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Neural Entrainment Indexes Statistical Learning in Children

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Abstract

Statistical learning is proposed as a mechanism for discovering structural patterns in speech through incidental exposure. However, studies have largely relied on assessing explicit memory after learning has occurred, which does not capture the time course and process of statistical learning per se. To better understand the dynamics of statistical learning, we assessed 8- to 12-year-old children using an EEG measure of learning, which captures changes in neural entrainment to words embedded in a continuous artificial language. Statistical learning was assessed post-learning using implicit and explicit behavioural tests. The neural entrainment results demonstrated rapid learning of word-level information, while post-learning tasks demonstrated syllable prediction and recognition of the trisyllabic words. These results replicate findings in adults and hint to the possibility that children and adults use similar language learning mechanisms. Importantly, this is the first study to demonstrate that neural entrainment is a sensitive indicator of statistical learning in children.

Keywords

Statistical learning, EEG, neural entrainment, explicit learning, implicit learning, language learning

Summary for Lay Audience

The ability to learn language relies on our sensitivity to structural patterns in speech. Statistical learning is proposed as a mechanism for discovering these patterns through incidental exposure. This means that language is implicitly learned and does not require explicit learning strategies. Statistical learning has largely been assessed through a single explicit memory task and has been assessed only after learning has occurred. This approach does not capture the time course and process of statistical learning on its own. Additionally, while prior studies have demonstrated that children do as well as adults on statistical learning tasks, we do not know the degree of statistical learning in children. To better understand the dynamics of statistical learning, we assessed the degree of learning to a six-minute artificial language in 8- to 12-year-old children. The artificial language was made up of pseudowords and knowledge of the language was tested via implicit and explicit post-learning behavioural tests. We also assessed the time course of learning by using a direct electroencephalography (EEG) measure, which records electrical potentials in the brain created by external stimuli. The EEG measure captured changes in neural entrainment to words embedded in a continuous artificial language stream. Neural entrainment is an especially useful measure of EEG as it determines whether brainwave frequencies are temporally synchronizing to the external stimuli. The neural entrainment results demonstrated rapid implicit learning of word-level information, while post-learning behavioural tasks demonstrated significant syllable prediction and recognition of the trisyllabic words. Importantly, this is the first study to demonstrate that neural entrainment is a sensitive indicator of statistical learning in children. These results replicate previous findings in adults and hint to the possibility that children and adults use similar language learning mechanisms. Our results also demonstrate that there are age-related differences in statistical learning that may be due to the development of attention.

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Chapter 1

1 Introduction

We are born unable to produce and understand speech but quickly learn language simply by listening to others speak. What is even more remarkable is that language is implicitly learned and does not require explicit learning strategies (Reber, 1967). Years of research on language learning have culminated in the proposal that humans rapidly learn language via a mechanism that picks up patterns from the environment through incidental exposure. This process, known as statistical learning, is thought to play an essential role in speech segmentation and language acquisition (Saffran, Newport, & Aslin, 1996).

In natural speech, there are no reliable acoustic cues for word boundaries, therefore language learners must use other information to segment words (Saffran, 2003). The term “statistical learning” was first coined by Saffran, Aslin and Newport (1996) to explain infants’ ability to segment words from connected speech. Specifically, they determined that 8-month-old infants and adults were capable of segmenting words by simply using transitional probabilities of syllables, defined as the relative probability of syllables co-occurring (Saffran, Newport, & Aslin, 1996; Saffran, Aslin & Newport, 1996). Transitional probabilities can be calculated as follows:

$$p(Y|X) = \frac{frequency\ of\ pair\ XY}{frequency\ of\ x}$$

Transitional probabilities between syllables are higher within words than between words. As an example, in “yellow flower”, the syllables “yell” and “o” have a higher transitional probability. Transitional probabilities between word boundaries are lower because syllable pairs such as “o-flow” occur less frequently in natural speech than “yell-o”. This is because the word “yellow” can be followed by many other words, such as “yellow dress” or “yellow banana”. The lower transitional probability for the syllable pair “o-flow” also provides a cue that these are separate words.

1.1 How statistical learning has traditionally been tested

Auditory statistical learning tasks begin with a familiarization phase in which participants listen to an artificial language (Saffran, Aslin, & Newport, 1996). This artificial language is usually made up of trisyllabic pseudowords (hereafter, words). These words are combined in a pseudorandom order to ensure that the same word is not repeated twice in a row (Saffran, Newport, & Aslin, 1996). For instance, the first statistical learning study had the trisyllabic words *pabiku*, *tibudo*, *golatu*, and *daropi*, play continuously for two minutes at a rate of 270 syllables per minute (Saffran, Aslin, & Newport, 1996). The only cues to word boundaries are the transitional probabilities of syllable pairs. The transitional probabilities between syllable pairs within word boundaries is 1.0 as these syllables always co-occur and .33 across word boundaries as these syllables co-occur a third of the time.

In infants, knowledge of the artificial language stream is assessed via listening times (Saffran, Aslin, & Newport, 1996). Infants heard words and nonword or partword foils. The partword foils were created by using the last syllable of a word and the first two syllables of another word (*pipabi*). Nonwords were made up of three-syllable sequences that would not have co-occurred in the speech stream (*pilado*). Longer listening times to the foils would indicate a dishabituation effect, demonstrating that infants distinguished novel from familiar syllable strings. In adults and older children, knowledge of the artificial language stream has traditionally been tested with a post-learning two-alternative forced choice (2AFC) task. Participants would hear a word paired with a nonword foil or a partword foil (Saffran, Newport, & Aslin, 1996). Chance performance is 50% and if the group performs significantly better than chance, this provides evidence for statistical learning.

Using similar methodologies, statistical learning has been found to occur in other sensory modalities, such as vision and touch (e.g., Conway & Christiansen, 2005). Kirkham, Slemmer and Johnson (2002) investigated visual statistical learning. Infants were familiarized with six colored shapes that they saw one at a time, grouped into hidden pair sequences. The test trials consisted of a task with familiar sequences and novel sequences. Looking times were recorded to determine whether infants dishabituated to the presentation of novel sequences. Novel sequences had longer looking times, meaning previously seen sequences were more familiar, evidencing statistical learning of visual shape sequences. Conway and Christiansen (2005) found additional evidence for visual statistical learning as well as tactile statistical learning. Non-linguistic stimuli were used so that the training and test phases were comparable across the visual, auditory and touch modalities. For each modality, the stimuli were presented for 250 ms. The stimuli appeared in five spatial locations for the visual modality, sequences of five pure tones were played for the auditory modality and sequences of pulses were delivered to five fingers on one hand for the touch modality. Statistical learning was tested through legality judgements. The authors found that statistical learning occurred in all three modalities; however, the auditory modality had a quantitative and qualitative learning advantage. In other words, participants were better at learning the auditory sequence and had a better memory for the final part of the auditory sequence. These studies provided support for statistical learning outside of the auditory domain and opened the door to more diverse research.

1.2 The introduction of additional post-learning measures

Saffran et al.'s (1996a) work provided the basis for research on statistical learning in language. The research following this study has painted an increasingly detailed picture of statistical learning as a learning mechanism. The process of statistical learning has not only been found in infants but has also been found to occur in older children and adults (e.g., Arciuli & Simpson, 2012; Campbell, Healey, Lee, Zimerman, & Hasher, 2012), and in participants who speak languages other than English (e.g., Frost, Siegelman, Narkiss, & Afek, 2013; Hay, Pelucchi, Graf Estes, & Saffran, 2011; Toro, Sinnett, & Soto-Faraco, 2005).

However, past studies have mostly tested statistical learning with a single explicit learning measure, the 2AFC task. This task alone is not sensitive enough to detect individual differences and may underestimate the amount of knowledge acquired from the artificial language (Batterink, Reber et al., 2015; Siegelman, Bogaerts, & Frost, 2017). Performance on the post-learning 2AFC task is primarily sensitive to explicit learning. However, statistical learning has been described to occur primarily implicitly (e.g., Conway & Christiansen, 2005; Kirkham et al., 2002). This is problematic as this task cannot capture the full range of learning abilities. This affects the task's validity to assess statistical learning (Siegelman, Bogaerts, & Frost, 2017). Therefore, the full breadth of individual variation in statistical learning cannot be captured by the 2AFC task per se.

Alternatives to the 2AFC task were first introduced in visual statistical learning procedures. Turk-Browne, Jungé, and Scholl (2005) introduced a post-learning task that assessed implicit learning of visual shapes by measuring reaction times (RTs) and accuracy to responses to target shapes in a sequence. Participants had faster RTs to final shapes, demonstrating that they were anticipating the final shapes of the triplet sequences. The authors concluded that statistical learning can be accurately assessed without the use of familiarity judgement tasks like the 2AFC task. Alternative explicit learning tasks were also introduced, such as the pattern completion task (Kim, Seitz, Feenstra, & Sham, 2009). Participants were shown one shape and had to complete the triplet sequence. Eleven options were shown, perhaps making this task too complicated as participants did not perform significantly above chance. Even though this explicit learning task was not sensitive enough to pick up on statistical learning, other pattern completion tasks have been more successful (e.g., Siegelman, Bogaerts, & Frost, 2017).

Siegelman and colleagues (2017) recently proposed a set of explicit learning measures that improve upon the validity and reliability of post-learning tasks by varying the level of difficulty and variability of the test items. Their task introduced a mixture of 2, 3, and 4AFC tasks of pair and triplet sequences, as well as pattern completion tasks of shape pairs and triplets. Since the introduction of this more psychometrically sound task, studies have successfully employed these measures to test visual statistical learning in various populations (e.g., Parks & Stevenson, 2018; Perfors & Kidd, preprint). However, these tasks were designed to assess visual statistical learning and would be difficult to translate to the auditory domain as the 4AFC and pattern completion tasks could interfere with the elements learned during the familiarization period.

Batterink, Reber and colleagues (2015) were the first to address the methodological issues of post-learning tasks in the auditory domain by introducing tasks that capture a larger range of individual variability and tap into explicit and implicit learning. Batterink, Reber et al. (2015) used a speeded target detection task (TDT), similar to the one used by Turke-Browne et al. (2005), to assess statistical learning of their artificial language. For this task, participants heard short speech streams made up of the words from the language and had to respond every time they heard the target syllable (e.g., “ta”). RT was fastest for the final syllable and slowest for the first syllable, providing evidence of implicit statistical learning. There was also no correlation between the TDT and the 2AFC task, demonstrating that statistical learning produces both implicit and explicit knowledge that may be dissociable. Statistical learning in participants who performed at or below chance on the 2AFC task was still observed on the TDT. These findings demonstrate that this task is a more sensitive post-learning measure of statistical learning compared to the 2AFC task.

Batterink, Reber and colleagues (2015) also introduced additional explicit learning tasks which improve upon the traditional 2AFC task as graded differences between individuals’ responses can be observed. For instance, a meta-memory judgement task, the remember/know procedure, was completed after each response on the 2AFC task which provided information on participants’ awareness of their knowledge of the artificial language. Additionally, in order to get a better picture of participants' ability to learn the trisyllabic words from the artificial language, Batterink and Paller (2017) introduced a familiarity rating task. Words, partwords and nonwords were presented one at a time and participants were asked to give a familiarity rating. Participants rated words as significantly more familiar than partwords, with nonwords having the lowest familiarity rating. This task is a direct and sensitive measure of explicit learning as we can visualize participants' familiarity with words and foils. This task also demonstrates that transitional probabilities do play an important role in discrimination between words and foils. Nonword foils have the lowest transitional probabilities as they are made up of syllables that never co-occurred in the artificial language, and partword foils have intermediate transitional probabilities as they include a syllable pair from a word. Therefore, foils containing syllable pairs with the lowest transitional probabilities are least familiar, whereas foils with intermediate transitional probabilities are more familiar and still discriminable from words.

1.3 The use of online measures in statistical learning

Even though the aforementioned tasks provide us with richer data on participants' explicit and implicit learning of the artificial language, post-learning measures do not track learning as it unfolds and only assess knowledge after learning has occurred (Siegelman, Bogaerts, Kronenfeld, & Frost, 2017). This means that these tasks do not tap into the full scope of learning. In fact, due to the nature of post-learning tasks, it is difficult to disentangle statistical learning from other cognitive processes, which impinges on the validity of post-learning tasks (Batterink & Paller, 2017; Siegelman, Bogaerts, & Frost, 2017). Specifically, because there are robust individual differences in long-term memory abilities (Unsworth, 2019), differences found on the post-learning tasks could in part be due to long-term memory abilities and not solely due to differences in statistical learning. In addition, because data are not collected during the learning phase, it can be difficult to differentiate the good from the bad performers and the slow from the fast learners. Thus, a more sensitive measure of statistical learning would be one that measures online learning. Online measures can provide us with information on individual learners' time course of learning (Batterink & Paller, 2017).

To address these methodological issues, electroencephalography (EEG) has been recorded to capture electrical activity in the brain during familiarization and post-familiarization of the artificial language. EEG recordings provide a useful measure of the time course and degree of speech segmentation (Sanders, Newport, & Neville, 2002). Event-related potentials (ERPs), which are waveforms that represent the average of EEG changes to repeated sensory or cognitive events (Sur & Sinha, 2009), have been used to investigate neural evidence of statistical learning. Studies have looked at various ERP components, which are component waves of the ERP waveform, as each component refers to different cognitive processes and provides varied information on the nature of learning (Woodman, 2010). The first experiments studying the relationship between ERPs and word segmentation looked at the N100 component, which has been proposed to reflect attention to word onsets. These studies found that a larger N100 was elicited at word onset rather than acoustically similar mid-word syllables, providing neural evidence for statistical learning (Sanders & Neville, 2003; Sanders et al., 2002). Following these initial findings, other studies have looked at various ERP components involved in the process of statistical learning.

The ERP studies following Sanders et al.'s (2002) seminal work led to several important findings. Cunillera et al. (2009) examined the time course of learning during a speech segmentation task. The results demonstrated that speech segmentation was achieved after only one minute of exposure to the artificial speech stream. ERP components have also successfully been used with post-learning measures, such as with the 2AFC task and the TDT (Batterink, Reber et al., 2015). The ERP components on the post-learning tasks demonstrated a facilitation effect due to learning of the statistical probabilities in the continuous speech stream.

One of the hallmarks of statistical learning in the context of speech segmentation is that syllables are gradually represented as whole words. However, the continuous nature of the speech stream poses a problem for a traditional ERP analysis as listeners are producing discrete ERPs to each individual acoustic event, thereby complicating the computation of a baseline voltage level to the acoustic event of interest. This decreases signal to noise ratio in ERPs (Buiatti, Peña, & Dehaene-Lambertz, 2009). Buiatti et al. (2009) proposed using a "frequency tagging" approach when measuring neural activity to a continuous stream. This approach allows the quantification of neural entrainment at the syllable and word frequencies. Neural entrainment can be explained as the brain's tendency to oscillate at the same frequency as rhythmic stimuli. For instance, if a sound were to play in a repeating pattern, we would observe that the brainwave frequencies correspond to the frequency of the sound (Luck, 2005). In this case, the frequencies are based on the rate at which syllables and whole words are presented. This paradigm differed slightly from the typical statistical learning paradigm in that words were created in families with a non-adjacent AXC rule. The first and third syllables remained constant within each family, and the middle syllable was different for each word. This “frequency tagging” approach was found to be a sensitive measure of online word learning of non-adjacent dependencies (Buiatti et al., 2009). Specifically, we can observe whether an individual is learning the words from the novel language depending on their entrainment at the word and syllable frequencies. Increasingly higher entrainment at the word frequency and lower entrainment at the syllable frequency indicate learning.

This neural entrainment measure was later used in studies measuring auditory statistical learning. EEG phase-locking to the word frequency was found to increase as a function of time, while phase-locking to the syllable frequency was found to decrease as a function of time, providing evidence of a perceptual shift of syllable units into integrated words (Batterink & Paller, 2017, 2019). The syllable frequency was measured at 3.3 Hz as it corresponded to the presentation rate of each syllable and the word frequency was measured at 1.1 Hz as it corresponded to the presentation rate of each word. Batterink and Paller (2017) further quantified learning across time via the *Word Learning Index* (WLI). A greater WLI value would indicate greater neural entrainment at the triplet frequency instead of at the syllable frequency. The WLI also increases as a function of time, indicating statistical learning of the hidden triplet sequences. Furthermore, the WLI predicted performance on the TDT, validating it as a sensitive measure of online statistical learning. These online measures provide critical information on the dynamics of learning, providing data on individual learners' time course and degree of learning. Neural entrainment also provides a "purer" measure of statistical learning as peripheral cognitive processes, such as decision-making biases and meta-cognition, are not intermixed with online learning.

1.4 Current Study

The purpose of the current study is to further understand the dynamics of statistical learning in children, especially as it relates to the use of online and implicit measures of learning. While prior studies have demonstrated that children do as well as adults on statistical learning tasks (e.g., Saffran, Newport, Aslin, Tunick, & Barrueco, 1997), we do not know the degree and time course of statistical learning in children. To address this, we assessed auditory statistical learning to a six-minute artificial language in 8- to 12-year-old children. We chose this specific age range for two reasons. The first was that we needed children to be able to sustain their attention on the tasks and evidence suggests that there is a rapid growth in sustained attention around the age of eight (Betts, Mckay, Maruff, & Anderson, 2006). The second reason was that implicit sequence learning becomes adult-like in adolescence (Janacsek, Fiser, & Nemeth, 2012). Previous studies only provide us with information on whether statistical learning occurs and do not answer the question of when word segmentation begins. Moreover, because the 2AFC task relies heavily on explicit memory, it is difficult to draw concrete conclusions without better measures. Because of these limitations, we used implicit and explicit behavioural tests, as well as an online measure of learning to test knowledge of the artificial language.

Given previous findings on explicit and implicit statistical learning, we used a rating task, a 2AFC task in conjunction with the remember/know procedure and the TDT

(Batterink & Paller, 2017; Batterink, Reber et al., 2015). Other than the 2AFC task, these statistical learning tasks have not been used in children. Because auditory statistical learning abilities in children and adults have not been found to be significantly different (Saffran et al., 1997), we expect that children will perform similarly to the adults who were previously tested on these tasks (Batterink & Paller, 2017, 2019; Batterink, Reber et al., 2015; Batterink, Reber, & Paller, 2015). For the rating task, children should rate words as most familiar, followed by partwords and nonwords. For the 2AFC task, most children should perform significantly better than chance (50%). Children should also have a higher accuracy rate for the "remember" option for the remember/know task, indicating that children have a higher accuracy when they are more confident with their answers. The "familiar" option should have the second highest accuracy, with "guess" being lowest. However, it would not be unexpected if the memory judgement effect is not significant, as Batterink and Paller (2017) did not find a significant judgement effect in their adult participants, likely due to the low number of trials within each category. As in previous studies (e.g., Batterink et al., 2015; Batterink & Paller, 2017), on the TDT, it is expected that participants will have a faster RT on word-final syllables and the slowest RT on word-initial syllables.

Even though EEG has been shown to be a valid and sensitive measure of statistical learning, few studies have used EEG to measure online statistical learning in children. Most studies have focused on the online process of learning in adults, which excludes important information on the dynamics of statistical learning in childhood and throughout the lifespan. The few studies that have looked at online learning in children via EEG have used grand averaged ERPs (i.e., Jeste et al., 2015; Mandikal Vasuki, Sharma, Ibrahim, & Arciuli, 2017). This makes it difficult to visualize any changes in learning throughout the exposure period. Mandikal Vasuki et al. (2017) did look at the "triplet onset effect", the changes in ERPs for the initial and the final shape or tone of a sequence. No significant changes in ERPs were found at these time points in typically developing children. Jeste et al.'s (2015) study did not focus on the time course of learning, therefore it is impossible to determine whether typically developing children quickly or gradually learned the hidden shape sequence over the course of exposure.

We used an online measure of learning during the six minutes of exposure to the artificial language. The online measure will capture changes in neural entrainment to words embedded in the continuous artificial language stream (Batterink & Paller, 2017, 2019). We chose to use this measure of neural entrainment as it has been shown to be a sensitive indicator of the time course of word segmentation in adults. Similar to previous studies, we averaged neural entrainment into three blocks of two minutes. This method indexes the perceptual shift of single syllables into whole words throughout the six-minute period.

This is the first study to look at online neural entrainment of statistical learning in children. We hypothesize that children's neural entrainment will be comparable to online learning in adults. We expect that throughout the six minutes of exposure to the artificial language, children's WLI, the index of overall word learning, will increase with time. In addition, we expect that neural entrainment at the syllable frequency will decrease and neural entrainment at the word frequency will increase as a function of time.

Chapter 2

2 Methods

2.1 Participants

Forty-five English monolingual speakers ages 8-12 (23 female, M = 9.98 years, SD = 1.23 years, range: 8.08-12.67 years) were recruited from London, Ontario. Parents completed a screening questionnaire via e-mail before participating, which included questions about children's sex, handedness, age, and language history. Children were excluded if they had visual impairments that were not corrected or auditory impairments, motor dysfunctions, and intellectual impairments. Parents rated language proficiency on a scale of 0 to 10 (0 being not at all and 10 being perfect) for speaking, understanding, reading, and writing (see Appendix A). Children enrolled in French immersion and/or whose parents rated their proficiency higher than a 5/10 in a language other than English were considered bilingual and excluded from the study. Children received a small gift and parents were compensated for their time and travel expenses.

2.2 Materials

The auditory statistical learning task was programmed using Neurobehavioral Systems' Presentation and was run on a Windows 10 laptop. An external number pad was used to record children's responses. They sat in a quiet room in front of a 22-inch cathode-ray tube (CRT) monitor placed at a comfortable viewing distance. Children listened to the speech stream through a pair of computer speakers.

2.3 Tasks

See Figure 1 for a visual summary of all the statistical learning tasks. Children were passively exposed to an auditory speech stream and then completed three tasks designed to assess both implicit and explicit knowledge of the artificial language.

Artificial Language Exposure. Stimuli consisted of 12 synthetic speech syllables from Batterink and Paller (2017), recorded at a sampling rate of 44100 Hz. Syllables were combined into an artificial language consisting of four unique trisyllabic words (*pautone, nurafi, gabalu,* and *mailoki*). These four words were presented auditorily in a six-minute continuous speech stream constructed such that each word immediately followed the next with no acoustic word onset cues (i.e., no pauses between words, and no other changes in pitch, length or amplitude that could have indicated the onset of any given word). Each of the four words was presented 100 times at a rate of 300 milliseconds per syllable, for a total of 400 words over the 6-minute exposure. The only restriction for the ordering of the speech stream was that the same word could not repeat twice in a row. As such, the transitional probability of neighbouring syllables within words was higher than between words (within: 1.00; between: 0.33). During the exposure phase, children passively listened to the speech stream presented via speakers at a comfortable volume. As a secondary task to prevent boredom, children watched a silent six-minute video clip of “Shaun the Sheep” on the CRT monitor in front of them (Cary & Symanowski, 2008).

Rating task. We next assessed children’s explicit knowledge of the artificial language using a familiarity rating task similar to Batterink and Paller (2017). On each trial the children heard a three-syllable word or foil and rated their familiarity for the utterance. There were 12 trials: the four words from the speech stream, four partword foils and four nonword foils. The partword foils were created by using the last syllable of a word and the first two syllables of another word. Nonwords were made up of syllables that would not have occurred in the same order as words from the speech stream. For each trial, children listened to the stimulus and were then prompted with a response cue, “Please give a familiarity rating”. They then had to indicate on a scale of one to four how familiar the stimulus sounded. We labelled one as “very unfamiliar” and four as “very familiar”. A rating score was calculated by subtracting the mean score for partwords and nonwords from the mean score for words. A score of three would indicate perfect sensitivity to the language and a score significantly above zero would demonstrate that there is explicit learning of the artificial language (Batterink & Paller, 2017).

Two-alternative forced choice task (2AFC). This task was originally used by Saffran, Aslin, and Newport (1996) to assess explicit memory of the words from the speech stream. On each trial, the children heard a word from the training set and a nonword or partword foil, separated by a 1500 ms pause. Children responded by pressing one of two buttons indicating which word was most familiar to them. After each 2AFC, the children were asked to provide a remember/familiar/guess response, known as the remember/know procedure (Batterink & Paller, 2017). The children were instructed to give a meta-memory judgement for their choice. “Remember” indicates they specifically remembered hearing the word, “familiar” indicates that they did not specifically remember hearing the word, but that it sounded familiar, and “guess” indicates that they had no confidence in their response. There was a total of eight test items (i.e., four words from the speech stream, two nonwords, and two partwords). The words were exhaustively paired with the partwords and nonwords to create 16 trials. The trials were presented in random order. The answer order (i.e., whether the correct answer was the first stimulus or the second stimulus) was counterbalanced across children.

Target detection task. This task assesses RTs to each syllable position (Batterink et al., 2015). The logic behind this task is that word-final syllables should be the most predictable and elicit the fastest RTs if listeners have acquired statistical information that would allow them to implicitly predict upcoming syllables. First, the children completed three practice trials, in which they heard syllables that were not part of the alien language but were presented at the same rate (350 ms/syllable). This was to ensure that the children understood how to complete this task. After the practice trials, the children listened to 24 short speech streams containing the four words from the artificial language repeated four times each. Each speech stream therefore contained a total of four targets. The words were presented at a slower rate than the continuous speech stream (350 ms/syllable). Because this task had not been used in children before, we slowed the syllable presentations by 50 ms compared to the exposure period to ensure that children were able to successfully complete the task. Children were instructed to press the Enter key on the number pad every time they heard the target syllable. Each syllable served as the target syllable twice across the 24 streams, yielding a total of 32 targets in each syllable position. The children had the option to take a short break at the halfway point of this task. The order of the speech streams was randomized; however, the ordering of individual words for each speech stream was predetermined and consistent across children, such that a target was constrained not to occur within the first three syllables or last three syllables of the stream. A square at the bottom of the screen changed colour with each button press, which was designed to keep children's attention on the task and to decrease false alarms (i.e., every time the square changed colour, the participant would know that their response was recorded). RT and accuracy were calculated for each syllable position (first, second, and third).

Auditory Exposure

pautonenurafigabalupautonemailoki

Rating Task

1-4 familiarity rating

pautone (word)

kipauto (partword)

nepaunu (nonword)

Two-Alternative Forced Choice Task

Choose which utterance is more familiar

pautone ***or*** **kipauto**

word **partword**

pautone ***or*** **nepaunu**

word **nonword**

remember, familiar, or guess?

Target Detection Task

Target syllable "**ga**"

pautonegabalumailokigabalu

Figure 1. Auditory statistical learning tasks completed in the order shown.

EEG analyses. EEG was recorded for the exposure phase using an Active-Two Biosemi system, with 32 Ag/AgCl-tipped electrodes attached to an electrode cap, placed according to the International 10-20 system. A total of six electrooculogram (EOG) electrodes were placed under, above and next to each of the eyes, and an additional two electrodes were placed behind the left and right mastoid. The EEG data was processed using EEGLAB (Delorme & Makeig, 2004) and the ERPLAB open-source toolbox (Lopez-Calderon, & Luck, 2014). EEG signals were recorded relative to the Common Mode Sense (CMS) active electrode and re-referenced offline to the average of the left and right mastoids. EEG was recorded at a sampling rate of 512 Hz and were filtered offline using a 60 Hz notch filter and a band-pass filter from 0.5 to 20 Hz.

Data were time-locked to the onset of each word and extracted into epochs of 10.8 seconds, corresponding to 12 trisyllabic words. Epochs overlap for 11/12 of their length. A measure of event-related phase locking, called inter-trial coherence (ITC), was calculated at the word (1.1 Hz) and syllable (3.3 Hz) frequencies (Batterink et al., 2017). An ITC value of zero indicates purely non-phase locked activity and an ITC value of one indicates strictly phase-locked activity. ITC was calculated using a continuous Morlet wavelet transformation from 0.2 to 6.2 Hz with the use of the *newtimef* function of EEGLAB. Sensitivity to the structure of the language was quantified using the Word Learning Index (WLI) formula (WLI = ITC at word frequency divided by ITC at syllable frequency; Batterink & Paller, 2017). A higher WLI score indicates stronger sensitivity to the words embedded in the artificial language. ITC was computed across the entire exposure period and then averaged across a subset of 14 fronto-central electrodes where

ITC at the word and syllable frequencies showed the strongest distribution (i.e., F3, Fz, F4, FC5, FC1, FC2, FC6, C3, Cz, C4, CP1, CP2, AF3, AF4).

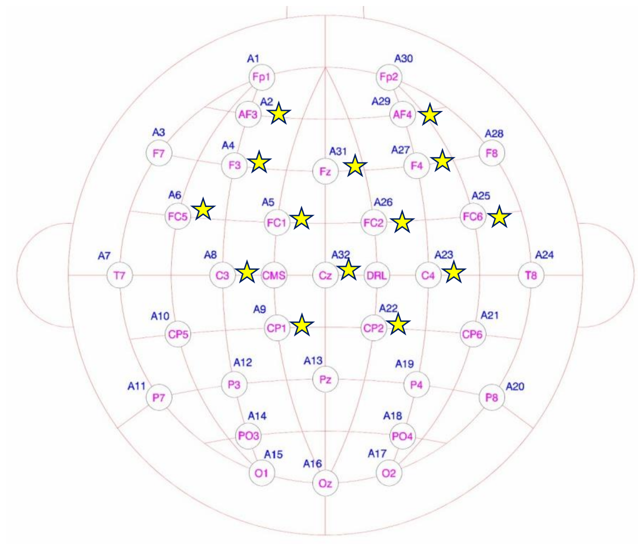


Figure 2. Map of electrodes used for the computation of ITC values. The stars are located to the right of each electrode used in the ITC computation. BioSemi layout 32 + 2 electrodes (n.d.).

Next, we examined the time course of learning by dividing the exposure phase into three separate two-minute blocks of 137 epochs each. ITC within each of the three blocks was calculated once again with a continuous Morlet wavelet transformation from 0.2 to 6.2 Hz. For this block analysis, ITC values were averaged across all 32 scalp electrodes. We included all electrodes in the time course analysis because the topographical plots of the ITC distribution across the scalp demonstrated that activation at each electrode site changed as a function of time and frequency. WLI values were computed for each block, using the same formula as above.

Chapter 3

3 Results

3.1 Rating Task

Data from one child was excluded from the rating task analyses as they did not complete it as instructed. Mean rating scores for words, partwords and nonwords are plotted in Figure 3. Children performed significantly above chance on the rating task. Children had a mean rating score of .500, (SD = .531), which was significantly above zero ($t(43) = 6.246$, $p < .001$, Cohen's d = .942). In addition, a repeated measures ANOVA was used to examine the effect of word category (word, partword and nonword stimuli) on familiarity ratings. Children rated words as most familiar, followed by partwords, and nonwords were rated as the least familiar (Word Category Effect: $F(2, 86) = 23.524$, $p < .001$, $\eta_p^2 = .354$; linear contrast: $F(1,43) = 37.285$, $p < .001$, $\eta_p^2 = .464$). Paired sample t-tests demonstrated that words were significantly different from partwords and nonwords ($t(43) = 5.087$, $p < .001$, Cohen's d = .656; $t(43) = 6.106$, $p < .001$, Cohen's d = .834); however, partwords and nonwords were not significantly different ($t(43) = 1.446$, $p = .155$, Cohen's d = .199).

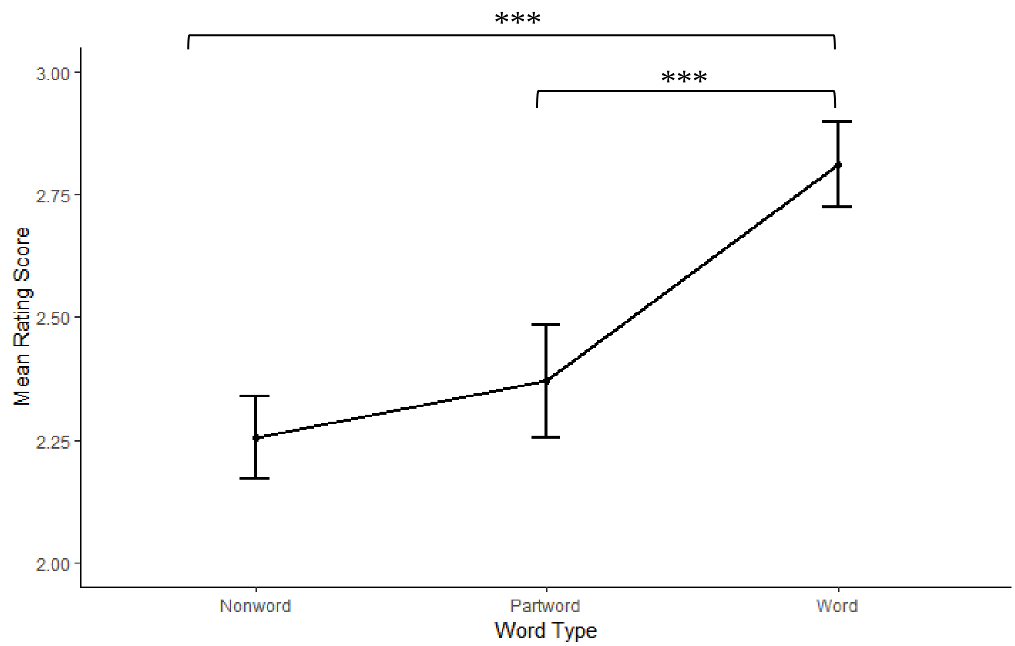


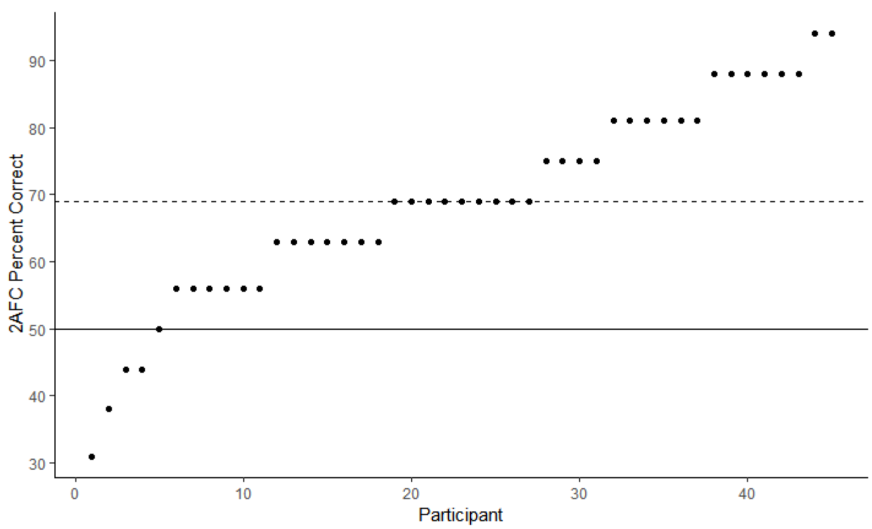
Figure 3. Mean rating scores for nonword, partword, and word stimuli. Error bars represent standard error of the mean. Significant differences of $p < .001$ are denoted with ***.

3.2 Two-alternative Forced Choice Task

Children's mean accuracy scores on the 2AFC task are plotted in Figure 4A. A one-sample t-test demonstrated that children performed significantly above chance (50%) on the 2AFC task (M = 68.89%, SD = 14.81%, $t(44) = 8.557$, $p < .001$, Cohen's d = 1.276). A repeated measures ANOVA for all response categories was conducted for the remember/know procedure. Accuracy did not significantly differ as a function of familiarity judgement (remember/know effect: $F(2, 68) = .559$, $p = .574$, $\eta_p^2 = .016$; linear contrast: $F(1, 34) = .282$, $p = .599$, $\eta_p^2 = .008$). The result may be non-significant because children significantly chose "guess" less often than "remember" and “familiar” ($t(44) = 6.164$, $p < .001$, Cohen’s d = .919; $t(44) = 9.157$, $p < .001$, Cohen’s d = 1.365, respectively). In fact, 10 children did not choose “guess” at all, which limited statistical power. Because of the lower number of responses for “guess”, an exploratory paired samples t-test was conducted to determine whether “familiar” and “remember” responses had a significantly different accuracy. Accuracy for “remember” and “familiar” responses were not significantly different ($t(44) = 1.968$, $p = .055$, Cohen’s d = .293).

A one-sample t-test was also conducted for response accuracy on each category (remember, familiar, guess) to determine if recognition was above chance. Figure 4b demonstrates that all categories are significantly above chance (remember: $t(44) = 5.770$, $p < .001$, Cohen’s d = .860; familiar: $t(44) = 5.278$, $p < .001$, Cohen’s d = .787; guess: $t(34) = 3.609$, $p = .001$, Cohen’s d = .610).

A)



B)

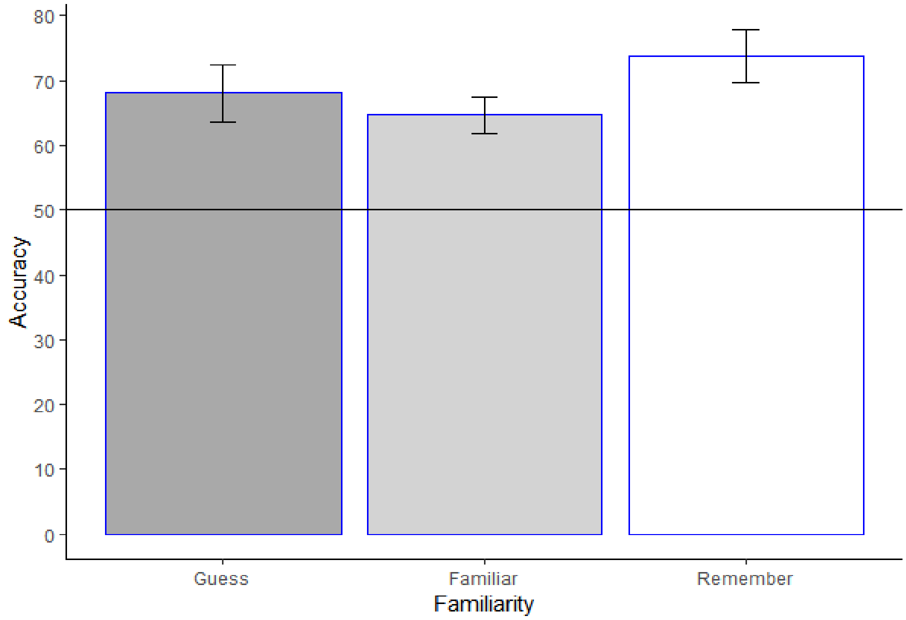


Figure 4. Performance on the 2AFC task. A) Children's mean accuracy scores on the 2AFC task. The solid line represents chance and the dashed line represents the group mean. B) Children's mean accuracy for each familiarity judgement for the remember/know procedure. The solid line represents chance. Error bars represent standard error of the mean.

3.3 Target Detection Task

One participant was excluded from the TDT analyses as they did not complete the task. Responses that were not between 0-1400 ms of syllable onset were considered false alarms and not included in the RT analyses. Mean RTs for each syllable position (initial, middle, and final) are plotted in Figure 5. A repeated measures ANOVA was conducted to determine whether RTs differed as a function of syllable position. Children had progressively shorter RTs for the first, second and third syllables (Syllable position effect: $F(2,86) = 13.211$, $p < .001$, $\eta_p^2 = .235$; linear contrast: $F(1,43) = 26.484$, $p <$

.001, η_p^2 = .381). A paired samples t-test was conducted. Syllable position three was significantly faster than syllable positions one and two (t(43) = 5.146, p < .001, Cohen's d = .685; t(43) = 3.126, p = .003, Cohen's d = .473, respectively). Syllable position one and two were not significantly different (t(43) = 1.715, p = .094, Cohen's d = .245).

We calculated an RT priming effect, which is defined as the magnitude of the difference in RTs between the final syllable and first syllable [$(S_1 – S_3)/S_1$]. This formula was used because it controls for individual differences in RT baselines (Batterink & Paller, 2019). The RT priming effect was significantly above zero (M = .132, SD = .168, t(43) = 5.205, p < .001, Cohen's d = .785), providing evidence for implicit statistical learning. Split-half reliability was calculated to determine whether RTs changed throughout the task. Reliability between the first twelve trials and the last twelve trials was acceptable (α = .783), demonstrating modest differences between individuals' RTs. The split-half reliability for the overall number of syllable misses and false alarms was also acceptable (α = .764; α = .701, respectively). This suggests that accuracy tended to be stable over the course of the TDT. Children missed an average of 26.705 syllables (SD = 4.169) out of the 96 target syllables and made an average of 23.455 false alarms (SD = 13.741). Sensitivity and response bias of signal and noise discrimination was calculated via d' and β (d' = 2.137, β = 2.767). The d' value was significantly above zero indicating that the children were able to discriminate the signal over the noise (t(43) = 25.613, p < .001, Cohen's d = 3.864). The β value was significantly above one indicating that participants were less likely to respond when the target was absent (t(43) = 7.425, p < .001, Cohen's d = 1.119).

In addition, we looked at mean target misses per syllable position (see Figure 6). There was a significant effect of syllable position for target misses ($F(2,86) = 8.661$, $p < .001$, $\eta_p^2 = .168$; Linear contrast: $F(1,43) = 8.055$, $p = .007$, $\eta_p^2 = .180$). Paired samples t-tests demonstrated that the number of target misses at the first syllable was lower than the second and third syllables ($t(43) = -4.760$, $p < .001$, Cohen's d = .544; $t(43) = -2.838$, $p = .007$, Cohen's d = .372, respectively). The second and third syllable positions were not significantly different ($t(43) = .936$, $p = .354$, Cohen's d = .122).

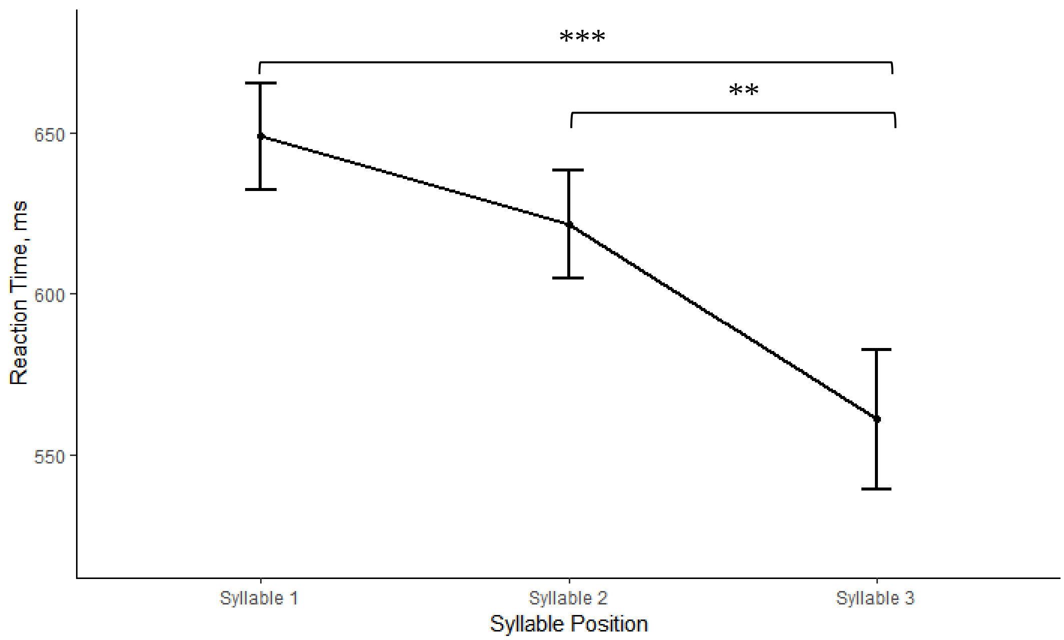


Figure 5. Mean RTs for each syllable position for the target detection task. Error bars represent standard error of the mean. Significant differences of $p < .001$ are denoted with *** and $p < .01$ with **.

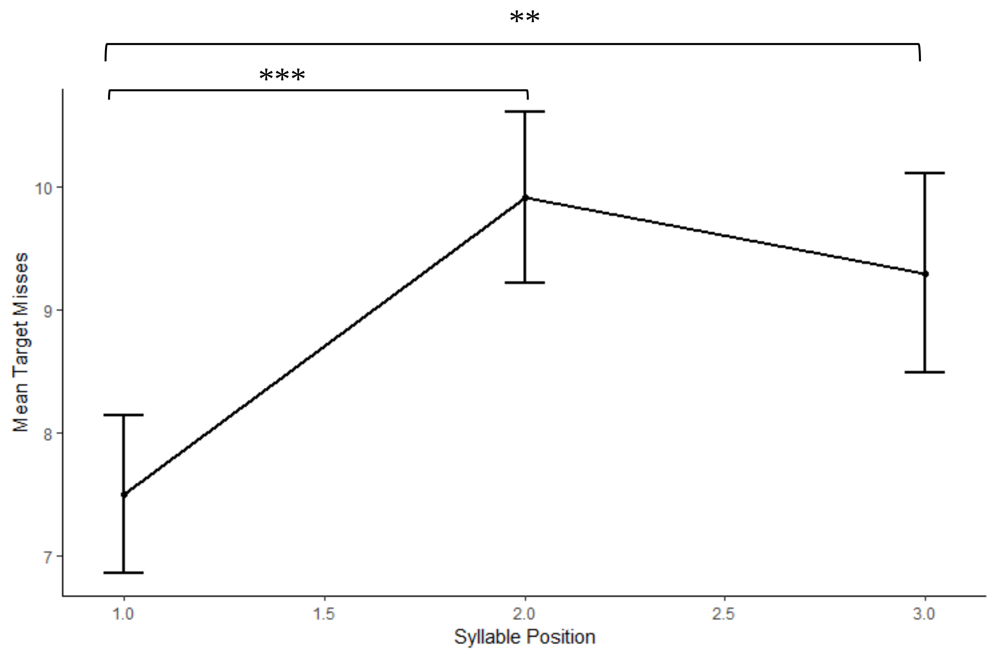
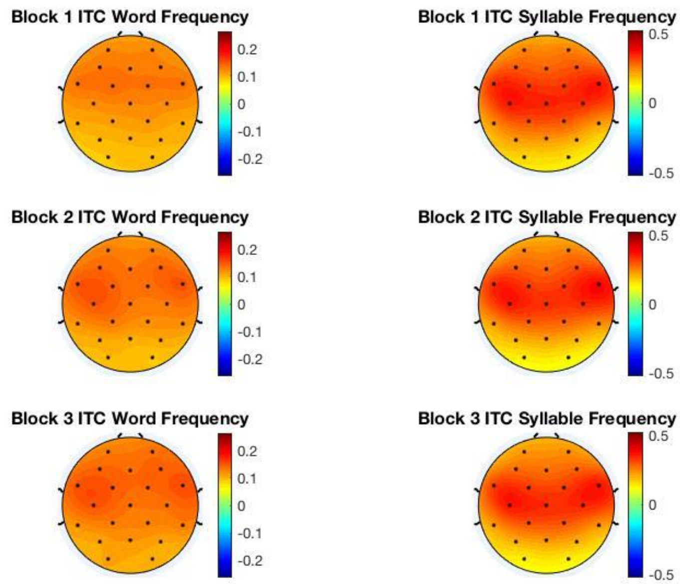


Figure 6. Mean target misses per syllable position. Error bars represent standard error of the mean. Significant differences of $p < .001$ are denoted with *** and $p < .01$ with **.

3.4 Neural Entrainment

Figure 7 demonstrates neural entrainment at the predicted word (1.1 Hz) and syllable frequencies (3.3 Hz). ITC_{Word} increased and $ITC_{Syllable}$ decreased with exposure; however, the effect was not significant (ITC_{Word} Effect: $F(1.620, 71.295) = 1.848$, $p = .172$, $\eta_p^2 = .04$; linear effect: $F(1,44) = 2.677$, $p = .109$, $\eta_p^2 = .057$; $ITC_{Syllable}$ Effect: $F(2,88) = .702$, $p = .498$, $\eta_p^2 = .016$; linear Effect: $F(1,44) = 1.356$, $p = .251$, $\eta_p^2 = .030$). As expected, the WLI, representing the ratio of the word frequency versus the syllable frequency, significantly increased throughout the exposure period (WLI effect: $F(2,88) = 3.424$, $p = .037$, $\eta_p^2 = .072$; linear effect: $F(1,44) = 6.374$, $p = .015$, $\eta_p^2 = .127$; see Figure 8). The WLI results are consistent with previous findings in adults (Batterink & Paller, 2017, 2019). A paired samples t-test demonstrates that WLI is only significantly different between the first and third blocks ($t(44) = 2.525$, $p = .015$, Cohen's d = .433). Block two was not significantly different from block one and three ($t(44) = -1.686$, $p = .099$, Cohen's d = .263; $t(44) = -.975$, $p = .335$, Cohen's d = .141).

A)



B)

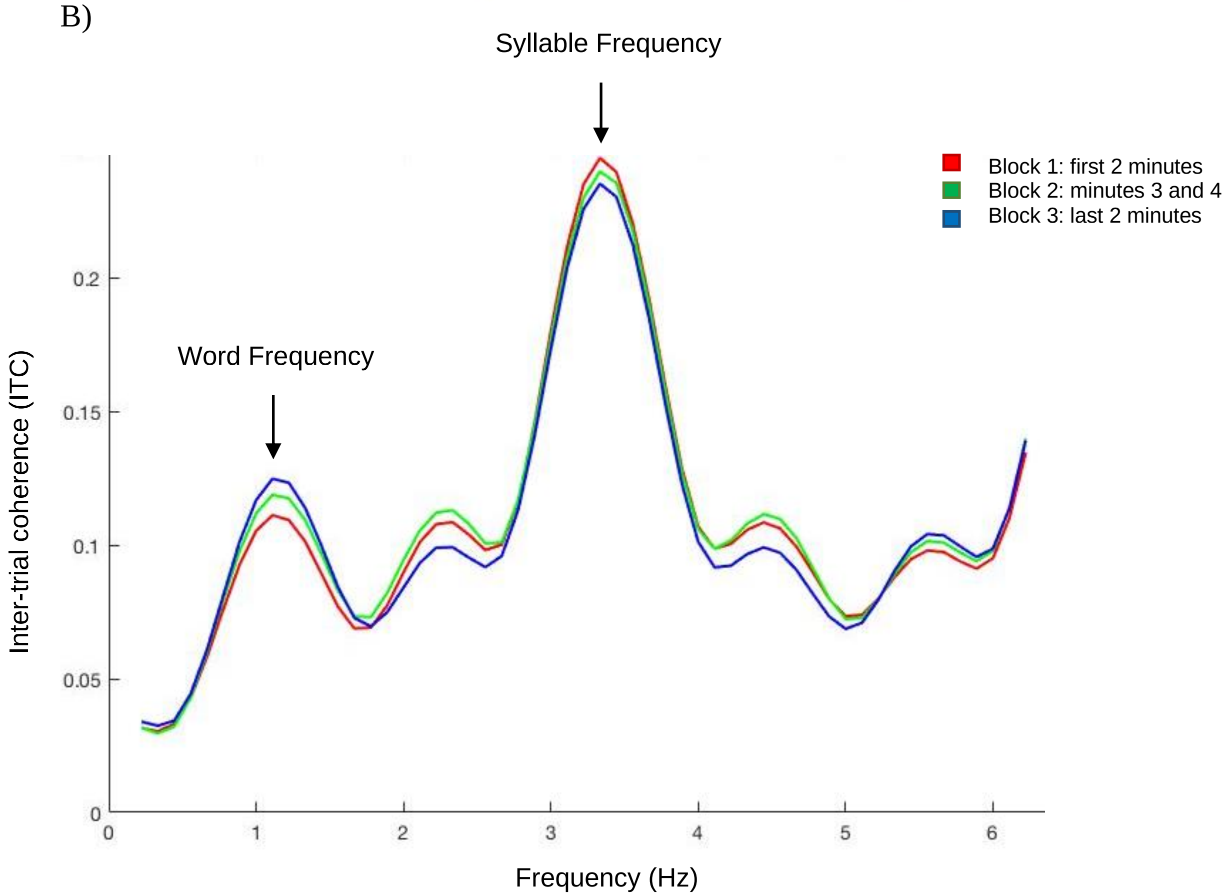


Figure 7. Neural entrainment results. A) Topographical plots of the distribution of ITC word and syllable frequencies across the scalp. Different scales are used for the word and syllable frequency plots. B) ITC at the word and syllable frequencies.

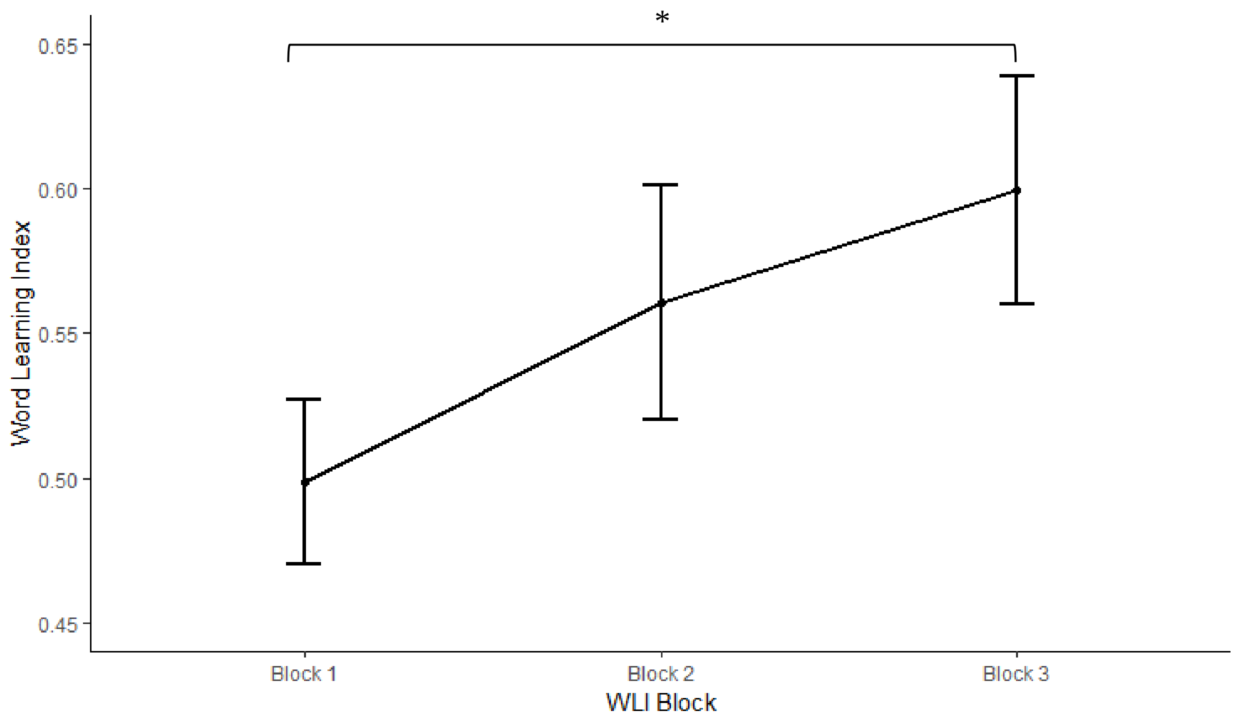


Figure 8. Mean WLI values denoting the ratio of word frequency versus syllable frequency for the first two minutes (Block 1), middle two minutes (Block 2), and last two minutes (Block 3). Error bars are standard error of the mean. Significant differences of $p < .05$ are denoted with *.

3.5 Correlations

We also used correlations to assess whether there were age-related effects in statistical learning. Age was not correlated with the rating score ($r(41) = .098$, $p = .534$), the 2AFC task ($r(42)$ .093, $p = .48$), the TDT ($r(42) = .174$, $p = .259$) or number of false alarms on the TDT ($r(42) = -.154$, $p = .317$); however, it was significantly correlated with the number of syllable misses on the TDT ($r(42) = -.383$, $p = .010$) and *d'*, our sensitivity measure for the TDT, ($r(42) = .333$, $p = .027$). See Figure 9 for the correlation scatter plots.

Next, we correlated performance on the post-learning tasks. The 2AFC task was positively significantly correlated with the rating task and the RT priming effect ($r(42) = .440$, $p = .003$; $r(42) = .344$, $p = .022$, respectively). The rating task and the RT priming effect were not correlated ($r(43) = .268$, $p = .075$).

We correlated the WLI with age and the explicit and implicit post-learning tasks. We removed two extreme outliers before conducting the correlations as the data points were above the third quartile by more than three times the interquartile range (IQR). WLI was not significantly correlated with age ($r(41) = -.298$, $p = .053$), ITC_{Word} was not correlated with age ($r(41) = -.106$, $p = .499$). However, $ITC_{Syllable}$ was significantly correlated with age ($r(42) = .321$, $p = .033$). We did not find any significant correlations between the WLI and the post-learning tasks (rating task: $r(40) = .236$, $p = .132$; 2AFC: $r(41) = .147$, $p = .346$; TDT: $r(40) = .252$, $p = .108$).

As an exploratory step, we correlated ITC_{Word} with the behavioural tasks. After excluding one extreme outlier, we found a significant correlation between ITC_{Word} and the RT priming effect ($r(41) = .341$, $p = .025$). The rating task and the 2AFC task were not significantly correlated with ITC_{Word} ($r(41) = .292$, $p = .057$; $r(42) = .177$, $p = .252$, respectively). $ITC_{Syllable}$ was not correlated with any of the post-learning measures (rating task: $r(42) = .095$, $p = .538$; 2AFC: $r(43) = -.128$, $p = .402$; TDT: $r(43) = .042$, $p = .788$).

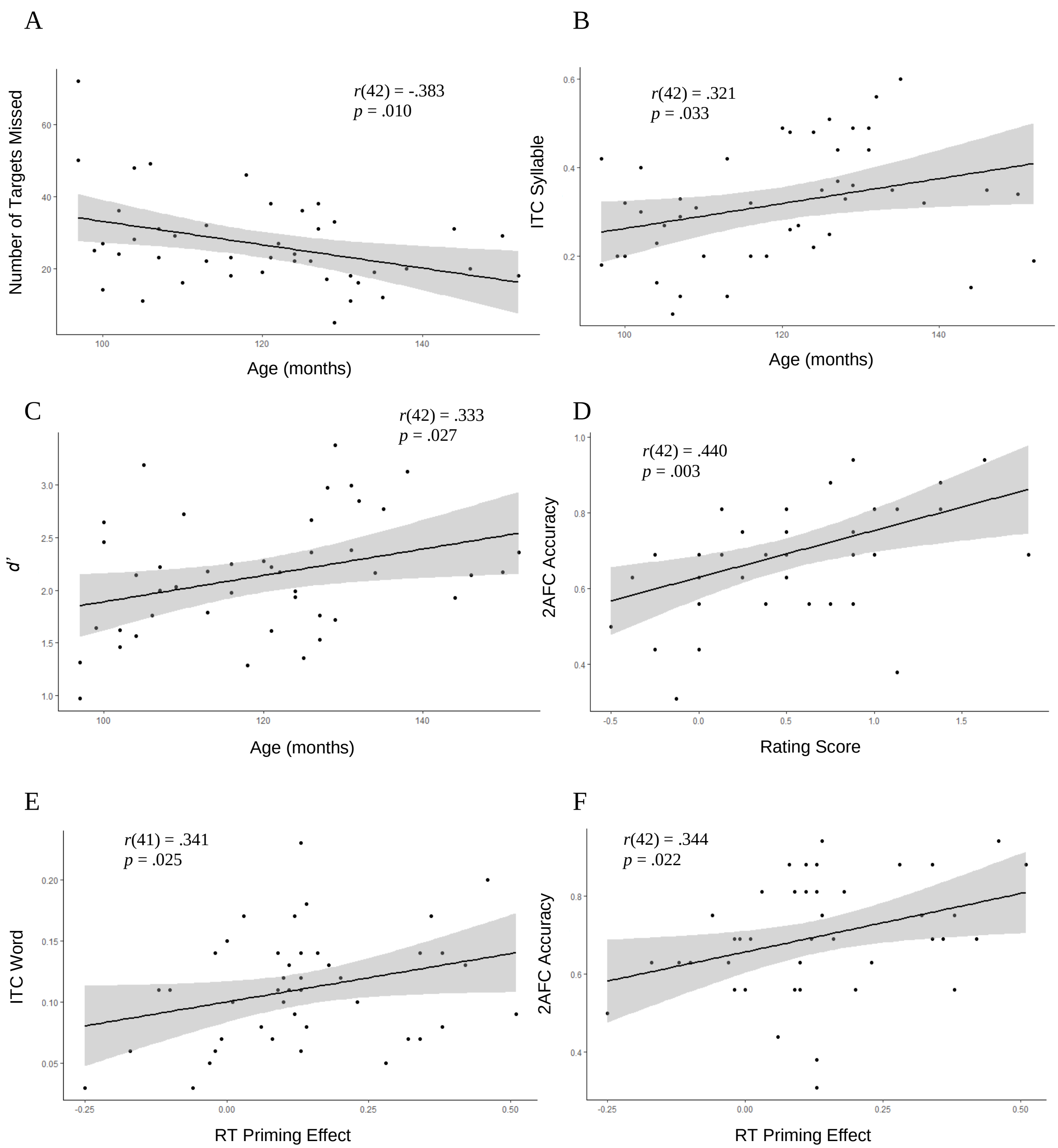


Figure 7. Correlations between A) number of targets and age (months), B) ITC$_{\text{Syllable}}$ and age (months), C) *d'* on TDT and age (months), D) 2AFC task and rating score, E) ITC$_{\text{Word}}$ and RT priming effect and F) 2AFC task and RT priming effect. Scatter plots include the 95% confidence interval.

Chapter 4

4 Discussion

In contrast to the abundance of research on statistical learning as a language learning mechanism in adults, few studies have looked at auditory statistical learning in children, and none have used measures of EEG to record online statistical learning. As cognition in childhood is ever-changing, studying statistical learning in children is crucial as it provides information on the development of language learning processes. We examined online statistical learning through EEG neural entrainment to a six-minute artificial language, in addition to examining offline statistical learning with a range of explicit and implicit post-learning tasks. The measures used in the present study have been shown to be sensitive indicators of individual differences in statistical learning in adults. The aim of this research was twofold; to determine whether the EEG neural entrainment measure is a sensitive indicator of statistical learning in children and to determine whether the implicit TDT is a valid indicator of individual differences in statistical learning in a younger population. Indeed, our study demonstrates that the implicit and online learning measures are sensitive indicators of individual differences of statistical learning in children.

Our results replicate and extend previous findings of statistical learning in children. As in previous studies, children were able to pick up on the statistical patterns of a novel artificial language (e.g., Arciuli, & Simpson, 2012; Evans, Saffran, & Robe-Torres, 2009; Saffran et al., 1997). Our results demonstrate significant explicit learning through the 2AFC task and the rating task. As anticipated, the group performed significantly above chance on the 2AFC task, with only a handful of participants below or at chance. The remember/familiar/guess responses for the remember/know procedure were all significantly above chance, demonstrating that judgements did not differ according to accuracy. These findings are divergent from Batterink, Reber and colleagues' (2015) findings in adults as they found a significant effect of meta-memory judgements on accuracy, indicating that participants had knowledge and awareness of their own memories (Dienes & Berry, 1997). One explanation for the divergent findings for the remember/know procedure is that we had fewer trials than Batterink, Reber et al. (2015). Their study had 36 trials, whereas our study had 16 trials. This could have affected the task's sensitivity to detect a significant meta-memory effect.

As expected, children had an average rating score that was significantly above chance, with words rated as the most familiar then partwords, followed by nonwords. These findings replicate previous findings in adults (e.g., Batterink & Paller, 2017), indicating that the rating task is a sensitive measure of explicit statistical learning in both children and adults. Interestingly, the rating score is lower than the average rating score previously found in adults (Batterink & Paller, 2017). Children's rating score was .50, whereas the adults' rating score was .78. A likely explanation for the differences found between our study and Batterink and Paller's (2017) study is the way in which the partwords were made. The partwords in our study may have been more difficult to distinguish from the words because the transitional probabilities were higher (.33 for syllables one and two and 1.0 for syllables two and three), whereas the partwords in previous studies had lower transitional probabilities (0.0 for syllables one and two and 1.0 for syllables two and three; Batterink & Paller, 2017, 2019).

Consistent with our hypothesis and previous findings in adults (e.g., Batterink, Reber et al., 2015), the RT priming effect for the TDT was significant and children showed increasingly faster RTs for more predictable syllable positions. These findings indicate that children used their knowledge of the structure of the speech stream to predict upcoming syllables. Sensitivity and response bias, as measured by *d'* and *β*, demonstrate that children have a greater sensitivity to target syllables rather than noise.

Saffran and colleagues (1997) did not find a significant difference in performance in auditory statistical learning between adults and children. With the use of additional measures, our results provide information on the extent of statistical learning in children, which allows us to further quantify the differences in statistical learning between age groups. By comparing our results to previous findings in adults, we can observe that, although children and adults do perform significantly above chance on the implicit and explicit learning tasks, there are quantitative differences between age groups. Children had slower RTs than adults in previous studies, even though the task was made easier by slowing syllable presentation (Batterink & Paller, 2017, 2019; Batterink, Reber, et al., 2015). One explanation for the slower RTs could be explained by developmental differences in motor processes. In a study on the differences in motor sequence learning in adults and children, young children's RTs were significantly slower than older children's and adults' RTs (Du, Valentini, Kim, Whitall, & Clark, 2017). Children also missed more targets than the adults (15.7 target misses in adults) and their false alarm rate was almost doubled the adults' rate of 12.3 (Batterink & Paller, 2017). Interestingly, the children's false alarm rate was only slightly higher than the adults' 18.9 false alarms from Batterink and Paller's (2019) study on attention. It is possible that the adults' higher false alarm rate could be due to the amalgamation of the results for the full attention group with the divided attention group. The slower RTs, higher false alarm rate and target misses in children could be due to a shorter attention span during the exposure period. Previous studies have found that sustained attention does increase with age, especially between the pre-teen years and adulthood (Lin, Hsiao, & Chen, 1999; McKay, Halperin, Schwartz, & Sharma, 1994). As was found by Batterink and Paller (2019), statistical learning still occurs when attention is not directly on the speech stream; however, less attention on the speech stream can negatively impact long-term memory storage of the encoded trisyllabic words.

In addition to our post-learning tasks, we measured neural entrainment because it provides information on statistical learning that is dissociable from long-term memory. Our measure of event-related phase locking, inter-trial coherence (ITC), increased at the word level and decreased at the syllable level; however, this change was not significant. One explanation for these findings is that the change in entrainment over time within a single frequency is too weak to reach significance. Once the two frequencies are calculated together via the WLI, we see a significant increase in word learning over time. This effect suggests that children started perceiving syllables as whole word units rather than individual syllable parts, providing evidence of statistical learning. These findings demonstrate that the WLI is more sensitive to changes in entrainment over time than the ITC frequency values alone. The increase in WLI over time is consistent with the findings in adults (Batterink & Paller, 2017, 2019). This demonstrates that both children and adults seem to transition from representing the speech stream to representing whole words. The WLI also provides a sensitive measure of individual differences in children as individual variability can be observed during online encoding at the syllable and word frequencies.

An additional explanation for the differences found between the children in this study and adults in previous studies, is that children's explicit memory and working memory are not as developed as adults' (Finn et al., 2016). Working memory, responsible for the temporary storage and manipulation of information, and explicit memory have been linked to language learning abilities (Baddeley, 2003), which could explain why it looks like children do not perform as well or as quickly as adults on the post-learning tasks. However, when comparing WLI values, it seems as though the effect is consistent across age groups. These findings support Batterink and Paller's (2019) findings that attention does not affect neural entrainment to words but can affect performance on the post-learning tasks due to constraints on memory retrieval. This supports the theory that differences found between age groups are due to memory processes and not statistical learning capabilities. Future studies should directly compare statistical learning between adults and children to determine whether the differences across age groups are significant.

4.1 Correlations

Interestingly, when we correlated the behavioural measures, the 2AFC task was positively correlated with the rating task and the RT priming effect. Therefore, the 2AFC task is predictive of performance on the rating task and the TDT. These findings are unlike previous findings in adults as the TDT was not found to be significantly correlated with the 2AFC task (Batterink, Reber et al., 2015). One explanation for these differences in findings is that our sample size was larger. It is possible that with a larger sample size, we were able to detect a correlation due to having more statistical power. An additional explanation for these findings is that recognition on the 2AFC task taps into both implicit and explicit knowledge. This notion fits in with Voss, Baym and Paller's (2008) findings that recognition mechanisms are allied with both implicit and explicit memory. Our findings support the notion that implicit knowledge of statistical probabilities is acquired in parallel with explicit knowledge.

Contrary to previous findings, we did not find a significant correlation between the WLI and the post-learning measures. These findings are unexpected as previous studies looking at the relationship between the WLI and post-learning tasks found a significant positive correlation with the RT priming effect (i.e., Batterink & Paller, 2017, 2019). This could mean that the WLI is not as sensitive of an indicator of statistical learning in children as it is in adults. However, when we correlated ITC_{Word} with the RT priming effect, we did find a significant positive correlation. This means that children who have greater neural entrainment at the word frequency show better performance on the speeded TDT. It appears that normalizing word frequency by syllable frequency may produce a less sensitive measure of statistical learning in children. Furthermore, $ITC_{Syllable}$ was found to be significantly correlated with age, demonstrating that older children have a higher entrainment at the syllable level. This is likely due to the maturation of attentional processes. Older children may be able to attend to the speech stream longer than younger children, which leads to stronger neural responses at the syllable frequency. Since younger children have less neural entrainment at the syllable frequency, normalizing neural entrainment would be inappropriate as the WLI values would be inflated for younger children relative to older children.

In addition, age was found to be negatively correlated with the number of syllable misses on the TDT and positively correlated with *d'*, our measure of sensitivity for the TDT. This means that the number of syllable misses decreased with age and sensitivity to targets increased with age. These results provide further evidence for the role of age in attentional processes related to implicit statistical learning.

4.2 Limitations and Future Directions

One of the limitations of our study is that even though we shortened the TDT by 12 streams, it still seemed to be too long for children. Their attention would wander, which likely led to more false alarms and missed targets. If the task is further shortened; however, the results may not be as powerful. One possibility is to make the task more engaging. Our task had a square at the bottom of the screen that would change colour with each button press. In the future, a more engaging cover task should be created to direct and maintain children's attention on the TDT.

Our study used tasks that remedy the psychometric shortcomings of statistical learning tasks detailed by Siegelman et al. (2017). However, there are other psychometric concerns that were not addressed. A recent study examining task reliability on several statistical learning tasks found that the tasks were not reliable indicators of performance in children across time and had low internal consistency (Arnon, 2019). From this study, we know that the 2AFC task has some additional psychometric shortcomings that make it difficult to predict individual variation in statistical learning in children. The tasks that we used in the present study have not been tested for reliability. Future work on statistical learning should determine the tasks' test-retest reliability to determine whether statistical learning as assessed by these tasks is a reliable individual predictor of statistical learning across time.

The measures used in this study are sensitive and powerful predictors of individual variation in statistical learning (e.g., Batterink & Paller, 2017, 2019), therefore they could provide useful information on differences between groups. As previously mentioned, there were differences on post-learning measures of statistical learning between adults and children. However, it is not known whether these differences are significant and to what extent they differ. The statistical learning results from our study and previous studies in adults cannot be directly compared as there are key differences between the studies. Some of these differences include a longer exposure period and different syllable presentation rates, which could affect the degree of statistical learning and influence the results on the post-learning tasks and the WLI (Batterink & Paller, 2017, 2019). A direct comparison between children and adults is needed to further understand the dynamics of statistical learning across the lifespan. In addition, these tasks could be used to discover differences in statistical learning between special populations. For instance, there is some debate over whether children with developmental dyslexia perform significantly worse than children who are typically developing (Schmalz, Altoè, & Mulatti, 2017). Some studies have reported that typically developing participants have better statistical learning abilities than participants with dyslexia (e.g., Sigurdardottir et al., 2017), whereas other studies have reported that there are no group differences (e.g., Nigro, Jimenez-Fernandez, Simpson, & Defior, 2015). The neural entrainment and implicit learning measures may shed some light on whether there are truly differences between various groups.

4.3 Conclusions

This is the first study to look at online neural entrainment during statistical learning in children. The current study has provided important information on the dynamics of statistical learning by demonstrating that children acquire both implicit and explicit knowledge of a novel language. These findings replicate prior findings that explicit and implicit memory play a role in learning the probabilities of a novel language. Importantly, these findings demonstrate that both adults and children use similar underlying mechanisms of statistical learning. Furthermore, we found that there were age-related effects in neural entrainment at the syllable level. Less neural entrainment at the syllable level could be due to a shorter attention span in younger children, which could have led to more syllable misses and lower sensitivity to target syllables on the TDT.

These findings could have implications for future research on statistical learning in children. The neural entrainment results demonstrated rapid implicit learning of word-level information, while post-learning behavioural tasks demonstrated significant syllable prediction and recognition of the trisyllabic words. This opens the door to the possibility of using these measures in populations with developmental disabilities. These measures could provide important information on the developmental trajectory of statistical learning in a wide range of children and inform us on the cognitive mechanisms underpinning language learning impairments.

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Appendices

Appendix A: Background Questionnaire

Section 1: General Information

Sex: □Male □ Female You don't have an option that applies to my child. They identify as (please specify): ____________________

Age (years; months): __________ Grade: __________

Is your child right or left-handed (circle one)? Left Right Both

Section 2: Language History

Age at which your child learned to speak: ____________________

Age at which your child began to form full sentences: ____________________________

Age at which your child learned to read: ___________________________________

Age at which your child began to read fluently: ____________________

Is English your child's first language (circle one)? Y N

If no, please list which language(s) they learned from birth:

Using the table below, please list the languages that your child can speak, understand, read and write. For each, indicate years of experience and rate how well they can speak, understand, read and write in that language.

For number ratings, please use the following scale:

Not at all	*Very low*	*Low*	*Fair*	*Less than adequate*	*Adequate*	*More than adequate*	*Good*	*Very good*	*Excellent*	*Perfect*
0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*

Language	Exposure	Speak	Understand	Read	Write
E.g., English	Entire life	10	10	10	10

E.g., French	2 years	5	5	8	8

Section 3: Learning Challenges

Does your child currently or has ever been diagnosed with any type of reading or language disorder (circle one)? Y N

If yes, please explain:

Does your child currently or has ever been diagnosed with any type of visual or auditory impairment (circle one)? Y N

If yes, please explain:

Has your child ever been diagnosed with a learning disorder or neurological impairment (ADHD, autism, epilepsy)? Y N

If yes, please specify:

Has your child ever had a serious head injury (i.e., concussion)? Y N

If yes, please specify:

Does your child take medications regularly? Y N

If yes, please specify:

Comments:

Appendix B: Letter of Information

Project Title: Statistical Learning in Children

Document Title: Letter of Information and Consent

Principal Investigator and Contact: Dr. Marc Joanisse, Ph.D. (Western)

Additional Research Staff Contacts: Christine Moreau

Introduction

Your child is invited to participate in a study that examines visual and auditory learning in children with language and reading impairments. We are exploring whether children with reading and language impairments differ from typically developing children on an artificial language learning task and a visual sequence learning task. Your child is being asked to participate in this research because they are English monolingual, are neurologically healthy, and are between the ages of 8 to 12 years.

Purpose of the Study

The purpose of this study is to collect information on the underlying causes of language and reading disorders. We will examine your child's brain activity through the use of electroencephalography (EEG), which will allow us to observe the neural components involved in language and sequence learning. Information we obtain in this study will provide us with knowledge on the underlying structures involved in language and reading disorders in children.

Inclusion Criteria

Children who are English monolingual between the ages of 8 and 12 years, with normal or corrected-to-normal vision, no history of hearing, neurological or psychiatric disorders. We are looking for children with language and reading impairments, whether they be diagnosed or undiagnosed with, for example, dyslexia, and developmental language disorder. We are also looking for children who do not have any reading or language impairments.

Exclusion Criteria

Children who are not between 8 and 12 years old are not eligible. Children who are bilingual or who have another language other than English as their first language is not eligible. Children who have been diagnosed with other developmental/learning disorders not related to language or reading are not eligible (i.e., ADHD, autism spectrum).

Study Procedures

This study will involve a single testing session that will take place in the Western Interdisciplinary Research Building on the Western University campus and will take approximately two hours to complete. We will explain the procedures to you and your child and ask them if they agree to participate. During the study, you will be asked to fill out a demographic/language background questionnaire. While you are filling out this questionnaire, your child will complete a series of reading, language and cognitive tasks. Some will be done with pen and paper and others will be done on the computer. Next, your child will be asked to listen to a short speech stream and afterward respond to tasks related to the speech stream. This includes being tested on reaction time responses to the auditory stimuli by pressing buttons on a computer or response pad. For the visual sequence learning task, your child will be asked to respond to a visual sequence presented on a computer screen by pressing buttons on a computer keyboard or response pad and filling out a short questionnaire. During the auditory and visual sequence learning tasks, we will monitor your child's brain activity with an electroencephalogram (EEG).

EEG Procedure

We will put a cap with electrodes on your child's head and secure it with a chin-strap. These electrodes will monitor small changes in neuronal activity during the auditory and visual sequence learning tasks. The EEG is non-invasive and completely safe to use. Your child will be seated comfortably on a chair positioned in front of the computer. The EEG cap will be placed on your child's head and gel will be applied to the sensors on the cap. The electrodes never come into direct contact with your child's skin and the gel used is safe, non-toxic and easily washes off hair and clothes. Afterwards, if needed, there is a washing station where you can wash your child's hair. The set-up of the EEG takes approximately 30 minutes to complete, and your child has the option of watching a short child-friendly movie. Once the set-up is complete, your child will complete the auditory and visual sequence learning tasks on the computer.

Compensation

You will receive $20 to cover any travel expenses, in addition to free parking at Western University. Your child will also receive a $20 gift certificate for the movies. If your child does not complete the entire study, you will still be compensated for participating in the study.

Possible Risks and Harms

There are no known or anticipated risks associated with participating in this study. The sensors in the EEG cap do not emit electricity or electromagnetic fields. There may be some minor discomfort during the set-up of the EEG cap (i.e., while gel is being put on the cap sensors). We will be in constant communication with your child and we will be as gentle as possible during the set-up process. During all stages of the experiment, your child's comfort level will be monitored. If, at any point, your child feels tired or uncomfortable they can take a break or withdraw from the study at any time.

Possible Benefits

You and your child may not directly benefit from participating in this study, but information gathered may provide benefits which include advancing knowledge on how children with language and reading disorders learn new auditory and visual sequences. Participation in this study is voluntary. Even if you and your child consent to participate, you and your child have the right to not answer any question or to withdraw from the study at any time. If you decide to withdraw from the study, there will be no effect on your child's academic standing. Any new learned information that may affect your decision to stay in the study will be reported to you. By signing this consent form, you do not waive any legal rights.

Confidentiality

Representatives of The University of Western Ontario Non-Medical Research Ethics Board may require access to your study-related records to monitor the conduct of the research. Paper copies of consent forms and participant demographic data will be kept in a secure location for a minimum of 7 years before being destroyed. Password protected and encrypted electronic files that contain only de-identified data will be stored on a secure computer. Anonymized electronic data will be retained indefinitely. The anonymized electronic data will not be stored alongside personal information. If you indicate that you are interested in participating in future studies, we will need your e-mail address or phone number for correspondence purposes. If you provide it, the e-mail address or phone number will not be linked to study data and it will be stored in a secure location. Your data will be coded with a unique number, and a list linking your name with your study number will be securely stored separate from your data for a minimum of 7 years. If the results of the study are published, your child's name will not be used.

In addition, the de-identified research data will be stored on the osf.io website, keeping with best practices of open and transparent scientific research. This means that any member of the public will have access to your child's research records indefinitely. Raw data linked to your child's unique study ID will be shared on the osf.io website; however, the data we release to the general public will, to the best of our knowledge, not contain information that can directly or easily identify your child. The research records from this study might be used for other, future research projects. Once research records have been shared with the general public, it will not be possible for us to fully withdraw or recall it. However, if you do indicate you wish for your child's data to be withdrawn in the future, we can only remove it from the public repository to prevent any further access to it.

Your contact and demographic information will be stored in a secure, password-protected database. If you would like to be contacted about future research studies for which you (or your child) may be eligible, you can choose to have your information entered into "OurBrainsCAN: University of Western Ontario's Cognitive Neuroscience Research Registry". This is a secure database of potential participants for research at the University of Western Ontario that aims to enroll 50,000 volunteers over a period of 5 years. The records are used only for the purpose of recruiting research participants and will not be released to any third party.

Further Information

If you have questions about this research study, please contact Christine Moreau at X. You may also contact Dr. Marc Joanisse at X. If you have any questions about your rights as a research participant or the conduct of this study, you may contact The Office of Human Research Ethics.

This letter is yours to keep for future reference.

Appendix C: Ethics Approval

Western Research

Date: 13 November 2018

To: Prof. Marc Joanisse

Project ID: 112673

Study Title: Statistical Learning in Children with Reading and Language Impairments

Application Type: NMREB Initial Application

Review Type: Delegated

Full Board Reporting Date: December 7 2018

Date Approval Issued: 13/Nov/2018

REB Approval Expiry Date: 13/Nov/2019

Dear Prof. Marc Joanisse

The Western University Non-Medical Research Ethics Board (NMREB) has reviewed and approved the WREM application form for the above mentioned study, as of the date noted above. NMREB approval for this study remains valid until the expiry date noted above, conditional to timely submission and acceptance of NMREB Continuing Ethics Review.

This research study is to be conducted by the investigator noted above. All other required institutional approvals must also be obtained prior to the conduct of the study.

Documents Approved:

Document Name	Document Type	Document Date	Document Version
Assent Letter_Statistical Learning in Children	Written Consent/Assent		
Background questionnaire_Children	Paper Survey		
Example of visual stim (Ariculi & Simpson, 2012)	Paper Survey		
Examples of tasks	Paper Survey		
Facebook ad	Recruitment Materials		
LOI and consent form_Statistical Learning in Children	Written Consent/Assent		
Phone Script for Recruitment	Recruitment Materials		
Poster_ad_kids	Recruitment Materials		
Recruitment_Email_children	Recruitment Materials	11/Oct/2018	
Recruitment_London District Catholic School Board	Recruitment Materials	06/Nov/2018	1
Visual task questionnaire	Paper Survey		

Documents Acknowledged:

Document Name	Document Type	Document Date	Document Version
Eligibility Questionnaire	Screening Form/Questionnaire		

No deviations from, or changes to the protocol should be initiated without prior written approval from the NMREB, except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

The Western University NMREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the Ontario Personal Health Information Protection Act (PHIPA, 2004), and the applicable laws and regulations of Ontario. Members of the NMREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB. The NMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000941.

Please do not hesitate to contact us if you have any questions.

Curriculum Vitae

Christine Moreau

Education

2017-2019	Western University London, Ontario, Canada MSc Psychology
2011-2016	University of Ottawa Ottawa, Ontario, Canada Honour's BSc Psychology

Honours and Awards

2019	Ontario Association on Developmental Disabilities: Research Special Interest Group Student Travel Award, Research Special Interest Group Research Day
2017-2019	Western Graduate Research Scholarship, Western University, London, ON
2015-2016	Dean's Honour List, Faculty of Sciences, University of Ottawa, Ottawa, ON
2011	Admission Scholarship, University of Ottawa, Ottawa, ON

Relevant Work Experience

2018-2019	Co-supervised undergraduate students, Western University
2017-2019	Teaching Assistant**,** Western University
2016-2017	Research Assistant, Cognitive Psychology of Language Laboratory, University of Ottawa, ON, Supervisor: Dr. Alain Desrochers
2015	Research Assistant, Social Psychology of Language and Communication Laboratory, University of Ottawa, ON, Supervisor: Dr. Richard Clément

Conference Presentations

Moreau, Joanisse, Batterink, Liesemer, & Child. (2019). Statistical Learning and How it Relates to Language and Reading Abilities: An EEG Study. Poster presented at the Canadian Society for Brain, Behaviour and Cognitive Science, Waterloo, ON.

Moreau, Joanisse, Batterink, Liesemer, & Child. (2019). Statistical Learning and How it Relates to Language and Reading Abilities: An EEG Study. Poster presented at the Developmental Disabilities Research Day, London, ON.

Moreau, Liesemer, Child, Batterink, & Joanisse. (2019). A look at statistical language learning and how it relates to the emergence of language and reading disorders. Data blitz (3-minute oral presentation) and poster presented at the Research Special Interest Group Research Day, Niagara Falls, ON.

Moreau, Joanisse, & Batterink. (2019). Statistical learning across visual and auditory modalities. Five-minute oral presentation and poster presented at Western Research Forum, Western University, London, ON.

Moreau, Joanisse, & Batterink. (2019). Statistical learning across visual and auditory modalities. Poster presented at the Lake Ontario Visionary Establishment (LOVE) conference, Niagara Falls, ON.

Moreau, & Fennell. (2017). The Effects of Mobile Media Use on Language Acquisition in Monolingual and Bilingual Infants. Poster presented at the International Symposium on Bilingualism (ISB11) University of Limerick, Limerick, Ireland.

Moreau, & Fennell. (2016). The Effects of Mobile Media Use on Language Acquisition in Monolingual and Bilingual Infants. Poster presented at the Ontario Psychology Undergraduate Thesis Conference Wilfrid Laurier University, Waterloo, ON.