Prelingual infants discover statistical word patterns at similar rates as adults: evidence from
neural entrainment

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Abstract

The discovery of words in continuous speech is one of the first challenges faced by infants during language acquisition. This process is partially facilitated by statistical learning, the ability to discover and encode relevant patterns in the environment. Here, we used an EEG index of neural entrainment in 6-month-olds ($n=25$) to track their segmentation of words from continuous speech. Infants showed neural entrainment to embedded words that increased logarithmically over the learning period, consistent with a perceptual shift from isolated syllables to word-like units. Moreover, infants' neural entrainment during learning predicted post-learning behavioural measures of word discrimination ($n=18$). Finally, the logarithmic increase in entrainment to words was comparable in infants and adults, suggesting that infants and adults follow similar learning trajectories when tracking probability information among speech sounds. Statistical learning effects in infants and adults may reflect overlapping neural mechanisms, which emerge early in life and are maintained throughout the lifespan.

One of the first challenges faced by infants during language acquisition is the discovery of word boundaries in continuous speech. This process, known as word segmentation, is not trivial, as the speech signal does not contain reliable phonetic cues to word boundaries (e.g., Klatt, 1980). Despite the computational challenges of word segmentation, by 6 months of age infants have already learned some word forms of their native language (Bergelson & Swingley, 2012). *Statistical learning*, the process of becoming sensitive to statistical regularities in the environment, has been proposed as a learning mechanism that supports the initial process of word segmentation. In a given language, the probability of two syllables co-occurring is higher within than across word boundaries (Swingley, 2005). Tracking this probability information may be one mechanism by which infants segment words from natural speech (Saffran, Aslin, & Newport, 1996; Saffran & Kirkham, 2018).

Saffran, Aslin, and Newport (1996) provided the first evidence that infants can extract word-like units by tracking the statistical patterns between speech sounds. They used an artificial language that was created by concatenating four trisyllabic nonsense “words” (e.g., “babupu”, “padoti”) in a pseudorandom sequence, without any acoustic cues to word boundaries. After 2 minutes of exposure to this language, infants discriminated words from nonword foils (trisyllabic sequences composed of recombined syllables), as reflected by longer listening times to nonwords. Successive work has demonstrated that infants are sensitive not only to probabilistic sequences of syllables, but also to non-linguistic auditory and visual stimuli (see Saffran & Kirkham, 2018 for a review). There is also evidence that statistical word segmentation facilitates other aspects of language acquisition, such as vocabulary learning (Graf Estes, Evans, Alibali, & Saffran, 2007). Neuroimaging studies of newborns provide evidence that a statistical learning ability for speech segmentation is already present at birth (Teinonen et al., 2009; Flo et al.,

2019). Taken together, these results suggest that infants can extract embedded words from continuous speech by tracking the statistical probabilities between syllables.

To date, most evidence for statistical learning in infants comes from post-learning behavioural tests, in which infants' responses to both previously encountered words and novel foil items are measured *after* familiarization. Although this approach has yielded key insights into infants' statistical learning abilities, it has several limitations. First, the infant's response to the segmented words reflects the outcome of learning but not statistical learning itself. Thus, test performance may be influenced by extrinsic factors, such as general interest in the task, motor abilities, and memory retrieval. Second, post-learning tests cannot reveal the time-course or dynamics of learning. Previous research has shown that infants can learn syllabic chunks from speech streams after variable lengths of familiarization, but little is known about *when* an infant becomes sensitive to the underlying statistical structure. Finally, behavioural tests using looking-time preference measures are not suitable beyond infancy, precluding meaningful comparisons of statistical learning across the lifespan. As such, the different methodologies used for infants versus older children and adults impedes our understanding of how the mechanisms and dynamics of statistical learning change with maturation and experience.

The present study aims to overcome these limitations by using a direct neural index of statistical learning to track learners' sensitivity to hidden embedded words *during* familiarization using an EEG-based measure of neural entrainment (e.g., Batterink & Paller 2017, 2019; Buiatti et al., 2009; Kabdebon et al., 2015). Neural entrainment refers to the synchrony between neural oscillations and external stimuli that emerges during the processing of rhythmic or predictable visual and auditory stimuli, including speech. For example, electrophysiological measures of speech processing reveal peaks in time-locked cortical activity at different linguistic units including single syllables, words, and phrases (Ding et al., 2016). Importantly, neural

entrainment does not merely reflect acoustic features of the signal, but is sensitive to higher-level cognitive processes, such as listeners' extant knowledge and subjective perception as guided by syntactic rules (Ding et al., 2016) or imagined rhythms (Nozaradan et al., 2011). In the context of statistical learning, the central assumption is that as learners gradually discover words in continuous speech, neuronal firing should progressively entrain more strongly to the word frequency relative to the low-level syllable frequency, representing a shift in perception from syllables to words (Buiatti et al., 2009).

Consistent with the hypothesis that there is a relationship between neural entrainment and learning the probabilistic relationships between syllables, recent EEG studies of statistical learning in adults confirmed that neural entrainment can indeed reveal emergent word sized units, and that such entrainment predicts word recognition on a subsequent behavioral test (Batterink & Paller, 2017; 2019). These results indicate that an EEG-based measure of neural entrainment can successfully track statistical learning as it occurs. This methodology was also applied to investigate the statistical learning of nonadjacent structures (Buiatti et al., 2009; Kabdebon et al., 2015), although in these latter studies the insertion of brief pauses between words provided a low-level cue to segmentation.

In the present study, we applied the EEG frequency-tagging approach to study statistical learning in 6-month-old prelingual infants. We exposed infants to an artificial language similar to one developed by Saffran et al. (1996), in which trisyllabic "words" were concatenated without acoustic cues to word boundaries. To examine the temporal dynamics of statistical learning, we measured infants' EEG during familiarization and used a sliding-time-window analysis to index the trajectory of neural entrainment at a fine-grained scale. We hypothesized that there is a relationship between synchronization of ongoing neural oscillations to the embedded word structure and statistical learning. We therefore predicted that while infants would, from the

beginning, entrain to the individual syllables, over the course of familiarization infants would show a relative increase in word-level entrainment, reflecting a progressive acquisition of word knowledge through statistical learning.

After familiarization, we used an established behavioural paradigm to assess infants' ability to discriminate previously encountered words from novel nonwords. We predicted that word-level entrainment would correlate with the magnitude of infants' preference for nonwords. Such a finding would be consistent with previous findings in adults (Batterink & Paller, 2017, 2019), in which neural entrainment observed during exposure predicted later behavioural measures of statistical learning. Finally, we compared these infant data to existing adult data that were previously collected under comparable conditions (Batterink & Paller, 2017). We investigated the learning trajectory in each group to test whether infants and adults show differences in the rate or efficiency of statistical learning.

Materials and Methods

Participants

Twenty-five full-term 6-month-old monolingual English-learning infants ($M = 175.4$ days, $SD = 10.4$ days) from the greater Vancouver area were included in the familiarization phase analyses. An additional eight infants were tested but excluded from analysis due to behavioural issues ($n = 6$), and equipment or experimenter error ($n = 2$). Sample size was estimated based on effect sizes from data reported in Batterink & Paller (2017) which produced an estimated Cohen's d effect size of .56 and observed power of .98. We estimated that a comparable effect and an estimated power of .8 would require a minimum sample size of 22 infants (G*Power 3.1). We selected 24 infants as target, since that parallels the original Saffran, Aslin, and Newport study (1996). One additional infant was recruited during the recruitment

window, leaving a final sample of 25 infants in the EEG entrainment analysis. Eighteen of the twenty-five infants yielded sufficient test phase data (see SOM-R for details). The research was approved by University of British Columbia Ethics Certificate H95-80023 (University of British Columbia Behavioural Research Ethics Board).

Stimuli

Familiarization phase. The stimuli consisted of 12 consonant-vowel (CV) syllables (range in duration: 185-228 ms) that followed the phonemic conventions of English, arranged into four trisyllabic words (see SOM-R table S1 for the list of words) . To control for potential idiosyncratic stimulus effects, we constructed two separate artificial languages from the same twelve syllables (see SOM-U for further details). Infants were randomly assigned to listen to one of the two artificial languages.

The individual syllables were generated using an artificial speech synthesizer (built-in Mac text-to-speech application; voice “Samantha”) and recorded in Audacity at a sampling rate of 44100 Hz. During familiarization, infants heard a continuous auditory stream (minimum 120 s, maximum 400 s) generated by concatenating the four trisyllabic words in a pseudorandom order without pauses. Syllable-to-syllable onset was 300 ms (3.3 Hz); word-to-word onset was 900 ms (1.1 Hz). The boundaries between words were cued only by the transitional probabilities between the syllables (i.e., the probability that two syllables will co-occur based on the overall frequency of the first syllable; 1.0 within a word and 0.33 across words).

Test phase. Infants heard two words from the artificial language, and two nonword foils. For each trial, infants heard repetitions of the test item separated by 1100 ms of silence. The syllable-to-syllable onset within each word was 300 ms, as in the familiarization phase.

Procedure

The experimental protocol consisted of two separate phases: an initial familiarization phase and a test phase. Throughout the experiment, the infant sat on his or her caregiver's lap in a sound-attenuated booth. The caregiver listened to masking music through a pair of headphones to prevent hearing the auditory stimuli.

Familiarization phase. Infants were exposed to the artificial language playing over speakers (range in total number of syllables presented: 602 to 1317; $M = 1123$; $SD=201$). A computer monitor in front of the infant displayed a dynamic attention-getter to hold the infants' attention. We implemented a minimum 120 s exposure criterion since previous studies have shown that 2 min of exposure is sufficient for infants to learn. We set the maximum exposure duration to 400 s in order to maximize the amount of data for EEG analyses. If the infant began to vocalize or move excessively or if the parent signaled to stop the speech stream, the familiarization phase was paused or terminated. If the infant was successfully calmed within 2-3 min, we proceeded to the test phase.

Test phase. We used a central-fixation looking-time paradigm (Shi & Werker, 2001) to test infants' ability to discriminate words and nonword foils (see Table S1 in SOM-R). Sequences of repeating test items (words and nonwords) were paired with a rotating spiral displayed on the screen. Infants controlled the duration of the repeating auditory stimuli through their looking behaviour, such that a sustained shift in visual attention away from the screen terminated the trial. Infants' looking time to each trial represented our key measure of statistical learning. We predicted longer looking times to foil items, reflecting a novelty preference, as has been found in most previous statistical learning research using similar paradigms (Saffran et al., 1996; Graf Estes & Lew-Williams, 2015).

A camera mounted above the computer monitor allowed the experimenter to observe the infant. A yellow ball preceded each trial to direct the infant's attention to the screen. When the infant looked at the screen, the experimenter, who was blinded to the trial condition, initiated the trial presentation. On each trial, the infant heard a repetition of either a word or a nonword. The experimenter monitored and indicated online when the infant's gaze moved away from or returned to the screen. The trial ended when the infant looked away from the screen for at least 2 consecutive s, or after a maximum trial duration of 30 s. Trials were presented pseudorandomly such that infants heard each of the two words and two nonwords every four trials, which constituted a block. Infants progressed through the test items until fuss-out or until they completed a maximum of 16 trials. Infants who completed at least one test block were included. Figure 1 summarizes the experimental protocol.

Figure 1. Summary of the experimental protocol. The experiment consisted of a familiarization phase followed by a test phase. **(A)** The familiarization phase consisted of passive listening to an artificial language composed of repeating trisyllabic nonsense words. Neural entrainment to the auditory speech stream was measured throughout familiarization. **(B)** In the test phase, infants controlled the duration of each trial, made up of a single repeating test item (word or nonword), by keeping their eyes focused on a rotating spiral. Infants' looking times to words and nonwords were measured.

EEG Recording and Analysis

EEG data were collected throughout the familiarization and testing phases at a sampling rate of 1000 Hz with the 64-electrode geodesic sensor net (Electrical Geodesics Inc., Eugene, OR, USA, Net Amps 400 amplifier) referenced to the vertex (Cz). The maximal impedance was kept under 40 k Ω .

Quantification of neural entrainment across the familiarization phase

EEG neural entrainment analyses were carried out using EEGLAB (Delorme & Makeig, 2004) and followed the same general procedure as in previous studies (Batterink & Paller, 2017; 2019), with some modifications to accommodate the noisier infant data. First, a 60-Hz notch filter and a band-pass filter from 0.5 to 20 Hz were applied to the raw data. Next, following a previous study of neural entrainment in infants (Cirelli et al., 2016), artifact correction was carried out using the Artifact Block (AB) algorithm in Matlab (Mourad et al., 2007). The AB algorithm improves the signal-to-noise ratio in infant data relative to conventional trial rejection and can be applied to both continuous and epoched EEG (Fujioka et al., 2011). As recommended by Fujioka et al. (2011), the algorithm was applied after removing the outer ring of channels from further analysis, and the threshold θ within the AB algorithm was set at $\pm 50 \mu\text{V}$. The artifact-corrected data were then re-referenced to a common average and data epochs of 9.0 s were extracted. Epochs were time-locked to the onset of each word and corresponded to the duration of 10 trisyllabic words or 30 syllables (with no pre-stimulus interval), such that neighboring epochs overlapped for 9/10ths of their length.

We quantified neural entrainment by measuring inter-trial coherence (ITC), a measure of event-related phase locking. ITC values range from 0, indicating purely non-phase-locked activity, to 1, indicating strictly phase-locked activity. A significant ITC indicates that the EEG

activity in single trials is phase-locked at a given time and frequency, rather than phase-random with respect to the time-locking experimental event. ITC was computed using a continuous Morlet wavelet transformation from 0.555 to 5.0 Hz via the *newtimef* function of EEGLAB. Wavelet transformations were computed in 0.11 Hz steps with two cycles at the lowest frequency (0.555 Hz) and increasing by a scaling factor of 0.5, reaching nine cycles at the highest frequency (5.0 Hz). This approach was selected to optimize the tradeoff between temporal resolution at lower frequencies and frequency resolution at high frequencies (Delorme & Makeig, 2004). As an initial step, ITC was computed across all epochs for each infant and plotted as a function of frequency (Figure 2A; topographical voltage map represents ITC from all scalp electrodes retained after the AB correction step). We selected a group of 23 fronto-central electrodes for all subsequent ITC computations.

Electrode selection was based on visual inspection of the topographical distribution of the entrainment effect in our sample, on the general finding that auditory event-related potentials are mainly fronto-centrally distributed, and on our previous finding with adults showing that entrainment effects are maximal at fronto-central sites (Batterink & Paller, 2017). Note that strong entrainment was also observed over posterior electrodes (Figure 2A), despite the fact that auditory EEG signals generally show a fronto-central distribution; these channels were not included in ITC computations. This observed shift in the distribution of ITC relative to our original analysis in adults is likely due to the use of a common average reference instead of a mastoid reference, which results in the subtraction of higher amplitude EEG signals from the relatively weak signals over posterior regions. This use of an average reference was necessary as peripheral channels, which includes the mastoids, are often noisy in infant data (Fujioka et al., 2011), and thus are not suitable references.

Neural entrainment time-course analysis (familiarization phase)

We predicted a relative increase in word-level neural entrainment over the course of exposure, reflecting a progression in sensitivity to the word structure in the speech stream. To test this hypothesis, we used a sliding-time-window analysis to examine the trajectory of learning at a fine-grained scale. We grouped every 10 consecutive epochs together into “bundles” (i.e., epochs 1-10, 11-20); thus, each word was represented equally across bundles, except for 9 words occurring at the beginning and 9 words at the end of the familiarization period. ITC was computed within each bundle of ten consecutive epochs using the same *newtimef* function and parameters described previously. A relative measure of sensitivity to the trisyllabic word structure was then computed for each bundle by dividing ITC at the word frequency (1.1 Hz) with ITC at the syllable frequency (3.3 Hz). This measure is referred to as the Word Learning Index (WLI; $WLI = ITC_{word}/ITC_{syllable}$; Batterink & Paller, 2017). Higher WLI values indicate greater neural entrainment towards the word frequency relative to the raw syllable frequency, indicative of statistical learning. The sliding-time-window analysis provides a fine-grained (bundle-by-bundle) relative measure of word-level entrainment throughout the familiarization period. Because each bundle consists of only 10 epochs (resulting in relatively noisy WLI time-course data), data were smoothed using a moving-average filter with a span of 3 data points (i.e., each n th data point was averaged with data points $n-1$ and $n+1$). As values for the first and final bundle for each participant cannot be smoothed, they were excluded from further analysis. The remaining smoothed WLI values were used in all subsequent statistical analyses.

WLI values for each bundle produced a learning curve over the familiarization period. At the group level, the learning curve was better characterized by a logarithmic function compared to a linear function (Figure 2B; Results), consistent with previous research on the time-course of statistical learning in adults (Siegelman et al., 2018). Thus, as an estimate of statistical learning

at the individual level, we modelled each infant's learning curve with a logarithmic function ($y = a + b \cdot \log(x)$, where y = WLI value and x = cumulative number of "words" each participant was exposed to during familiarization). Positive b values indicate that the WLI increases logarithmically as a function of exposure; larger b values reflect faster (steeper) learning rates. To examine our first hypothesis that infants would show a relative increase in word-level neural entrainment over the course of exposure, a one-sample t-test was used to test whether $b > 0$, which would indicate an increase in WLI over the course of exposure to the speech stream. As a control, we assessed the distribution of randomly ordered bundles using a repeated random sampling approach. For each participant, WLI values for each bundle were randomly shuffled and then smoothed using the same parameters and constraints as in the original analysis. A b value was calculated for each participant based on these shuffled bundles, and an average b value across participants was then computed. This procedure was repeated a total of 1000 times, producing a distribution of 1000 surrogate b values for randomly ordered bundles. We then tested whether our observed b value (for the real data) fell within the upper 5% of this shuffled surrogate distribution.

Finally, for each infant, the logarithmic function fit to his or her individual time-course data was used to compute a starting and final WLI value, based on the total number of words heard during familiarization (range in number of words presented = 200 – 439). Conceptually, the final WLI value represents each individual's final endpoint of learning (i.e., reflecting the level of knowledge achieved by the end of the familiarization period) and critically, is predicted to correlate with behavioural learning outcomes. This computed final WLI value was used in the correlational analysis with the behavioural test measure, as described in detail below.

Behavioural Data Analyses

We compared infants' looking-times to words from the artificial language versus nonword foils. For each infant, a cumulative looking-time score was computed per trial, excluding periods during which the infants' gaze was directed away from the screen before the trial offset. Because only a small subset of infants (~30%) completed blocks 3 and 4, data were truncated to include only the first two blocks. Looking-time data were analyzed with a linear mixed effects model including condition (word vs. nonword) and block as fixed effects, and block-by-subject as a random slope. The analysis was implemented using R (R Core Team, 2013), and *lme4* (Bates et al., 2015). To establish the significance of the effect of the condition, p-values were obtained by likelihood ratio tests of the full model against the null model without the effect of interest (Winters, 2013).

Correlation Between Neural Entrainment (Familiarization Phase) and Preferential Looking Time (Test Phase)

To test the hypothesis that the WLI predicts infants' behavioural discrimination of words versus foils, we calculated the correlation between the individual log-fitted final WLI values (representing each infant's final sensitivity to the word structure after familiarization, based on the individual's logarithmic learning curve) and looking-time preferences to words versus nonwords. We transformed the looking-time scores to reflect infants' preferential listening to nonwords over words while accounting for each individuals' baseline looking time (proportional preference score = $\text{mean LT}_{\text{nonwords}} / [\text{mean LT}_{\text{nonwords}} + \text{mean LT}_{\text{words}}]$; Lany, Shoaib, Thompson, & Estes, 2018). A proportional score greater than 0.5 is indicative of longer looking to nonwords (novelty preference), and a score below 0.5 indicates longer looking to words (familiarity preference).

Comparison of Neural Entrainment in Infants and Adults (Familiarization Phase)

To compare statistical learning trajectories in infants and adults, we analyzed data previously collected in adults ($n = 44$) under similar learning and testing conditions (Batterink & Paller, 2017). Briefly, EEG was recorded while adults were passively exposed to 12 min of an artificial language made up of four trisyllabic words, as in the present study. After familiarization, adults completed both an explicit rating task and a reaction-time target detection task (see SOM-U for further details). We equated the language exposure between adults and infants by using an individual “yoking” procedure. For each adult, data from only the initial part of the 12 min familiarization period were included in the analysis, with this exact duration matched to one of the 25 infants. We applied the same data analysis pipeline as described for the infant data. Potentially due to differences in skull size, adults showed a more focal distribution in both word-level and syllable-level entrainment compared to infants. Thus, for ITC and WLI computations in adults, we used a subset of nine fronto-central electrodes (F1, Fz, F2, FC1, C1, FCz, Cz, FC2, and C2), to avoid diluting our effects of interest (see Figure S2 for distribution of the entrainment effect in adults).

To compare the time-course of statistical learning in infants and adults, an independent-samples t-test was used to test whether b differed between the two groups, with significantly different b values taken to indicate that infants and adults show differences in statistical learning rates.

Validation of Analysis Procedure in Adults

Because data collected in infants and adults were subjected to identical data analysis procedures, we tested the robustness of our infant analysis pipeline by independently validating these analyses in data collected in adults. All validation checks were confirmed; see SOM-R for further details.

Results

Familiarization Phase

Overall neural entrainment. Similar to prior results in adults (Batterink & Paller, 2017), neural entrainment in infants across the familiarization period was characterized by clear peaks at the word and syllable frequencies, with no clear peak observed at the bisyllable frequency (corresponding to 1.67 Hz). The ITC distribution at the word and syllable frequencies was relatively widespread across the scalp (Figure 2A).

Neural entrainment time-course. Consistent with our predictions, WLI increased significantly as a function of exposure, providing evidence of online statistical learning of the underlying word units. Individual time-course data were modelled logarithmically, because a logarithmic curve fit the average group-level data better than a linear curve (Log $R^2 = 0.25$, Linear $R^2 = 0.086$). The increase in WLI over familiarization was reflected by a significant positive b value, representing a logarithmic increase ($y = a + b \cdot \log(x)$; mean $b = 0.027$, $SE = 0.012$, $t(24) = 2.16$, $p = .041$; Cohen's $d = 0.43$). The mean modelled WLI intercept was 0.87 ($SE = 0.074$) and the mean modelled final WLI value was 1.04 ($SE = 0.025$). The observed b value of 0.027 corresponded to the 99th percentile in the distribution of b values to shuffled surrogate bundles, indicating that the WLI increase in the experimental data is unlikely to occur by chance and is not a general result of the analysis procedure. This result provides evidence that rapid word-level entrainment is a signature of statistical learning.

Figure 2B shows the logarithmic learning curve modelled on group-averaged data in infants (red). The increase in WLI was most pronounced over the first ~10 bundles, corresponding to approximately the first 100 word presentations, or ~90 s of exposure (Figure 2B).

For comparison, the same analysis was conducted with ITC_{syllable} as the dependent variable. Consistent with our previous finding showing that syllable-level entrainment in adults decreases over the course of exposure (Batterink et al, 2017; 2019), ITC_{syllable} in the average group-level data showed a logarithmic decrease ($\text{Log } R^2 = 0.48$; $\text{Linear } R^2 = 0.21$). Across infants' individual learning curves, the decrease in ITC_{syllable} over familiarization was reflected by a significant negative b value ($y = a + b \cdot \log(x)$; mean $b = -0.012$; $SE = 0.004$; $t(24) = -2.90$, $p = 0.008$; Cohen's $d = 0.58$).

Figure 2. (A) Neural entrainment across the familiarization period in infants ($n=25$). Peaks in neural entrainment were observed at both the syllable and word frequencies. Topographical plots show the distribution of ITC across the scalp. Note that different scales are used for word and syllable frequencies. The dots on the upper scalp plot denote the approximate locations of the 23 centro-frontal electrodes used for all ITC analyses. (B) Time course of statistical learning over the familiarization period, as indexed by the Word Learning Index (WLI), in infants (red) and adults (blue). Each line represents the best logarithmic fit for the group-averaged data. Shaded regions represent the standard error of each data point. Note that because ITC is highly influenced by trial number, ITC and corresponding WLI values cannot be directly compared between Figure 2A and 2B, since ITC in Figure 2A is computed across all epochs.

Test Phase

Consistent with our predictions, infants' looking times were significantly longer for nonword trials compared to word trials, reflecting a novelty preference (M nonword = 13.87 s, $SE = 1.22$; M word = 11.74 s, $SE = 0.94$; Figure 3A). This difference was significant, as determined via likelihood ratio test (condition: $\chi^2(1) = 4.27, p = .039$; see Table S2 in SOM-R for further details).

Correlation Between Neural Entrainment (Familiarization Phase) and Preferential Looking Time (Test Phase)

Infants' proportional preference score was significantly positively correlated with the modelled final WLI value, which we hypothesize reflects each infant's ultimate learning attainment ($r = 0.54, n = 18, p = .022$). We conducted a leave-one-out analysis after standard diagnoses for influential points using an inspection of the individual beta values and Cook's distance (See SOM-R for details). When the data were reanalyzed without a single identified influential point, the overall conclusion was maintained but the effect became stronger ($r = 0.73, n = 17, p < 0.001$; Figure 3B).

Figure 3. (A) Mean looking time difference between the two trial types. Infants looked significantly longer to nonwords than to words. (B) Correlation between modelled final WLI value (representing relative neural entrainment to words during the familiarization phase) and proportional looking time measure at test ($r = 0.73$, $n = 17$, $p < 0.001$; influential point excluded).

Comparison of Neural Entrainment in Infants and Adults

Similar to infants, a logarithmic curve better fitted the adult data in comparison to a linear curve (Log $R^2 = 0.30$, Linear $R^2 = 0.17$). Individual learning curves in infants and adults did not show significantly different WLI slopes (mean slope in adults = 0.028, $SE = 0.010$; $t(67) = -0.087$, $p = 0.93$; Cohen's $d = 0.022$; Table S3 in SOM-R; Figure 2B). To quantify evidence for the alternative hypothesis that the slopes differ between infants and adults versus the null hypothesis that the slopes do not differ between the two groups, we computed a Bayes Factor (BF). The BF revealed that the observed data are > 5 times more likely to arise under the null hypothesis compared to the alternative hypothesis ($BF_{01} = 5.28$). This is considered as moderate (Wagenmakers et al., 2017) or substantial (Jarosz and Wiley, 2014) evidence for the null hypothesis of no difference between groups. These results suggest that infants and adults became sensitive to the statistical structure of the speech stream at similar rates. We note that WLI values were numerically higher in adults than infants across the familiarization period (Figure 2B; Figure S1 in SOM-U), though we restricted our statistical comparisons to the learning trajectories between the groups. A direct comparison of the overall entrainment values between groups is not straightforward, as anatomical differences and age-related changes in EEG spectral power (both across and between frequency bands) may influence neural entrainment effects between groups, independently of learning-specific effects. In summary, there was no evidence of statistically different learning trajectories between infants and adults (see Table S3 in SOM-R).

Figure 2B shows the logarithmic learning curves modelled on group-averaged data for infants and adults. This analysis produces roughly similar estimated parameters between groups (infants $b = 0.016$, modeled initial WLI value = 0.98, modelled final WLI value = 1.04; adults b

= 0.025, modeled initial WLI value = 1.00, modelled final WLI value = 1.09). Again, WLI values were numerically higher in adults compared to infants.

Finally, as a comparison, the same analysis was conducted on the adult data with ITC_{syllable} as the dependent variable. ITC_{syllable} in the average group-level data decreased numerically over familiarization, though did not follow a clear logarithmic function (Log $R^2 = 0.17$; Linear $R^2 = 0.15$). ITC_{syllable} across individual learning curves showed a marginally significant decrease when modelled both linearly ($p = 0.065$) and logarithmically ($p = 0.087$).

Discussion

Summary of Results

These results provide evidence that prelingual infants rapidly attune to the statistical structure of an artificial language. During the 6 min familiarization period, we observed an increase in the WLI, the ratio of neural entrainment to the word-rate relative to the syllable-rate. We interpret this logarithmic increase as reflecting a shift in perception from isolated syllables to coherent word-like units. In the test phase, infants showed a preference for nonword foils compared to words, and crucially, infants' WLI scores during familiarization significantly correlated with their preference for nonwords during the test phase. Finally, the overall pattern of neural entrainment and the rate of WLI progression in infants was comparable to the effects observed in adult learners (Batterink & Paller, 2017).

New Insights into Statistical Learning in Infants

To our knowledge, this research is the first to shed light on the time-course and dynamics of statistical learning in prelingual infants. The WLI time-course data were best modelled using a logarithmic function rather than a linear one. WLI values showed the most rapid increase within

the first ~100 word presentations, or ~90 s of familiarization (Figure 2B). These findings support a number of previous studies of statistical learning in infants showing successful learning even after only 2 min periods of familiarization (e.g. Saffran et al., 1996; Saffran, 2001). At least within the context of this artificial speech-segmentation paradigm, our results suggest that 90 s to 2 min may represent a “sweet spot” for learning, with infants showing only incremental gains after this point. Our finding of a logarithmic learning curve converges with previous statistical learning work in adults (Siegelman et al., 2018), and across other learning domains (Karni & Sagi, 1993; Dayan & Cohen, 2011).

We also report the first evidence in infants linking neural mechanisms engaged *during* statistical learning to subsequent behavioural outcomes. We observed a significant positive correlation between infants’ WLI score during familiarization and their preference for nonwords during the test phase. Along with previous results in adults (Batterink & Paller, 2017, 2019), this finding provides additional support for an association between proportional phase-locking of ongoing neural oscillations to the word frequency and the successful discovery and encoding of words in continuous speech. The directionality of the effect was such that infants with stronger entrainment to the word frequency relative to the syllable frequency were more likely to prefer nonwords — that is, novel, not-yet-learned structures. Conversely, infants with lower WLI scores allocated more attention to the familiar words. We propose that infants with higher WLI scores were more efficient learners, and thus were more likely to show increased attention towards the novel structures relative to the words acquired by the end of familiarization. Infants with lower WLI could have been less efficient learners, and showed a familiarity preference as they may be continuing to acquire information about those structures. This interpretation is consistent with the ‘processing load account’, which suggests that infants are more likely to show a familiarity preference when stimuli are relatively complex and difficult to process, and to

show a novelty preference when stimuli are simpler and easier to process (Ferguson, Franconeri, & Waxman, 2018; Hunter, Ames, & Koopman, 1983).

Our neural entrainment time-course results suggest that infants and adults follow similar learning trajectories when tracking probability information among speech sounds. We found no evidence of significant differences between groups on either time-course or overall WLI values, and a Bayesian approach indicated substantial evidence for the null hypothesis of no difference in the learning trajectory between groups. These results suggest an equally robust and efficient statistical learning mechanism throughout the lifespan, and inform discussions on whether SL is developmentally continuous (Saffran et al., 1997) or discrete (Thiessen, Hill & Saffran, 2005). This – in combination with the evidence that statistical learning is a domain-general mechanism (Aslin, 2017) -- suggests statistical learning may have a relatively unconstrained profile of plasticity. If statistical learning ability were considered in isolation, critical-period effects and differences in the acquisition of first and second languages would be unexplained. However, other aspects of language learning that are known to be more dependent on age, such as acquisition of phonetic categories and syntactic dependencies, may impact statistical learning. Previous studies suggest that statistical learning interacts with prior linguistic knowledge, and that variance in statistical-learning performance can be predicted by the resemblance of stimuli to participants' native language (Siegelman et al., 2018).

The current findings raise the theoretical possibility that neural entrainment may represent a common mechanism underlying statistical learning in both infants and adults. In both age groups, relative neural entrainment to words correlated with post-familiarization behavioural measures of statistical learning. Although these results cannot directly speak to *causality* between neural entrainment and statistical learning, there is theoretical grounding for the idea that neural entrainment to structure may contribute to statistical learning. Synchrony between

neural oscillations and external stimuli allows for phases of high neural excitability to align with stimulus events, enabling more efficient processing (Thut et al., 2012). In the context of statistical learning, aligning phases of neural excitability to an ongoing temporal pattern may facilitate processing of predictable stimuli (Schroeder & Lakatos, 2009), promoting the emergence of cohesive word percepts. Consistent with the idea that neural entrainment plays a causal role in processing, recent studies in the domain of speech perception have demonstrated that enhancing neural entrainment to the auditory envelope of speech, via electrical brain stimulation, improves speech intelligibility (Riecke et al., 2018; Wilsch et al., 2018). These results provide additional evidence for the idea that stronger neural entrainment to relevant features of the acoustic signal leads to more effective auditory processing.

Nonetheless, it is also possible that our measure of neural entrainment reflects downstream effects of the causal learning process itself, rather than directly indexing the underlying mechanism. For example, neural entrainment in this context may directly reflect participants' perception of the speech stream (cf. Nozaradan et al, 2011; Ding et al., 2016 for evidence of neural entrainment reflecting perception), which may merely *follow from* a causal mechanism responsible for identifying the most relevant or parsimonious units in an input stream.

To conclude, statistical learning has been proposed to be an important mechanism for both first- and second-language acquisition. The demonstration of similar online statistical learning in both adults and infants provides support for this idea, suggesting an early emerging cognitive mechanism that is maintained throughout the lifespan.

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Author Contributions

DC, LJB, AKB and JFW developed and designed the study. DC and LJB programmed the experiment and implemented the study. Infant testing and data collection were performed by DC and AKB. Adult data collection was previously conducted by LJB. LJB analyzed and interpreted the EEG data. DC and AKB analyzed and interpreted the behavioural data. DC analyzed the EEG-behaviour correlation. DC, LJB and AKB drafted the manuscript. KAP and JFW provided revisions and critical feedback on the manuscript.

Open Practices

The sample size, design and analysis of the experiment reported in this article were registered on OSF. The registration was completed shortly after data collection had begun but prior to data analysis. The data and the analysis scripts will be made available on a third party archive after publication.

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