extracting the regularities is congruent with adult studies showing
8 neural entrainment at the word rate even when participants are distracted by a primary task
9 (Batterink & Choi, 2021; Benjamin et al., 2021), revealing the automaticity of TP
10 calculations.

11 In adult experiments, the word rate entrainment is accompanied by decreased syllabic rate
12 entrainment (Batterink & Choi, 2021). Our results revealed a more complex pattern. The
13 syllabic rate entrainment increased at the beginning of the Structured stream and decreased
14 when word rate entrainment became significant. The initial increase entrainment at the
15 syllabic rate might reflect stronger activation of the language network during the
16 uncovering of the structure compared to random syllable presentation. This hypothesis
17 would be consistent with an adult functional magnetic resonance imaging (fMRI)
18 experiment showing that activity in the left-temporal cortex is modulated by the level of
19 complexity of speech sequences (Pallier et al., 2011). The subsequent decrease might result
20 from top-down inhibition of the syllabic response once the stream has been segmented.

21 While neural entrainment demonstrated that infants were sensitive to the rhythmic structure
22 of the stream, this might result from an automatic error response elicited by the
23 unpredictability of the first syllable (TPs) or by a neural response to tri-syllabic chunks
24 (segmentation). The responses to isolated triplets dissociated these two alternatives.

25 **4.2. Memory representation of the segmented words**

26 ERPs to the isolated triplets revealed the format of the memorized information. ERPs
27 differed from the first syllable between *ABx* triplets (Words and Edge-Words) and *BCx*
28 triplets (Parts-Words and Non-Words); thus, before any TP violation (*AB* and *BC*

1 transitions were both equal to 1). Additionally, we observed no specific ERP component
 2 after a TPs violation, that is to say, between Words and Edge-Words on one side and Part-
 3 Words and Non-Words on the other side. It is important to note that in Non-words, the first
 4 syllable was presented at the last position without evoking a particular response (i.e., a
 5 difference with Part-Words). The absence of a distinctive response to the first syllable at
 6 the wrong position favors the hypothesis that it is not a particular familiarity with this
 7 syllable that caused the difference between *ABx* and *BCx* triplets, but its position as a first
 8 syllable in the triplet.

9 Two approaches have been proposed for flat continuous speech segmentation. From one
 10 perspective, the TPs are computed, and the drops in TPs serve as cues to word boundaries
 11 (Saffran et al., 1996). From another perspective, recurrent chunks of co-occurring syllables
 12 are identified and stored in memory (Perruchet & Vinter, 1998). Our experiment did not
 13 attempt to disentangle these two mechanisms. However, the lack of difference between
 14 heard and un-heard triplets revealed that neonates retained neither the full TP matrix nor
 15 the entire Words. Instead, they remained limited to the memorization of the first syllable.
 16 Meanwhile, adults scored Words as highly familiar, Edge-words as more familiar than
 17 Non-words, and finally Edge-Words and Part-words as equally familiar (although Edge-
 18 words never appeared in the stream). These results suggest that adults memorized the
 19 complete Words, but also that the format of the representation depended on both TPs and
 20 ordinal encoding, in agreement with other recent studies (Fló, 2021; Henin et al., 2021).

21 Altogether, our results suggest a multistep process. Segmentation occurred either because
 22 the drop in TP produced a prediction error that singularized the non-predicted syllable (i.e.,
 23 the first syllables) or because the association of the syllables within words increased their
 24 similarity, leading to boundaries at the landscape lower points. In a second step, the
 25 segmented triplets are stored in memory, and therefore, any memory constraints might
 26 affect the retained representation.

27 **4.3. Word memorization is incomplete in neonates**

28 Neonates are thus memorizing at least the first syllable of the chunk pointing to an ordinal
 29 encoding, the third level of complexity in Dehaene et al. taxonomy (Dehaene et al., 2015).

However, they did not distinguish Words ($A_iB_iC_i$) and Edge-words ($A_iB_iC_k$), suggesting that neonates' words memory was not complete. A limited memory capacity in neonates for middle positions has already been described. A NIRS study showed a better encoding of the syllables at the edges of a six-syllable pseudo word than in intermediate positions (Ferry et al., 2016). Unfortunately, the conditions in that study do not allow disentangling if the effect was due to a better encoding of the first, the last, or both syllables. A memory capacity limited to the first syllable might explain previous neonates studies such as the recognition of bi-syllabic pseudo-words from a new pseudo-word presented two minutes later (Benavides-Varela et al., 2012; Benavides-Varela & Mehler, 2011) and of words conforming a structured stream (Fló et al., 2019).

This memory limitation might be due either to immaturity or to sleep. Sleep is primarily considered as consolidating memories, and while learning is suppressed during deep non-REM stage in adults, implicit word learning is present during REM sleep (Andrillon et al., 2017). Thus, sleep might not represent the limiting factor here, and this question should be further studied.

4.4. Putative underlying neural networks

While EEG has an excellent temporal resolution, it does not provide accurate spatial resolution and information regarding the activity of brain structures. However, we may speculate from the adults' results and the few brain imaging studies in infants investigating the maturation of the pertinent brain regions. Henin and colleagues (Henin et al., 2021) isolated three main networks in a similar task in epileptic patients that might already be at work in neonates. The superior temporal region, which might be related to local processes involved in TP computations, and two memory structures: the dorsal linguistic pathway supporting verbal working memory, and the hippocampus, recently reported as engaged in sequence learning (Schapiro et al., 2014; Schlichting et al., 2017). Although these two structures have been considered immature in infants, fMRI has revealed that they support cognitive functions in the first trimester. Notably, whereas the superior temporal regions are affected by the immediate repetition of a sentence (Dehaene-Lambertz, 2017), repetition at a longer time-scale of 14 seconds produces activation in the inferior frontal

gyrus in three-month-old infants (Dehaene-Lambertz et al., 2006). Moreover, a NIRS study in sleeping neonates revealed that a correlated activity between left-temporal and left-frontal regions, compatible with activation in the dorsal linguistic pathway, is crucial for word learning (Benavides-Varela et al., 2017). As for the hippocampus, activity has been reported in infants as young as 3-months when performing a visual sequence learning task, with no modulation by infant's age (Ellis et al., 2020). Thus, future work should investigate whether hippocampal circuits considered fundamental to SL, such as the monosynaptic pathway, are involved in such a word-learning task since birth. fMRI in infants might help determine how the network highlighted in adults (Henin et al., 2021) is similarly involved in infants to support the two stages we have isolated the relative role of the hippocampus and the linguistic network.

5. Conclusions

Despite their unquestionable immaturity, neonates reveal sophisticated learning abilities. From drops in TPs, they were able to segment a continuous speech stream and start to encode the first syllables of the chunks. While the present study remains a toy experiment far from the complexity of a real-life environment, it reveals the necessary integration between successive functional processes computed in different neural structures that is at the core of learning in infants.

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Author Contributions

A.F. and G.D.L. designed the research; A.F., L.B. and M.P. performed the research; A.F. analyzed the data; and A.F., L.B., and G.D.-L. wrote the paper

References

- 1 Adibpour, P., Lebenberg, J., Kabdebon, C., Dehaene-Lambertz, G., & Dubois, J. (2020). Anato-
2 functional correlates of auditory development in infancy. *Developmental Cognitive*
3 *Neuroscience*, 42, 100752. <https://doi.org/10.1016/j.dcn.2019.100752>
- 4 Andrillon, T., Pressnitzer, D., Léger, D., & Kouider, S. (2017). Formation and suppression of
5 acoustic memories during human sleep. *Nature Communications*, 8(1), 179.
6 <https://doi.org/10.1038/s41467-017-00071-z>
- 7 Batterink, L. J., & Choi, D. (2021). Optimizing steady-state responses to index statistical learning:
8 Response to Benjamin and colleagues. *Cortex*.
9 <https://doi.org/10.1016/j.cortex.2021.06.008>
- 10 Benavides-Varela, S., Hochmann, J.-R., Macagno, F., Nespor, M., & Mehler, J. (2012). Newborn's
11 brain activity signals the origin of word memories. *Proceedings of the National Academy*
12 *of Sciences*, 109(44), 17908–17913. <https://doi.org/10.1073/pnas.1205413109>
- 13 Benavides-Varela, S., & Mehler, J. (2011). Memory in the Neonate Brain. *PLoS ONE*, 6(11), 7.
- 14 Benavides-Varela, S., Siugzdaite, R., Gómez, D. M., Macagno, F., Cattarossi, L., & Mehler, J.
15 (2017). Brain regions and functional interactions supporting early word recognition in the
16 face of input variability. *Proceedings of the National Academy of Sciences*, 114(29), 7588–
17 7593. <https://doi.org/10.1073/pnas.1617589114>
- 18 Benjamin, L., Dehaene-Lambertz, G., & Fló, A. (2021). Remarks on the analysis of steady-state
19 responses: Spurious artifacts introduced by overlapping epochs. *Cortex*.
20 <https://doi.org/10.1016/j.cortex.2021.05.023>
- 21 Buiatti, M., Peña, M., & Dehaene-Lambertz, G. (2009). Investigating the neural correlates of
22 continuous speech computation with frequency-tagged neuroelectric responses.
23 *NeuroImage*, 44(2), 509–519. <https://doi.org/10.1016/j.neuroimage.2008.09.015>
- 24 Bulf, H., Johnson, S. P., & Valenza, E. (2011). Visual statistical learning in the newborn infant.
25 *Cognition*, 121(1), 127–132. <https://doi.org/10.1016/j.cognition.2011.06.010>
- 26 Bushneil, I. W. R., Sai, F., & Mullin, J. T. (1989). Neonatal recognition of the mother's face. *British*
27 *Journal of Developmental Psychology*, 7(1), 3–15. [https://doi.org/10.1111/j.2044-](https://doi.org/10.1111/j.2044-835X.1989.tb00784.x)
28 [835X.1989.tb00784.x](https://doi.org/10.1111/j.2044-835X.1989.tb00784.x)
- 29 de Cheveigné, A., & Simon, J. Z. (2008). Denoising based on spatial filtering. *Journal of*
30 *Neuroscience Methods*, 171(2), 331–339. <https://doi.org/10.1016/j.jneumeth.2008.03.015>
- 31 DeCasper, A. J., & Fifer, W. P. (1980). Of human bonding: Newborns prefer their mothers' voices.
32 *Science (New York, N.Y.)*, 208(4448), 1174–1176.
33 <https://doi.org/10.1126/science.7375928>

- 1 Dehaene, S., Meyniel, F., Wacongne, C., Wang, L., & Pallier, C. (2015). The Neural Representation
2 of Sequences: From Transition Probabilities to Algebraic Patterns and Linguistic Trees.
3 *Neuron*, 88(1), 2–19. <https://doi.org/10.1016/j.neuron.2015.09.019>
- 4 Dehaene-Lambertz, G. (2017). The human infant brain: A neural architecture able to learn
5 language. *Psychonomic Bulletin and Review*, 24(1), 48–55.
6 <https://doi.org/10.3758/s13423-016-1156-9>
- 7 Dehaene-Lambertz, G., Dehaene, S., Anton, J. L., Campagne, A., Ciuciu, P., Dehaene, G. P.,
8 Denghien, I., Jobert, A., LeBihan, D., Sigman, M., Pallier, C., & Poline, J. B. (2006).
9 Functional segregation of cortical language areas by sentence repetition. *Human Brain*
10 *Mapping*, 27(5), 360–371. <https://doi.org/10.1002/hbm.20250>
- 11 Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial
12 EEG dynamics including independent component analysis. *Journal of Neuroscience*
13 *Methods*, 134(1), 9–21. <https://doi.org/10.1016/j.jneumeth.2003.10.009>
- 14 Dutoit, T., Pagel, V., Pierret, N., Bataille, F., & van der Vrecken, O. (1996). The MBROLA project:
15 Towards a set of high quality speech synthesizers free of use for non commercial purposes.
16 *Proceeding of Fourth International Conference on Spoken Language Processing. ICSLP*
17 '96, 3, 1393–1396. <https://doi.org/10.1109/ICSLP.1996.607874>
- 18 Ellis, C. T., Skalaban, L. J., Yates, T. S., Bejjanki, V. R., Córdova, N. I., & Turk-Browne, N. B.
19 (2020). Re-imagining fMRI for awake behaving infants. *Nature Communications*, 11(1),
20 4523. <https://doi.org/10.1038/s41467-020-18286-y>
- 21 Endress, A. D., & Johnson, S. P. (2021). When forgetting fosters learning: A neural network model
22 for statistical learning. *Cognition*, 104621.
23 <https://doi.org/10.1016/j.cognition.2021.104621>
- 24 Ferry, A. L., Fló, A., Brusini, P., Cattarossi, L., Macagno, F., Nespor, M., & Mehler, J. (2016). On
25 the edge of language acquisition: Inherent constraints on encoding multisyllabic sequences
26 in the neonate brain. *Developmental Science*, 19(3), 488–503.
27 <https://doi.org/10.1111/desc.12323>
- 28 Fiser, J., & Aslin, R. N. (2002). Statistical learning of new visual feature combinations by infants.
29 *Proceedings of the National Academy of Sciences of the United States of America*, 99(24),
30 15822–6. <https://doi.org/10.1073/pnas.232472899>
- 31 Fló, A. (2021). Evidence of ordinal position encoding of sequences extracted from continuous
32 speech. *Cognition*, 104646. <https://doi.org/10.1016/j.cognition.2021.104646>
- 33 Fló, A., Brusini, P., Macagno, F., Nespor, M., Mehler, J., & Ferry, A. L. (2019). Newborns are
34 sensitive to multiple cues for word segmentation in continuous speech. *Developmental*
35 *Science*, 0(0), e12802. <https://doi.org/10.1111/desc.12802>

- 1 Fló, A., Gennari, G., Benjamin, L., & Dehaene-Lambertz, G. (2021). Automated Pipeline for
2 Infants Continuous EEG (APICE): A flexible pipeline for developmental studies. *BioRxiv*,
3 2021.05.21.445085. <https://doi.org/10.1101/2021.05.21.445085>
- 4 Friederici, A. D., Friedrich, M., & Christophe, A. (2007). Brain Responses in 4-Month-Old Infants
5 Are Already Language Specific. *Current Biology*, 17(14), 1208–1211.
6 <https://doi.org/10.1016/j.cub.2007.06.011>
- 7 Gennari, G., Marti, S., Palu, M., Fló, A., & Dehaene-Lambertz, G. (2021). Orthogonal neural codes
8 for phonetic features in the infant brain. *BioRxiv*, 2021.03.28.437156.
9 <https://doi.org/10.1101/2021.03.28.437156>
- 10 Hauser, M. D., Newport, E. L., & Aslin, R. N. (2001). Segmentation of the speech stream in a non-
11 human primate: Statistical learning in cotton-top tamarins. *Cognition*, 78(3), 53–64.
12 [https://doi.org/10.1016/S0010-0277\(00\)00132-3](https://doi.org/10.1016/S0010-0277(00)00132-3)
- 13 Henin, S., Turk-Browne, N. B., Friedman, D., Liu, A., Dugan, P., Flinker, A., Doyle, W., Devinsky,
14 O., & Melloni, L. (2021). Learning hierarchical sequence representations across human
15 cortex and hippocampus. *Science Advances*, 7(8), eabc4530.
16 <https://doi.org/10.1126/sciadv.abc4530>
- 17 Henson, R. N. A. (1998). Short-Term Memory for Serial Order: The Start-End Model. *Cognitive*
18 *Psychology*, 36(2), 73–137. <https://doi.org/10.1006/cogp.1998.0685>
- 19 Jusczyk, P. W., Houston, D. M., & Newsome, M. (1999). The beginnings of word segmentation in
20 english-learning infants. *Cognitive Psychology*, 39(3–4), 159–207.
21 <https://doi.org/10.1006/cogp.1999.0716>
- 22 Kabdebon, C., Pena, M., Buiatti, M., & Dehaene-Lambertz, G. (2015). Electrophysiological
23 evidence of statistical learning of long-distance dependencies in 8-month-old preterm and
24 full-term infants. *Brain and Language*, 148, 25–36.
25 <https://doi.org/10.1016/j.bandl.2015.03.005>
- 26 Kirkham, N. Z., Kirkham, N. Z., Slemmer, J. a, Slemmer, J. a, Johnson, S. P., & Johnson, S. P.
27 (2002). Visual statistical learning in infancy: Evidence for a domain-general learning
28 mechanism. *Cognition*, 83, 4–5.
- 29 Kudo, N., Nonaka, Y., Mizuno, N., Mizuno, K., & Okanoya, K. (2011). On-line statistical
30 segmentation of a non-speech auditory stream in neonates as demonstrated by event-related
31 brain potentials. *Developmental Science*, 14(5), 1100–1106.
32 <https://doi.org/10.1111/j.1467-7687.2011.01056.x>
- 33 Lavenex, P., & Banta Lavenex, P. (2013). Building hippocampal circuits to learn and remember:
34 Insights into the development of human memory. *Behavioural Brain Research*, 254, 8–21.
35 <https://doi.org/10.1016/j.bbr.2013.02.007>

- 1 Lebenberg, J., Mangin, J. F., Thirion, B., Poupon, C., Hertz-Pannier, L., Leroy, F., Adibpour, P.,
2 Dehaene-Lambertz, G., & Dubois, J. (2019). Mapping the asynchrony of cortical
3 maturation in the infant brain: A MRI multi-parametric clustering approach. *NeuroImage*,
4 *185*(September 2017), 641–653. <https://doi.org/10.1016/j.neuroimage.2018.07.022>
- 5 Leroy, F., Glasel, H., Dubois, J., Hertz-Pannier, L., Thirion, B., Mangin, J.-F., & Dehaene-
6 Lambertz, G. (2011). Early Maturation of the Linguistic Dorsal Pathway in Human Infants.
7 *Journal of Neuroscience*, *31*(4), 1500–1506. [https://doi.org/10.1523/JNEUROSCI.4141-](https://doi.org/10.1523/JNEUROSCI.4141-10.2011)
8 [10.2011](https://doi.org/10.1523/JNEUROSCI.4141-10.2011)
- 9 Marlier, L., Schaal, B., & Soussignan, R. (1998). Neonatal Responsiveness to the Odor of Amniotic
10 and Lacteal Fluids: A Test of Perinatal Chemosensory Continuity. *Child Development*,
11 *69*(3), 611–623. <https://doi.org/10.1111/j.1467-8624.1998.tb06232.x>
- 12 Mehler, J., Jusczyk, P. W., Lambertz, G., Halsted, N., Bertoncini, J., & Amiel-Tison, C. (1988). A
13 precursor of language acquisition in young infants. *Cognition*, *29*(2), 143–178.
14 [https://doi.org/10.1016/0010-0277\(88\)90035-2](https://doi.org/10.1016/0010-0277(88)90035-2)
- 15 Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J.-M. (2011). FieldTrip: Open Source Software
16 for Advanced Analysis of MEG, EEG, and Invasive Electrophysiological Data.
17 *Computational Intelligence and Neuroscience*, *2011*, 1–9.
18 <https://doi.org/10.1155/2011/156869>
- 19 Pallier, C., Devauchelle, A.-D., & Dehaene, S. (2011). Cortical representation of the constituent
20 structure of sentences. *Proceedings of the National Academy of Sciences of the United*
21 *States of America*, *108*(6), 2522–2527. <https://doi.org/10.1073/pnas.1018711108>
- 22 Pascalis, O., de Schonen, S., Morton, J., Deruelle, C., & Fabre-Grenet, M. (1995). Mother’s face
23 recognition by neonates: A replication and an extension. *Infant Behavior and Development*,
24 *18*(1), 79–85. [https://doi.org/10.1016/0163-6383\(95\)90009-8](https://doi.org/10.1016/0163-6383(95)90009-8)
- 25 Perruchet, P., & Vinter, A. (1998). PARSER: A Model for Word Segmentation. *Journal of Memory*
26 *and Language*, *39*, 246–263. <https://doi.org/10.1006/jmla.1998.2576>
- 27 Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). *Statistical learning by 8-month-old infants*.
28 (Vol. 274). <https://doi.org/10.1126/science.274.5294.1926>
- 29 Saffran, J. R., Johnson, E. K., Aslin, R. N., & Newport, E. L. (1999). Statistical learning of tone
30 sequences by human infants and adults. *Cognition*, *70*(1), 27–52.
31 [https://doi.org/10.1016/S0010-0277\(98\)00075-4](https://doi.org/10.1016/S0010-0277(98)00075-4)
- 32 Saffran, J. R., & Kirkham, N. Z. (2018). Infant Statistical Learning. *Annual Review of Psychology*,
33 *69*(1), 181–203. <https://doi.org/10.1146/annurev-psych-122216-011805>

- 1 Schapiro, A. C., Gregory, E., Landau, B., McCloskey, M., & Turk-Browne, N. B. (2014). The
2 Necessity of the Medial Temporal Lobe for Statistical Learning. *Journal of Cognitive*
3 *Neuroscience*, 26(8), 1736–1747. https://doi.org/10.1162/jocn_a_00578
- 4 Schlichting, M. L., Guarino, K. F., Schapiro, A. C., Turk-Browne, N. B., & Preston, A. R. (2017).
5 Hippocampal Structure Predicts Statistical Learning and Associative Inference Abilities
6 during Development. *Journal of Cognitive Neuroscience*, 29(1), 37–51.
7 https://doi.org/10.1162/jocn_a_01028
- 8 Shi, R., Werker, J. F., & Morgan, J. L. (1999). Newborn infants' sensitivity to perceptual cues to
9 lexical and grammatical words. *Cognition*, 72(2), B11–B21.
10 [https://doi.org/10.1016/S0010-0277\(99\)00047-5](https://doi.org/10.1016/S0010-0277(99)00047-5)
- 11 Stahl, A. E., & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and
12 exploration. *Science*, 348(6230), 91–94. <https://doi.org/10.1126/science.aaa3799>
- 13 Teinonen, T., Fellman, V., Näätänen, R., Alku, P., & Huotilainen, M. (2009). Statistical language
14 learning in neonates revealed by event-related brain potentials. *BMC Neuroscience*, 10, 21.
15 <https://doi.org/10.1186/1471-2202-10-21>
- 16 Toro, J. M., & Trobalón, J. B. (2005). Statistical computations over a speech stream in a rodent.
17 *Perception & Psychophysics*, 67(5), 867–875. <https://doi.org/10.3758/BF03193539>

18