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Examining the Neural Correlates of Vocabulary and Grammar Learning Using fNIRS

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Abstract

Adults struggle with learning language components involving categorical relations such as grammar while achieving higher proficiency in vocabulary. The cognitive and neural mechanisms modulating this learning difference remain unclear. The present thesis investigated behavioural and neural differences between vocabulary and grammar processing in adults using functional Near-Infrared Spectroscopy (fNIRS). Participants took part in an artificial language learning paradigm consisting of novel singular and plural words paired with images of common objects. Findings revealed higher accuracy scores and faster response times on semantic vocabulary judgement trials compared to grammar judgement trials. Singular vocabulary judgement was associated with neural activity in part of the pars triangularis of the right inferior frontal gyrus associated with semantic recall. On the other hand, bilateral portions of the dorsolateral prefrontal cortex were more active during grammar judgement tasks. The results are discussed with reference to the roles of memory mechanisms and interference effects in language learning.

Keywords

Language learning, functional Near-Infrared Spectroscopy, vocabulary, grammar, artificial language, morphology, semantics, declarative memory, procedural memory.

Summary for Lay Audience

Adults struggle with some aspects of second language learning more than others. Particularly, their proficiency outcomes in grammar are lower than in vocabulary. It remains unclear why differences between vocabulary and grammar learning exist in adults, and what brain areas are involved in contributing to this difference. Using an artificial language, this thesis investigated both performance and brain activity differences between processing novel vocabulary words and grammatical patterns. We used functional Near-Infrared Spectroscopy (fNIRS) which is a neuroimaging method that measures brain activity through light diffraction measured through the skull. Participants were taught an artificial language consisting of novel singular and plural words paired with images of common objects. Grammatical plural patterns were learned implicitly through repeated exposure to the language. On the other hand, vocabulary was learned explicitly through the pairing of a word and its meaning. As in natural second language learning, participants learned vocabulary more accurately than grammar. During a vocabulary judgement task, brain activity was greater in areas known to be involved in semantic recall. On the other hand, during grammar judgement tasks, brain activity was greater in areas known to be involved in complex executive functioning that develop into young adulthood. The results are discussed with reference to the roles of memory processes and interference effects in language learning.

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Chapter 1

1 Introduction

1.1 Language Learning in Adults

A leading tenet in language research posits that while adults demonstrate superior cognitive abilities compared to children, language learning is an exception (Craik & Bialystok, 2006; Newport, 1990). This discrepancy applies to some components of language more than others. Particularly, adults struggle with learning categorical relations of language such as morphology and syntax. For example, adults may make errors in morphological use such as errors using plural "-s" or past tense "-ed" morphemes when learning a second language. On the other hand, vocabulary learning in adults is not as detrimental (Newport, Bavelier, & Neville, 2001).

In terms of first language learning, adults' shortfalls are famously outlined by studies of Genie, a girl secluded from language input until after puberty (Curtiss, 1977), and Chelsea, a deaf woman only exposed to language through auditory amplification at age 32 (Curtiss, 1989). Neither Genie nor Chelsea obtained normal linguistic proficiency, but most importantly, proficiency was especially poor in morphological domains (Newport, 1990). Likewise, a similar negative relationship has been found between age of acquisition and morphological proficiency in learning a second language. These age-dependent differences were not attributable to exposure length or amount of linguistic input received (Johnson & Newport, 1989).

It remains unclear why differences in vocabulary and grammar learning occur in adulthood and which neural mechanisms contribute to this discrepancy. Overall, language learning utilizes an intricate network of both linguistic and non-linguistic neural mechanisms. Accordingly, it may be the case that vocabulary and grammar learning differences in adults develop as a result of neural maturation of linguistic-specific or domain-general cognitive mechanisms. Precisely, during language learning, adults may naturally rely on more developed neural mechanisms that counterintuitively inhibit optimal grammar learning.

However, vocabulary and grammar are often studied independently from one another despite their interdependent relationship in natural language acquisition. Therefore, I aim to investigate the neural correlates of both vocabulary and grammar learning using fNIRS via an artificial language learning paradigm. Importantly, the artificial language was designed to mimic natural second language learning free of learning manipulation to examine the cognitive mechanisms that adults would naturally rely on during second language learning.

1.2 Maturational Constraints on Language Learning

Early foundational theories of language learning have posited that language acquisition and learning restrictions are driven by linguistic-specific processes and constraints (Chomsky, 1986). However, more recent evidence has challenged this view, instead arguing that language processing and acquisition strongly depend on domain-general learning mechanisms (Chater & Christiansen, 2010; Folia, Uddén, De Vries, Forkstam, & Petersson, 2010; Reali & Christiansen, 2009). This theory stems from Newport's (1990) work suggesting that age-dependent differences in language learning are due to maturational constraints. She found that age of acquisition is an important factor in determining proficiency outcomes in both first and second language learning and argued that this effect may occur as a result of maturational growth of non-linguistic cognitive mechanisms.

Drawing upon Newport's (1990) theory of maturational constraints, recent studies have focused on a somewhat paradoxical theory suggesting that the greater developed prefrontal cortex (PFC) that gives rise to adults' superior explicit and executive functions may result in weaker learning of grammatical components of language (Finn, Lee, Kraus, & Hudson Kam, 2014; Smalle, Panouilleres, Szmalec, & Möttönen, 2017). This hypothesis is in line with the timeline observed in first and second language learning whereby proficiency outcomes change linearly throughout childhood but plateau in early adulthood (Newport, 1990) around the time the PFC finishes developing.

1.3 The Declarative/Procedural Model

Building upon research suggesting that language learning and processing heavily rely on non-linguistic cognitive processes (e.g., Bates, Devescovi, & Wulfeck, 2001; Ellis, 2005; Saffran, Pollak, Seibel, & Shkolnik, 2007), a growing body of research focuses on language's relationship with domain-general long-term memory (Hamrick, Lum, & Ullman, 2018). Long-term memory can be further divided into declarative and procedural memory systems (Mishkin, Malamut, & Bachevalier, 1984; Squire & Zola, 1996). Declarative memory involves explicitly learning novel facts and events while procedural memory involves implicitly learning skills and patterns without awareness (Cohen, Poldrack, & Eichenbaum, 1997).

The procedural memory system is supported by frontal and basal ganglia regions. Particularly, the basal ganglia circuits are involved in learning and consolidating procedural skills and knowledge while frontal regions play a greater role in further processing those automized skills. Declarative memory strongly relies on medial temporal structures and neocortical regions (Cohen & Squire, 1980; Davis & Gaskell, 2009; Eichenbaum, 2003; Squire, 2004; Ullman, 2004, 2016). The pars triangularis of the inferior frontal gyrus may be especially important for explicit semantic recall (Nevat, Ullman, Eviatar, & Bitan, 2017; Ullman, 2004, 2016).

According to the Declarative/Procedural Model outlined by Ullman (2001), both language learning and use rely on declarative and procedural memory. However, distinct components of language rely on different memory systems. On the one hand, language components that are based on arbitrary associations such as vocabulary and irregular words are learned and stored using declarative memory. The semantic component of vocabulary words is arbitrarily paired with the word's phonological form. For example, the pairing between the phonological word-form of "apple" and its semantic representation of the fruit is arbitrary. Therefore, the phonological word-form of an object or concept must be memorized explicitly. Likewise, Ullman (2001) argued that since irregular words are exceptions to regular morphological rules, they must also be memorized explicitly. Failure to retrieve the correct form of an irregular word results in overregularization errors. For example, English speakers explicitly learn that the plural form of "goose" is not "gooses" as the regular plural "-s" rule would predict, but rather "geese". On the other hand, like its singular form, the plural of "moose" is "moose" rather than "mooses" or "meese". These irregular words do not follow systematic patterns and are therefore argued to be memorized explicitly.

In contrast, rule-governed grammatical patterns can be learned through either explicit or implicit systems. Ullman (2001) argued that the declarative system operates faster than the procedural system, with only one incidence of exposure required to learn a word, fact, or event. As a result, it may be the case that some grammatical components are initially learned using declarative memory through exemplars of various word-form tokens. However, as natural languages are extremely complex, optimal rule learning eventually occurs using implicit procedural memory through increased exposure to the language patterns. An optimal procedural grammar system operates similarly to implicit statistical learning where in the absence of other acoustic word-boundary cues such as pauses, word-forms are implicitly learned through exposure to varying probabilities of syllables co-occurring (Saffran, Aslin, & Newport, 1996). Likewise, the Declarative/Procedural Model proposes that grammatical patterns such as inflectional morphemes are best learned implicitly through repeated exposure to linguistic patterns via transitional probabilities between a stem and a suffix.

Recently, Hamrick and colleagues (2018) provided evidence to corroborate the declarative-to-procedural shift in grammar learning. The authors found that grammar was associated with declarative memory in early experience but shifted to procedural memory as more experience and proficiency was acquired. The validity of these findings was further supported through consistency across different languages, structures, and tasks.

Ullman and colleagues (1997) argued that evidence stemming from patients with various brain injuries and neurodegenerative diseases supports a dissociation between declarative and procedural memory in language. Particularly, patients with damage to temporal or parietal neocortex such as Alzheimer's and Posterior Aphasia patients have been found to exhibit deficits with irregular verb use. For example, these patients demonstrate overregularization errors such as incorrectly applying the regular "-ed" suffix to an irregular verb such as “run”. Characteristically, Alzheimer’s Disease causes impairments in remembering and forming new declarative memories in both linguistic and non-linguistic domains (Corkin, 1982; Nebes, 1989; Sagar, Cohen, Sullivan, Corkin, & Growdon, 1988). Likewise, those with Posterior Aphasia exhibit word-finding deficits, especially for content words such as nouns and verbs (Goodglass, 1993). On the other hand, processing rule-governed procedural components of language, including morphology and syntax, has been found to remain intact in both Alzheimer’s Patients (Nebes, 1989; Schwartz, Marin, & Saffran, 1979) and patients with Posterior Aphasia (Goodglass, 1993).

Contrarily, patients with frontal and basal ganglia damage, such as Parkinson’s and Anterior Aphasia patients, have been found to exhibit opposite patterns to those with Alzheimer’s and Posterior Aphasia. Patients with Parkinson’s Disease exhibit grammar deficits (Grossman, Carvell, Stern, Gollomp, & Hurtig, 1992; Illes, 1989; Lieberman et al., 1992) while vocabulary and declarative memory processes remain intact (Growdon & Corkin, 1987; Lees & Smith, 1983; Sagar et al., 1988). Likewise, those with Anterior Aphasia exhibit syntax comprehension deficits and agrammatism such as omitting and incorrectly using inflectional morphemes. Additionally, opposite to those with Alzheimer’s and Posterior Aphasia, a case study of a patient with Anterior Aphasia revealed a deficit in inflecting regular verbs while exhibiting intact irregular word processing without making overregularization errors (Ullman et al., 1997). From this evidence, Ullman and colleagues (1997) concluded that irregular forms are learned explicitly using declarative memory since only those with declarative deficits exhibited irregular and overregularization errors.

However, alternative theories to the Declarative/Procedural Model have been put forth. One posits that both regular and irregular words are rule-computed (Chomsky & Halle, 1968; Halle & Mohanan, 1985) while another eliminates rules altogether and argues for a connectionist associative approach (MacWhinney & Leinbach, 1991; Rumelhart & McClelland, 1986). The latter provides evidence explaining the double dissociation between regular and irregular past tense word processing provided by Ullman et al., (1997) without the use of contrasting memory systems. Joanisse and Seidenberg (1999) found that simulating phonological deficits in a connectionist simulation model resulted in an increased impairment of past tense nonword performance while simulating semantic deficits resulted in an increased impairment of irregular verb performance. Therefore, the dissociation was explained as a difference between phonological and semantic reliance. The current study does not aim to distinguish between the models. Instead, it builds on theories pertaining to the argument that competition between some cognitive mechanisms affect language learning. Whether they are linguistic-specific or domain-general memory systems is undetermined. However, I focus on the declarative/procedural distinction as this model is best in line with explaining differences between semantic vocabulary and grammatical pattern processing.

1.4 Declarative/Procedural Competition

Although declarative and procedural memory systems have been thought to be independent of one another, various evidence suggests that they indeed interact in various ways (Cohen et al., 1997; Kim & Baxter, 2001; Mathews et al., 1989; Squire & Zola, 1996). An apparent negative relationship between declarative and procedural memory may particularly be important in further explaining vocabulary and grammar learning differences. The seesaw effect coined by Ullman (2004) refers to the competition exhibited between declarative and procedural memory systems where the enhancement of one system directly interferes with the successful operation of the other system (Nevat et al., 2017; Poldrack & Packard, 2003; Ullman, 2004, 2016). Notably, these two memory systems change with age. Nevat and colleagues (2017) argued that adults should exhibit an increased reliance on declarative memory in second language learning since declarative memory improves across adolescence while procedural memory diminishes. Thus, a decreased reliance on procedural mechanisms may directly inhibit optimal grammar learning in adulthood.

One piece of evidence for an interference effect between declarative and procedural learning in language comes from Finn and colleagues (2014) who examined the role that effort plays in artificial vocabulary word segmentation and phonologically defined grammatical category learning. The authors found that compared to passively listening to an artificial language, instructing participants to effortfully learn words, categories, and category orders facilitated vocabulary segmentation while hindering grammatical category learning. Therefore, the authors concluded that explicitly trying to figure out the rules of a language can interfere with optimal grammar learning. They further speculated that adults may naturally put in more explicit effort in learning grammatical patterns, thereby driving differences in vocabulary and grammar in natural second language learning.

Further support for an interference effect emerges from theories of neural maturation. The dorsolateral prefrontal cortex (DLPFC), which is involved in executive functions and declarative memory, does not completely develop until early adulthood.

Recently, Smalle and colleagues (2017) examined the interference hypothesis using Transcranial Magnetic Stimulation (TMS) via a syllable sequence learning paradigm. The authors found that inhibiting the left DLPFC facilitated word-form learning. Further, they found that word-form learning negatively correlated with executive function tasks in control participants. Likewise, disrupting the ventrolateral prefrontal cortex (VLPFC) resulted in similar patterns regarding procedural syntactic learning (Uddén et al., 2008). Overall, these findings support the interference hypothesis by demonstrating that executive functions supported by the DLPFC and the VLPFC in adults negatively interact with implicit procedural learning in language.

1.5 Functional Near-Infrared Spectroscopy (fNIRS)

fNIRS has become an increasingly popular neuroimaging technique especially in the field of neurolinguistics. fNIRS uses near-infrared light to measure concentration changes of both oxygenated (HbO) and deoxygenated (HbR) hemoglobin in the cortex. Comparable to how the blood oxygenation level dependent (BOLD) signal is measured in fMRI, an fNIRS signal measuring neural activity is dependent on neurovascular coupling which refers to increases in HbO and decreases in HbR (Logothetis & Wandell, 2004; Tsunashima, Yanagisawa, & Iwadate, 2012). However, fNIRS differs from fMRI in terms of how the signal is obtained. Through detector probes, fNIRS measures the scatter of NIR light emitted by source probes placed on the scalp. Hemoglobin, the protein in red blood cells that carries oxygen, allows for a relatively high attenuation of NIR light. Human tissue is moderately transparent to light in the 650-1000 nm of the near-infrared spectrum (Quaresima, Bisconti, & Ferrari, 2012). In fact, NIR light is 100 times more likely to scatter rather than be absorbed by human tissue (Delpy & Cope, 1997). The proportion of reflected as opposed to absorbed light is then used to calculate neural activity in the cortical tissue between a source-detector pairing called a channel. Given that the relative oxygenation of hemoglobin changes its absorption spectrum, light intensity changes in various wavelengths are then converted into concentration changes of both HbO and HbR hemoglobin using the modified Beer-Lambert law (Delpy et al., 1988).

Several advantages of fNIRS make it an ideal neuroimaging method to study language in a wide range of populations including patients, elderly participants, and children. fNIRS' advantages include being non-invasive, less susceptible to head movement compared to fMRI, portable, affordable, and quiet. Although not completely immune to speech-related artifacts (Zhang, Noah, Dravida, & Hirsch, 2017), compared to other neuroimaging methods, fNIRS allows for verbal responses and verbal repetition, especially useful for language research. fNIRS is argued to be a reliable tool to study higher cognitive functions such as language due to its good spatial and temporal resolution when mapping cortical processes (Dieler, Tupak, & Fallgatter, 2012).

Regarding neurolinguistic research, fNIRS has been used to localize both Broca's area during object naming (Cannestra, Wartenburger, Obrig, Villringer, & Toga, 2003), and Wernicke's area during phoneme discrimination (Minagawa-Kawai, Mori, Furuya, Hayashi, & Sato, 2002). Other neurolinguistic research has utilized fNIRS to examine language lateralization (e.g., Kennan, Kim, Maki, Koizumi, & Constable, 2002), syntactic decision tasks (e.g., Noguchi, Takeuchi, & Sakai, 2002), intonational pitch (Sato, Sogabe, & Mazuka, 2007), language processing in young children (Wartenburger et al., 2007), dyslexia (Zhang et al., 2006) and even speech representation in neonates

(Peña et al., 2003; For reviews on fNIRS' use in language research, see Dieler et al., 2012; Quaresima et al., 2012). Thus, fNIRS allows for increased possibilities in language research that may not be possible using other neuroimaging methods.

1.6 Artificial Languages

Natural languages' multifaceted complexity has made it exceptionally difficult to study various components and factors of language learning in a controlled manner. Artificial languages have been used as proxies for natural second language learning research due to multiple advantages. Most importantly, artificial languages provide better control of external factors that can affect language learning such as language exposure, morphological complexity, similarity of the experimental language to the learner's native language, and the possibility of manipulating various morphological factors (e.g., Nevat et al., 2017). Further advantages of artificial language learning paradigms include their simplicity and size which allow for learning and higher proficiency achievement to be reached in a limited time period.

However, artificial languages' simplicity advantage also gives rise to one of their biggest concerns. When using artificial languages as proxies for natural second language learning, an assumption is made that the same mechanisms are at play during learning and processing of both artificial and natural languages. A growing body of research has set out to examine the ecological validity of artificial language use. Indeed, in a review, Folia and colleagues (2010) provided evidence from fMRI, electroencephalography (EEG), and TMS that the neural mechanisms involved in artificial language learning are shared with those during natural language learning and processing. Likewise, behavioural developmental trajectories in natural languages highly correlate with artificial language development (Gomez & Maye, 2005). Moreover, brain lesion studies have provided evidence of parallel impairments in language processing and artificial sequence learning (e.g., Christiansen, Kelly, Shillcock, & Greenfield, 2010; Evans, Saffran, & Robe-Torres, 2009; Richardson, Harris, Plante, & Gerken, 2006). This wide range of converging evidence suggests that performance and processing of artificial languages can be generalized to natural second language learning and processing.

However, not all artificial languages may be ideal measures of all aspects of language learning. Recently, Ettlinger, Morgan-Short, Faretta-Stutenberg, and Wong (2016) examined the relationship between lab-based artificial language learning and natural second language learning in a classroom environment. Critically, performance on both tasks were found to positively correlate, especially when the artificial language included a semantic component along with complex grammatical patterns. Consequently, the artificial grammar must be complex enough to represent the complexities of natural languages, and the inclusion of semantics in the language paradigm is imperative.

1.7 The Current Study

The goal of the current study is to examine distinct language components of second language learning in adults. The study utilized an artificial language learning paradigm to examine the behavioural and neural differences between semantic vocabulary and inflectional morphology learning. A behavioural-only study (Study 1) was conducted to assess whether the artificial language employed is sensitive enough to capture vocabulary and grammar learning differences observed in natural second language learning. Study 2 was conducted using the same artificial language learning paradigm with the addition of fNIRS to examine the neural correlates of both vocabulary and grammar learning.

The artificial language used in the current study was adapted from Nevat and colleagues (2017) who examined affix type frequency and predictability in inflectional learning using fMRI. The current study controlled for both affix type frequency and predictability and included semantic representations of words to directly compare grammar with vocabulary learning. The artificial language included singular and plural words for common objects where regular distinct plural suffixes were determined by the phonological rhyme of the root. The language also included irregular and inconsistent words that did not follow any grammatical patterns. Following training, both trained and untrained test items were used to assess learning of semantic vocabulary recall and grammatical generalization.

For Study 1, it was expected that the artificial language employed in the current study would reveal behavioural differences in terms of accuracy and response time (RT) between vocabulary and grammar learning. For Study 2, HbO and HbR concentration differences were expected in frontal and temporal brain regions, aligning with differences in procedural and declarative mechanisms involved in grammar and vocabulary processing.

Chapter 2

2 Methods

2.1 Participants

The present study included 59 monolingual English speakers recruited from The University of Western Ontario and the surrounding London, Ontario community through student participant pools, posters, and Facebook advertisements. Study 1 consisted of 40 (31 female) participants ages 18-29 (M = 23.1, SD = 2.92) and Study 2 included 19 (11 female) participants ages 18-21 (M = 18.84, SD = .96). All participants reported being neurologically healthy with normal hearing and normal or corrected-to-normal vision. Additionally, all participants reported English as their first language while rating their ability to speak, understand, read and/or write in any other language as poor. Seven additional participants were recruited but excluded from analyses due to technical malfunctions (three participants) and language exclusion criteria (four participants). All participants were compensated for their time and informed consent was obtained from each participant. These studies were approved by the University of Western Ontario Non-Medical Research Ethics Board (see Appendix A and Appendix B).

2.2 Stimuli

2.2.1 The Artificial Language

All auditory stimuli were recorded in a soundproof booth using a Blue Snowball iCE condenser microphone. Recordings were made by a female speaker. Stress was placed on the first syllable of each word. Each word was recorded three times and the version with the best sound quality and most natural pitch contour was used. Audio was recorded, edited, and amplified using Audacity software.

The artificial language used in the present study was adapted from Nevat and colleagues (2017). The present study used similar word-forms and grammatical patterns modified for the purpose of comparing vocabulary and grammar learning. As displayed in Table 1, the language was composed of 54 novel words taking a regular or irregular plural ending. Singular words consisted of two syllables (CVCVC; where C = consonant, V = vowel) and plurality was marked by an additional third syllable suffix (CVCVC+VC). Each word was randomly paired with an image of a common inanimate object. Singular words were paired with an image of a single object such as an apple while plural words were paired with an image of four identical objects such as four apples.

2.2.2 Regular Words

42 of the 54 words were regular and were comprised of two groups, each attaching a distinct suffix to mark plurality based on the phonological rhyme of the root. Group 1 consisted of 21 words, each with a root ending in '-oz', '-ig', or '-ul' and were assigned the suffix '-an' to mark plurality. Group 2 consisted of another 21 words ending in '-od', '-iv', or '-un' and were assigned the plural suffix '-esh'. For example, the plural form of a Group 1 word such as 'nifoz' was 'nifozan' while the plural form of a Group 2 word such as 'napod' was 'napodesh'.

30 of the 42 regular words were included in the training phase. 18 of the 30 regular trained words were trained on both the singular and plural forms. Singular and plural words appeared once in separate trials randomized within each training session. The 12 remaining regular trained words were trained on one form only (six words were trained on the singular form only and another six words were trained on the plural form

only). This was done for the purpose of distinguishing vocabulary from grammar testing, further explained in the subsequent test items section. Words trained on one form only appeared twice within each training session to control for equivalent vocabulary exposure to the regular words trained on both forms. The remaining 12 of the 42 total regular words were untrained. For untrained words, neither the singular nor plural forms were included in the training phase but were included in testing to assess generalization of plural rules to novel words.

2.2.3 Irregular and Inconsistent Words

In addition to the regular words, the artificial language included six irregular and six inconsistent words. Irregular words comprised of root rhymes consistent with regular words but were combined with one of the irregular plural suffixes '-ev', '-ak', or '-ur' not associated with either Group 1 or Group 2. For example, although a word such as 'pomoz' contains a Group 1 rhyme, it took on the irregular suffix '-ev' to mark plurality. On the other hand, inconsistent words took on the regular suffix that was not associated with the rhyme of that word. For example, a word with a Group 2 rhyme such as 'shalod' took on the Group 1 plural suffix becoming 'shalodan' rather than 'shalodesh' in its plural form. Irregular and inconsistent words were trained on both singular and plural forms appearing in separate trials randomized within each training session.

Table 1. The Artificial Language

List of trained and untrained items displaying singular regular and irregular word-forms and plural inconsistent word-forms.

Form appearing in training	Group 1: Regular suffix '-an'			Group 2: Regular suffix '-esh'		
	Regular trained words			**Regular trained words**		
Singular only	nifoz	nishig	tizul	napod	paniv	koshun
Plural only	tuvoz	posig	shuzul	nezod	tepiv	rosun
Singular and plural	kufoz	bolig	mupul	resod	lekiv	ligun
	laloz	dedjig	suful	moshod	sibiv	batun
	refoz	rekig	tedjul	lurod	fritiv	wupun
	Regular untrained words			**Regular untrained words**		
Not trained	getoz	mikig	nisul	minod	comiv	sopun
	teloz	latig	hunul	filod	nofiv	zufun
	Inconsistent words: suffix '-esh'			**Inconsistent words: suffix '-an'**		
Singular and plural	gishoz	givig	bikul	shalod	gukiv	gitun
	Irregular words			**Irregular words**		
Singular and plural	pomoz-ev	dipig-ak	shibul-ur	sapod-ev	riniv-ak	tikun-ur

2.3 Procedure

Prior to completing the artificial language tasks, participants completed a general demographics and language history questionnaire (see Appendix C). The experiment took place in a quiet testing room using a laptop computer. Participants were instructed that they were going to learn a new language called Brainish using visual and auditory stimuli. The experiment consisted of a 30-minute training phase and a 10-minute testing phase. All auditory stimuli were presented to participants through speakers and all visual stimuli were presented on a laptop screen via E-Prime 2.0 experiment presentation software (Schneider, Eschman, & Zuccolotto, 2002).

2.3.1 Training Procedure

After providing informed consent and completing the questionnaire, participants took part in an artificial language learning training phase comprising of three 10-minute training blocks with optional breaks provided in between each block. Each of the three training blocks were identically composed of 84 trials randomized between blocks and participants. As depicted in Figure 1 and Figure 2, participants were presented with an image in conjunction with an auditory word for 1000 ms. After a 500 ms inter-stimulus interval, the image was presented again, prompting the participant to repeat the novel word out loud. Repeating the words out loud allowed for a naturalistic experience of second language learning and enhanced memory encoding through pronunciation (Hopkins & Edwards, 1972; Hopman & MacDonald, 2018). In addition, repeating the words out loud provided a method of ensuring sustained attention throughout the task along with masking the purpose of the task.

For participants in Study 1, a Chronos button response device and microphone were used to record verbal responses to assess whether participants were correctly repeating the words. No additional information regarding the nature of the language or experiment was given. In order to minimize explicit grammar learning during training, participants were not told to memorize the words or that a testing phase would follow.

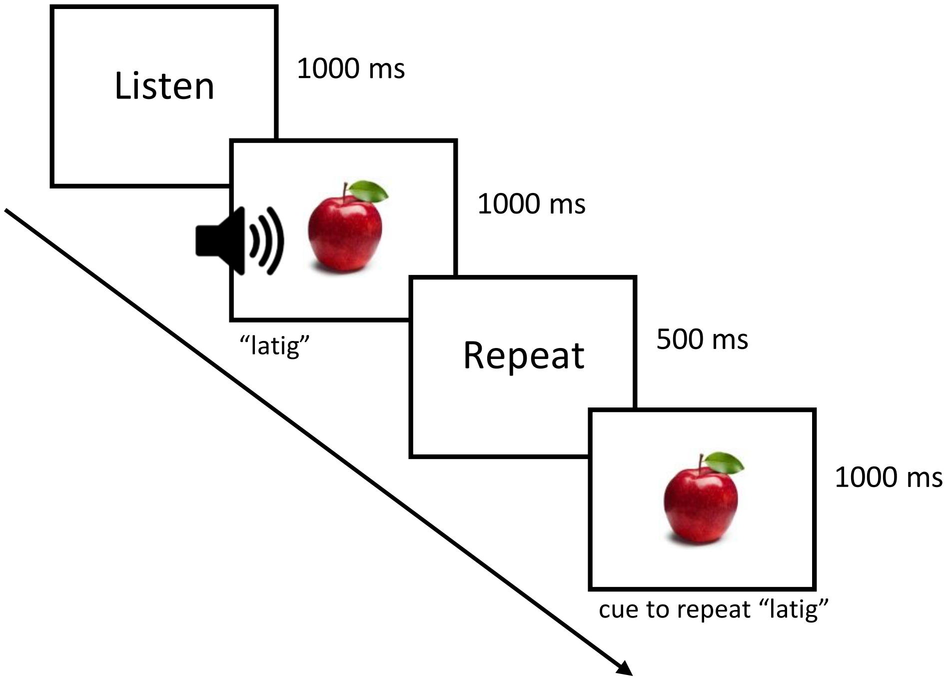

Figure 1. Example of a training trial for a singular item. Participants were instructed to repeat the word out loud when the image was presented for the second time.

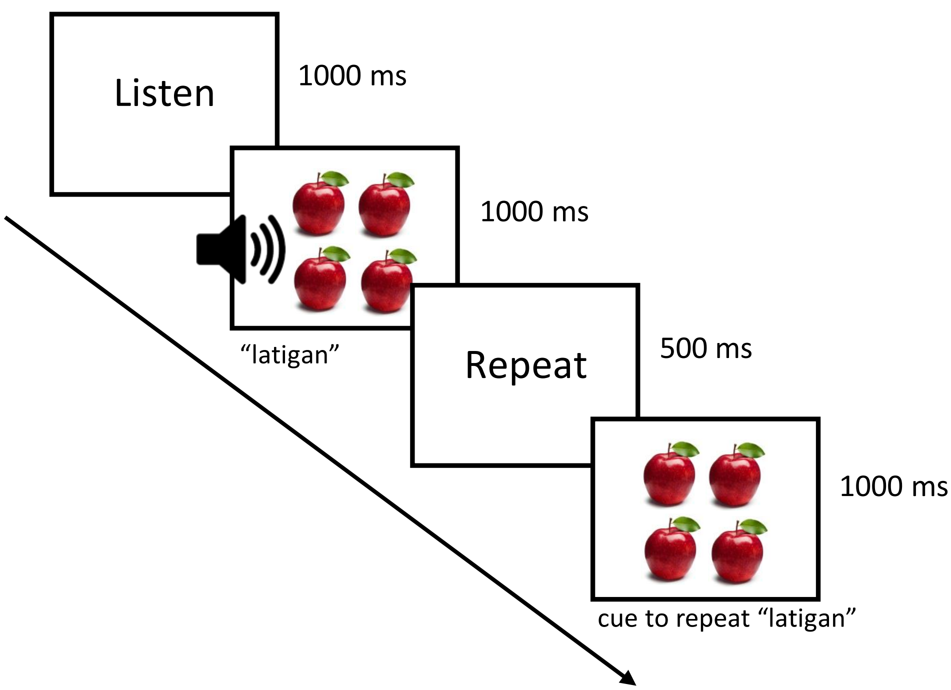

Figure 2. Example of a training trial for a plural item.

2.3.2 Testing Procedure

Recall that words were either trained on the singular, plural, or both forms while other words were not included in training at all. After a short break following the training phase, participants completed two sets of testing blocks, one for trained words and one for untrained words. The first testing block consisted of judgement tasks where participants were instructed to determine whether a given word was correctly paired with a given image (Figure 3). There were 36 singular and plural test words in the first testing block, each of which was included in training in either singular, plural, or both forms.

Immediately following the first testing session, the second testing session for untrained words was administered. Participants were instructed that new Brainish words would be presented and were tasked to judge whether a novel test item was correct or incorrect. As depicted in Figure 4, a novel singular or plural word was paired with an image of a common object that did not appear in training. Immediately following the novel word-object pairing, the form of the word that was not previously presented acted as a test item. Participants' task was to judge the pairing of the singular or plural form of the word.

For participants in Study 1, a Chronos button response device was used for all responses. Trials were randomized within each session. For participants in Study 2, responses were entered through an external keyboard. Trials were reorganized into three-trial blocks with 10-second rests between each block in order to obtain better hemodynamic response measures. Button responses and reaction times for both groups were recorded via E-Prime 2.0 (Schneider et al., 2002). Upon completion of the tasks, participants were provided a debriefing form detailing the study goals.

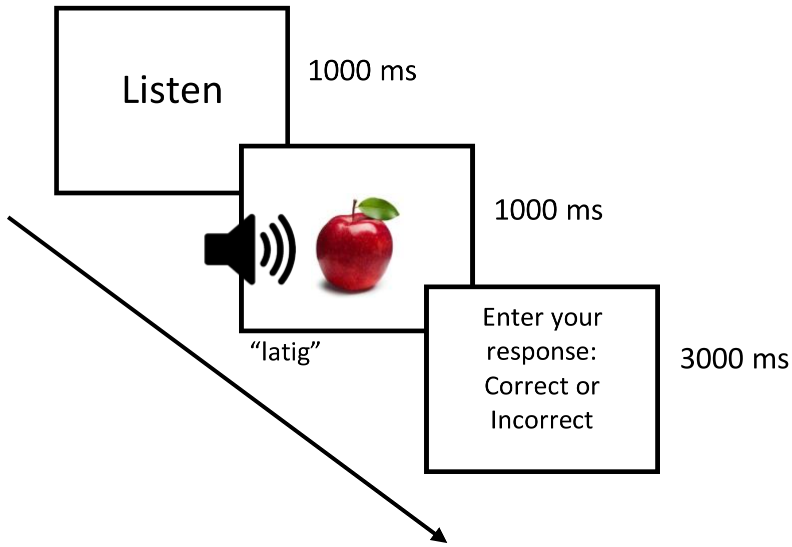

Figure 3. Example of a testing trial for a trained item. Participants judged whether a word was correctly paired with the corresponding image.

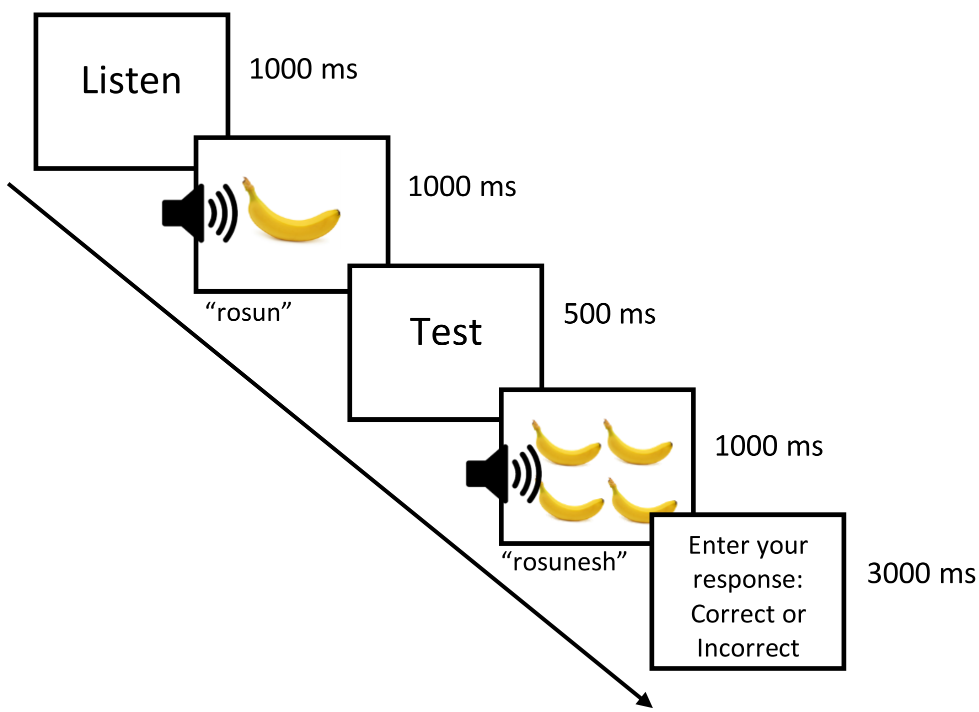

Figure 4. Example of a testing trial for a plural untrained item. A novel word and image not included in the training phase were presented. Participants completed a judgement task of whether the second word presented correctly corresponded to the second image.

2.3.3 Test Items: Vocabulary

12 regular singular items, six irregular plural items, and six inconsistent plural items were tested to assess vocabulary and declarative memory. Each of these items were explicitly exposed to three times throughout the training phase and did not contain a regular pattern to the grammar. Half of the test trials for each item type were correct and half were incorrect. Incorrect trials of regular singular words consisted of mismatched pairs of Brainish words and objects. For example, the Brainish word for apple was paired with the image of a pen. Incorrect trials of irregular and inconsistent plural words were composed of roots incorrectly followed by the regular suffix instead of the irregular or inconsistent suffix. For example, an irregular plural word such as “pomozev” was incorrectly presented as “pomozan”.

2.3.4 Test Items: Grammar

12 untrained words and 12 words trained on the singular form only or plural form only were used to assess grammar and procedural memory. Recall that each of the 12 words that were trained on one form only were tested on the form that did not appear in training. For example, words that were trained on the singular form only were tested on the plural form. This test type assessed participants’ ability to generalize the plural grammatical rule to novel word forms. On the other hand, words that were trained on the plural form only were tested on the singular form to test participants’ ability to extract the roots and suffixes of the words.

The incorrect test items for words trained on the singular form only and tested on the plural form contained the incorrect plural suffix. For example, a word such as “nifoz” ending in a Group 1 rhyme incorrectly contained the Group 2 ‘-esh’ plural suffix. The incorrect test items of the words trained on the plural form only and tested on the singular form consisted of the root of the word excluding the final coda, rendering the test item a CVCV word-form rather than CVCVC. For example, a word such as “tuvoz” which was only trained on its plural form “tuvozan” was tested as a singular item as “tuvo”.

12 untrained words were additionally used to test grammatical judgement. Recall that in the second testing block, word-object pairs were presented and immediately after, participants completed judgement tests on the form that was not previously presented. This test type provided an additional measure of assessing participants’ ability to generalize plural grammatical suffixes to completely novel words while eliminating the possibility of reliance on semantic or declarative memory. Incorrect untrained plural items consisted of roots paired with incorrect suffixes while singular test items consisted of the root of the word without the final coda. As the rules of the language were not explicitly taught to participants, grammatical rules were only exposed to participants implicitly and learning would be optimized through procedural learning. Although it may be the case that adults might explicitly attempt to figure out the grammatical rules of the language, by testing word forms not included in training, use of explicit declarative memory can be ruled out for these test items.

2.4 fNIRS Data Acquisition

Prior to beginning the artificial language tasks, the 19 participants taking part in the fNIRS study had their heads measured and were fitted with an fNIRS probe placement cap. Participants watched television on the laptop screen while the cap was fitted with probes. Hair was gently parted to ensure that the probes maintained contact with the scalp and to reduce any light obstruction caused by hair. A black cap was then placed over the probes to block out any light emitted from the external environment. Channels were calibrated using NIRStar 15.2 NIRScout acquisition software (NIRx Medical Technologies, LLC). Set-up and calibration took approximately 30 minutes. The participants wore the fNIRS caps throughout both the training and testing phases, a total of approximately 40 minutes post set-up.

Neural data was collected using a whole-head NIRx NIRScout device via NIRStar 15.2 NIRScout acquisition software (NIRx Medical Technologies, LLC). Calibration was conducted prior to starting the experiment in order to optimize the gains for each channel. Data was continuously sampled at 1.95 Hz. As depicted in Figure 5, 32 laser sources, 30 detectors, and eight short distance detectors were included in the probe array resulting in 112 channels of interest during sampling. Neural data was recorded during both training and testing phases. Only testing phase data is included for the purpose of the present study.

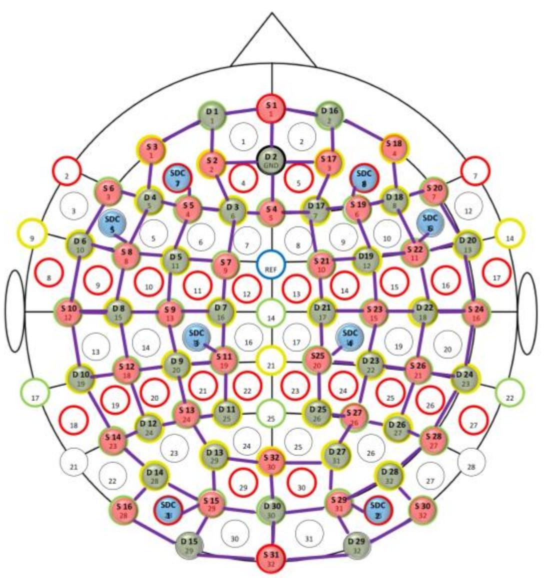

Figure 5. fNIRS 2D probe array with 3 cm mean distance between probes. Distance is not to scale. Red filled circles represent sources and green circles represent detectors. Blue circles represent short distance detectors. Purple lines represent channels.

2.5 Behavioural Analysis

Participants' data in Study 1 and Study 2 was analysed separately. For both groups, paired samples t-tests were conducted for accuracy (percent of correct responses) and RT (ms) between declarative and procedural test items. The vocabulary condition comprised of regular singular words, irregular plural words, and inconsistent plural words. The grammatical generalization condition comprised of untrained words and words trained on one form only. As additional exploratory measures, paired samples t-tests of accuracy scores were conducted between the sub-types within vocabulary and grammar conditions. Performance was compared between regular singular test items and the combination of irregular and inconsistent plural test items (Hereon grouped as irregular items). Likewise, differences between trained and untrained grammar items were compared.

2.6 fNIRS Preprocessing and Analysis

2.6.1 Preprocessing

Preprocessing and data analyses were conducted using the MATLAB-based nirsLAB analysis software (NIRx Medical Technologies, LLC). Eight short distance channels were excluded from analyses due to incompatibility with the NirsLAB software resulting in 104 channels of interest. Two wavelengths at 785 nm and 808 nm were included in analyses assessing both deoxygenated (HbR) and oxygenated (HbO) hemoglobin concentration changes.

For each participant, raw data was thresholded according to gain factors and coefficient variations (CV) calculated during calibration conducted prior to data sampling. As electronic gain factors and CVs are negatively correlated with signal-to-noise ratio, any channels with gain factors greater than eight or CVs at either wavelength equal to or greater than 10% were excluded from analyses. Discontinuity corrections were performed to correct for artifacts. Long-term and short-term fluctuations distributed at regular time intervals over the entire measure were corrected using band pass filtering with low cut-off frequency thresholded at 0.01 Hz and high cut-off frequency thresholded at 0.2 Hz. Concentration changes of HbO and HbR were calculated for each channel using the modified Beer-Lambert law (Delpy et al., 1988).

2.6.2 Analysis

NirsLAB single-subject general linear model (GLM) analyses were first conducted for both HbO and HbR data. A canonical hemodynamic response function (HRF) was used as a basis function to account for hemodynamic response delays in neural activity and convolved with a design matrix corresponding to each condition block within the testing phase. HRF pre-colouring was applied to correct for serially-correlated noise. Next, a group-level analysis was conducted using the GLM coefficients calculated from the single-subject analyses. Paired samples t-tests were conducted for HbO and HbR concentrations between vocabulary and grammar test blocks and between their sub-conditions.

Chapter 3

3 Results

Recall that for Study 1, test trials were presented in a randomized order. On the other hand, the testing phase was organized into three-trial blocks for Study 2 in order to obtain better hemodynamic response measures. As the study designs for the testing phase were different between the two studies, the results for Study 1 and Study 2 are presented separately. This allows for direct comparison between behavioural and neural results within Study 2.

3.1 Study 1 Behavioural Results

Paired t-tests were conducted between vocabulary and grammar response accuracy scores and RT. There were significant mean differences in accuracy scores between vocabulary (M = .688, SD = .098) and grammar (M = .554, SD = .099) test trials; $t(39) = 6.237$, $p < .001$, $d = .986$ (see Figure 6). One-sample t-tests indicated that accuracy for both vocabulary test items ($t(39) = 12.146$, $p < .001$, $d = 1.92$) and grammar test items ($t(39) = 3.443$, $p = .001$, $d = .554$) were above chance level (50%). Additionally, significant mean differences were found in RT between vocabulary (M = 784.897, SD = 294.357) and grammar (M = 887.525, SD = 356.844) test trials; $t(39) = -2.889$, $p = .006$, $d = -.457$ (see Figure 7).

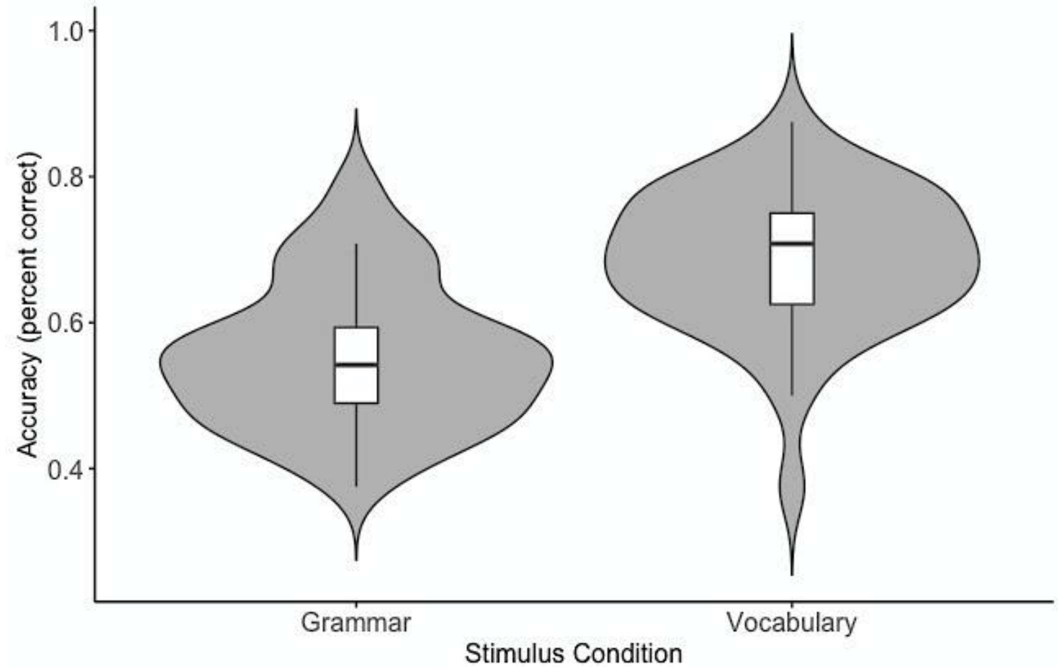

Figure 6. Study 1 accuracy plot displaying the median, quartiles, upper and lower limits (1.5 x IQR), and frequency probability densities for grammar and vocabulary test items.

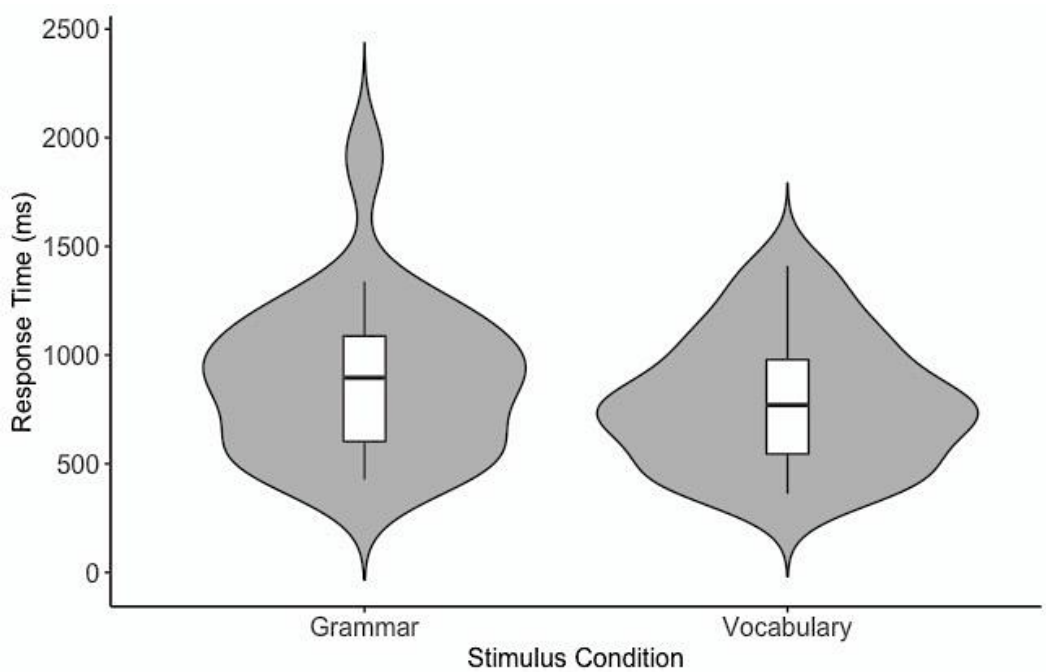

Figure 7. Study 1 RT plot displaying the median, quartiles, upper and lower limits (1.5 x IQR), and frequency probability densities for grammar and vocabulary test items.

Additional exploratory paired-samples t-tests were conducted between the vocabulary sub-conditions (singular regular items vs. plural irregular items) and the grammar sub-conditions (trained grammar items vs. untrained grammar items). Table 2 portrays the descriptive statistics for each sub-condition. There were significant mean differences between regular items compared to irregular items ($t(39) = 8.058$, $p < .001$, $d = 1.274$). No significant differences were found between trained grammar items (items trained on one form only) and untrained grammar items ($t(39) = -1.718$, $p = .094$, $d = -.272$).

Table 2. Study 1: Descriptive statistics for accuracy of sub-conditions.

	N	Mean	SD	SE
Singular regular	40	.806	.147	.023
Plural irregular	40	.569	.122	.019
Trained grammar	40	.531	.113	.018
Untrained grammar	40	.577	.145	.023

3.2 Study 2 Behavioural Results

Paired t-tests were also conducted between vocabulary and grammar response accuracy scores and RT for Study 2. Significant mean differences were found in accuracy scores between vocabulary (M = .679, SD = .114) and grammar (M = .507, SD = .069) test trials; $t(18) = 5.804$, $p < .001$, $d = 1.332$ (see Figure 8). Likewise, significant mean differences in RT were found between vocabulary (M = 805.763, SD = 201.054) and grammar (M = 912.716, SD = 191.030) test trials; $t(18) = -2.913$, $p = .009$, $d = -.668$ (see

Figure 9). However, unlike Study 1, one-sample t-tests indicated that only the accuracy mean for vocabulary test items ($t(18) = 6.853$, $p < .001$, $d = 1.572$) but not for grammar test items ($t(18) = .466$, $p = .647$, $d = .107$) was above chance (50%).

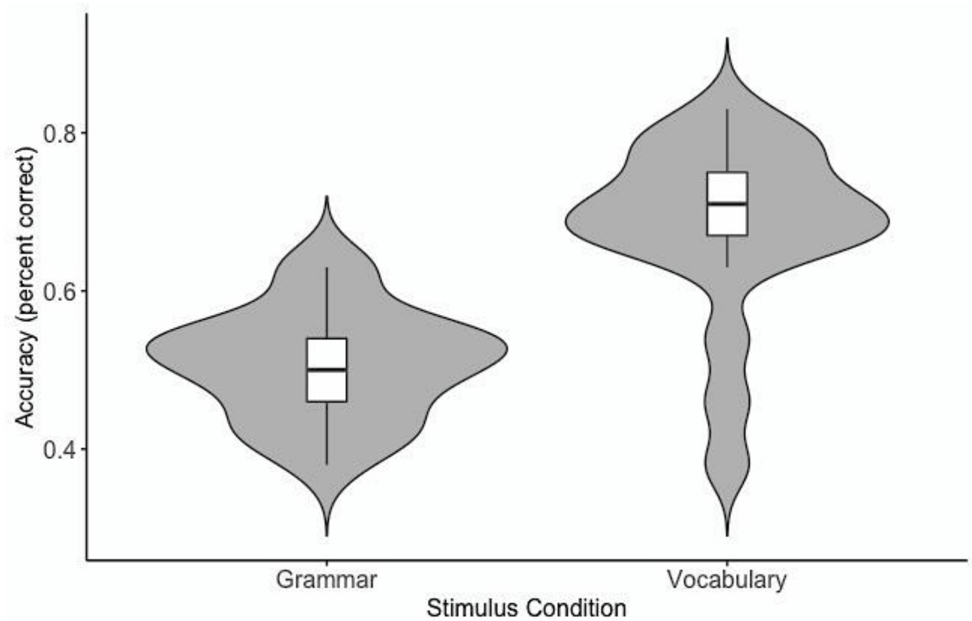

Figure 8. Study 2 accuracy plot displaying the median, quartiles, upper and lower limits (1.5 x IQR), and frequency probability densities for grammar and vocabulary test items.

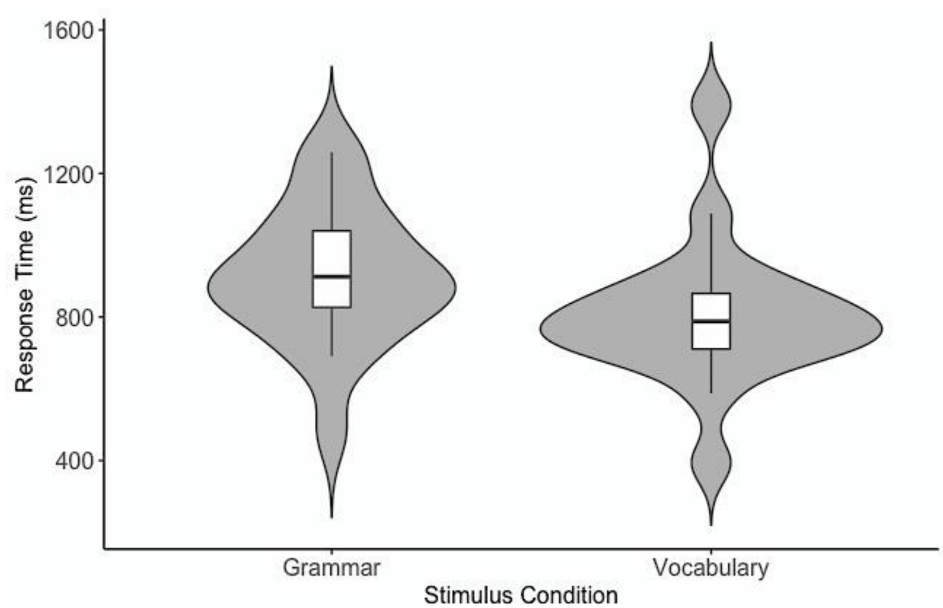

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Figure 9. Study 2 RT plot displaying the median, quartiles, upper and lower limits (1.5 x IQR), and frequency probability densities for grammar and vocabulary test items.

Table 3 portrays the descriptive statistics for each sub-condition. Similar to Study 1, there were significant mean differences between singular regular items and plural irregular items ($t(18) = 7.142$, $p < .001$, $d = 1.639$). No significant differences were found between items trained on one form only and untrained grammar items ($t(18) = .549$, $p = .590$, $d = .126$).

Table 3. Study 2: Descriptive statistics for accuracy of sub-conditions

	N	Mean	SD	SE
Singular regular	19	.785	.159	.037
Plural irregular	19	.570	.098	.023
Trained grammar	19	.517	.131	.030
Untrained grammar	19	.497	.075	.017

3.3 fNIRS Results

Significant differences were found in HbR concentration changes between vocabulary judgement tasks and grammar judgement tasks in channel 59 corresponding to the anterior part of the right DLPFC region; $t(18) = -2.106$, $p < .05$ (see Figures 10 and 11) and channel 20 corresponding to the posterior part of the left DLPFC region; $t(18) = -2.651$, $p < .05$ (see Figure 10 and 12). Moreover, when analyzed independently, both regular and irregular test blocks each showed significantly less activation compared to grammar test blocks in channel 20; $t(18) = -2.415$, $p < .05$; $t(18) = -2.278$, $p < .05$, respectively. No significant differences in HbO concentrations were found for these contrasts at $p < .05$.

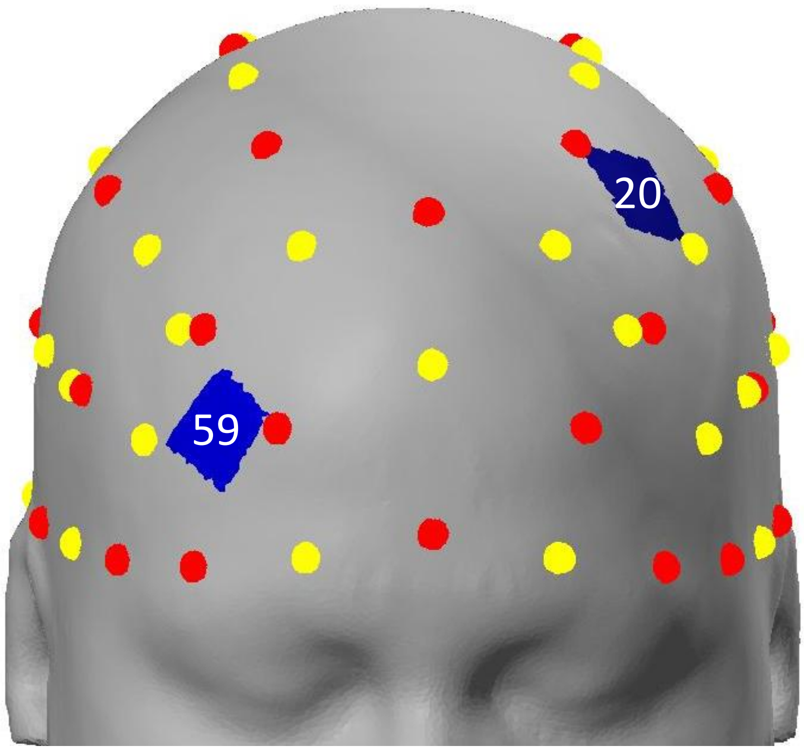

Figure 10. Thresholded SPMt image at p < .05 for HbR.

Contrast: vocabulary > grammar. Numbers represent significant channels.

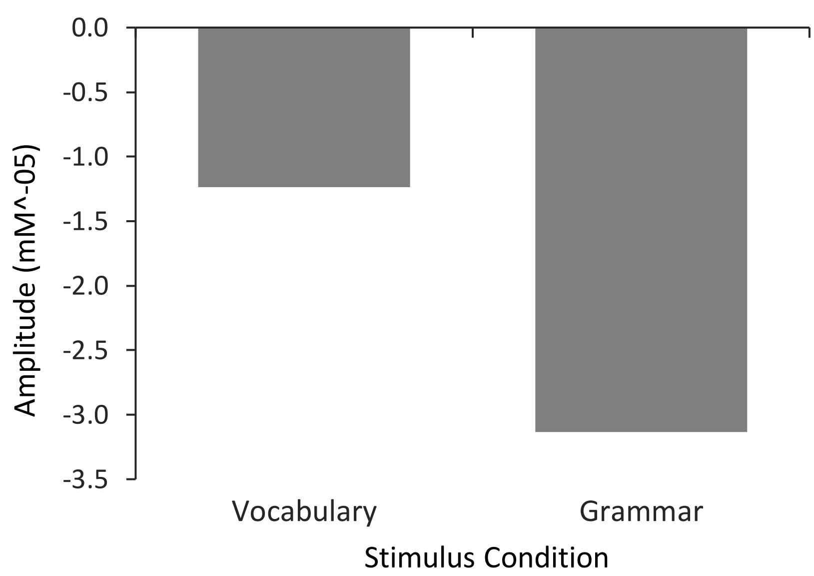

Figure 11. HbR amplitude difference in millimoles between vocabulary and grammar block averages for channel 59 part of the right DLPFC region.

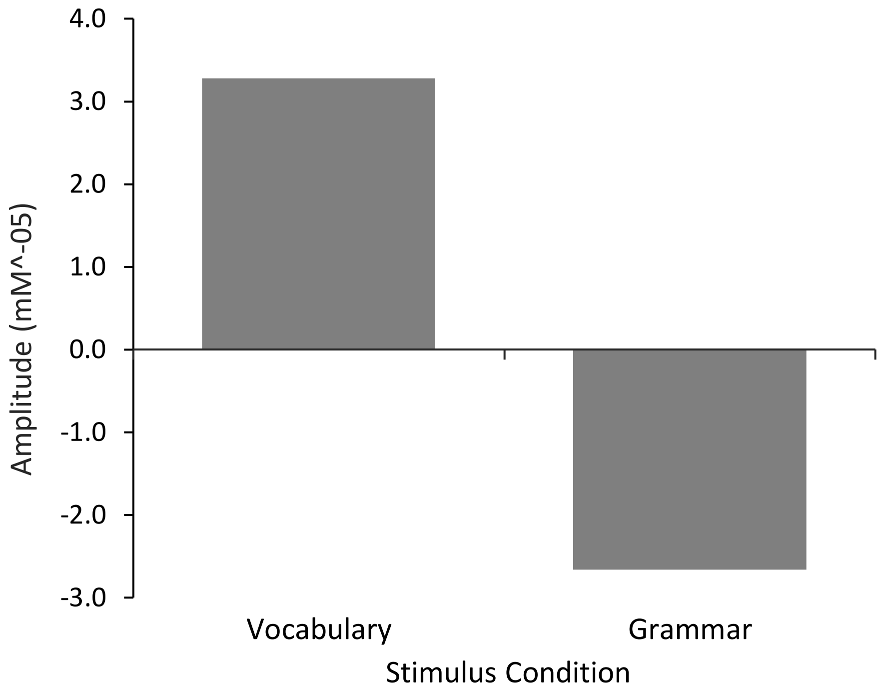

Figure 12. HbR amplitude difference in millimoles between vocabulary and grammar block averages for channel 20 part of the left DLPFC region.

Despite differences in accuracy scores between regular and irregular vocabulary trials, no significant HbO or HbR differences were found at $p < .05$. Likewise, no significant differences were found between the grammar sub-conditions (trained vs. untrained items). However, additional exploratory analyses revealed significant differences in HbO concentrations between regular vocabulary blocks and trained grammar blocks (blocks with items trained on one form only) in channel 71 corresponding to part of the pars triangularis in the right inferior frontal gyrus (IFG) region; $t(18) = 2.4331$, $p < .05$ (see Figures 13 and 14).

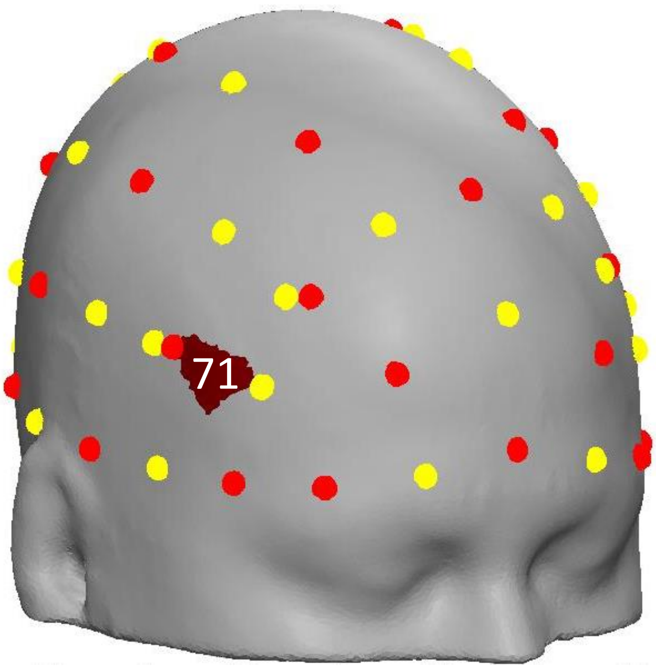

Figure 13. Thresholded SPMt image at p < .05 for HbO.

Contrast: regular vocabulary > trained grammar. Numbers represent significant channels.

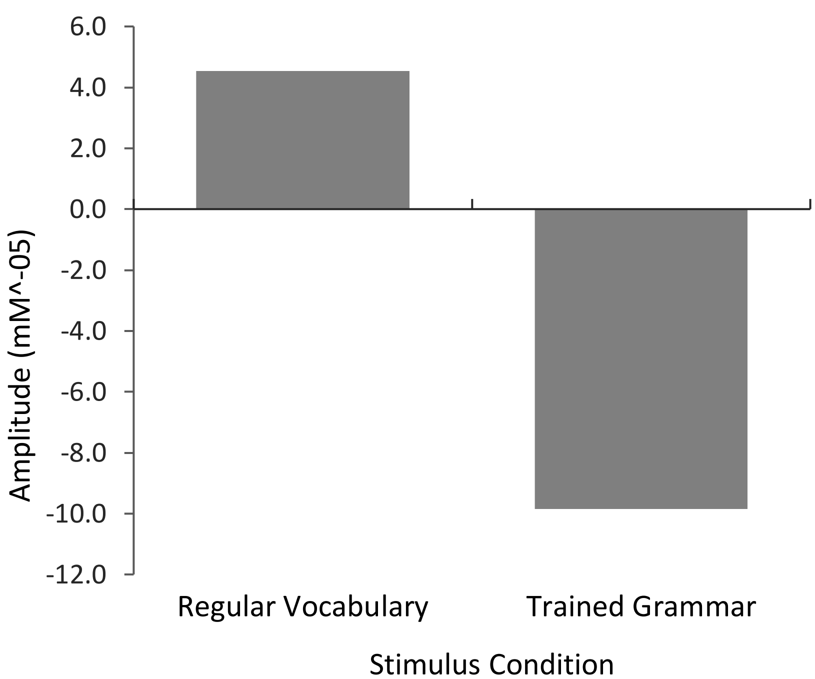

Figure 14. HbO amplitude difference in millimoles between regular vocabulary and trained grammar block averages for channel 71 part of the right IFG region.

Chapter 4

4 Discussion

When learning a second language, adults achieve much higher proficiency in vocabulary than in grammatical components of language such as morphology and syntax (Finn et al., 2014; Johnson & Newport, 1989; Newport, 1990). It has been argued that vocabulary and grammar learning rely on distinct explicit and implicit memory processes, respectively (Ramscar & Gitcho, 2007; Ullman, 2001). Therefore, it may be the case that vocabulary and grammar learning differences in adults are due to competition between non-linguistic cognitive processes. However, the neural mechanisms involved in vocabulary and grammar learning differences are unclear.

The present thesis was designed to examine the neural correlates of semantic vocabulary and grammatical pattern processing. Participants completed an artificial language learning task composed of novel singular and plural words paired with images of common objects. The grammatical rules of the language consisted of two plural suffixes that were systematically attached to six distinct root rhymes. Judgement tasks of word-object pairings were used to measure proficiency on vocabulary learning and grammatical generalization. Vocabulary judgement trials were composed of singular vocabulary words and plural irregular words. According to the Declarative/Procedural Model (Ullman, 2001), both types of words must be learned explicitly as the pairing between a word and its semantic representation is arbitrary, and irregular words do not follow regular grammatical patterns. On the other hand, grammatical judgement trials were composed of words trained on the singular or plural form only and tested on the untrained form, as well as untrained words where neither the singular nor plural form appeared in training. Unlike the vocabulary test trials, the grammar test trials required generalizing the learned grammatical patterns to items that were not explicitly exposed at training.

Study 1 was conducted to determine whether the artificial language learning paradigm appropriately represented second language vocabulary and grammar proficiency outcomes in adults. This was done by explicitly exposing participants to novel vocabulary items while also implicitly exposing morphological plural patterns. The inclusion of irregular and inconsistent words masked the regular grammatical rules while also constrained participants to learn the rules using methods similar to implicit statistical learning (Saffran et al., 1996). Particularly, the regular plural suffix agreement relied on the phonological rhyme of the root and occurred more frequently than irregular and inconsistent suffix patterns. Therefore, the grammar of the language must be learned through implicit exposure to the transitional probabilities between stems and suffixes.

Study 2 incorporated the use of fNIRS to further examine the neural correlates of language learning using a non-invasive measure of hemodynamic response. This has important advantages over other neuroimaging measures such as EEG and fMRI. Most importantly, fNIRS allows for more naturalistic language learning experiences including allowing for speech production and more comfortable periods of exposure to linguistic stimuli.

4.1 Behavioural Findings

Behavioural findings indicated that the present artificial language paradigm was successful in mimicking natural second language learning in adults. As expected, higher proficiency was achieved in vocabulary compared to grammar as indicated by higher accuracy scores and faster RT on vocabulary judgement tasks. No differences were found between the grammar sub-conditions (items trained on one form only vs. untrained items) indicating that both are comparable forms of measuring grammatical generalization to novel words. On the other hand, significant differences were found between the vocabulary sub-conditions. Specifically, participants achieved higher accuracy on regular vocabulary items compared to irregular items. A possible explanation for this difference may be that all regular vocabulary items were singular words designed to measure judgement ability of a word's semantic representation. On the other hand, the irregular and inconsistent items were composed of plural words to assess participants' ability to explicitly learn pattern-less exceptions to morphological rules. While both singular regular words and plural irregular words have been argued to be learned explicitly using declarative memory (Ullman et al., 1997), plural irregular words are not independent of morphology in the same nature that singular regular words are. Rather, participants must comprehend the morphological nature of the plural suffix while remembering that it is an exception to the rule. Therefore, the added morphological nature of irregular plural words compared to singular words may make the judgement task more difficult.

4.2 fNIRS Findings

HbO results revealed significant differences between regular vocabulary blocks and trained grammar blocks in the right IFG part of the pars triangularis of a right-hemisphere homologue of Broca's area. Specifically, part of the right pars triangularis was more active during judgement of singular vocabulary items compared to regular words that were trained on one form only and tested on the untrained form (e.g., a word trained on the singular form only and tested on the plural form, or vice versa). The distinction between these conditions involves judging a semantic association of a word compared to the generalization of a learned plural suffix to a novel item. Therefore, differences in the IFG are not surprising as this area has been found to play a large role in declarative semantic retrieval and working memory (Chein & Fiez, 2001; Demb et al., 1995; Demonet et al., 1992; Nevat et al., 2017).

What is surprising is the right-lateralization of the activation found in the current study. Language has been widely found to be left lateralized, especially for right-handed subjects (Frost et al., 1999; Knecht et al., 2000; Steinmetz, Volkmann, Jäncke, & Freund, 1991) which composed 95% of our sample. This has also been observed specifically for the pars triangularis (Foundas, Leonard, Gilmore, Fennell, & Heilman, 1996; Nevat et al., 2017). Nevertheless, lateralization findings of the pars triangularis are not consistent. For example, Keller and colleagues (2007) found significant left-hemisphere volume asymmetry in the pars opercularis but not the pars triangularis. Furthermore, second-language processing may not display the same neural organization as native language processing. Specifically, later-learned languages have been found to be less lateralized or in some cases, even right-lateralized, and exhibit greater neural variability between individuals (Dehaene et al., 1997; Kim, Relkin, Lee, & Hirsch, 1997).

It is also important to note that the tasks between the vocabulary and grammar conditions were the same: judging a word-object pairing. The manipulation was whether the test item was previously explicitly exposed to participants during training. While the trained grammar test items were never explicitly exposed during training in the form that appeared at testing, these test items were not independent of their semantic associations. Therefore, the neural differences exhibited in the pars triangularis reflect the explicit nature of semantic retrieval only for vocabulary items tested in the exact forms exposed during training.

Interestingly, HbR results revealed greater activation in a portion of the posterior left DLPFC (part of Brodmann area 46) and the anterior right DLPFC (part of Brodmann area 9) during grammar judgement blocks compared to vocabulary judgement blocks. However, recall that grammatical judgement proficiency was lower compared to vocabulary as demonstrated through lower accuracy scores and slower RT. Therefore, the increased activation during grammatical judgement observed may be reflecting an interference effect in adults. Specifically, a possible explanation for these findings may be a role of explicit memory and executive function interference during implicit procedural learning. Explicit declarative memory has been found to interfere or compete with procedural memory systems in various domains including language learning (Brown & Robertson, 2007; Finn et al., 2014; Howard & Howard, 2001; Nevat et al., 2017; Poldrack & Packard, 2003; Smalle et al., 2017; Ullman, 2001, 2004). This may be especially true for our sample of young adults due to their maturing prefrontal brain regions. Developing regions such as the DLPFC may directly interfere with implicit procedural learning (Cochran, McDonald, & Parault, 1999; Smalle et al., 2017). Consequently, adult proficiency is poorer in language aspects that rely on repeated implicit exposure to patterned sequences such as grammar (Gupta, 2012; Krishnan, Watkins, & Bishop, 2016; Ramscar & Gitcho, 2007; Ullman, 2001, 2004).

Moreover, it may be the case that adults are putting in explicit effort to figure out the rules of the language. Directing increased effort during language learning facilitates vocabulary word segmentation but hinders grammatical category learning (Finn et al., 2014). Additionally, inhibiting neural areas such as the DLPFC significantly facilitates word-form learning (Smalle et al., 2017). The present study is in line with these findings by revealing that even without direct manipulation, adults may naturally exhibit DLPFC interference during grammatical judgement, resulting in poor grammar proficiency as depicted in the behavioural findings.

Finally, as expected, no significant differences were found between the trained and untrained grammar sub-conditions. However, despite significant behavioural differences in accuracy scores between regular and irregular vocabulary items, no significant neural differences were observed between these vocabulary sub-conditions either. This may be because both forms may rely on the same mechanisms, namely, explicit declarative memory (Ullman et al., 1997). Nevertheless, accuracy scores were significantly higher for singular vocabulary items compared to plural irregular items. Perhaps deeper sub-cortical structures that cannot be captured with the limited depth penetration of fNIRS may reflect the behaviourally-observed difference.

4.3 Limitations

Although the current artificial language was able to mimic natural second language learning differences between vocabulary and grammar in adults, accuracy on grammar items was exceedingly low for both Study 1 and Study 2 and was not significantly above chance for Study 2 which consisted of a smaller sample size. Future research may need to further simplify the grammatical patterns so grammar can be learned within the limited time span of lab-based experiments. However, grammatical simplification may come at a cost of accurately representing natural second language learning as natural languages are complex and encompass a greater variety of rules and exceptions. This highlights the main difficulty of studying language learning in a constrained lab-based manner.

Nevertheless, artificial languages have been found to mimic natural language learning both behaviourally and in the neural domain (for a review see Folia et al., 2010). For example, Ettlinger and colleagues (2016) found a positive correlation between artificial and natural second language learning performance, especially for artificial languages with a semantic component and complex grammatical systems such as our own. One of the greatest benefits of using artificial languages is the ability to control for external variables that may affect language learning such as exposure, cross-linguistic similarity, grammatical complexity, and frequency of lexical token and type. By controlling external variables that may influence language learning, more confident conclusions can be drawn about the variables of interest in experimental designs.

In terms of measuring semantic and grammatical language learning, the behavioural testing methodology used in the current paradigm can be enhanced. In the current testing task, participants made explicit judgements on word-object pairings. The grammar of the language was not explicitly taught to participants and all grammar test items were novel in that they did not appear in training in the same form that was tested on. Nevertheless, the judgement measure of grammatical generalization was itself explicit. Future studies could incorporate implicit measures of grammatical learning such as using online event-related potential (ERP) measures (e.g., Tokowicz & MacWhinney, 2005). In fact, it may be the case that grammatical proficiency is higher than explicit measures reveal. Having participants make explicit judgement decisions on lexical items involving grammatical suffixes may not be a sensitive measure of implicit grammar learning. Moreover, half of the grammar test items were not independent of their semantic representations. These were the items in which a word was trained on one form only and tested on the untrained form. While there were no significant accuracy or neural differences between trained and untrained grammar items, it may be sufficient to only include completely untrained words to test grammatical generalization independent of semantic retrieval. However, the benefit of including trained grammar test items is its ecological similarity to natural language processing where vocabulary and grammar are both learned and recollected concurrently and are not independent of one another.

Finally, fNIRS and its available analyses tools run into some limitations. As discussed, the data yielded different results for HbO compared to HbR concentration differences. Possible reasons for this may be the way that the two measures are recorded and affected by various variables. Importantly, HbO concentration amplitudes are larger than those of HbR changes, while HbR changes may be more spatially focal (Strangman, Culver, Thompson, & Boas, 2002). The two measures also rely on different wavelengths that may affect one another, producing cross-talk-related errors that disproportionately affect HbO and HbR concentration calculations (Boas *et al.*, 2001).

In terms of software limitations, the NirsLAB analysis software (NIRx Medical Technologies, LLC) excludes some functions. As a result, acquired short channel data were not included in analyses to remove superficial hemodynamic responses in the NIRS signals. Furthermore, NirsLAB does not include multiple comparison corrections across different contrasts, which can lead to type I errors. Overall, as fNIRS research is still relatively new, it lacks a coherent standard signal processing and analysis protocol as other neuroimaging systems have developed (Dieler et al., 2012). Further research will make use of various software with more flexible preprocessing and optional multiple comparison correction and short channel regression functions.

Additionally, fNIRS' spatial resolution is considered to be quite good but of course is lower than MRI and runs into the limitation that its penetration depth is a few centimeters (Lloyd-Fox, Blasi, & Elwell, 2010). As a result, fNIRS cannot capture differences in deeper sub-cortical areas that may be critical in dissociating the memory processes involved in language learning. On the other hand, fNIRS' temporal resolution is better than fMRI although not as good as EEG's (Minagawa-Kawai, Mori, Hebden, & Dupoux, 2008). Therefore, fNIRS can be seen as a middle ground between fMRI's good spatial resolution and EEG's good temporal resolution. While keeping these limitations in mind, fNIRS nevertheless includes several advantages over other imaging methods. Its affordability, portability, noiselessness, convenience, comfort, and lower susceptibility to head movement and speaking allow for a greater variety of experimental designs and study populations (Dieler et al., 2012).

4.4 Future Directions

The present study sets up a good foundation for further research exploring memory and language learning. Next steps include examining individual differences in language learning during the initial learning phase. Drawing on the pioneering theory of encoding specificity (Tulving & Thomson, 1973), the manner in which a memory is initially encoded highly affects the way it is later retrieved. Thus, the encoding specificity principle may strongly apply to language learning. As previously discussed, adults may rely on explicit declarative processes during initial language exposure explaining their proficiency differences in acquiring vocabulary compared to grammar. If this is the case, explicit memory and executive function processes may interfere with optimal grammar learning during early language exposure. The present paradigm may be used to examine this hypothesis by examining individual differences regarding the neural mechanisms involved in initial language exposure during training and behavioural performance outcomes.

The current study can also be extended to examine language learning differences between children and adults. Adults initially acquire certain language components more quickly than children, but rarely achieve the same native proficiency that children do in the long run (Snow & Hoefnagel-Höhle, 1978). The critical period hypothesis (Lenneberg, 1967; Penfield & Roberts, 1959) states that a critical period for optimal language learning occurs between infancy and approximately until puberty. Studies examining second language learning found that individuals who immigrate at a younger age are more likely to reach higher proficiency in their second language than those immigrating later in life (e.g., DeKeyser, Alfi-Shabtay, & Ravid, 2010; Flege et al., 1999; Hakuta, Bialystok, & Wiley, 2003; Johnson & Newport, 1989). Again, this is especially true for grammatical components of a language such as gender agreement and morphology (Dewaele & Véronique, 2001; Laufer & Waldman, 2011; Lew-Williams & Fernald, 2010). While the existence of a specific critical period is under debate (Flege, Yeni-Komshian, & Liu, 1999; Friederici, Steinhauer, & Pfeifer, 2002), it is clear that language learning changes across age. Drawing back to the encoding specificity hypothesis, a large portion of language proficiency differences between children and adults may be explained by differences in their reliance on procedural mechanisms during exposure. As Newport's (1988) "Less is More" hypothesis posits, children's limitations in executive information processing can counterintuitively lead to better language acquisition outcomes. It is important to note that the grammatical rules used in the current study must be simplified in order to appropriately use with children. Nonetheless, the current paradigm along with fNIRS' child-friendly advantage allows for an optimal method of examining developmental language theories.

Furthermore, the present artificial language learning paradigm can be adapted to examine whether age-dependent differences in language learning are due to domain-general memory changes as opposed to linguistic-specific processes. If language learning differences between children and adults are modulated by adults' developed DLPFC and executive functioning, it is probable that these cognitive abilities interfere with implicit language learning in a domain-general manner. One possibility is to compare explicit and implicit language aspects with non-linguistic declarative and procedural memory and learning tasks in both children and adults.

Finally, the current paradigm assesses linguistic comprehension but could be extended to compare production with comprehension proficiencies. Measuring language production may be especially important since production processes are more difficult than comprehension and may result in greater differences between children and adults as exist in natural second language learning. Overall, the comparison between production and comprehension proficiencies can further contribute to the growing research of how production and comprehension interact during language learning (Pickering & Garrod, 2013).

Chapter 5

5 Conclusion

The present study investigated behavioural and neural differences between vocabulary and grammar processing in adults using fNIRS via an artificial language learning paradigm. The paradigm included a training phase consisting of novel singular and plural words paired with images of common objects. Plurality was marked by distinct inflectional suffixes that varied by phonological cues in the stem. Following training, comprehension of vocabulary and grammar generalization was assessed while hemodynamic responses were measured using fNIRS.

Behavioural results revealed better performance on vocabulary compared to grammar processing as indicated through higher accuracy and faster RT. Overall, the artificial language paradigm was successful in mimicking natural second language outcomes where adults are less successful in reaching fluent grammatical proficiency compared to semantic vocabulary representations. Neural results suggest differential neural activation during vocabulary vs. grammatical processing. Specifically, activity in part of the pars triangularis of a right-hemisphere homologue of Broca's area was found to correlate with semantic vocabulary judgement tasks. On the other hand, activation in both the left and right DLPFC during grammar tasks paired with low grammar performance may reflect competition between explicit and implicit processing. Specifically, the greater developed DLPFC in adults may interfere with optimal procedural grammar learning.

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Appendix A

Appendix A. Study 1 Ethics Approval

Western Research

Date: 18 April 2018

Study Title: Memory Processes and Language Learning in Adults

Application Type: NMREB Initial Application

Review Type: Delegated

Full Board Reporting Date: 04/May/2018

Date Approval Issued: 18/Apr/2018 13:22

REB Approval Expiry Date: 18/Apr/2019

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
Ad_Facebook	Recruitment Materials		
Ad_Poster	Recruitment Materials	06/Apr/2018	2
Ad_SONA	Recruitment Materials	06/Apr/2018	2
Artificial Language Word Bank	Other Data Collection Instruments		
Debriefing Form	Debriefing document	18/Apr/2018	2
Demographic Questionnaire	Paper Survey		
Letter of Information and Consent - Paid	Written Consent/Assent	18/Apr/2018	3
Letter of Information and Consent - Student	Written Consent/Assent	18/Apr/2018	3
Sample Stimuli	Other Data Collection Instruments		

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

Appendix B

Appendix B. Study 2 Ethics Approval

Western Research

Date: 19 October 2018

Study Title: The Neural Bases of Memory and Language Learning in Adults using fNIRS

Application Type: NMREB Initial Application

Review Type: Delegated

Full Board Reporting Date: November 2 2018

Date Approval Issued: 19/Oct/2018

REB Approval Expiry Date: 19/Oct/2019

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
Ad_Poster	Recruitment Materials		
Ad_SONA	Recruitment Materials		
Artificial Language Word Bank	Other Data Collection Instruments	27/Aug/2018	
Debriefing Form	Debriefing document	27/Aug/2018	
Demographic Questionnaire	Paper Survey		
Letter of Information and Consent - Paid	Written Consent/Assent	12/Oct/2018	2
Letter of Information and Consent - Student	Written Consent/Assent	12/Oct/2018	2
Sample Stimuli	Other Data Collection Instruments	27/Aug/2018	

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

Appendix C

Appendix C. Demographics and Language History Questionnaire

Section 1: General Information

Sex: ☐Male ☐ Female ☐ You are welcome to provide your self-chosen gender identity here ___________________

Age (years): __________

Highest level of education attained (grade or certificate/diploma/degree level):

Are you right or left-handed (circle one)? Left Right

Do you currently or have you ever been diagnosed with any type of reading, visual or auditory impairment (circle one)? Y N

If yes, please explain:

Do you currently or have you ever been diagnosed with any type of learning impairment or neurological impairment (circle one)? Y N

If yes, please explain:

Section 2: Language History

Is English the first language you learned (circle one)? Y N

If no, please list which language(s) you learned at birth:

Please list the languages that you are currently able to speak, understand, read and/or write in order of fluency (i.e., list the language that you are most familiar with first). For each of these languages, please indicate your length of exposure to the language, and a number rating of how well you can speak, understand, read and write in that language. For number ratings, please use the following scale:

Badly	Adequately	Well	Almost Fluently	Like a Native Speaker
1	2	3	4	5

Language	**Exposure**	**Speak**	**Understand**	**Read**	**Write**
E.g., English	Entire life	5	5	5	5
E.g., French	2 years	3	3	4	4

Comments:

3. For each of the languages listed in Question 2, please indicate the primary method of learning, such as from family members, while visiting a foreign country, through a tutor or immersion-type course, etc. E.g., English = from family; French = university course

Curriculum Vitae

Leah Brainin

Post-Secondary Education

2017 – 2019	University of Western Ontario London, Ontario, Canada M.Sc. Psychology
2013 – 2017	University of Toronto Toronto, Ontario, Canada B.A. High Distinction Cognitive Science, Major Linguistics, Minor; Sociology; Minor
2012	École D'immersion Française De Trois-Pistoles French 1010

Honours and Awards

2019	Ontario Graduate Scholarship (OGS)
2019	Best Oral Presentation: Western Research Forum
2018	Reva Gerstein Fellowship for Master’s Study in Psychology
2017	Canada Graduate Scholarship-Masters (CGS-M: declined)
2017	Woodsworth College Scholarship
2016	Undergraduate Scholarship Travel Award
2016	The Undergraduate Awards Highly Commended: Psychology Category
2016	The Undergraduate Awards Highly Commended: Linguistics Category
2015	Arts and Science Scholarship for Excellence in Cognitive Science
2014	Claude T. Bissel Scholarship
2014 – 2017	University of Toronto Dean’s Honour List

Related Experience

2017 – 2019 Graduate Teaching Assistant
University of Western Ontario

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2016 Research Assistant
University of Toronto
- Psycholinguistics Lab
- Computational Cognitive Development Lab
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- Social Psychophysiology and Quantitative Methods Lab

Research Presentations

Brainin, L., & Joanisse, M. F. (2019). Differences between explicit and implicit memory processes during language learning: Evidence from fNIRS. Canadian Society for Brain, Behaviour and Cognitive Science Conference. Waterloo, Canada. Poster Presentation.

Brainin, L. (2019). Explicit and implicit memory processes in language learning. Western Research Forum. London, Canada. Oral Presentation.

Brainin, L., & Joanisse, M. F. (2019). Enhanced explicit vocabulary learning compared to implicit grammar learning in adults. Western Research Forum. London, Canada. Poster Presentation.

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