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Relating Neural and Behavioural Measures of Statistical Learning to Children's Reading Abilities

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Supervised by: Dr. Laura Batterink and Christine Moreau

Western University

Abstract

The process of reading is guided by statistical regularities between orthographic and phonological properties embedded in the English language system. Reliance on these probabilistic cues suggest statistical learning (SL) may be an underlying mechanism in reading ability and variance in SL could explain why those with reading impairments struggle to become proficient readers. Previous research has found a relationship between SL and reading ability; however, majority of these studies use offline measures of SL that are sensitive to secondary processes. The current study examined the link between SL and reading ability in 32 children using traditional measures of SL and a relatively new online measure of electroencephalogram neural entrainment for a pure assessment of SL. Participants showed evidence of SL as measured by online and offline methods; however, no relation between SL and reading ability was found. The implications of this study may inform the ways in which children are taught to read such as implementing more explicit compared to implicit reading activities and instructions.

Relating Neural and Behavioural Measures of Statistical Learning to Children's Reading Ability

From the time we are infants, humans are able to learn statistical regularities in their environment and make predictions based off of those patterns (Saffran, Aslin, & Newport, 1996). This powerful learning mechanism, known as statistical learning (SL), has been shown to take place during passive exposure to complex patterns (Yang & Flombaum, 2015). While SL can occur during a variety of learning processes, it is most commonly understood through the context of speech segmentation. For example, when listening to the phrase "what a pretty baby", English speakers are able to implicitly identify higher transitional probabilities within words (e.g., pre-tty) and lower transitional probabilities across word boundaries (e.g., ty-ba). Despite the fact that there are no reliable pauses between words in spoken language, utilizing this transitional probability information allows one to distinguish boundaries between words (e.g., "pretty" and "baby"; Romberg & Saffran, 2010). Moreover, previous research has found typically developing (TD) children are not only able to identify transitional probabilities from an artificial speech stream of non-sense words but they can also recognize newly learned non-words when compared to highly similar non-words (Raviv & Arnon, 2018). Notably, this precise ability to segment speech is an important reading skill when decoding words (White, Mattys, & Wiget, 2012).

Reading as Statistical Learning

When applying SL to the context of reading acquisition, Arcuili (2018) explained that children learn orthographic (letter combinations) to phonemic (sound) mapping regularities, such as identifying a grapheme (single letter) "a" with the specific phoneme /a/. English is a deep orthographical language system meaning each grapheme can correspond to multiple different phonemes compared to a shallow language system (e.g., Spanish, Croatian) which has a one to one correspondence of graphemes to phonemes (Miller, Kargin, & Guldenoglu, 2014). For example, the grapheme “a” has inconsistent phonemic representations among words like, “case”, “cat”, and “car” resulting in different orthographic combinations that follow different phonetic patterns, or rule exceptions. Arcuili (2018) explained that the patterns within the English language system follow a number of exceptions and while the majority of these rules are taught using explicit instruction within the classroom, a large portion of language learning involves passive exposure and implicit learning. It could be that certain aspects of SL relate to certain areas within the reading process. More specifically, the complex regularities and exceptions involved in orthographic to phonetic mappings suggests individuals with a precise ability to identify these patterns could have stronger underlying SL abilities.

Arciuli and Simpson (2012) showed that variability in SL is related to variability in reading for TD participants. They used a visual SL (VSL) paradigm where a stream of 12 aliens were arranged in four groups of three. Each group formed a specific pattern and aliens were presented on a computer screen one at a time in a continuous stream. Following this exposure phase, participants saw two groups of aliens: a group following the pattern from the stream and a group in an unfamiliar pattern. They had to choose the pattern that was more familiar. Accuracy on this task had a significant correlation to participants standardized scores of reading. Notably, the relationship between VSL and reading suggests that SL ability may be domain general mechanism opposed to domain specific as shown with the non-linguistic stimulus in this study.

As further support, native English speakers learning Hebrew showed VSL abilities that were correlated with second language reading ability (Frost, Siegelman, Narkiss, & Afek, 2013). In Hebrew there are two forms of spelling: “pointed” where vowels are included and “un-pointed” where no vowels are included (Kutscher & Kutscher, 1982). Better performance on the VSL task resulted in higher un-pointed non-word and pointed word reading ability. Together, these findings highlight the idea that an ability to distinguish non-linguistic patterns aids in reading ability. As noted previously, language provides probabilistic cues to orthographical and phonological mappings (Arciuli, 2018); it could be that SL is an underlying tool used to learn complexities within the reading process. While it is clear that variability in SL is related to variability in reading for TD participants, past research has not yet looked at SL in children with a range of reading abilities.

Reading Impairments and Statistical Learning

SL abilities have been known to differ significantly between TD participants and those with reading impairments such as developmental language disorder (DLD; also known as Specific Language Impairment) or developmental dyslexia (DD; Evans, Saffran, & Robe-Torres, 2009; Gabay, Thiessen & Holt, 2015). As a general overview, DLD is defined as difficulties or delays in receptive and expressive language that cannot be explained by another disorder or cause (Powers, Brooks, Obeid, Gillespie-Lynch, & Lum, 2016). In comparison, DD is defined as difficulties with correct word recognition and spelling in the presence of normal IQ and sensory abilities (Snowling, 2000). While these are two separate disorders, both have been implicated in deficits during SL tasks (Bishop & Snowling, 2004; Tomblin, Mainela-Arnold, Zhang, 2007; Gabay, Schiff, & Vakil, 2012).

Previous work by Evans et al. (2009) found a deficit in auditory SL (ASL) ability for those with DLD. Participants listened to an artificial speech stream consisting of six tri-syllabic non-sense words that were formed so transitional probabilities were higher within words than between words. After the familiarization phase, children distinguished which word was more familiar between a word from the stream and an unfamiliar word. TD participants performed better than children with DLD; however, when presented with a longer familiarization phase, children in the DLD also showed equal SL ability as reflected on post measure tasks. Moreover, impaired SL in those with DD has also been found during similar ASL experiments (Gabay et al., 2015). Participants with DD performed significantly worse compared to TD controls during an ASL experiment. These results were correlated with reading ability.

The deficits in SL for those with DLD is not only limited to ASL but VSL as well (Sigurdardottir, Danielsdottir, Gudmundsdottir, Hjartarson, Thorarinsdottir, & Kristjánsson, 2017). During a VSL paradigm, 12 shapes grouped into two pairs were presented on at a time in a continuous stream on a computer screen. The shape pairs were counter-balanced so that each pair was always seen together but the pairs were presented in a random order. After being familiarized to the shape patterns, TD participants and participants with DLD were asked to choose which pair of shapes was the most familiar from the stream. Participants with DLD identified a significantly smaller quantity of correct pairs than TD participants. The results of these studies go on to suggest that domain general impairments in SL may explain why those with reading impairments struggle to become proficient readers.

Neural Entrainment as a Measure of Statistical Learning

The majority of research on SL has used behavioural outcomes such as a familiarization phase followed by a behavioural task; these measurements target long term memory and SL ability (Vlach & Sandhofer, 2014). One way of teasing apart these two mechanisms is by introducing online measurements of neural activity to assess SL through neural entrainment. This occurs when the brain naturally synchronizes brain wave frequency to the rhythm of an external stimulus such as visual or speech patterns (Schroeder & Lakatos, 2008;2009). For example, Paller and Batterink (2017) used electroencephalogram (EEG) data to show that participants perceived tri-syllabic words while listening to an artificial speech stream as whole words compared to individual syllables. They examined this through participants' ability to neutrally entrainment the word frequencies compared to the syllable frequencies. Participants were also able to learn these novel words by using high and low transitional probabilities. This was further demonstrated by using a Target Detection Task (TDT) where participants were able to predict final syllables in a word faster than the first syllable, indicating learning.

Traditional behavioural methods of assessing SL do so after the learning has occurred through secondary tasks resulting in a delay from the actual learning process. For the current study, we used neural entrainment to test SL as it assesses this mechanism in real time (during the exposure phase) to identify the exact time course pattern identification takes place. Incorporating neural entrainment as an online measure also means the results were not dependent on behavioural tasks that could be influenced by other mechanisms such as memory, alertness, or general test taking abilities (Battrink & Paller, 2017). Finally, by using neural entrainment as a measurement we were also able to tease apart retrieval memory and focus solely on SL abilities, something that has not been done in children with a variety of reading and language abilities.

The goal of the current study was to examine ASL and VSL as a domain general or domain specific mechanism underlying the reading process. It was expected that online and offline measures of ASL would predict reading ability in children. More specifically, participants who showed neural entrainment at the word frequency during the auditory familiarization phase should have greater SL accuracy on post exposure tasks. During the TDT we expected response times (RTs) to be faster for the final syllable condition in a speech stream when participants showed strong neural entrainment and SL abilities. These results reflect learning and were predicted based on Batterink and Paller's (2017) research. The VSL portion of the experiment was exploratory, and EEG measures of neural entrainment were collected during the exposure phase but not analysed due to a time limit; however, it was predicted that participants who performed above chance during the post exposure tasks would have strong scores of standardized reading ability.

Method

Participants

Thirty-three children participated in the study; however, the first participant was excluded because the protocol changed after we ran this participant. We analysed data from 32 children (17 males; 15 females) between the ages of 8 to 12 years old (*M* = 10.15, *SD* = 1.26, r*ange* = 8.08-12.67). All children had normal or corrected vision and were fluent monolingual English speakers, with the exception of taking core French at school. None of the participants had a history of neurological, psychiatric, or other learning disorders. Additionally, three children were excluded from the VSL portion of the experiment due to boredom, tiredness, or requesting to stop early. Children showed similar reading developmental trajectories as reflected in the age (in years) at which they began to read (*M* = 4.38, *SD* = 1.09) and read fluently (*M* = 6.17, *SD* = 1.48). Recruitment took place through the Language, Reading, and Cognitive Neuroscience Lab where a list of participants who had agreed to participate in future studies were contacted via email. Additionally, recruitment posters (see Appendix A) were distributed throughout the London community.

Before participating in the study, caregivers completed an eligibility questionnaire to ensure their child met the inclusion criteria of the study (see Appendix B). Following this, a time was arranged for them to come into the lab. The researchers read aloud the letter of information (LOI; see Appendix C) and caregivers and participants signed a consent (see Appendix D) and assent form (see Appendix E). Following this, caregivers completed a more in-depth language and reading questionnaire (see Appendix F) in a separate room while children remained in the testing room. Children were given multiple breaks and a snack over the duration of the study. After completing the experiment, caregivers were given twenty-dollars for gas and children received a twenty-dollar gift card to Cineplex movies as compensation.

Measures and Procedure

Reading ability. Children completed the Test of Word Reading Efficiency – Second Edition (TOWRE-II) to measure their ability in pronouncing printed words accurately and fluently (Torgesen, Wagner, & Rashotte, 2012). In the first portion of the test, participants were given forty-five seconds to read aloud a list of words which progressed in orthographic complexity (e.g., *is, jump, inside, absentee*). The number of words they accurately pronounced was recorded into a standardized score. This portion of the test assessed participant's ability to recognize whole words, a critical skill in reading known as sight word efficiency (SWE). In the second portion of the test, participants were given the same instructions but with a list of non-words (e.g., *ip, stip, ritlun, drepnort*). The number of non-words they accurately pronounced was recorded as a standardized score (e.g., *drepnort* pronounced as *drɛpnoɚt*). This portion of the test assessed individuals' phonemic decoding efficiency (PDE) in their ability to sound out words quickly and accurately. Standardized scores of overall reading as well as SWE and PDE were correlated to each of the SL measures.

Phonological Processing. Phonological awareness is known to be a component of the reading process when decoding words and so participants completed the Comprehensive Test of Phonological Processing (CTOPP; Torgesen et al., 2012; Wagner, Torgesen, & Rashotte, 1999). During this assessment, participants were instructed to orally repeat a word while omitting a phoneme (e.g., "*Say snail without saying the /l/ sound*"). As a subsequent task, participants listened to a blended recording and after hearing separated syllables from a whole word, they were asked to put the syllables together and repeat it as a full word unit (e.g., "*What word do these sounds make? /k /æ /n /d /ɪ* / [candy]"). Standardized scores of phonological processing were correlated with each measure of SL.

Performance Intelligence. To ensure the link between reading and SL was not explained by performance intelligence quotient (IQ), participant's IQ was assessed using the Weschler Abbreviated Scale of Intelligence (WASI; Weschler, 1999). In the first portion of the WASI, participants were instructed to recreate a matrix block design where we recorded accuracy and response time. In a subsequent task, participants were shown pictures following a pattern, they were asked to choose a picture that completed the pattern and their accuracy was recorded. The results of these two tasks were used to create a standardized score of performance IQ. During the Pearson Correlation analysis between SL and reading, performance IQ scores were used as a control variable to ensure the relationship was not due to general intelligence.

Auditory statistical learning exposure task. Participants were exposed to an artificial speech stream of 12 syllables grouped into four tri-syllabic non-sense words (e.g., *pautone, nurafi*, *gabalu*, *mailoki*). The syllables were made with an artificial speech synthesizer and recorded with Audacity at a sampling rate of 44100 Hz. Each syllable was presented for 300ms. The transitional probabilities for syllables within words were higher (1.0) than the transitional probabilities for syllables between words (.33). For example, within the word *pautone, pau* was always followed by *to* which was always followed by *ne.* However, *ne* (the last syllable in the word) was equally likely to be followed by *nu, ga,* or *mai* (the initial syllable in the other words). The four non-sense words repeated in a continuous stream with no word onset cues (e.g., no pauses between words) and no word repeating after itself. Participants passively listened to the speech stream through speakers at a comfortable volume for six minutes. To avoid boredom, a silent cartoon video was played at the same time as the speech stream. The actions within the video were random and did not synchronize to the speech stream to ensure it had no effect on participant's neural activity when perceiving words or syllables. Finally, during this phase we recorded participant's EEG data to analyze for patterns of neural entrainment to the auditory stimuli.

Electroencephalogram neural entrainment. Neural entrainment was measured at the syllabic and word frequencies by measuring inter-trial coherence (ITC). ITC is a measurement of EEG phase-locking and ranges from no phase-locking (indicated by 0) to pure phase-locking (indicated by 1). A significant ITC indicates that EEG across trials is phase-locked to an experimental event, rather than a phase-random. As a relative measure of sensitivity to statistical structure in the speech stream, we computed a Word Learning Index (WLI) which is the ITC at the word frequency divided by the ITC at the syllable frequency (Batterink & Paller, 2017). Higher WLI scores will indicate stronger neural entrainment at the word level relative to the syllable level, indicating statistical learning.

Word frequency, which was the presentation frequency to the tri-syllabic words was 1.1 Hz. The syllable frequency, which was the presentation frequency of individual syllables was 3.3Hz. The syllable and word frequency had the strongest value at 10 centro-frontal midline electrodes (F3, Fz, F4, FC5, FC1, FC2, FC6, C3, Cz, C4) were used to compute the WLI. We used a 32-channel Biosemi to record EEG data and recorded eye blinks with eight electrodes placed on the mastoids as well as under, above, and next to the eyes. We used a repeated measures ANOVA to test whether the word frequency increased as a function of exposure. We divided the exposure EEG data into three equal blocks (e.g., block 1: first two minutes, block 2:

the third and fourth minutes, block 3: last two minutes) and compared ITC for each block. If word level ITC increased over time, it would provide us with evidence that participants became sensitive to the word structure as the exposure phase went on.

Rating task. Following the exposure task, children completed a rating task. Participants were presented with a non-sense word and rated how familiar the sound was to the previous speech stream from the exposure phase. Each trial presented either a word from the speech stream (e.g., *pautone*), a part-word containing a syllable pair from a word in the speech stream and a random syllable from the speech stream (e.g., *kipauto*), or a non-word containing individual syllables that were never paired within the speech stream (e.g., *nepaunu*). There was a total of 12 trials made up of four words exhaustively paired with four part-words, and four non-words. After each trial participants rated how familiar the word was to the speech stream during the exposure phase on a scale from 1 to 4 (e.g., *1 = very familiar, 2 = somewhat familiar, 3 = somewhat unfamiliar, 4 = very unfamiliar*). Accuracy on this task was used to assess participants' explicit memory of non-sense words.

For the rating task, participants were given a rating score to test whether they learned the words from the speech stream. Their rating score was computed by subtracting the average score given by part-words and non-words from the average score of words. A rating score of three or four on words and one or two on part-words and non-words defined a correct rating. Values above zero were indicative of learning and perfect sensibility is reflected in a score of 3. We used a one sample t-test to examine significance above zero for performance on this task using the rating scores. Additionally, a repeated measures ANOVA was used to test for an effect of word category (e.g., word, non-word, part-word).

Recognition task. As an additional test of explicit memory, participants completed a recognition task in combination with a remember/know/guess procedure. First, participants heard two words: a word from the speech stream and a part-word or a non-word. They were instructed to choose the most familiar word (i.e., indicated by pressing 1 on the keyboard for the first sound and 2 for the second). Next, they identified whether they remembered the word (i.e., by pressing the smiley face), guessed the word (i.e., by pressing the neutral face), or the word just sounded familiar (i.e., by pressing the sad face). This task consisted of 16 trials including: eight words, four part-words and four non-words. During this task, we collected participants' accuracy data.

To determine whether participants preformed above chance on the recognition task, we tested their significance against .5 (chance) using a one sample t-test. Additionally, a repeated measures ANOVA was computed to analyse an effect of memory judgement during the remember/guess/know procedure.

Target detection task. During the TDT participants were given target syllables and asked to identify the syllable within a shorten version of the artificial speech stream. The speech stream included the four words from the original exposure phase repeated four times presented at a slower pace (350ms/syllable compared to 300ms/syllable). Each of the 12 syllables in the stream served as the target syllable twice (e.g., word-initial, word-medial, word-final) for a total of 24 streams and 32 targets in each syllable position. Participants were instructed to press the "*enter*" button each time they heard the target syllable within the speech stream. To test whether implicit learning occurred, accuracy and RTs were recorded.

During this task, mean RTs were collected for each participant at every target syllable position. Responses that were not within 0-1200ms of the target were labelled as false alarms. The RTs for the final syllable position were subtracted from RTs from initial syllable position;

scores above zero were indicative of word learning. A one sample t-test was used to test whether participants' performance was above zero for initial compared to final syllable position. A positive score would indicate that participants had a faster reaction time to final syllable position, indicating that participants were anticipating the final syllable. A repeated measures ANOVA was used to examine any effects of syllable condition by comparing mean RTs for each target position. Based on the previous findings of Paller and Batterink (2017) we expected participants to have faster RTs for targets in the final syllable position as a reflection of learning the non-sense words. For a visual summary of the ASL portion of the experiment, refer to Figure 1.

Visual statistical learning exposure task. During the VSL exposure phase, participants passively watched a stream of aliens appear on a computer screen. The stream consisted of 12 aliens grouped into four families of three aliens (four base triplets) referred to as *ABC*, *DEF*, *GHI*, *JKL* (see Appendix G). Each alien appeared individually on a computer screen with a blue background for 800ms, followed by a 200ms inter-stimulus interval. All the aliens in one triplet were always presented before aliens in another triplet. The transitional probabilities within families (1.0) were always higher than between families (.33). For example, in the triplet *ABC, A* was always followed by *B*, which always preceded *C*. However, *C* (the last alien in the triplet) was equally likely to precede *D, G*, or *J* (the first alien in the other triplets). The four families of aliens repeated in a continuous stream with no family repeating after itself. The familiarization phase lasted for 4.8 minutes. During this task, we collected EEG data; however, due to time limitation an analysis of neural entrainment could not be done for this task.

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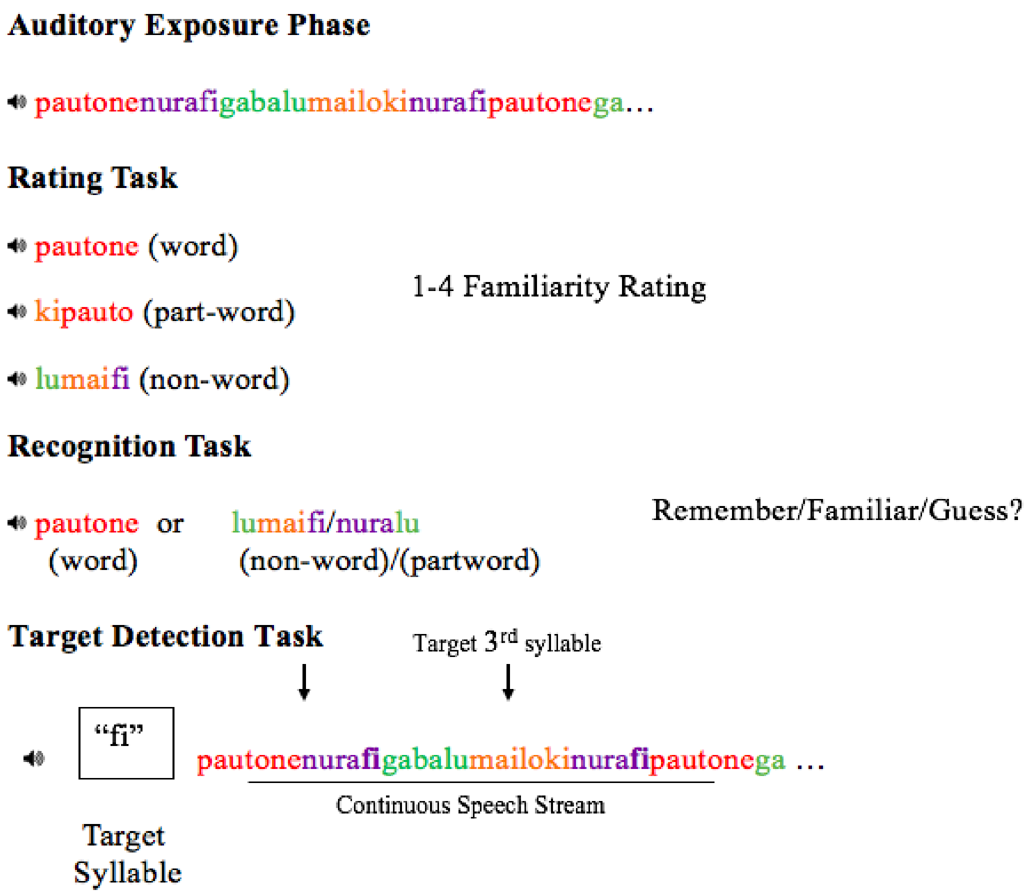

Figure 1. A visual summary of the auditory statistical learning portion of the experiment. During the exposure phase, EEG data was collected to analyze for neural entrainment. The rating and recognition tasks measured participants' explicit memory. The TDT measured participants' implicit memory.

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Recognition task. After the exposure phase, children were given a recognition task where they saw three separate families of aliens on the computer screen where each trial consisted of: a true family (e.g., *ABC*), a part-family (e.g., *ABF*), and a non-family (e.g., *AJF*). There was a total of 24 trials made up of four true families, four part-families, and four non-families. Participants had to decide which family of the three aliens came from the exposure stream. On this task of explicit memory, participant’s accuracy data was collected.

To determine whether participants preformed above chance on the recognition task, their significance against .33 was computed using a one sample t-test with overall accuracy. A repeated measure ANOVA was used to analyse an effect of family category (e.g., true family, part-family, non-family). For a visual description of each SL task in the study, refer to Figure 2.

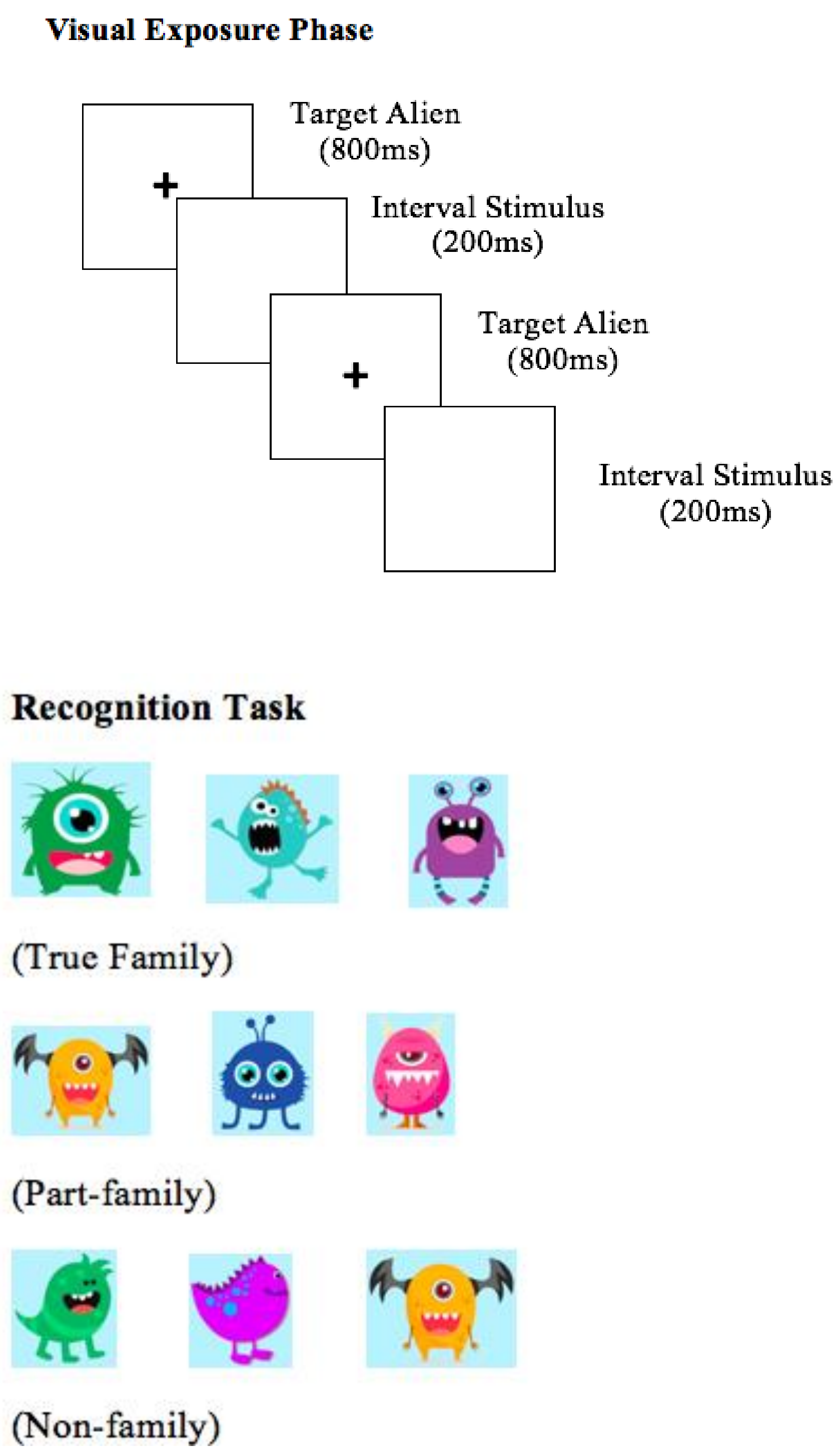

Figure 2. Summary design of the visual statistical learning portion of the study. The recognition task measured participants' explicit memory.

Results

The descriptive statistics for children's performance on SL tasks, WLI, CTOPP, TOWRE-II (subscales: SWE, PDE), performance IQ and are shown in Table 1. Overall, participants showed significant evidence of learning during the offline ASL measures. During the rating task, participants performed above chance, $t(31) = 6.15$, $p = .000$. Additionally, there was a significant word category effect, $F(2, 62) = 20.08$, $p = .000$ where words were rated as the most familiar ($M = 2.94$), followed by part-words ($M = 2.45$) and non-words ($M = 2.23$; refer to Figure 3).

During the recognition task, participants also performed above chance, $t(31) = 7.55$, $p = .000$, and overall mean accuracy was 69.92%. Remember ($M = .72$) and guess responses ($M = .72$) were the most accurate followed by familiar ($M = .63$). The effects of memory judgement on accuracy was not found to be significant, $F(2, 44) = .64$, $p = .532$. During the TDT, final compared to initial syllables were significantly faster, $t(31) = 5.36$, $p = .000$. There was also a significant effect of syllable position, $F(2, 62) = 12.06$, $p = .000$, where final syllables showed the fastest response ($M = 523.52$ms), followed by medial ($M = 581.52$ms) and initial ($M = 614.59$ms) positions (refer to Figure 4). During the exposure phase, participants showed a peak at the ITC for word frequency and syllable frequency. It was found that word frequency increased significantly as time went on, $F(62, 2) = 3.44$, $p = .038$ (refer to Figures 5 and 6). The first two minutes showed the lowest word level ITC ($M = .48$), followed by the third and fourth minutes ($M = .57$), and the last two minutes showed the highest word level ITC ($M = .59$; refer to Figure 7).

The recognition task for the VSL portion of the experiment revealed no significant learning, $t(28) = -.80$, $p = .429$. and there was no significant family category effect,

Table 1

Descriptive Statistics for Predictor and Control Variables

	M	*SD*
Rating Score	.56	.51
Recognition Task (ASL)	.69	.14
TDT	91.62	95.71
Recognition Task (VSL)	901.07	906.21
WLI	.46	.37
CTOPP	100.66	11.67
TOWRE-4th	98	13.20
SWE	100.39	12.08
PDE	96.42	14.36
Performance IQ	112.93	13.66

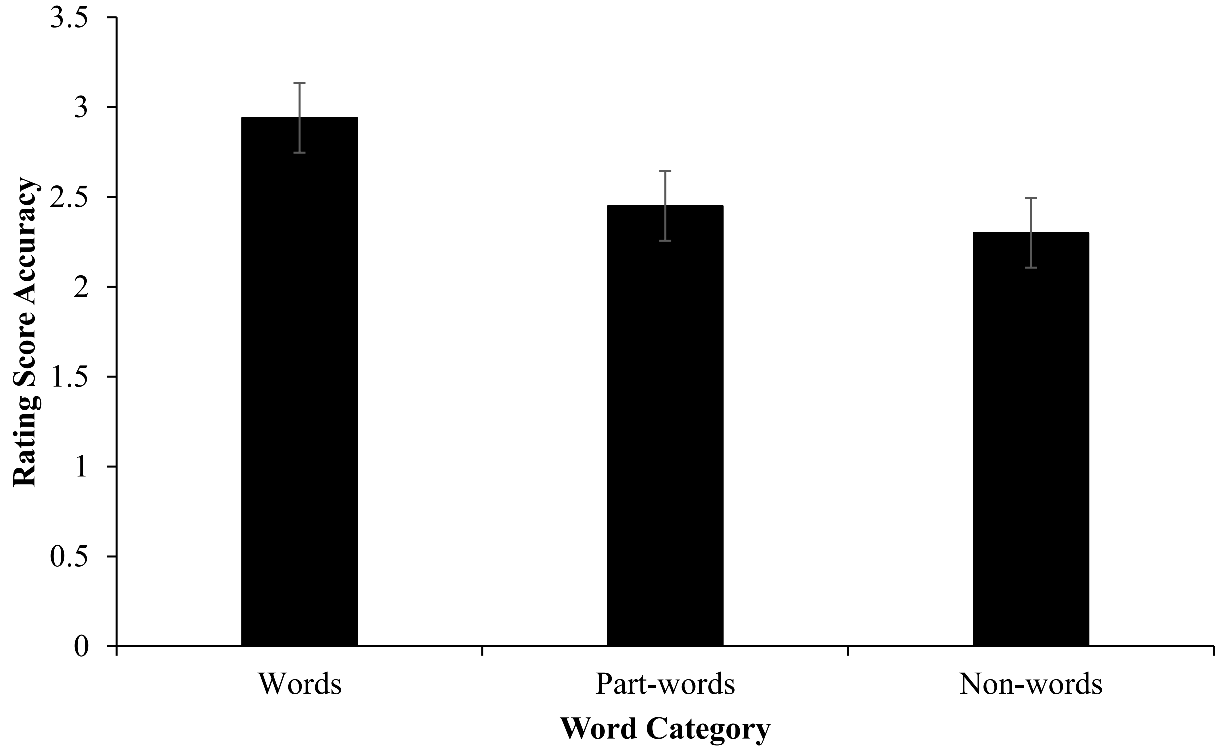

Figure 3. Mean rating score accuracy for each word category. Standard error bars represent standard error mean. Higher scores indicate higher accuracy on this task.

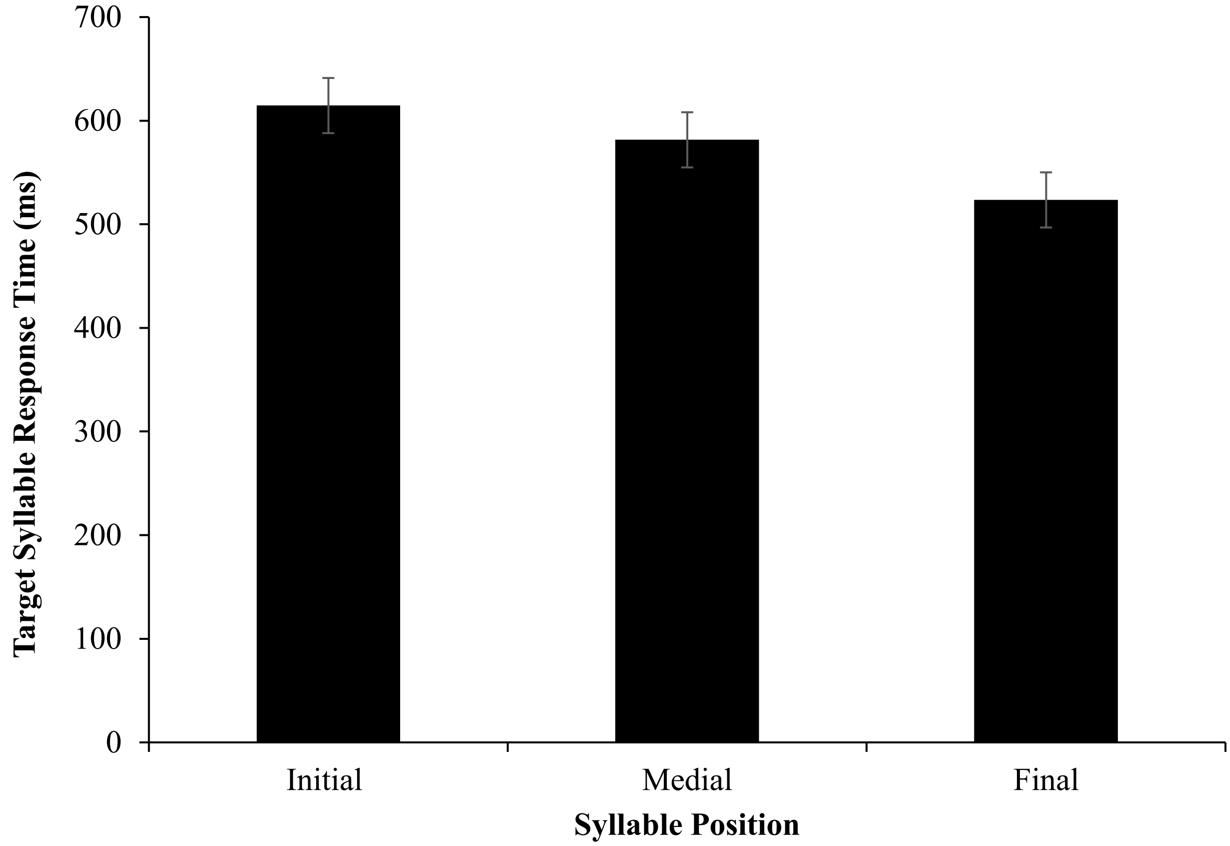

Figure 4. Response times during the target detection task based on target syllable position. Standard error bars represent the standard error mean. Smaller values indicate faster response times.

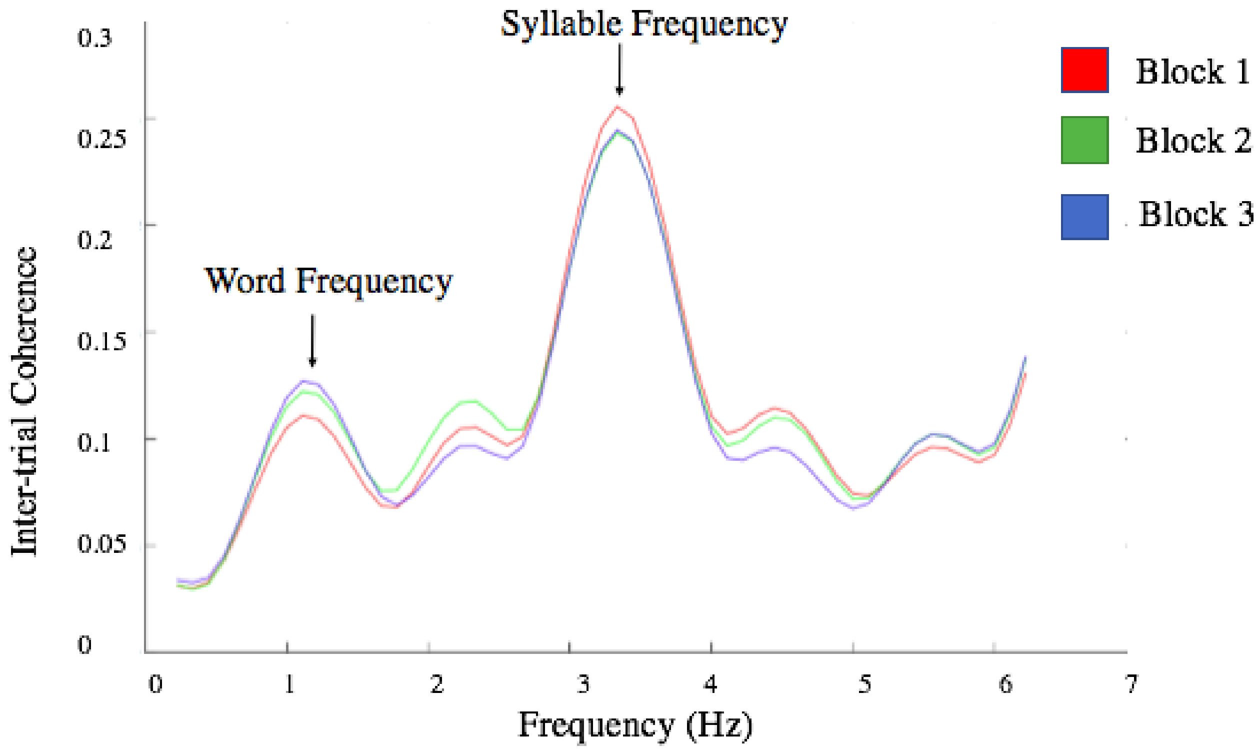

Figure 5. Inter-trial coherence as a function of exposure over time revealing an increase at word level from block one to block three. The peak in word frequency and decrease in syllable frequency at time three indicates greater sensitively to words over time.

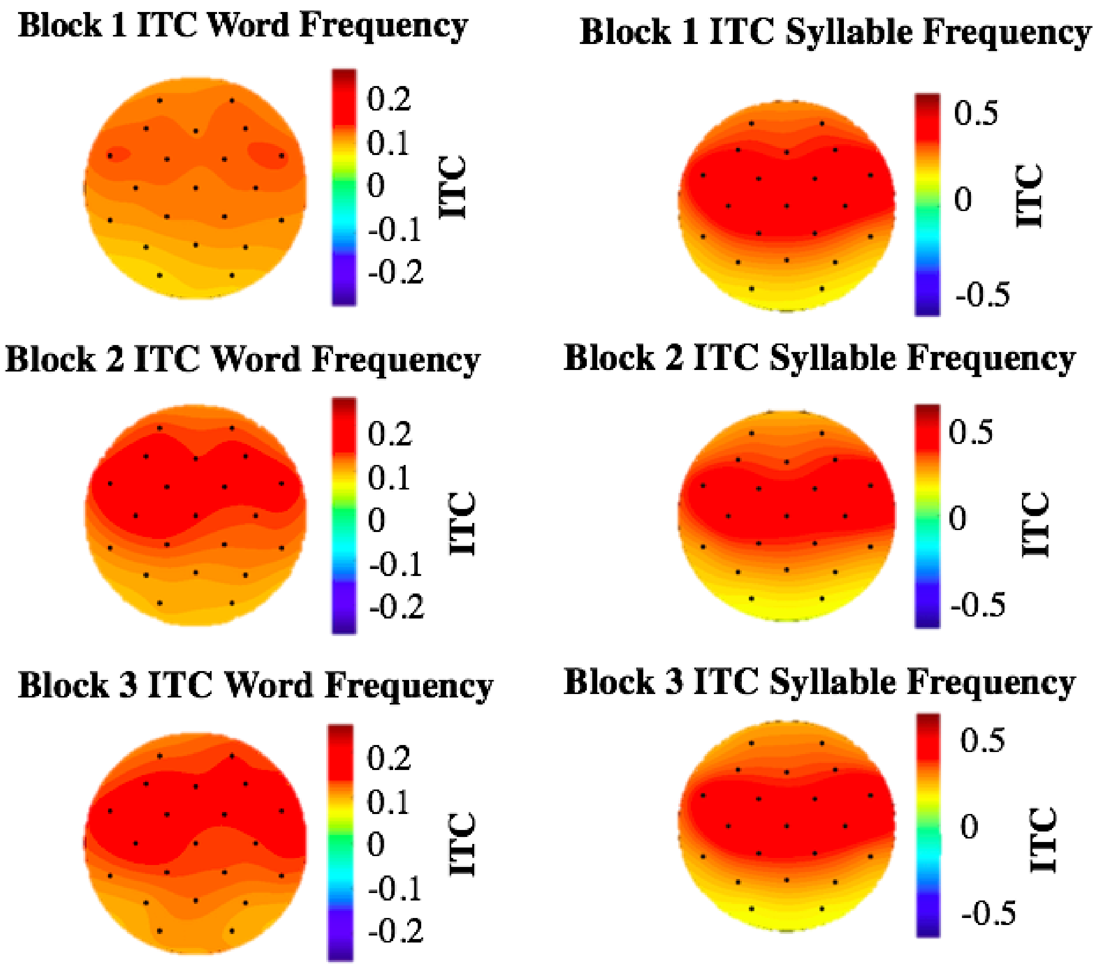

Figure 6. Topographical plots showing the distribution of inter-trial coherence (ITC) across the scalp over blocks 1, 2, and 3. ITC increases at the word level and decreases at the syllable level over time. Note that different scales are used for word and syllable frequencies.

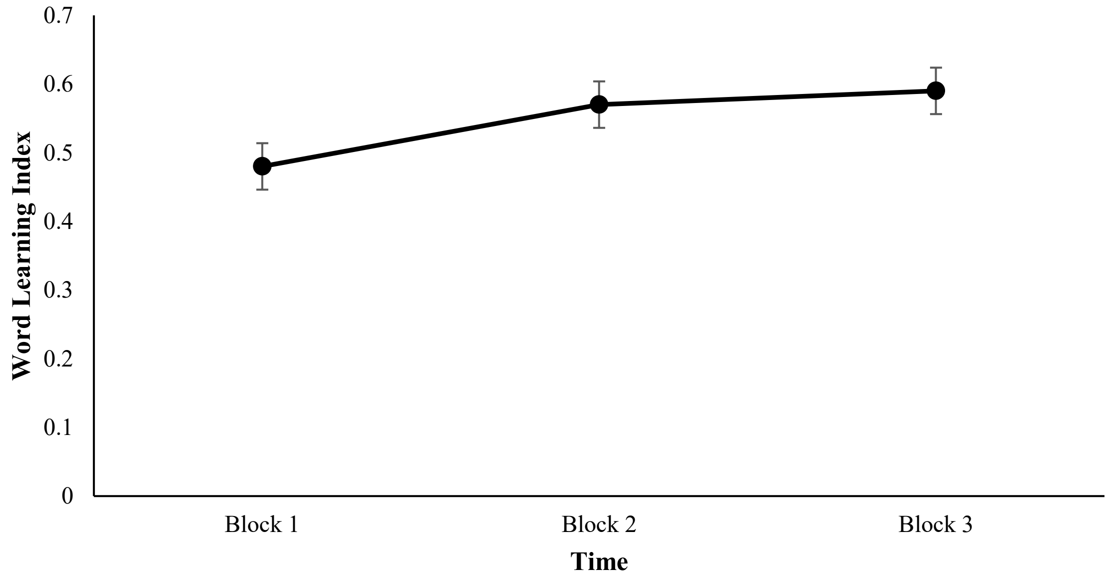

Figure 7. Average word learning index as a function of time across blocks 1, 2, and 3. Higher points indicate higher word learning averages. Standard error bars represent the standard error mean.

$F(2, 56) = .75$, $p = .477$. To see if the online measure of SL predicted offline measures, Pearson correlations were computed between WLI and each ASL behavioural measure. The analyses revealed that WLI and the rating task showed a significant correlation (refer to Table 2). Finally, to test whether SL is related to reading ability, Pearson partial correlations were computed between each SL measure (online and offline) to standardized scores of reading from the CTOPP, overall TOWRE-II score, and the subscale measures of SWE and PDE while controlling for performance IQ (refer to Table 2). No significant relationship between reading ability and SL was found.

Discussion

The current study examined whether SL was associated with children's reading ability. Our hypothesis was not supported as participants' online and offline measures of SL did not significantly correlate with children's reading ability, as measured by the TOWRE-II and CTOPP. This finding is inconsistent with previous work reporting a link between SL and reading ability (Arciuli & Simpson, 2012). Arciuli and Simpson (2012) found a significant link between SL and reading when using the Wide Range Achievements Test, 4th Edition (WRAT-4th; Wilkinson & Robertson, 2006) which assesses sentence reading fluency and accuracy. The current study measured single word reading, so it is possible that assessing children's reading ability through sentences opposed to single words may give a wider depiction of their true ability.

The PDE subtest in the TOWRE-II assessed children's ability to actively pair orthographical information to phonemes among non-words. This process required children to segment speech into individual syllables to sound out the word. It was thought that specific aspects of reading, such as the ability to quickly learn these mappings, were specifically related

Table 2

Pearson Correlations Between SL and Reading Measures

	WLI	CTOPP	TOWRE-II-4th	SWE	PDE
Rating task	.395*	-.151	-.037	.040	.018
Recognition Task (ASL)	.341	.110	.145	.139	.017
TDT	.167	-.106	.007	-.034	.149
Recognition Task (VSL)	.025	.321	.308	.246	.264

Note. *$p < .05$, two-tailed

to SL. Interestingly, SL did not correlate with this measure, suggesting that there may be additional patterns or regularities within the English Language that were not accounted for in this assessment. Comparatively, the SWE test is more representative of children's ability to recognize a whole word. The words used in this test were known to participants; thus, words were more likely to be represented as whole word units. Compared to the PDE, participants did not have to actively decode and pair orthographic to phoneme regularities.

As an extension, Arciuli (2018) explained that lexical stress during reading follows patterns within English. For instance, when saying aloud the word, "zeBRA", where the initial syllable is unstressed while the final syllable is stressed. Thus, Arciuli argued that patterns of lexical stress are additional regularities within the English language that are acquired more implicitly than orthographic to phoneme patterns. Including a more naturalistic reading assessment, such as the WRAT-4th edition (Wilkinson & Robertson, 2006) and measuring lexical stress, may result in finding subtle reading cues that SL plays a more active role in.

The results of the current study reflect similar findings from Nigro, Jiménez-Fernández, Simpson, and Defior (2015) who reported no link between SL and reading in Spanish children. Interestingly, this study used similar single word tests to that of the TOWRE-II when measuring reading ability. The authors noted that this finding might have been a result of the shallow orthographical structure of Spanish which results in one to one mappings between graphemes and phonemes. They concluded that these one to one mappings result in reading regularities that can easily be taught explicitly with little need for SL abilities. However, the current study suggests that this finding is not specific to shallow orthographical languages, but deep orthographical languages as well. It may also reflect the single word reading assessment, which was used in both studies on older age groups (grades 3 and up). Notably, the single word reading assessment may reflect less variability in older children's reading ability. More specifically, single word reading ability may only highlight the major group differences and fail to recognize subtle differences, especially between TD participants who have spent years learning orthographic to phoneme mappings. For more variability in reading scores among older children, it may be important for future studies to include a more complex measurement that elicits this individual variation.

Moreover, Paller and Batterink (2017) found that adult participants were able to learn non-words using transitional probabilities in an artificial speech stream as reflected in their above chance performance on post exposure tasks (rating, recognition, and TDT). The current study found similar results showing children were able to learn the non-words as shown in the rating and recognition tasks of explicit memory and the TDT of implicit memory. The results of the TDT demonstrate that participants were able to predict the final syllable of a word by utilizing the initial and medial syllables. Consistent with the work of Paller and Batterink (2017), participants also showed an increase over time in their ability to neurally entrain words. Thus, the significant above chance performance on ASL tasks as well as the increase in word level frequency over time, suggests participants became sensitive to the transitional probabilities across and within words.

It is important to note that the evidence in learning the non-words may also be explained by a competing learning theory known as chunking. The chunking hypothesis explains that after repeated exposure to individual units, such as syllables, units are perceived in short term memory as a whole unit, such as a word (Miller, 1994). Previous work by Franco and Destrebecqz (2012) attempted to tease apart theories of SL and chunking. They found participants used chunking to learn non-words when exposed to a speech stream if there were cues for word boundaries such as pauses. Comparatively, participants were thought to use SL when identifying non-words while exposed to a continuous speech stream with no pauses and only transitional probabilities as cues to word boundaries. Similar to our experiment, it is thought that participants used only SL to learn non-words, not chunking.

The significant correlation between the WLI to the rating task give reason to suggest that explicit ASL is related to online implicit word learning. The null results for the correlation between the WLI to the recognition and TDT are also inconsistent with previous literature (Batterink and Paller, 2017). The children in our study had difficulty with the TDT, making this measurement noisier. Due to the fact that it was a speed response time task, some of the kids missed multiple targets. It is recommended that future research on SL should use this measure exclusively with adult participants for a more representative measure of SL. Additionally, the correlation between the WLI and the recognition task did not reach significance but was in the expected direction (p = .056). This finding may have been a result of the equal average accuracy scores of the familiar and guess responses. Children could have used the guess response as a default choice for when they were unsure of what decision to make, resulting in this measure being somewhat noisy among younger samples as well.

Finally, participants did not show any evidence of learning the alien families during the VSL portion of the experiment. While this task was more of an exploratory part of the study, the results were inconsistent with past literature (Arciuli & Simpson, 2012). The null results may have been due to the absence of a cover task which was used in a previous study to keep children engaged (Arciuli & Simpson, 2012). Additionally, previous visual recognition tasks have used only two groups of families, a true family and a non-family (Arciuli & Simpson, 2012). Introducing a third, part-family, option may have made this task too difficult for children.

Finally, the VSL portion of the current study took place at the 1.5-hour mark making it a long task for them to complete. Given that some children requested to stop or showed visual signs of boredom, the result of the VSL task may have been influenced by children's lack of attention.

Conclusion

While the process of reading is guided by statistical regularities between orthographic and phonological properties embedded in the English language system, it is still unknown as to whether SL ability aids with reading proficiency. While the current study shows passive exposure to the speech stream was indicative of learning the target non-words, this was not related to reading ability. It may be that the reading skills we measured are best learned when children engage in explicit instructions regarding orthographic to phoneme mappings opposed to learning through passive exposure. Programs such as Lexia (Lexia Learning, 2019) offer explicit and personalized reading lessons for children from kindergarten to grade 12 to learn reading regularities. This program begins with an initial assessment which frames the individualized lesson plans that focus on the areas of reading students struggle with. Notably, each lesson comes with well-defined explicit instructions on the specific rules governing the reading process which may be more beneficial than learning these regularities through mere exposure.

To conclude, further research regarding the relationship between SL and reading must be done to fully understand the role SL does or does not play in the reading process. Based on the findings of the current study, it is suggested future studies looking at this relationship should use reading assessments specific to the participants' age. Finally, it is also encouraged that future research in this area use both online and offline measures of SL for a more direct and holistic investigation into SL.

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Appendix A

Recruitment Flyer

Western
The Brain and
Mind Institute

PARTICIPANTS NEEDED FOR RESEARCH
ON LANGUAGE AND READING IN CHILDREN

We are looking for volunteers to take part in a study investigating how children with language and reading impairments perform on an artificial language and a visual learning task. Participants must be between 8 to 12 years of age, neurologically healthy, **must be English monolingual** (some French is okay), and have normal or corrected-to-normal vision. We are recruiting children who do and do not have language and reading impairments.

If you are interested and agree to participate, your child would be asked to complete some computer-based tasks that involve responding to auditory and visual stimuli.

Participation would involve 1 session that is approximately 2 hours long.

As compensation for your time, you will receive $20 for travel costs and free parking, your child will also receive a $20 gift card to the movies.

For more information about this study, or to volunteer for this study,
please contact:

Christine Moreau
Brain and Mind Institute
E-mail: cmoreau5@uwo.ca

Learning in children
cmoreau5@uwo.ca
519-661-3529

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cmoreau5@uwo.ca
519-661-3529

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519-661-3529

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cmoreau5@uwo.ca
519-661-3529

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cmoreau5@uwo.ca
519-661-3529

Appendix B

Eligibility Questionnaire

How old is your child (years; months)? ____________

Is English your child’s first language? Y N

If no, please list which language(s) they learned at 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

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:

Appendix C

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)
Brain and Mind Institute, WIRB 5174
Email: marcj@uwo.ca
Phone: (519) 661-2111 ext. 86582

Additional Research Staff Contacts: Christine Moreau, Psychology
Email: cmoreau5@uwo.ca

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.

Further Information
If you have questions about this research study, please contact Christine Moreau at cmoreau5@uwo.ca. You may also contact Dr. Marc Joanisse at (519) 661-2111 ext. 86582; marcj@uwo.ca. 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 (519) 661-3036, email: ethics@uwo.ca.

This letter is yours to keep for future reference.

Appendix D

Consent

Project Title: Statistical Learning in Children

Principal Investigator and Contact: Dr. Marc Joanisse, Ph.D. (Western)
Brain and Mind Institute, WIRB 5174
Email: marcj@uwo.ca
Phone: (519) 661-2111 ext. 86582

Additional Research Staff Contacts: Christine Moreau, Psychology
Email: cmoreau5@uwo.ca

I have read the Letter of Information, have had the nature of the study explained to me and I agree to have my child ________________________ participate. I _________________ also agree to participate by filling out the demographic/language background questionnaire. All questions have been answered to my satisfaction.

May we contact you about future studies? Yes No

If you agreed to be contacted for future research studies, please provide us with your e-mail address or phone number: ____________________________

____
Print Name of Child

_____________________	__________________	_________________
Print Name of Parent	Signature	*Date (DD-MM-YYYY)*

My signature means that I have explained the study to the participant named above. I have answered all questions.

__________________	_________________	________________
Print Name of Person Obtaining Consent	Signature	*Date (DD-MM-YYYY)*

Appendix E

Assent Form

Project Title: Statistical learning in children with developmental language and reading disorders
Document Title: Letter of Assent
Principal Investigator and Contact: Dr. Marc Joanisse, Ph.D. (Western)
Brain and Mind Institute, WIRB 5174
Email: marcj@uwo.ca
Phone: (519) 661-2111 ext. 86582

Additional Research Staff Contact: Christine Moreau, Psychology
Email: cmoreau5@uwo.ca

Why are you here?

You are here because researchers would like to know more about the processes involved in language and reading. They want to see if you would like to be in this study because you are between 8 to 12 years old and may have problems with reading or problems with talking and understanding language. Dr. Marc Joanisse, Christine Moreau, and other researchers are doing this study.

Why are they doing this study?

They want to know more about how children learn language and how to read. They also want to know how reading and language is affected when children have problems with reading and language.

What will happen to you?

You will be asked to do a few reading activities, word games and block games. For the second part of the experiment, you will listen to some sounds and be asked to do activities related to those sounds. You will also complete a visual task where you have to respond to a target on the screen. Some of the activities will be completed on paper and some will be done on the computer.

We will also record your brain activity during the second part of the experiment. Your brain activity will be recorded by using a special cap. This cap will be placed on your head and a small amount of gel will be put on the cap's sensors. This part takes a little while, so you have the option of watching a short movie while you wait.

Will there be any tests?

No. There won't be any tests and nothing you do in this study counts for school.

Will the study help you?

No. This study will not help you directly, but it might help us understand the cause of children's language and reading problems.

Do you have to be in the study?

No, you don't have to be in this study. You can choose to leave the experiment at any time. Nobody will be angry with you if you choose not to be in this study or decide to leave after it started.

What if you have any questions?

Feel free to ask questions at any time. You can talk to the researchers, your parents or someone else. We just ask that you don't talk while there is sound playing from the speakers.

If you would like to participate, please fill out the information below.

____
Name of child (Print)

______________________________ ______________________________
Signature of child Date

____
Name of person obtaining assent (Print)

______________________________ ______________________________
Signature of person obtaining assent Date

Thank you for your participation!

Appendix F

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 G

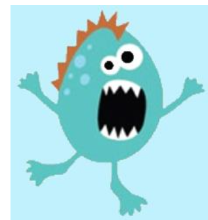
Alien Families


A


B


C


D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