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Examining the Paradox of Adult Second Language Word and Grammar Learning

Leah Brainin, *The University of Western Ontario*

Supervisor: Joanisse, Marc F., *The University of Western Ontario*

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Abstract

Background: Adults generally demonstrate advanced cognitive skills compared to children, with second language (L2) learning being a key exception, particularly within the grammar domain. As optimal vocabulary and grammar learning are believed to engage in distinct explicit and implicit learning mechanisms, respectively, the advanced neurocognitive mechanisms underpinning adults' higher-order cognitive skills may particularly interfere with implicit grammar learning. The *objective* of this dissertation was to examine select neural and cognitive factors that may contribute to word and grammar learning differences. In *Study 1*, I investigated the neural correlates of artificial vocabulary and morphology learning using functional Near-Infrared Spectroscopy (fNIRS). Despite adults outperforming in explicit vocabulary outcomes compared to implicit grammar generalization, cortical differences between processing the two language components were minimal. On the other hand, significant changes in neural activity were observed in all four cortical lobes over the course of the initial language learning period, demonstrating the widespread cortical engagement inherent in the process of L2 learning. In *Study 2*, I examined the impact of effortful learning on implicit word and grammar learning outcomes using a modified statistical language learning paradigm with an underlying grammatical pattern. Performance on speeded syllable detection tasks using familiar and unfamiliar targets revealed that effortful and passive learning conditions resulted in comparable implicit learning outcomes related to word segmentation and grammar generalization. Thus, directing effort towards learning neither facilitated nor interfered with implicit L2 attainment. In *Study 3*, I investigated whether individual differences in statistical learning of words and/or grammatical patterns were related to domain-general cognitive abilities. The findings indicate that performance on tasks evaluating short-term memory, attention, strategic thinking, reasoning, and planning skills were not related to implicit word or grammar learning outcomes. *Conclusion*: Together, this dissertation presents empirical evidence that adults learn vocabulary more easily than grammatical patterns, but learning success is not related to domain-general cognitive mechanisms, at least concerning implicit representations of language. These findings are discussed in relation to existing literature and emerging theories of L2 learning. This research has important methodological implications and provides valuable insights to inform pedagogical practices for foreign language instruction.

Keywords: Language, Second Language Learning, Statistical Learning, Vocabulary, Grammar, Word Learning, Morphology, fNIRS, Neuroimaging, Cognition, Memory, Implicit, Explicit, Procedural Memory, Declarative Memory.

Summary For Lay Audience

Compared to children, adults typically demonstrate advanced cognitive skills. Yet, the older we get, the more difficult it is to learn a new language. This is especially true for learning new grammatical patterns, whereas we can learn new vocabulary words more easily. Some research suggests that learning new words and grammatical patterns rely on different brain regions and learning mechanisms that compete with one another. Specifically, adults advanced cognitive skills may be beneficial for learning new words but may interfere with learning new grammatical patterns. I aimed to address this theory using three research studies that examined neural and cognitive differences between word and grammar learning. In the first study, I used a neuroimaging tool to look at the cortical (outer brain) regions that are involved in learning a new language. The findings demonstrated that adults learned new words more easily than grammatical patterns, but there were only minimal differences in the brain activity between vocabulary and grammar processing. On the other hand, regions all over the cortex were found to be involved in the early stages of learning, suggesting that language learning involves a wide range of cognitive processes. In the second study, I tested whether applying effort towards learning a new language helps or interferes with language learning outcomes. The results revealed that putting extra effort into learning did not make a significant difference in either word or grammar learning success. In the third study, I explored the relationships between language learning and a variety of cognitive skills such as memory and attention. The results indicated that performance on cognitive tests were not related to how well individuals learned words or grammatical patterns. Together, these studies provide scientific evidence that adults have difficulty with learning grammatical patterns

more than new vocabulary words, but this difficulty may not be related to other cognitive skills or how hard we try to learn. I discuss these findings in relation to emerging theories and highlight the important implications that come from this work in terms of improving scientific methodology and foreign language instruction.

Co-Authorship Statement

Chapter 2: Conceptualization of research goals and development and design of methodology was conducted by Leah Brainin with supervision and guidance from Dr. Marc Joanisse. Kevin Stubbs contributed to the analyses of fNIRS data, including execution of data preprocessing, analyses and fNIRS figures. The manuscript was written by Leah Brainin, with feedback provided by Dr. Marc Joanisse and Kevin Stubbs (fNIRS preprocessing section). Note that a portion of the raw data was included in analyses in Leah Brainin's MSc thesis (Brainin, 2019). All analyses in this dissertation are novel. The manuscript is in prep to be submitted for publication.

Chapter 3: Conceptualization of research goals and development and design of methodology was conducted by Leah Brainin under supervision of Dr. Marc Joanisse, and feedback from Dr. Amy Finn and Dr. Carla Hudson Kam. All analyses and visualizations were executed by Leah Brainin. The manuscript was written by Leah Brainin with feedback provided from Dr. Marc Joanisse. The manuscript is in prep to be submitted for publication.

Chapter 4: Conceptualization of research goals and development and design of methodology was conducted by Leah Brainin under supervision of Dr. Marc Joanisse. All analyses and visualizations were executed by Leah Brainin. The manuscript was written by Leah Brainin with feedback provided from Dr. Marc Joanisse. The manuscript is in prep to be submitted for publication.

Dedication

With immeasurable love and gratitude,

I dedicate this dissertation to my incredible parents.

Without your unconditional love, support, encouragement, and guidance,

I could not be where I am today.

Thank you for all the sacrifices you made to get me here.

This is for you.

In loving memory of Sam,

my dear friend and brilliant colleague whose infectious passion,

wisdom, and determination will continue to inspire me,

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List of Abbreviations

DLPFC	Dorsolateral Prefrontal Cortex
EEG	Electroencephalography
EF	Executive Functions(s)
FDR	False Discovery Rate
fMRI	functional Magnetic Resonance Imaging
fNIRS	functional Near-Infrared Spectroscopy
GLM	General Linear Model
HbO	Oxygenated Hemoglobin
HbR	Deoxygenated Hemoglobin
IFG	Inferior Frontal Gyrus
IPA	International Phonetic Alphabet
IQ	Intelligence Quotient
IQR	Interquartile Range
L1	First Language
L2	Second Language
MTG	Middle Temporal Gyrus
OLS	Ordinary Least Squares
PFC	Prefrontal Cortex
PPF	Pathlength Factor
PSTM	Phonological Short-Term Memory
RFX	Random Effects
RSVP	Rapid Serial Visual Presentation
RT	Reaction Time
SCI	Scalp Coupling Index
SD	Standard Deviation
SE	Standard Error
SRT	Serial Reaction Time
STG	Superior Temporal Gyrus
TMS	Transcranial Magnetic Stimulation
TP	Transitional Probability
V3	Third Visual Cortex
WAIS-R	Wechsler Adult Intelligence Scale-Revised
WM	Working Memory

Chapter 1: Introduction

It is widely recognized that despite exhibiting advanced higher-order cognitive skills compared to children, adults encounter difficulties with learning a new language (Ausubel, 1964; Birdsong, 2006; Newport, 1990; Newport et al., 2001). As there is a vast amount of research demonstrating that language learning, at least in part, involves domain-general cognitive processes such as explicit and implicit memory processes (Hamrick et al., 2018; Morgan-Short et al., 2014; Pliatsikas et al., 2014; Ullman, 2004; Ullman & Lovelett, 2018; Wen et al., 2015), and executive function skills (Festman et al., 2010; Kapa & Colombo, 2014), the seemingly inverse developmental trajectories of domain-general cognition and language learning ability may seem paradoxical at first glance. However, an emerging theory, hereon referred to as the interference hypothesis, proposes that this inverse relationship is not coincidental. Rather, it posits that the differential maturation of distinct cognitive faculties introduces competition between opposing learning systems, consequently, contributing to age-related differences in certain learning domains (Finn et al., 2014; Smalle et al., 2021; Thompson-Schill et al., 2009).

Indeed, adults' difficulty with language learning is not uniform across all language components. Adults particularly face difficulty with learning novel grammatical rules and patterns including morphology (the grammatical composition of words) and syntax (the grammatical composition of sentences) more so than novel vocabulary words (DeKeyser, 2000, 2005; Johnson & Newport, 1989). Despite this apparent distinction, vocabulary and grammar learning are oftentimes examined independently of one another. Moreover, measures of learning primarily focus on recall or recognition abilities *post-*

learning, oftentimes focusing on explicit knowledge outcomes. Thus, my research aimed to examine potential factors that may contribute to differences in vocabulary and grammar attainment despite adults' advanced higher-order cognitive processing, with added emphasis placed on the language *learning* process, and implicit representations of language. To address this, through a series of three studies, I 1) examined the neural mechanisms involved in the initial stages of language learning and directly compared behavioural and neural differences between vocabulary and grammar processing, 2) examined whether directing effort and attention towards learning impacts implicit word and grammar learning outcomes, and 3) investigated whether individual differences in domain-general cognitive skills are related to implicit word or grammar learning outcomes.

1.1 The Sensitive Period for Language Learning

According to the sensitive period hypothesis, there is an optimal age for acquiring a second language (L2) with native-like proficiency (Lenneberg, 1967; Penfield & Roberts, 1959; Snow & Hoefnagel-Hohle, 1978). This theory is grounded in the observation that earlier exposure to foreign languages results in more efficient learning, and ultimately, higher levels of proficiency attainment. This phenomenon is particularly evident for phonological and grammatical components of language (Johnson & Newport, 1989; Kuhl et al., 1992; Mayberry & Lock, 2003; Newport, 1990; Werker et al., 1981). For example, individuals who immigrate to English-speaking countries later in life are more prone to making ungrammatical errors related to plural and past tense morphological rules (e.g., plural "-s" and past tense "-ed" suffixes in English) as well as syntactic placement of determiners such as “a” and “the” (DeKeyser, 2000; Johnson & Newport, 1989).

Age-related changes in neuroplasticity, the brain’s ability to change its structural, functional, and connective properties (Fuchs & Flügge, 2014; James, 1980; Mateos-Aparicio & Rodríguez-Moreno, 2019; Raisman, 1969), may be a driving proponent of the sensitive period for language learning. Early neurodevelopmental theories argued that neuroplasticity was especially evident in younger age groups (Mundkur, 2005; Newman et al., 2002), thus leading to the idea that neural structures and pathways become increasingly rigid as we age, resulting in diminished language learning skills. However, more recent evidence indicates that the adult brain is not as fixed as was once believed (see Fuchs & Flügge, 2014 for a review). Environmental and sociocultural factors may also contribute to age-related differences in L2 learning. For instance, children and adults may encounter different language immersion experiences, with children benefiting from formal education and more diverse immersion experiences through school and extracurricular activities (Huttenlocher, 1998). As such, diverse learning environments can contribute to differences in ultimate proficiency attainment. Nonetheless, it is important to acknowledge that learning experiences vary considerably among individuals, and the sole consideration of environmental factors is likely insufficient to fully explain the robust age-related differences observed in natural L2 learning. The sensitive period hypothesis and its underlying determinants continue to be a subject of debate within the developmental psycholinguistic community (Gürsoy, 2011; Hakuta et al., 2003; McDonald, 2006). If a domain-specific sensitive period for language acquisition exists, its manifestation is likely shaped by the intricate interplay of a combination of biological, environmental, and social factors. The focus of this dissertation is not to examine the sensitive period for language learning, but to investigate the process of adult L2 learning and processing. Nevertheless, I draw upon theories and hypotheses rooted in developmental perspectives, and therefore, this thesis has important conceptual implications for understanding age-related effects in L2 learning.

1.2 Declarative and Procedural Contributions to Language Learning

In order to gain a more comprehensive understanding of age-related differences in language learning, it is necessary to delve into specific language components in which adults demonstrate divergent abilities. One major aspect in which vocabulary and grammar are distinct from one another is their reliance on patterns, and thus, the mechanisms that govern their learning. Ullman's Declarative / Procedural Model proposes that vocabulary and grammar are learned and stored through distinct memory systems that operate in competition (Ullman, 2001, 2004, 2016). Declarative memory refers to the explicit consolidation and conscious recall of factual information, events, and experiences (Cohen et al., 1997; Manns & Eichenbaum, 2006; Squire, 1992; Squire & Zola, 1996). This type of memory enables individuals to consciously access and employ stored information to make decisions and engage in various cognitive tasks. In contrast, procedural memory refers to the unconscious, automatic, or implicit learning of skills, habits, and patterns (Cohen et al., 1997; Tulving, 1985). While declarative memory can occur rapidly, even following a single exposure to stimuli, procedural memory unfolds more gradually, improving after repeated practice or exposure to pattern exemplars (Cohen et al., 1997; Squire & Dede, 2015; Ullman, 2016).

According to this model, learning novel vocabulary words and the meanings they refer to relies on the explicit memorization of (usually) arbitrary associations between phonological word-forms and their semantic representations (e.g., learning the French word "maison" for the semantic representation of house). Thus, this type of learning is argued to engage more greatly in declarative memory processes. In contrast, languages' grammars encompass complex patterns whereby optimal learning occurs through more implicit / procedural engagement through repeated exposure to diverse exemplars of regular grammatical rules. As such, grammatical patterns can be learned without conscious awareness of the underlying rules that govern them (Ullman, 2001, 2016).

Importantly, there is evidence that implicit / procedural and explicit / declarative learning systems undergo distinct developmental trajectories. For example, in a study of implicit sequence learning of visuo-spatial patterns across the lifespan, Janacsek et al. (2012) reported a decline in performance on an implicit Alternating Serial Reaction Time (ASRT) task around the age of 12. Conversely, Finn et al. (2016) found comparable performance on procedural memory tasks between 10-year-old children and adults, whereas adults exhibited superior performance on declarative memory tasks and demonstrated increased working memory capacity compared to children. If optimal vocabulary and grammar learning differ in their engagement in distinct memory processes, the observed differences in developmental trajectories between opposing memory systems may play a key role in explaining age-related L2 learning differences. Indeed, Hamrick et al. (2018) reported meta-analyses in which they observed an interaction between the amount of L2 grammar learning experience and declarative versus procedural memory engagement such that less experienced adult L2 learners demonstrated reduced engagement of procedural memory and greater engagement of declarative memory processing compared to more experienced learners.

Notably, declarative and procedural memory processes compete with one another whereby increased engagement in explicit processes can hinder procedural learning (Mathews et al., 1989; Poldrack & Packard, 2003). This phenomenon has been observed in the domain of motor skill learning, where performing an explicit learning task can disrupt procedural memory and subsequently impede skill performance (Brown & Robertson, 2007). It has been suggested that explicit grammatical rule learning may therefore interfere with optimal grammatical acquisition (Ullman, 2016). The differential maturation of the two learning and memory systems may therefore contribute to age-dependent learning differences such that adults engage in more developed explicit processes that may impede with optimal procedural pattern learning. However, empirical support for this theory remains limited (e.g., see Finn et al., 2014), with some evidence that explicit versus implicit learning does not significantly impact language learning outcomes (Batterink & Neville, 2013; Morgan-Short et al., 2012; Ruiz et al., 2018).

1.3 A Brief Introduction to the Interference Hypothesis

Relatedly, and not often discussed in relation to the sensitive period hypothesis, is the late development of the prefrontal cortex (PFC) (Caballero et al., 2016; Gogtay et al., 2004; Segalowitz & Davies, 2004). This brain region is known to play a role in higher-order cognitive functioning including governing processes such as attention, working memory, and deductive reasoning that fall under the umbrella term of Executive

Functions (EF) (Casey et al., 2008; Friedman & Robbins, 2022; Funahashi & Andreau, 2013; Kesner & Churchwell, 2011; Moriguchi & Hiraki, 2013). Much like Ullman's theory of declarative and procedural competition, the interference hypothesis posits that the cognitive and neural maturation of higher-order functions, at least in part mediated by the PFC, may interfere with procedural aspects of sequence learning (Ambrus et al., 2020; Smalle et al., 2021; Thompson-Schill et al., 2009). Empirical support for the interference hypothesis comes from studies demonstrating that temporarily inhibiting PFC regions (Ambrus et al., 2020; Galea et al., 2010; Smalle et al., 2017, 2022; Uddén et al., 2008) or inducing cognitive fatigue prior to learning (Borragán et al., 2016; Cochran et al., 1999; Smalle et al., 2017, 2021) counterintuitively led to improved sequence learning outcomes. These findings will be discussed in greater detail in the introductory and interim discussion sections of the forthcoming chapters. Here, my aim is to draw theoretical connections between declarative and procedural memory competition and EF / PFC interference, emphasizing that greater reliance on more developed explicit cognitive skills may interfere with procedural grammar learning in adults while sparing vocabulary learning abilities that depend on more mature declarative memory consolidation and retrieval processes.

1.4 Overview of Dissertation

In the subsequent chapters of this dissertation, I present three related studies where I investigated the cognitive and neural mechanisms involved in vocabulary and grammar learning in adults. In Chapter 2, I present findings from a functional Near-Infrared Spectroscopy (fNIRS) investigation exploring the neural regions involved in the initial stages of novel language learning as well as behavioural and neural differences between vocabulary processing and morphological generalization post-learning. The artificial language paradigm used in this study (adapted from Nevat et al., 2017) draws inspiration from the Declarative / Procedural model (Ullman, 2001, 2004, 2016) by comparing explicit learning of arbitrary word-object associations with generalizing learned morphological patterns to novel, untrained words. This study addresses some of the discussed gaps in the literature by examining the relatively understudied domain of the initial stages of *learning*, and by directly comparing cognitive and neural distinctions between vocabulary and grammar learning.

In Chapter 3, I shift focus to investigating the interference hypothesis, particularly in relation to acquired *implicit* knowledge. Specifically, I ask whether directing effort towards learning differentially impacts implicit word and grammar learning outcomes. To address this question, I adapted a statistical learning paradigm with a grammatical component from Finn et al. (2014) which examined the role of effort on word and grammar learning outcomes using explicit measures. In contrast, drawing upon implicit methodologies measuring statistical learning of word segmentation (Batterink et al., 2015), I used speeded target detection tasks to measure differences in two key aspects: 1) the detection of learned syllables with varying predictability based on statistical properties (word segmentation), and 2) the detection of novel untrained syllables varying in grammatical positioning (grammar generalization). This study not only contributes to the existing literature investigating the role of attention and effort (and thus, engagement in higher-order cognitive faculties) on distinct aspects of language learning, but also demonstrates a novel approach of using implicit measures within the statistical learning framework to measure grammar generalization.

In Chapter 4, I set out to further address whether implicit language learning outcomes are related to individual differences in general cognitive abilities. Specifically, I used a cognitive test battery (via the Creyos Online Cognitive Assessment Platform) along with a version of the statistical learning paradigm from Chapter 3 to address whether performance on select cognitive tasks designed to assess explicit short term memory, deductive reasoning, attention, inhibition, strategic thinking, and planning skills were associated with implicit word or grammar learning outcomes. Here, I aimed to address some inconsistencies observed across the literature in terms of the facilitative versus interfering relationships between EF and L2 learning, and to overall gain a better understanding of whether individual differences in language learning abilities are related to domain-general cognition.

Finally, in Chapter 5, I review the findings from Chapters 2, 3, and 4, drawing connections between them and relating them to emerging theories in the field of language learning. Additionally, I discuss the methodological implications arising from the studies outlined here and identify future avenues of research needed to address open questions, limitations, and gaps in the field. Ultimately, this research not only contributes to the advancement of empirical methodologies for studying implicit language representations, but also carries practical implications for informing pedagogical practices for foreign language instruction.

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Chapter 2: Shedding Light on Language Learning: An fNIRS Investigation of Explicit Vocabulary and Implicit Morphology Learning

2.1 Introduction

When it comes to second language (L2) learning, adults are able to learn new words and their associated semantic representations more quickly and effortlessly than categorical and pattern-based grammatical components (Newport et al., 2001). Despite these observed differences, vocabulary and grammatical processes are often examined independently of one another, with the initial learning phase often overlooked. To address these issues, I used high-density functional Near-Infrared Spectroscopy (fNIRS) to investigate cortical activity across an artificial language learning task, with two main research goals: 1) identify the neural mechanisms that are involved in initial L2 learning, and 2) examine the distinct cortical correlates implicated in lexical and grammatical processing post-learning. As explained in greater detail below, a novel word learning task that concurrently engaged explicit word and implicit morphology learning was used. This paradigm was used in my master's research (Brainin, 2019) which demonstrated that the artificial language learning mirrors word and grammar attainment differences observed in natural L2 learning outcomes. Here, I extend this research to examine the neural processes governing the initial *learning* phase and use more up to date and validated fNIRS methodology and analysis techniques. Note that all analyses completed for the current study were novel.

2.1.1 Memory Processes Involved in Language Learning

The age at which individuals learn a second language (L2) plays a crucial role in determining their proficiency outcomes, with significant impacts observed on syntactic, morphological, and phonological components, while exerting a lesser influence on lexical and semantic learning (Flege et al., 1999; Johnson & Newport, 1989; Weber-Fox & Neville, 1996). Grammar learning abilities have been found to decline with age until early adulthood and thereafter plateau (Dekeyser et al., 2010). This age-dependent effect may stem from the neural maturation of both domain-specific linguistic and domain-general cognitive mechanisms (Newport, 1990). Indeed, language acquisition and processing, at least partly, depend on domain-general long-term memory consolidation and retrieval processes (Bates et al., 2001; Chater & Christiansen, 2010; Ellis, 2005; Folia et al., 2010; Hamrick et al., 2018; Reali & Christiansen, 2009; Saffran et al., 2007), through distinct declarative (semantic and episodic memory) and procedural memory systems (Cohen & Squire, 1980; Mishkin et al., 1984; Squire & Zola, 1996). Explicit long-term memory of facts, words, and concepts, known as semantic memory, is specifically supported by regions such as the anterior temporal lobe, superior parietal lobe, middle frontal gyrus, and the medial temporal lobe (Burianova & Grady, 2007; Levy et al., 2004; Ofen, 2012). On the other hand, implicit learning of skills and patterns, referred to as procedural memory, primarily relies on frontal and parietal lobe regions, as well as the cerebellum and basal ganglia (Mochizuki-Kawai, 2008; Ullman & Pierpont, 2005).

The Declarative / Procedural Model (Ullman, 2001) proposes that learning arbitrary associations between phonological word-forms and their semantic representations primarily relies on declarative memory. This includes learning novel lexical items, their semantic representations, and irregular exceptions to grammatical patterns. In contrast, although grammatical rules and patterns can be learned either explicitly or implicitly, the intricate complexity of grammatical patterns along with the abundance of exceptions to the rules necessitate optimal pattern learning to occur through implicit procedural mechanisms. Declarative and procedural memory systems have been demonstrated to, at least in part, operate independently (Cohen & Squire, 1980), although there is evidence that the two interact with one another (Cohen et al., 1997; Kim & Baxter, 2001; Mathews et al., 1989; Squire & Zola, 1996). Specifically, these memory systems may exhibit a negative or competing relationship, yielding a proposed “seesaw” effect whereby greater engagement in one system can interfere with the other (Poldrack & Packard, 2003; Ullman, 2004, 2016). Moreover, declarative and procedural memory systems have been found to mature incongruently such that procedural memory reaches adult-like performance by early adolescence while declarative memory continues to mature across adolescence into young adulthood (Finn et al., 2016). Consequently, adults may exhibit an increased reliance on declarative memory when learning a new language, potentially hindering optimal procedural grammar learning while facilitating word learning (Finn et al., 2014; Smalle et al., 2017, 2021, 2022).

2.1.2 Neural Correlates of Language Processing

There remain open questions and inconsistencies across the literature regarding the neural distinctions between L2 morphology and word learning and processing in adult learners. In terms of first language (L1) processing, compared to morphological decision-making, processing the semantic representations of words was associated with increased activation in anterior regions of the inferior frontal gyrus (IFG) and left middle temporal gyrus (MTG) (Palti et al., 2007). Further evidence has demonstrated functional anatomical differences when processing semantic compared to syntactic properties of words, with increased activity in the pars triangularis of the left IFG and MTG/Superior temporal gyrus (STG) during semantic processing, whereas syntactic processing demanded greater activity in the left frontal operculum and inferior frontal and precentral sulci (Friederici et al., 2000). It is important to note, however, that there is evidence suggesting that L1 and L2 processing involve distinct neural mechanisms or varying degrees of reliance on shared neural regions (Indefrey, 2006).

As few studies have directly compared vocabulary and morphological L2 learning, the neural mechanisms contributing to proficiency differences between these two fundamental language components remain inconclusive. When examined independently, any differences between word and morphological processing are likely influenced by variations in task demands (e.g., picture-naming vs. word-form generation) and numerous potential confounding variables (e.g., consolidation effects, prior language experience, and cross-language similarity). Thus, in the present study, I aimed to minimize task differences by using an artificial language learning paradigm that enabled a direct comparison of L2 declarative vocabulary processing and procedural morphological generalization within a unified task framework.

fNIRS was used to localize and quantify brain activity involved in L2 learning and word and grammar processing. Through the measurement of the absorption and reflection of near-infrared (NIR) light, fNIRS calculates changes in the concentration of oxygenated (HbO) and deoxygenated (HbR) hemoglobin in the cortex. Specifically, fNIRS neural signals are determined by neurovascular coupling, exhibited as increases in HbO and decreases in HbR. fNIRS proves especially advantageous to investigate language learning due to its reduced susceptibility to speech and movement artifacts compared to other neuroimaging modalities such as functional Magnetic Resonance Imaging (fMRI) and electroencephalography (EEG) (for comprehensive reviews on fNIRS in language research, see Dieler et al., 2012; Quaresima et al., 2012). In addition, the lightweight arrays of probes used in fNIRS can be comfortably worn for extended durations, allowing measurement of brain activity throughout longer experimental setups such as here across both learning and test phases of a language learning experiment. fNIRS is also less susceptible to artifacts associated with verbal responses that are known to complicate recordings for competing neuroimaging methods.

2.1.3 The Present Study

In this study, I aimed to determine the cognitive mechanisms and neural correlates of L2 learning and processing in adults, focusing on distinct language components that may differ in engagement of opposing memory systems. Specifically, I used fNIRS and an artificial language paradigm adapted from Nevat et al. (2017) to address two main goals: 1) identify the cortical regions involved in simultaneous word and grammar learning, and 2) identify the behavioural and cortical differences between vocabulary and inflectional morphology processing post-learning. Here, the focus was on learning novel vocabulary and morphological markers for pre-existing concepts rather than forming novel conceptual representations. The language was comprised of novel singular and plural words that represented common objects. Regular plural suffixes were cued by the phonological rhymes of word roots, whereas exceptions to the rules included irregular words with arbitrary suffixes or inconsistent words in direct violation of the regular plural suffix rules.

Immediately following training of the novel language, test items using trained and untrained words were used to evaluate vocabulary learning and grammatical morpheme generalization. The tests were shaped by the Declarative / Procedural Model (Ullman, 2001) by contrasting explicit word-semantic associations (vocabulary test), where learning should rely more on declarative memory, with inflectional morphological patterns (grammar test) where optimal learning is assumed to engage more in the procedural memory system. Regarding proficiency outcomes, replicating findings from my master's thesis, I hypothesized that learners would exhibit higher accuracy and faster response time (RT) for word compared to morphology judgement tasks, thereby mirroring language differences observed in natural L2 learning. Regarding the cortical correlates implicated in the initial learning process, I hypothesized engagement of temporal lobe regions throughout the training phase, reflecting particular reliance on declarative / semantic memory processes during learning. Additionally, I predicted differences in temporal and frontal lobe regions between vocabulary and morphology processing post-learning, indicative of distinct dependencies on declarative and procedural memory systems.

2.2 Methods

2.2.1 Participants

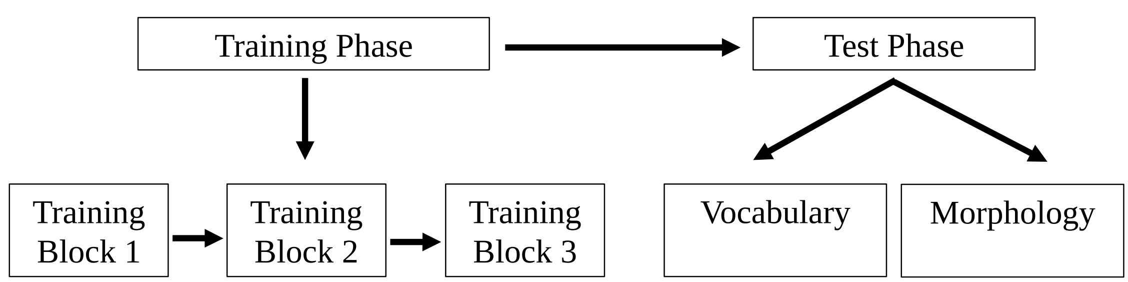
A total of 83 monolingual English speakers were recruited for participation in the study, with 45 participants completing the experiment without the neuroimaging component, and 38 participants completing the study with fNIRS recording. Behavioural data were combined across both groups. Participants were required to be neurologically healthy with no known learning impairments, have normal hearing and normal or corrected-to-normal vision, and report English as their native language. Following data exclusion from six participants due to fNIRS recording malfunctions and one participant due to diagnoses of a reading disorder and Attentional Deficit Hyperactivity Disorder (ADHD), 31 participants (20 female, M_{age} = 18.68, SD_{age} = .87) were included in the fNIRS analyses. The behavioural data from the six participants excluded from the fNIRS analyses due to recording malfunctions were included in the behavioural analyses. Behavioural data from an additional five participants were excluded due to language-related exclusionary criteria (four participants) and technical malfunctions (one participant), resulting in a final sample of 77 participants (56 female, M_{age} = 21.01, SD_{age} = 3.1) included in the behavioural analyses. Participants provided written informed consent and were compensated for their time. This study was approved by the University of Western Ontario Non-Medical Research Ethics Board (see Appendices A and B).

2.2.2 Procedure

Participants first completed a general demographics and language history questionnaire (Appendix C). As depicted in Figure 2.1, they then took part in an artificial language task which, as described in more detail below, consisted of a 30-minute training phase in which they learned novel singular and plural vocabulary words paired with images of common objects, followed by a 10-minute test phase in which explicit vocabulary and implicit morphology learning were evaluated through word-object association tests using trained and untrained words. Auditory stimuli were presented through speakers. Visual stimuli were presented on a computer screen via E-prime presentation software (*E-Prime* Version 2.0). Participants were informed that they would be learning a new language using visual and auditory stimuli. Participants were not told that there was a grammatical pattern to the language or that a test phase would follow. No additional information regarding the nature of the language or experiment was disclosed.

Figure 2.1

Experimental Design



2.2.3 Stimuli

The language used here (see Table 2.1) was adapted from Nevat et al. (2017) and altered in keeping with the specific goals of this study. Participants learned the meanings of novel words through simultaneous auditory and visual presentation of images of familiar objects such as fruit or furniture. The grammar of the language consisted of two inflectional suffixes marking plural nouns. In total, 54 disyllabic novel nouns were included (root = CVCVC; where C = consonant, V = vowel), with -VC plural suffixes. Singular words were presented alongside an image of a single object (e.g., one apple) whereas plural words were presented with an image of four identical objects (e.g., four apples). Auditory stimuli were composed of digital recordings of a female speaker recorded in a soundproof booth using a Blue Snowball iCE condenser microphone. All words had word-initial stress. Three recordings were made for each word in succession, and the recording with the most natural pitch and clearest sound quality was selected. Audio was recorded, edited, and amplified at 44.1 kHz and 16-bit quantization using Audacity software.

2.2.3.1 Regular Words

Of the 54 words in the language, 42 were evenly divided into two groups and followed a regular morphological pattern as follows: Group 1 contained 21 word-roots ending in "-oz", "-ig", or "-ul" that attached the plural suffix "-an". The other 21 words belonged to Group 2 with root endings of "-od", "-iv", or "-un", and were assigned the suffix "-esh" to mark plurality. Fifteen words from each group were included in the training phase. The remaining 12 regular words were untrained and were later included in the test phase to assess morpheme generalization. Eighteen of the 30 trained words were presented in both the singular and plural forms in separate training trials randomized within each of three identical but randomized training blocks. The 12 remaining trained words (6 from each group) were only trained on singular or plural forms (six words in each) and were later tested on the untrained form. This allowed us to independently test vocabulary (explicit memorization) and morphological (generalization) learning, as further explained below. To ensure an equal level of word exposure to the words trained on both singular and plural forms, words trained on only one form were included twice in each training block.

2.2.3.2 Irregular and Inconsistent Words

An additional six irregular and six inconsistent words were included. Irregular words were comprised of root rhymes matching those of regular words but were randomly assigned one of three irregular suffixes "-ev", "-ak", or "-ur" not associated with either Group 1 or Group 2 regulars (e.g., "pomoz" → "pomoz-ev" rather than "pomoz-an"). Inconsistent words were also comprised of root rhymes matching those of regular words but directly violated the regular rules by attaching the regular suffix of the other group (e.g., "shalod" → "shalod-an" rather than "shalod-esh"). At training, both irregular and inconsistent words were presented in singular and plural forms.

Table 2.1

The Artificial Language

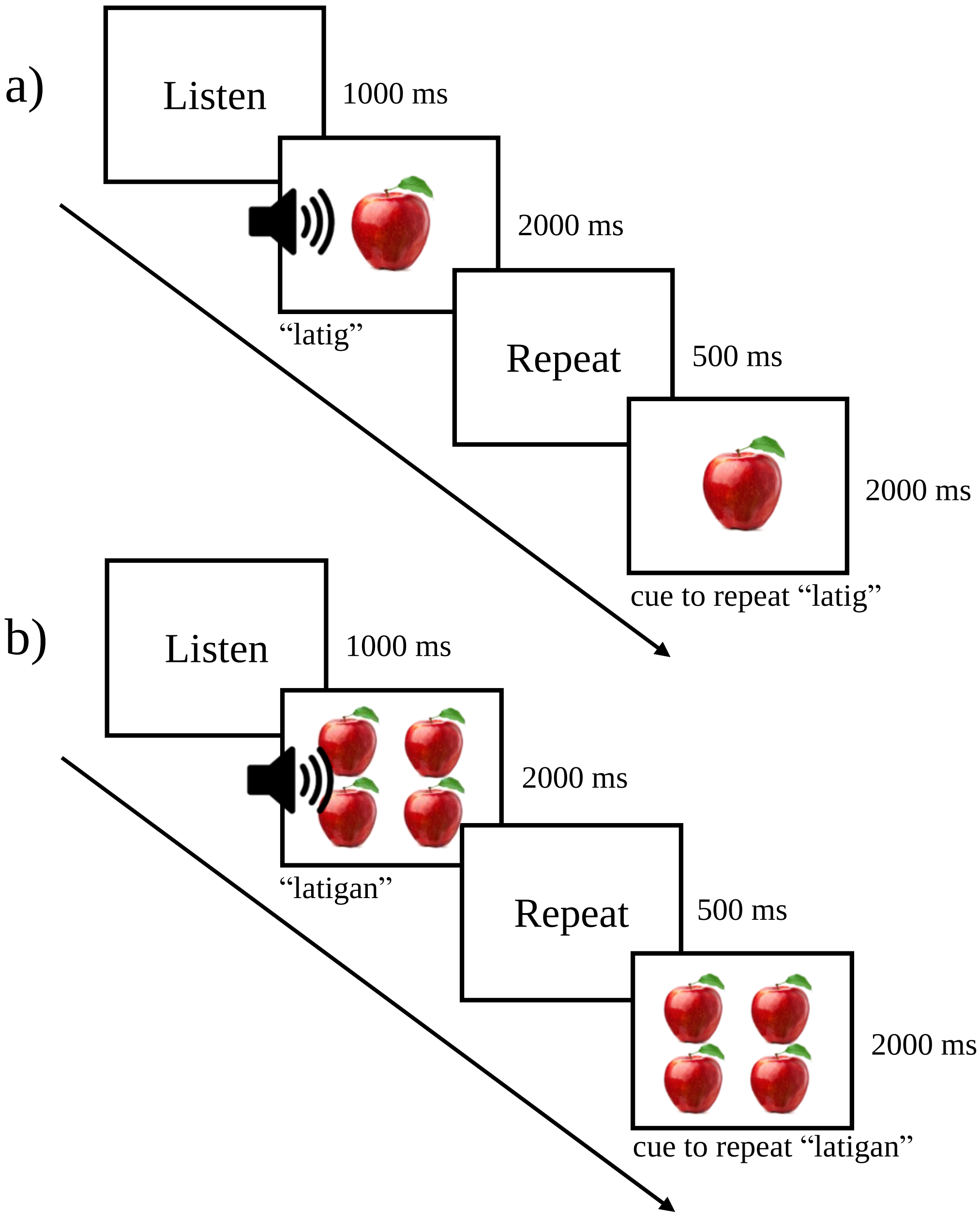
Training Form						
	Regular trained words					
	Group 1: Regular suffix "-an"			**Group 2: Regular suffix "-esh"**		
Singular only	nifoz	nishig	tizul	napod	paniv	koshun
Plural only	tuvoz	posig	shuzul	nezod	tepiv	rosun
Singular and plural	kufoz	bolig	mupul	resod	lekiv	ligun
	laloz	dedjig	suful	moshod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

2.2.3.3 Language Training Phase

The training phase included three 10-minute blocks, each composed of 84 identical trials, randomized across blocks and participants. Optional breaks were provided between each training block. As depicted in Figure 2.2, for each trial, an image was presented with an auditory word. Participants were prompted to repeat the word out loud once the image was presented again. This allowed for enhanced memory encoding through repetition and pronunciation (Hopkins & Edwards, 1972; Hopman & MacDonald, 2018), along with ensuring sustained attention throughout the task.

Figure 2.2

Training Phase Trial Design



Note. Examples of training trials for a) singular items and b) plural items. Participants were cued to repeat the word out loud upon seeing the image repeated.

2.2.3.4 Language Test Phase

Immediately following the training phase, a test phase was used to assess explicit vocabulary learning and implicit morphological generalization.

The vocabulary test entailed a word-object association judgement task. Here, participants determined whether an auditory word correctly matched the visually-presented object (see Figure 2.3a). The vocabulary test stimuli consisted of 12 regular singular items, six irregular plural items, and six inconsistent plural items. All vocabulary test items were included in the training phase prior. Half of the test trials were correct pairings of word and object and the other half incorrect. Incorrect trials of regular singular words were mismatched pairs of words and objects whereas incorrect trials of irregular plural words were composed of the roots incorrectly paired with the regular suffix.

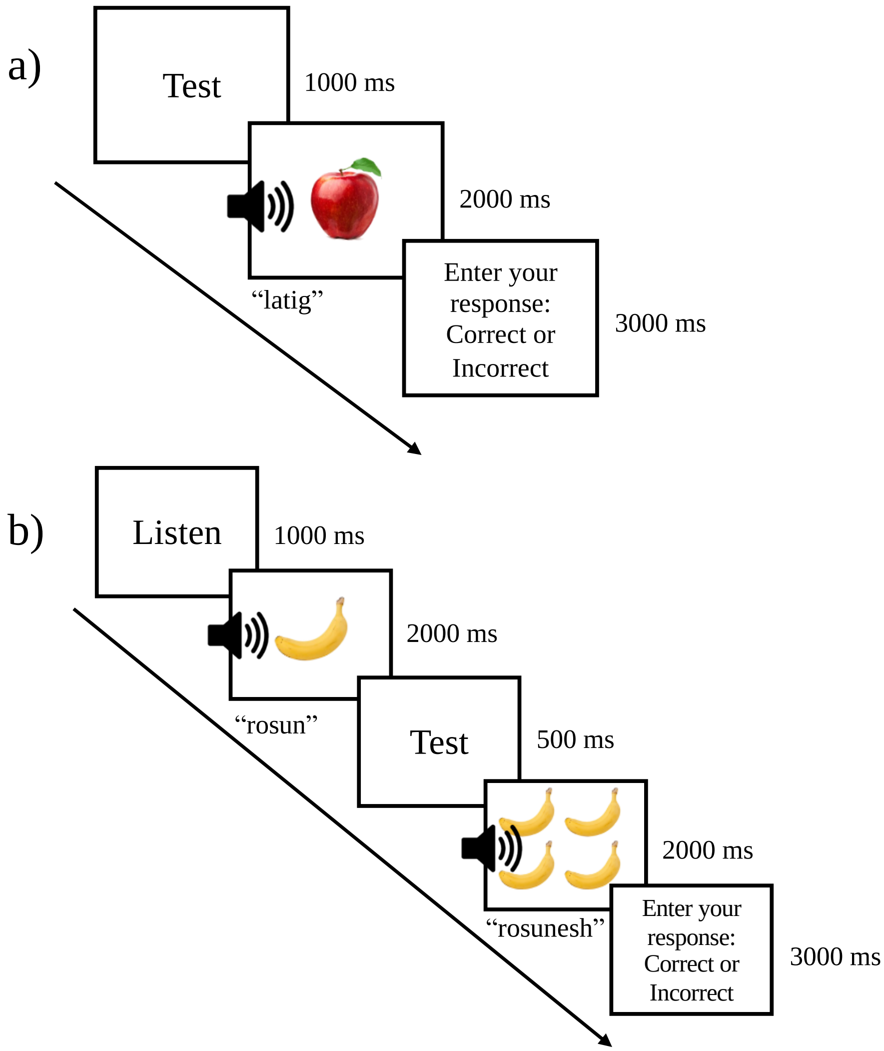
The morphology test also entailed a word-object association judgement task, this time, targeting morphological pattern generalization. Two test sets were used for the morphology condition with slightly altered task designs. Morphology Test Set 1 consisted of 12 words that were trained on only the singular or plural form and subsequently tested on the untrained form. The task for Morphology Test Set 1 followed the same design as the vocabulary test, with participants required to judge whether a presented word-object pairing was correctly matched (Figure 2.3a). On the other hand, Morphology Test Set 2 consisted of 12 novel untrained words (six singular and six plural) paired with objects omitted from the training phase (see Figure 2.3b). For both Morphology Test Sets 1 and 2, incorrect plural items were made of roots paired with incorrect suffixes (e.g., “nifoz” → “nifoz-esh” rather than “nifoz-an”). Incorrect singular morphology test items were word roots omitting the final coda, rendering the test word a CVCV word-form rather than CVCVC (e.g., "tuvoz-an" (trained in plural form only) → "tuvo" rather than "tuvoz").

While both vocabulary and morphology test conditions consisted of word-object association judgements tasks, successful performance of the morphology condition required participants to generalize the plural suffix pattern learned from the training phase to novel word-forms not previously exposed. This eliminated the possibility of relying on declarative memory while minimizing task differences between conditions. On the other hand, vocabulary test items did not follow any regular patterns, and thus targeted declarative memory knowledge of trained items.

Test trials were randomized within each test set in the behavioural study whereas in the fNIRS experiment, trials were reorganized into three-trial blocks with 10-second rest periods between each block in order to obtain appropriate hemodynamic response measures. The vocabulary test triplets and the morphology Test Set 1 triplets were counterbalanced. Button responses and reaction times (RT) for both groups were recorded via E-Prime (*E-Prime Version 2.0*).

Figure 2.3

Test Phase Trial Design



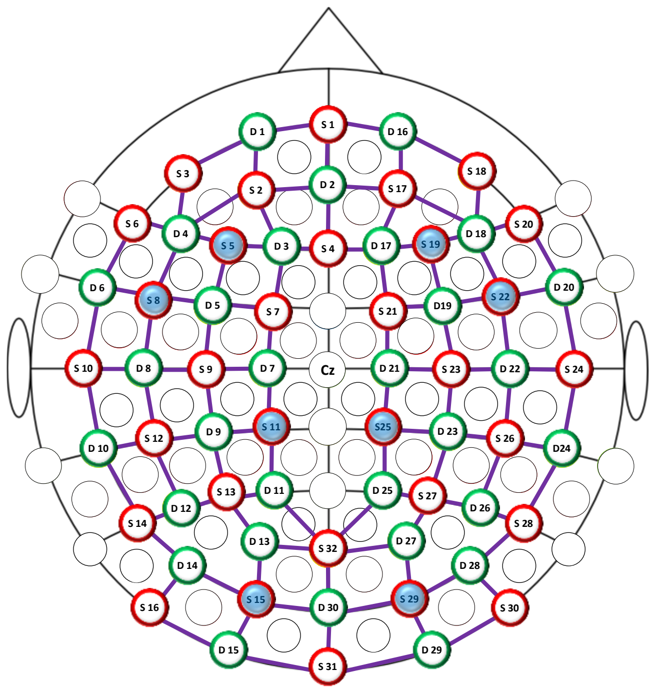
Note. Examples of test phase trials for a) all vocabulary test items and Morphology Test Set 1 (items trained on singular or plural form only and tested on the untrained form), and b) Morphology Test Set 2 (novel untrained items): a novel word and image pair was first introduced in either singular or plural form and immediately tested on the other form.

2.2.4 fNIRS Set-Up and Data Acquisition

Whole-head neural data were collected using a NIRx NIRScout system via NIRStar 15.2 acquisition software. Data were continuously sampled at 1.95 Hz. As depicted in Figure 2.4, 32 laser sources (wavelengths: 785, 808, 830, and 850) and 30 detectors were included in the probe array, making up 104 long-distance channels (source-detector pairings) with an average of 36 mm. An additional 8 short-channel detectors (8 mm) were included to measure extracerebral responses, later used to regress systemic noise from the data. Participants had their heads measured and fitted with an appropriately-sized high density fNIRS probe placement cap, positioning the Cz halfway between the nasion and inion, and between the pre-auricular points. During probe set-up, hair was parted under each probe to ensure optimal probe-scalp contact. Room lighting was dimmed, and a black cap was placed over the fNIRS cap to block out external light. Following probe set-up, NIRStar's built-in calibration system was used to assure optimal scalp contact and minimal intrusion of extraneous light sources. Any channels depicting poor light intensity were refitted, ensuring perpendicular contact of the probes with the scalp, with hair departed under the probes. This step was repeated until acceptable calibration was achieved. Participants were asked to refrain from making extraneous head movements and finger or foot tapping movements throughout the task to avoid confounding hemodynamic responses, although some movement was to be expected due to the spoken nature of the training trials and the button responses required at the test phase. All button responses were made using the right index finger to control for motor movements across trials.

Figure 2.4

2D Topographic fNIRS Source and Detector Montage



Note. Distance is not to scale. Red circles represent laser sources (32), green circles represent long-distance detectors (30), and sources filled in blue represent short-distance detectors which surrounded the sources (8). Lines between source and detector pairings represent long-distance channels (104).

2.2.5 Analyses

2.2.5.1 Behavioural Analyses

Behavioural data were combined across the behavioural-only group and the fNIRS group. Paired t-tests were conducted on accuracy scores (percent of correct responses) and RT (ms) differences between vocabulary and morphology test items. The vocabulary condition included regular singular words, irregular plural words, and inconsistent plural words. The morphology condition was comprised of untrained words and words tested on untrained word-forms (e.g., trained on singular only and tested on plural form).

2.2.5.2 fNIRS Preprocessing and Analyses

fNIRS preprocessing and analyses were implemented in MATLAB using the NIRS Brain AnalyzIR Toolbox (March 1, 2023, Santosa et al., 2018) and Homer2 (v2.8 p2.1, Huppert et al., 2009). Training and test phase runs were split, and data was preprocessed and analyzed separately. Raw data was first converted to optical density. Data quality control was conducted subject-wise. For each channel, the Scalp Coupling Index (SCI) was calculated on all possible pairs of the four wavelengths and then averaged. Channels with an SCI less than 0.1 or that had poor correspondence between wavelengths were excluded. As noisy data were down-weighted in later steps, an SCI threshold of 0.1 was chosen here to target pure system noise (e.g., when a probe is obstructed). An average of 3.23% and 3.06% of channels were excluded per participant from the training and test phase runs, respectively. Motion correction was performed using a combination of spline interpolation (Scholkmann et al., 2010) and Wavelet filtering (Molavi and Dumont, 2012), demonstrated to be effective artifact correction methods (Brigadoi et al., 2014; Cooper et al., 2012) especially when combined (Di Lorenzo et al., 2019). Specifically, an in-house Homer2-based tool was used to detect drift and baseline shifts based on subject-wise standard deviation thresholds (Training run: $M_{SD} = 11.39$, $min_{SD} = 3$, $max_{SD} = 15$; Test run: $M_{SD} = 9.8$, $min_{SD} = 5$, $max_{SD} = 17$) along with manual inspection. Homer2's spline interpolation method was used to correct these detected artifacts while being careful to avoid introducing new shifts. NIRS Toolbox was then used to apply a wavelet filter (symlet8) to remove spikes and slow trends by decomposing each signal into a set of wavelet components, thresholding, and then reconstructing the cleaned signal. Optimal thresholds were determined for each subject through visual inspection (Training run: $M_{IQR} = 0.91$, $min_{IQR} = 0.5$ to $max_{IQR} = 1.3$; Test run: $M_{IQR} = 0.97$, $min_{IQR} = 0.5$ to $max_{IQR} = 1.4$). Note that these thresholds were provided in the common interquartile range (IQR) format but were converted into standard deviation thresholds for NIRS Toolbox. Following motion correction, HbO and HbR concentration changes were calculated using the modified Beer-Lambert law (Delpy et al., 1988) with a partial pathlength factor (PPF) of 0.1. A pre-whitening filter was applied using a 10s model to remove potential type I errors caused by serial autocorrelation of signals (Barker et al., 2013).

A random effects (RFX) analysis was then conducted with a General linear model (GLM) analysis using an Ordinary Least Squares (OLS) approach including all short-distance channels as regressors of no interest, thereby subtracting scalp-level noise from the hemodynamic response. The regression was performed independently for HbO and HbR data. NIRS Toolbox's robust method was further used to detect and down-weight outliers. Paired t-tests were conducted separately for the training data (Training block 1 vs. Training block 3) and the testing data (vocabulary test vs. morphology test).

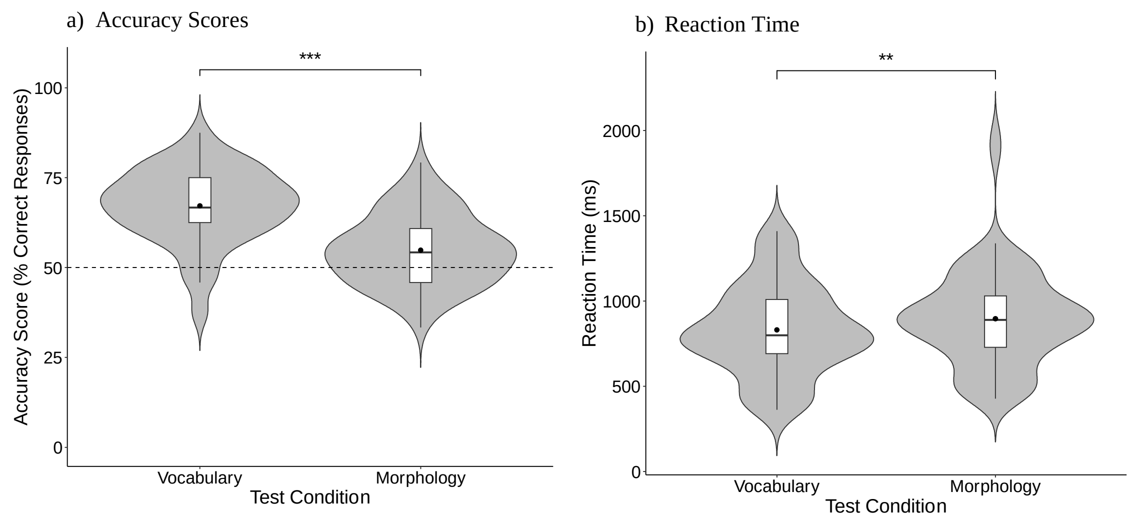
2.3 Results

2.3.1 Accuracy and RT Differences Between Vocabulary and Morphology Test Items

A paired t-test revealed a significant difference in mean accuracy scores between vocabulary (M = 67%, SD = .10) and morphology (M = 57%, SD = .10) test items ($t(76) = 7.86$, $p < .001$, $d = .90$), indicating that participants achieved higher vocabulary proficiency compared to morphology (see Figure 2.5a). One-sample t-tests further indicated that accuracy for vocabulary test items ($t(76) = 14.43$, $p < .001$, $d = 1.65$) and morphology test items ($t(76) = 4.31$, $p < .001$, $d = .49$) were significantly above chance level (50%), indicating successful learning of word-object semantic associations and morphological patterns. Significant mean differences were also found in RT between vocabulary (M = 830.70 ms, SD = 262.20) and morphology (M = 896.20, SD = 285.20) test trials such that participants responded faster to vocabulary than to morphology test items ($t(76) = -2.88$, $p = .005$, $d = -.33$) (see Figure 2.5b). These results align with the findings from Brainin (2019) where I reported similar effects demonstrating higher accuracy and faster RT for vocabulary compared to grammar test items.

Figure 2.5

Accuracy and Reaction Time Differences Between Vocabulary and Morphology Tests



** p < .01. *** p < .001.

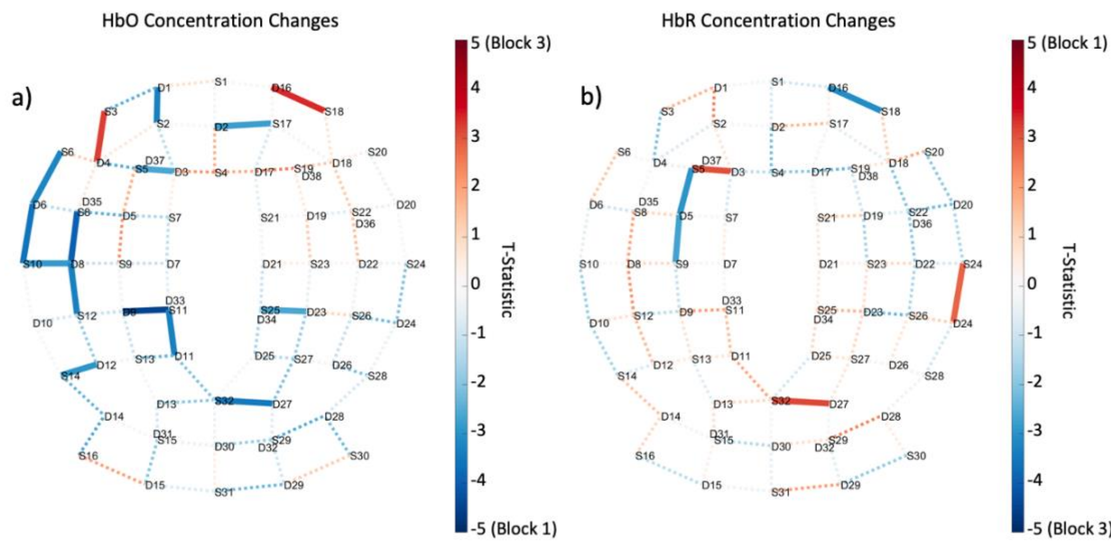
Note. Violin plots representing a) accuracy score, and b) reaction time (RT) frequency probability density differences between vocabulary and morphology tests. The dashed line represents chance level (50%). Box and whisker plots display the median (horizontal line), mean (dot), quartiles, and upper and lower limits (1.5 x IQR).

2.3.2 fNIRS Training Phase: Cortical Differences Between First and Final Training Blocks

Table 2.2 depicts a summary of the paired t-test statistics for channels with significant HbO and HbR concentration differences between the first and final training blocks. Due to the large number of sensors in the whole-head analysis used here, a threshold of $p < .01$ was adopted to be significant. Figure 2.6 displays topographic t-statistic maps for the HbO (Figure 2.6a) and HbR contrasts (Figure 2.6b), revealing clear decoupling between HbO and HbR signals. The results depict attenuation of neural activity across the learning phase (decrease in HbO and increase in HbR) in various regions of the left temporal lobe (temporal pole, MTG, and STG), one channel in the right temporal cortex (MTG/STG), bilateral parietal regions (Wernicke's area, bilateral supramarginal gyrus, subcentral gyrus, and left precuneus), one channel in the left occipitotemporal area, and one channel in the right occipital lobe overlapping with part of the visual cortex. However, the frontal lobe paints a different picture, with activity in some bilateral frontal regions attenuating over time (frontopolar cortex and dorsolateral prefrontal cortex (DLPFC)), and others increasing across the training phase (left IFG / Broca's area, left DLPFC, left premotor cortex, and right orbitofrontal cortex).

Figure 2.6

fNIRS Training Phase Topographic Maps



Note. Topographic t-statistic maps displaying channel-wise a) HbO, and b) HbR concentration changes between first and final training blocks. Bolded solid lines represent channels with significant ($p < .01$) differences between training blocks. Note that an increase in neural activity is reflected as an increase in HbO and a decrease in HbR.

Table 2.2

Summary of Paired T-Test Statistics for Channels with Significant HbO and HbR Concentration Changes Between First and Final Training Blocks

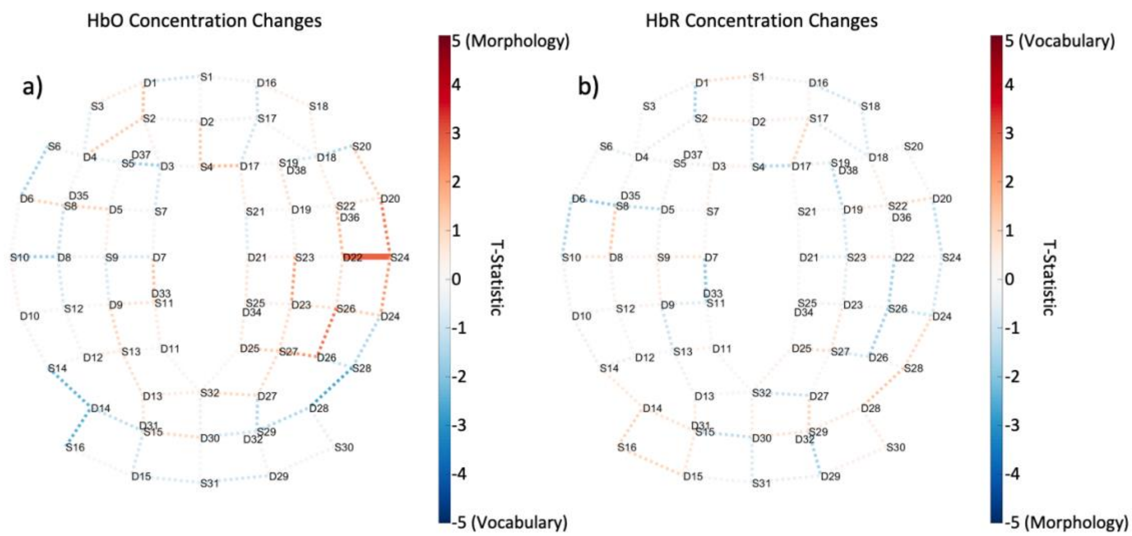
	Hemisphere	Source-Detector	10-10 coordinates	Brodmann Area	*t*	*df*	*p*
Increase in HbO	Left	3-4	AF7-F5	BA45 (Pars Triangularis Broca's part of IFG)	3.27	30	.002
	Right	18-16	AF8-FP2	BA11 (orbitofrontal)	3.4	30	.001
Decrease in HbO	Left	2-1	AF3-FP1	BA10 (frontopolar cortex)	-3.32	30	.001
		5-3	F3-F1	BA9 (DLPFC)	-2.63	30	.009
		6-6	F7-FT7	BA38 (Temporopolar)	-3.23	30	.002
		8-8	FC5-C5	BA43 (subcentral gyrus)	-3.94	30	<.001
		10-6	T7-FT7	BA21 (MTG)	-3.6	30	<.001
		10-8	T7-C5	BA21 (MTG); BA22 (STG)	2.84	30	.006
		11-9	CP1-CP3	BA40 (supramarginal gyrus & Wernicke's)	-4.56	29	<.001
		11-11	CP1-P1	7 (Precuneus)	-3.36	28	.001
		12-8	CP5-C5	BA22 (STG)	-3.32	30	.001
		14-12	P7-P5	BA37 (occipitotemporal cortex)	-2.94	30	.004
	Right	17-2	AF4-AFZ	BA9 (DLPFC); BA10 (frontopolar)	-2.77	30	.007
		25-23	CP2-CP4	BA40 (supramarginal & Wernicke's)	-2.67	29	.009
		32-27	POZ-PO4	BA19 (V3)	-3.48	28	<.001
Increase in HbR	Left	5-3	F3-F1	BA9 (DLPFC)	3.1	30	.003
	Right	24-24	T8-TP8	BA21 (MTG); BA22 (STG)	2.91	30	.005
		32-27	POZ – PO4	BA19 (V3)	3.2	28	.002
Decrease in HbR	Left	5-5	F3-FC3	BA9 (DLPFC)	-2.96	30	.004
		9-5	C3-FC3	BA6 (premotor cortex)	-2.72	30	.008
	Right	18-16	AF8-FP2	BA10 (frontopolar); BA11 (orbitofrontal	-3.1	30	.003

2.3.3 fNIRS Test Phase: Cortical Differences Between Vocabulary and Morphology Tests

Channel-wise paired t-tests between vocabulary and morphology test trials revealed only one channel (S24-D22 corresponding to the right hemisphere BA21 [MTG] & BA22 [STG]) with a significant ($p < .01$) HbR concentration difference between test conditions ($t(30) = 2.87$, $p = .006$), revealing greater neural activation for morphology compared to vocabulary test trials. Figure 2.7 illustrates topographic t-statistic maps for the HbO and HbR contrasts.

Figure 2.7

fNIRS Test Phase Topographic Maps



Note. Topographic t-statistic maps displaying channel-wise a) HbO and b) HbR concentration differences between morphology and vocabulary test trials. Bolded solid lines represent channels with significant ($p < .01$) differences between test conditions. Note that an increase in neural activity is reflected as an increase in HbO and a decrease in HbR.

2.4 Discussion

In this study, I examined the neural regions that support learning and processing distinct components of a rapidly-learned novel language. In particular, I sought to isolate the contrasting memory systems engaged by different language components. fNIRS was used alongside an artificial language learning task to measure the cortical processes involved in L2 learning and to directly compare the behavioural and cortical differences between declarative word processing and procedural morphological pattern generalization. Following three language training blocks, participants were tested on trained and untrained singular and plural nouns via a word-object association test. The complexity of the morphological regularities, along with the inclusion of irregularities and inconsistencies to the patterns, encouraged passive learning of the grammatical rules. The regular plural suffix agreement relied on the phonological rhyme of the root and occurred more frequently than irregular items and inconsistent items that directly contradicted the rule. Consequently, morphological patterns were learned through repeated exposure to transitional probabilities between word stems and suffixes, much like the properties that govern statistical language learning (Saffran et al., 1996).

The post-learning test phase was designed to differentiate between the distinct declarative and procedural memory systems on which vocabulary and morphology learning are argued to rely, respectively (Ullman, 2004), while controlling for task differences. While both the vocabulary and morphology tasks involved judging word-object associations, vocabulary test items were pattern-less lexical word-objects pairs explicitly exposed during training while morphology test items involved generalizing the learned inflectional morphological patterns to novel word-forms not previously exposed.

The latter eliminated the possibility of measuring explicit memorization of regular words in their plural forms.

While adults successfully learned both the semantic word-object associations and the inflectional morphological patterns of the artificial language, they performed significantly better and faster on vocabulary compared to morphology test items. These findings mirror natural proficiency differences observed in adult L2 learning whereby adults particularly struggle with learning grammatical language components (Newport et al., 2001). If vocabulary and grammar are learned through opposing memory systems as argued by a dual-system model (e.g., Ullman, 2001, 2004), proficiency differences between these language components may result from maturational differences of domain-general memory processes (Finn et al., 2014, 2016).

2.4.1 Neural Correlates of L2 Learning and Processing

2.4.1.1 Neural Correlates of Initial Language Learning (Training Phase)

To uncover the mechanisms that govern the initial language learning process, neural responses during early learning (Training Block 1) were contrasted with later learning (Training Block 3). As both training blocks involved the same words and objects, this contrast allowed us to cancel out any neural responses related to sensory processing and other task-related factors. Thus, any differences observed were due to learning and familiarization of the language across the exposure phase. With the exception of four channels in the frontal lobe, most channels with significant HbO and/or HbR concentration differences between training blocks showed significantly more neural activity in the first training block than the final training block. In the discussion that follows, I outline these regions and their particular roles in language and memory processing.

The left temporal lobe showed a consistent pattern of attenuation in various channels spanning the temporopolar area and middle and superior temporal gyri. Overall, these neural regions, which together encompass the anterior temporal lobe (ATL), are known to govern semantic declarative memory in the visual, auditory, and general linguistic domains (Patterson et al., 2007; Visser et al., 2010). The temporopolar area in particular mediates semantic memory processes (Noppeney & Price, 2002), speech comprehension (Giraud, 2004), and linguistic recall tasks (Andreasen et al., 1995). Neural lesions within the temporal pole are associated with semantic dementia (Mummery et al., 2000) and progressive primary aphasia with a particular difficulty in naming objects (Mesulam et al., 2013). Likewise, temporarily inhibiting activity in bilateral temporopolar areas using repetitive transcranial magnetic stimulation (TMS) has been found to disrupt selective semantic memory processes (Pobric et al., 2007, 2009, 2010). Similarly, the MTG has been found to be particularly important for learning and processing semantic representations of words (Chou et al., 2006; Démonet et al., 2005; Friederici & Gierhan, 2013; McDermott et al., 2003). While the STG is also involved in auditory word comprehension (Hillis et al. 2017), it additionally plays a role in processing intelligible speech (Overath et al. 2015) and more complex semantic information including combinatorial components of language (Friederici, 2011) and sentence comprehension (Vigneau et al., 2006).

Likewise, activity in Wernicke’s area was attenuated across the training phase. Located in the left posterior superior temporal gyrus and supramarginal gyrus, Wernicke's area has long been known to govern language comprehension and semantic processes, with receptive aphasia being associated with damage to this region (Naeser et al., 1987). However, more recent evidence links Wernicke's area to more general processing of phonological sequence representations used for speech and short-term memory tasks in addition to lexical recognition (Ardila et al., 2016; Binder, 2017).

Neighboring channels in regions of the parietal cortex, namely, bilateral regions of the supramarginal gyrus, the left precuneus, and the subcentral gyrus, also demonstrated neural attenuation over time. It has been suggested that the supramarginal gyrus acts as the dorsal stream lexicon (Gow, 2012) involved in word production, comprehension, and verbal working memory (Deschamps et al., 2014). Adjacent to the supramarginal gyrus, the precuneus is involved in a range of memory and language processes including episodic memory retrieval (Shallice et al., 1994), imagery of memories (Fletcher et al., 1995), word recollection (Henson et al., 1999), and attention during language tasks (McDermott et al., 2003). Neighboring the premotor cortex, the subcentral gyrus has been found to be play a role in speech-related movements (Eichert et al., 2020).

Interestingly, two channels in the occipital lobe, one likely overlaying a region of the third visual cortex (V3) in the right hemisphere, and the other in the left occipitotemporal area, also exhibited neural attenuation across time. While these regions primarily govern visual processes, they may also play select roles in the linguistic domain. For example, recent evidence suggests that the border of the visual cortex acts as a convergence centre between visual information and their semantic categories (Popham et al., 2021). Likewise, the occipitotemporal cortex has been implicated in word-form recognition, reading, and phonological access (Bolger et al., 2005; Dehaene & Cohen, 2011; Dong et al., 2020).

Given the importance of these temporal, parietal, and select occipital regions for language and memory processing, it might have been expected that engagement in regions would increase alongside experience with the novel language. However, I suggest there may be a number of factors that led to the opposite effect of attenuation across time in this data. Notably, within each training block, each word in the language was presented once in its singular form and once in the plural form, with the exception of the select words that were presented in one form only and were thus presented twice in each training block. Therefore, it seems that these regions may be especially important during the first exposure of a novel word when its semantic association is first encoded into long-term memory. Indeed, declarative memory learning operates quickly and can occur after a single exposure to stimuli (Alvarez & Squire, 1994; Lum & Conti-Ramsden, 2013). Furthermore, these regions may also be involved in the initial acquisition of grammatical patterns. As each item presented at training acted as an exemplar of the morphological regularities, a decrease in neural activity across time may reflect increased neural efficiency following continuous exposure to the patterns.

Unlike the regions discussed so far exhibiting robust attenuation primarily spanning the temporal and parietal lobes, mixed results in the frontal lobe were observed. In particular, bilateral regions of the frontopolar cortex and a channel in the left DLPFC were more active for the initial training block, again demonstrating attenuation across time. On the other hand, the pars triangularis part of Broca's area in the left IFG, the right orbitofrontal cortex, the left premotor cortex, and a neighbouring channel in the left

DLPFC displayed the opposite effect, showing increased activation during the final training block compared to the first block.

The frontal pole is known to mediate higher-order cognitive processes including planning, organizing, and managing goals, affective processing, and memory and perception (Bludau et al., 2014). The DLPFC is considered to be the hub for domain-general executive functions including cognitive control, planning, inhibition, task-switching, attention, and working memory, all important functions required for language learning and processing (see Hertrich et al. 2021 for a review on the DLPFC and Language). Given the complexity and breadth of functions the DLPFC is involved in, the contradictory patterns of activation observed in this data suggest that some sub-regions may be especially important for initial word and grammar encoding, while others may respond more for retrieval and repetition of familiar forms, or for grammatical processing following increased exposure to the language's patterns.

Also increasing in activation across time was the pars triangularis, a segment of Broca's area in the anterior region of the left IFG. The pars triangularis is primarily involved in both learning and processing semantic information, as well as converging written and spoken word meanings (Friederici et al., 2000; Liuzzi et al., 2017; Poldrack et al., 1999). While the orbitofrontal cortex is not typically known to mediate language learning, this region plays an important role in memory formation (Frey & Petrides, 2002). Finally, in terms of its involvement in language processing, the premotor cortex has been found to play a role in speech perception, processing complex speech sounds (Meister et al., 2007), and the repetition of pseudowords (Hartwigsen et al., 2013). Overall, these findings further support the involvement of these brain regions in language learning and word repetition, demonstrating that while temporal and parietal lobes are especially critical for initial exposure to novel words and grammatical patterns, the frontal lobe paints a more complex picture, with select regions increasing in activation over time, perhaps due to recognition and more complex learning of grammatical patterns.

Given that the novel words, their semantic representations, and the grammatical patterns were learned simultaneously in this design, as is usually the case in natural L2 learning, it is not possible to detangle vocabulary from grammar learning during the training phase. Thus, in the next section, I address specific vocabulary processing vs. grammatical generalization differences in the post-learning test-phase.

2.4.1.2 Neural Differences Between Vocabulary and Morphology Processing (Test Phase)

Recall that while the underlying word-object association tests entailed the same task for both vocabulary and grammar conditions, the conditions differed on whether the stimuli were explicitly exposed at training, and whether successful performance was based on word-object mapping or generalizing exposed grammatical patterns through incidental learning to novel words. Thus, the tests were designed to target distinct memory processes. Specifically, the vocabulary items were previously-exposed singular words and irregular plural words that did not follow regular patterns and thus had to be memorized explicitly. On the other hand, the morphology test items were not previously exposed in the tested form, and thus required participants to apply learned grammatical knowledge to novel word-forms. While the present sample displayed above-chance knowledge of both vocabulary and morphological patterns, morphology accuracy was significantly lower, as expected given adults' particular difficulty with L2 grammar learning. I therefore expected to see neural differences between the test conditions that either reflected superior knowledge of vocabulary in regions governing semantic recall, or alternatively, more engagement in frontal regions governing complex pattern learning and decision-making, reflecting increased cognitive demand when judging the novel untrained words.

Contrary to predictions, only one channel showed significant neural activation differences between morphology and vocabulary test items. This channel encompassed a region overlaying the right MTG/STG, exhibiting a significant increase in neural engagement during the morphology compared to vocabulary test. No regions were found to have the reverse effect despite the large observed difference in accuracy scores between the two test conditions. As both test conditions required participants to make explicit judgements of word-object associations, it is important to note that the morphology test items required both semantic processing and grammatical generalization. It may be the case that the increased activation in the temporal gyri may reflect an increase in cognitive demand needed when making more complex decisions beyond word recognition. Alternatively, as novel words and objects were introduced at the test phase for half of the morphology trials, the observed results may reflect encoding those novel lexical items into memory.

2.4.2 Considerations and Future Directions

In this section, I highlight several limitations to be considered when interpreting these results, along with avenues for future research. First, the complexity of natural language makes it difficult to study L2 learning in a controlled lab-based setting.

Artificial languages represent proxies of natural L2 learning, providing better control for external factors that can differentially affect distinct language components. They further allow for higher proficiency achievement to be reached in a limited time period. Although the artificial language used here was able to mirror natural L2 learning differences between vocabulary and morphology achievement in adults, accuracy scores for morphology items were low, likely due to the relatively brief exposure provided during the training phase. These lower scores could have led to cognitive demand differences between the two test conditions. Consequently, any neural observations may reflect cognitive demand differences rather than memory or learning differences. This might have been addressed by simplifying the grammatical patterns to boost morphological learning within the constrained timeframe of laboratory experiments. However, such simplification would sacrifice the accurate representation of the complexities of natural language structures, and the subsequent impact on L2 learning. This issue underscores the primary challenge inherent in studying L2 learning within the confines of laboratory settings where the pursuit of controlling confounding variables can compromise ecological validity. The limited training timeframe could be addressed by extending training over multiple days of exposure, but this may further identify sleep-related consolidation effects known to differentially influence explicit and implicit learning (Mirković et al., 2019; Mirković & Gaskell, 2016). The present results may therefore be strengthened or modulated by these effects and this approach may in turn be useful in further identifying how declarative and procedural systems mediating language learning are differentially affected by sleep-related consolidation.

Furthermore, when using artificial languages to represent natural L2 learning, the assumption is made that comparable cognitive mechanisms underlie learning and processing both artificial and natural languages. An increasing corpus of research is focusing on investigating the ecological validity of utilizing artificial languages for this matter. In a comprehensive review, Folia et al. (2010) outlined evidence from diverse neuroimaging methodologies suggesting that shared neural mechanisms are implicated in artificial and natural language learning and processing. Moreover, studies investigating the developmental trajectories of natural languages have revealed significant correlations with that of artificial languages (e.g., Gómez & Maye, 2005), while investigations of brain lesion analyses have reported concurrent impairments in language processing and artificial sequence learning (e.g., Christiansen et al., 2010; Evans et al., 2009; Richardson et al., 2006). These findings indicate that outcomes from learning and processing artificial languages can be applied to the broader context of natural L2 learning. Nonetheless, it should be noted that not all artificial languages may serve as optimal indicators of L2 learning. For example, the inclusion of semantic components and the complexity of grammatical patterns have been found to affect the strength of the correlation between artificial and natural L2 performance (Ettlinger et al., 2016). Accordingly, this design sought to incorporate both semantic representations in learning vocabulary, and an arguably complex morphological component with exceptions to the regular rules in order to increase this design's ecological validity to natural L2 learning.

In terms of the test measurements used, this study only assessed receptive knowledge of the language. It may be instructive to further include a production measure which may uncover even greater proficiency differences between vocabulary and compositional language components. Moreover, while the morphological patterns were not explicitly taught to participants and the morphology test items targeted pattern generalization to untrained word-forms, the word-object association task is nevertheless an explicit measure requiring learners to make explicit decisions based on their knowledge of the language. Future work should further incorporate implicit measures of morphological proficiency outcomes as it may be the case that explicit measures may not be sensitive enough to capture implicit grammatical pattern knowledge (Batterink et al., 2015). I address these concerns in Chapters 3 and 4 by introducing a novel method for examining implicit representations of grammar learning.

Lastly, although fNIRS possesses a commendable spatial resolution, it falls noticeably short in comparison to fMRI. Furthermore, a key limitation is its limited penetration depth, restricting recording to the cortex without being able to capture neural differences in sub-cortical regions that may additionally aid in dissociating the memory processes governing learning distinct language components such as the medial temporal lobe and basal ganglia regions (Mochizuki-Kawai, 2008; Ullman & Pierpont, 2005). This constraint may explain the limited fNIRS findings from the test phase despite the large proficiency differences observed from the behavioural data. In addition, while optimal cap alignment was ensured by measuring participants heads, using correctly-fitted caps, and aligning the caps based on physiological markers, there is no guarantee that probes and channels overlayed the exact same cortical regions across individuals of different head sizes and shapes. Consequently, I remain cautious about the anatomical specificity of fNIRS findings. Instead, I wish to highlight the broader frontal vs. temporal and parietal dissociations observed as potential reflexive effects of cortical dissociations related to memory systems and other higher-order cognitive processes involved in L2 learning.

2.5 Conclusion

In this study, I aimed to elucidate the neural correlates of L2 learning and processing by examining cortical regions involved in initial L2 learning and directly comparing differences between explicit vocabulary and implicit morphology processing post-learning. Learners achieved significantly higher proficiency outcomes in vocabulary compared to morphology learning, broadly reflecting the intuition that in adults, explicit word learning is achieved more quickly and easily than implicit learning of grammatical patterns. Despite this, scarce neural differences were found between the two test conditions, suggesting that differences may be mediated by sub-cortical regions that cannot be captured by fNIRS. On the other hand, extensive neural differences between the first and final training blocks were observed despite both blocks consisting of identical stimuli and tasks. This contrast was used as a measure of learning and familiarization, while cancelling out neural responses to more fundamental visual and auditory processing or task effects. Interestingly, the earliest stage of L2 learning was associated with greater engagement in widespread neural regions known to govern semantic memory and higher-order cognitive processes. However, select bilateral frontal lobe regions became more active over time, suggesting that sub-regions of the frontal lobe play distinct roles during the language learning process. These findings identify fNIRS' advantage in uncovering the learning mechanisms during initial language or pattern exposure, without relying on post-learning tests.

Another key implication of this study is the utility of a controlled but naturalistic language learning paradigm to explore distinct components of memory in language learning. Such an approach could be used to examine vocabulary and grammar learning differences between children and adults known to differ significantly in certain L2 abilities, or to explore mechanistic theories of developmental and acquired language impairments. Notably, fNIRS represents a powerful tool in this regard by allowing for overt word-repetition or verbal responses that are more difficult to compensate for with fMRI and EEG. fNIRS' child-friendly advantage would further allow for an optimal method of examining the neural mechanisms that subserve age-dependent L2 learning differences across various ages and learning abilities.

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Chapter 3: Trying Hard or Hardly Trying: The Impact of Effort on Implicit Word and Grammar Learning

3.1 Introduction

As clearly demonstrated in Chapter 2, adults have difficulty with learning grammatical components of a novel language (Johnson & Newport, 1989; Newport, 1990). On the other hand, adults can learn vocabulary words quite quickly, attaining a high level of proficiency (Snow & Hoefnagel-Hohle, 1978). In this chapter, I switch focus to address an emerging theory of why this discrepancy may develop. This age-related difficulty with grammar learning seems to be an exception to adults' otherwise superior cognitive skills such as attentional control and explicit memory processes (Craik & Bialystok, 2006). Here, I aimed to explore the interference hypothesis, a somewhat paradoxical theory which proposes that the advanced neural mechanisms that give rise to adults' superior cognitive skills may come with costs by interfering with implicit processes (Nozari & Thompson-Schill, 2013; Thompson-Schill et al., 2009).

Of particular interest to the interference hypothesis is the late maturation of the prefrontal cortex (PFC), consequently delaying complete development of explicit memory processes and executive functions such as attention and cognitive control until young adulthood (Casey et al., 2008; Finn et al., 2016). Given the competitive nature between explicit and implicit processes (Poldrack & Packard, 2003), adults' enhanced reliance on more developed explicit memory systems may impede implicit learning. This competition is central to language learning where optimal vocabulary and grammar learning are argued to vary in engagement of distinct explicit and implicit learning mechanisms, respectively (Ullman, 2001, 2004, 2016). Ultimately, the interference hypothesis may offer a potential explanation for the age-dependent differences observed in natural second language (L2) learning. However, certain measures commonly used to investigate language learning encounter limitations concerning their suitability for assessing implicit knowledge. The aim of this study was to examine the interference hypothesis through a statistical language learning paradigm that targets both novel word and grammar learning. Importantly, to address some of the limitations encountered by existing methodologies discussed further below, I employed a method specifically designed to measure implicit knowledge of grammatical patterns.

3.1.1 What is Statistical Learning?

Statistical learning refers to the cognitive process of learning patterns or sequences by extracting distributional regularities from the environment (Arciuli, 2017; Aslin, 2017; Saffran et al., 1996). Within the domain of language, statistical learning studies have primarily focused on the segmentation of multi-syllabic words from a continuous auditory stream of syllables, in the absence of acoustic cues to distinguish word boundaries. This method relies on incidental learning of transitional probabilities (TP) between stimuli, such as probabilities of syllables co-occurring, given that syllables within words co-occur more frequently than those across word boundaries. Initial evidence of statistical language learning was first demonstrated in eight-month-old infants (Saffran et al., 1996), and is still widely explored in developmental research (e.g., Arciuli & Simpson, 2011; Moreau et al., 2022; Palmer et al., 2018) and investigations of adult L2 learning (Batterink, Reber, Neville, et al., 2015; Batterink & Paller, 2019; Smalle et al., 2022).

It is important to note that statistical learning extends beyond the realm of language and has been demonstrated in various domains and modalities including music and tone sequences (e.g., Daikoku et al., 2015; Saffran et al., 1999), visual patterns (e.g., Daltrozzo et al., 2017; Fiser & Aslin, 2002a; Turk-Browne et al., 2005), visual scenes (e.g., Fiser & Aslin, 2002b), and motor skills (e.g., Monroy et al., 2017). These paradigms typically involve incidental learning of presented sequences in the absence of directed attention towards the stimuli. As statistical learning can occur without explicit instruction or attention (Batterink & Paller, 2019; Duncan & Theeuwes, 2020; Musz et al., 2015; Yang & Flombaum, 2015), it is commonly considered an implicit learning process (Perruchet & Pacton, 2006). However, there remains debate about how the learned items are stored in memory, with some evidence that the learned words can be stored and accessed explicitly (Batterink, Reber, Neville, et al., 2015).

3.1.2 Evidence for the Interference Hypothesis

As it is thought that interference of higher-order processes occurs naturally in adult language and pattern learning (Finn et al., 2014), empirical evidence supporting the interference hypothesis has typically come from studies demonstrating sequence-learning improvement after supressing or blocking interfering factors. For example, a number of studies have used transcranial magnetic stimulation (TMS) to inhibit various regions of the PFC, thereby examining the causal role of these regions in procedural learning. Particularly relevant to this discussion is a recent study conducted by Smalle et al. (2022), in which a modified continuous theta-burst stimulation (cTBS) procedure was applied over the left dorsolateral PFC (DLPFC) prior to a statistical language learning task. They found that temporary inhibition of the left DLPFC led to improved accuracy in recognizing novel words, but only for words judged as less familiar to the participants, and therefore, categorized as stored implicitly. These findings corroborate previous research demonstrating enhanced implicit learning following inhibitory TMS. For example, cTBS over the left DLPFC led to improved performance on a Hebb repetition task simulating incidental word-form learning (Smalle et al., 2017). Similarly, using repetitive TMS over the inferior frontal cortex following five consecutive days of artificial syntax learning improved both accuracy and reaction time (RT) in correctly rejecting non-grammatical sequences (Uddén et al., 2008). In the visual domain, supressing bilateral DLPFC activity immediately following a serial reaction time (SRT) task (Galea et al., 2010) and during an alternating serial reaction time (ASRT) task (Ambrus et al., 2020) facilitated procedural pattern repetition and the learning of non-adjacent statistical regularities, respectively.

Behavioural manipulations have also been used to investigate interference arising from PFC-mediated mechanisms, particularly, by exhausting or redirecting cognitive resources during or prior to learning novel sequences. For example, depleting cognitive resources through a dual working-memory task under a high cognitive load facilitated the learning of novel phonotactic constraints (Smalle et al., 2021) and statistical learning of novel words (Smalle et al., 2022), but again, only for words rated as unfamiliar by participants. This facilitating effect of cognitive fatigue on sequence learning is not limited to spoken language. For example, engaging in an attentional capacity-limiting task during unfamiliar sign language learning led to improved pattern generalization of the language to novel contexts, despite resulting in slower learning compared to those learning under a control condition (Cochran et al., 1999). Likewise, this facilitatory effect has been observed outside the linguistic domain when inducing cognitive fatigue prior to a visuo-motor SRT task (Borragán et al., 2016). Together, these findings provide support for a somewhat counterintuitive relationship between cognition and procedural learning, suggesting that later-developing cognitive mechanisms such as cognitive control, working memory, and attention may hinder implicit language learning in adults. As such, when reliance on these mechanisms is diminished, more optimal automatic procedural learning can take place.

Understanding the effects of learning manipulations on learning outcomes of distinct types of material is crucial, as inducing cognitive fatigue to enhance procedural learning might then come at a cost for explicit learning processes. This is particularly pertinent in the context of L2 learning where vocabulary and grammar are typically learned in conjunction. To address these considerations, Finn et al. (2014) examined how the allocation of effort towards learning influences distinct language learning components by using a statistical language learning paradigm with grammatical categories and patterns. The researchers found that compared to passive listening to a continuous speech stream of syllables, *trying* to learn facilitated word learning, but hindered grammatical category learning. Intentional effortful learning necessitates engagement of multiple higher-order cognitive processes, including sustained attention, cognitive control, searching hypothesis spaces, critical thinking, and explicit memory processes. Increased reliance on these mechanisms as they mature may therefore contribute to age-dependent L2 learning differences, particularly for grammatical components where engagement in procedural learning processes may result in more efficient learning and ultimately higher proficiency outcomes.

3.1.3 Implicit Measures of Sequence Learning

The methodologies used to assess statistical learning can significantly impact research outcomes, and consequently, our understanding of the learning process. Traditionally, statistical learning paradigms have relied on explicit tasks such as the 2-alternative forced choice (2AFC) test to assess learning outcomes. This task requires participants to make explicit decisions about which word or visual pattern belongs to the learned sequence. However, as this test relies on explicit recognition of items, it may not fully capture implicit knowledge of the learned sequence (Turk-Browne et al., 2009). Indeed, when examining word segmentation using both the 2AFC task and implicit reaction time (RT) measures, subjective ratings of familiarity of the test items only correlated with the explicit measure. In particular, accurate recognition, as measured by the 2AFC test, was observed only for words that were familiar to participants, suggesting that this test primarily reflects explicit memory recall (Batterink, Reber, Neville, et al., 2015). This becomes especially concerning for investigating grammatical components where abstract patterns may not be as easily learned and retrieved through explicit processes. Furthermore, explicit decision-making is mediated by slow-developing executive abilities, possibly associated with later-developing neural regions such as the PFC (Domenech & Koechlin, 2015). Consequently, tasks necessitating greater engagement of executive functions may be less suitable for use with children. Despite previous success in capturing statistical learning across various domains in infants and children, the 2AFC task has not always been a reliable measure in younger age groups (e.g., McNealy et al., 2010; Raviv & Arnon, 2018).

To address these challenges, the use of implicit measures has been gaining traction recently in statistical learning paradigms. In particular, target detection tasks have been used as indirect measures of sequence learning by comparing RT in detecting targets varying in predictability within a continuous stream of visual or auditory stimuli. This type of measure was first used in the visual domain through the use of the rapid serial visual presentation (RSVP) task (Kim et al., 2009; Olson & Chun, 2001; Turk-Browne et al., 2005). This paradigm was then adapted for language learning studies as an indirect measure of word segmentation. For example, following exposure to a sequence of trisyllabic words with within-word TPs of 1.0 and between-word TPs of 0.33, faster RT was observed for word-final target syllables compared to word-initial syllables, contingent upon the TP between the target and the preceding “cue” syllable (Batterink, Reber, Neville, et al., 2015). More recently, target detection tasks have also proven effective in capturing statistical language learning abilities in children (Moreau et al., 2022). However, in regard to L2 learning studies, this method has only been used as a measure of word segmentation, with limited research exploring the statistical learning mechanisms underlying grammatical components of language, up until now.

3.1.4 The Present Study

The objective of this study was to integrate, modify, and expand upon existing methodology in order to investigate the influence of directed effort and attention on word and grammar attainment in L2 learning, with a focus on the implicit representations formed following exposure to a novel language. To achieve this goal, I adapted a statistical language learning paradigm with a grammatical component from Finn et al. (2014) in which statistically-defined disyllabic words belonged to grammatical categories presented in a predefined order. During the exposure phase, adult participants were exposed to a continuous speech stream of syllables under passive versus effortful learning conditions. Importantly, to assess word and grammar learning outcomes using more implicit tasks, I adapted a target detection task (Batterink, Reber, Neville, et al., 2015) previously used as an indirect measure of word-segmentation, and I expanded its use to the grammar domain. Target detection tasks may be especially well-suited for evaluating grammatical generalization to novel untrained stimuli because they avoid explicit decision-making and reduce reliance on explicit recognition and higher-order cognitive processes. Thus, following exposure to the novel language, participants' abilities to detect 1) familiar syllables varying in levels of predictability, and 2) unfamiliar syllables presented in either grammatical or ungrammatical sequences, were assessed as indirect measures of word segmentation and grammar generalization, respectively.

Accordingly, this study aimed to address two primary research questions, each comprising two sub-components. First, *can target detection tasks be used to successfully capture 1) word segmentation of exposed words, and 2) grammar generalization to unfamiliar words?* While target detection tasks have been proven successful in assessing word segmentation abilities, the word-forms used in the present language differ in significant ways from typical statistical learning paradigms, which may impact the results. These differences will be outlined in the subsequent methodology section. Nonetheless, it was hypothesized that if participants successfully learned the statistical regularities governing word segmentation, RT should be faster for more predictable syllables compared to less predictable syllables. Similarly, if participants learned the underlying grammatical patterns of the language, RT for novel untrained syllables should be faster for targets appearing in grammatical than in ungrammatical positions.

Second, to address the interference hypothesis, I asked *does effort influence learning of 1) word segmentation, and 2) grammatical patterns, as measured by implicit target detection of familiar and unfamiliar targets, respectively*. By examining the impact of attention and effort on the *implicit* representations formed following language exposure, I aimed to explore whether similar effects to those reported by Finn et al. (2014) using 2AFC tests can be observed here. Specifically, it was hypothesized that directing effort towards learning during the exposure phase would facilitate implicit word segmentation but hinder grammatical generalization outcomes.

3.2 Methods

3.2.1 Participants

Participants were recruited online through the Prolific participant registry and were compensated for their time. Using Prolific's pre-screening criteria, participants were required to be 18 years of age or older, native monolingual English speakers, neurologically healthy with normal hearing and normal or corrected-to-normal vision. These criteria were further verified using a demographic and language background questionnaire (Appendix C). Recruitment was continuous until an a-priori final target sample of 120 participants was met. A total of 138 participants completed the study. Of those, 18 were excluded due to the following criteria: six reported having extensive proficiency in a language other than English, six missed over 30% of trial responses across the test phase, four experienced technical difficulties, and two reported having a clinically diagnosed learning impairment. The final sample included in analyses were ages 18-66 (M_{age} = 38.5, SD_{age} = 11.67, 60.8% female) divided into two learning groups: effortful learning (*n* = 60, M_{age} = 38.73, SD_{age} = 12.31) and passive listening (*n* = 60, M_{age} = 38.27, SD_{age} = 11.1). All study procedures were approved by the University of Western Ontario Non-Medical Research Ethics Board (Appendix D).

3.2.2 Procedure

All components of this study were completed online. Participants provided informed consent and completed a general demographics and language history questionnaire via a Qualtrics survey. Participants were then redirected to the experiment on the Pavlovia platform (https://pavlovia.org). The experiment began with a computer audio check followed by three target detection practice trials, a three-minute baseline target detection task, an eight-minute language exposure phase, and a test phase comprised of two 10-minute target detection tasks. Optional breaks were provided between each phase of the experiment.

3.2.3 Stimuli

3.2.3.1 The Artificial Language

Participants in each learning group were randomly assigned to one of two versions of an artificial language adapted from Finn et al. (2014). Two versions were used to ensure any inherent properties of the syllables were not driving the learning effects. Each language version was comprised of disyllabic words that followed English phonotactic constraints but carried no English meanings. Each word belonged to one of three categories (A, B, or C) differing based on the pattern of vowels (V) and consonants

(C) of the second syllable. Words in Category A ended in a C-V syllable such as “z-uh”, words in Category B ended in a V-C syllable such as “oo-k”, and words in Category C ended in a C-V-C syllable such as “g-e-f”. During the exposure phase, words were presented in the following grammatical sequence structure: Category A word → Category B word → Category C word → repeat. The TP between categories was therefore always 1.0. On the other hand, because there were two words from each category, the TP of syllables between words was 0.5 whereas the TP within words was 1.0. Both language versions followed the same grammatical patterns, but with exposed versus novel syllables switched. For simplicity, examples from one version only with be provided in this chapter (see Table 3.1).

The syllables were generated using Google Cloud’s Text-To-Speech Application Programming Interface (API), which synthesizes natural-sounding speech. A female American accent was used. Syllables were generated within the context of the carrier sentence “I will say _____ again,” to assure equal and natural prosody of each individual syllable. Syllables were then isolated using Audacity software by deleting the carrier sentence and adding exactly 40 ms silence in order to produce consistent gaps between syllables when presented repeatedly. The mean syllable length was 348 ms.

Table 3.1

The Artificial Language

Category A			**Category B**			**Category C**		
C-V	-	**C-V**	C-V	-	**V-C**	C-V	-	**C-V-C**
p-oy /pɔɪ/	-	z-uh /zʌ/	t-ay /teɪ/	-	oo-k /uk/	l-ee /li/	-	g-e-f /gɛf/
r-ee /ɹi/	-	j-ow /ʤaʊ/	s-ow /saʊ/	-	o-b /ɑb/	v-ay /veɪ/	-	n-i-v /nɪv/

Note. This table depicts one of the two versions of the artificial languages used. Phonetic pronunciation is presented in International Phonetic Alphabet (IPA) notation beneath each syllable.

3.2.3.2 Baseline Target Detection Phase

Prior to the exposure phase, participants completed 30 target detection trials to measure baseline RT to detecting unpredictable syllables. The purpose of this measure was to assess potential group differences in baseline RT that might be unnecessarily biasing target detection measures in the test phase. Trials were composed of novel counterbalanced CV, VC, or CVC syllables (see Table 3.2) that were not used in any other phases of the experiment and did not follow any order presentation patterns. Trials were between 7 to 11 syllables long and the target appeared in five possible positions within the trial stream (ranging from position 4 to 8).

Table 3.2

Syllables From Baseline Target Detection Task

Phonological Structure	**Target Syllable**	**IPA**
C-V	loy	/lɔɪ/
	feh	/fɛ/
	tauw	/taʊ/
	ruh	/rʌ/
V-C	eeb	/ib/
	auwf	/aʊf/
	oov	/uv/
	ayb	/eɪb/
C-V-C	meep	/mip/
	nuk	/nʌk/
	layf	/leɪf/
	reg	/rɛg/

3.2.3.3 Statistical Learning Exposure Phase

Following the baseline target detection task, an eight-minute exposure speech stream was presented auditorily through speakers or headphones. Both learning groups were exposed to the same speech stream consisting of the six disyllabic words (see Table 3.1) strung together in triplets, each presented 100 times following the [A → B → C → repeat] category order (see Figure 3.1 for an example segment of the speech stream). Thus, there were eight possible unique A→B→C sequences which were counterbalanced to ensure one sequence never repeated twice in a row. There were no acoustic cues such as pauses or tone changes between word or triplet sequence boundaries.

Figure 3.1

Example Segment of Exposure Speech Stream

poyzuhtayookleegefreejowtayookvayniv…

A B C A B C

Note. Participants heard syllables presented with no acoustic cues between word boundaries. Words were presented in Category A → B → C → repeat order.

While both learning groups were exposed to the same speech stream, they were given different instructions prior to the exposure phase. The passive listening group was not given any information about the language, and as such they were not given any clues that these syllables combined to form words, or that the order of these words was governed by a rule. Instead, they were told to listen to sounds in the background while completing a simple visual shape task. The visual task was irrelevant to the language and was presented in a way that it did not align with syllable presentation rate. As this was an online study, this task was aimed to mimic the distractor tasks such as colouring used in previous statistical learning studies to induce incidental learning. On the other hand, the effortful learning group was told that there were six words belonging to three categories, and that the categories were presented in a particular order. Their task was to determine what the three categories were and the order that they appeared in. Following Finn et al. (2014), participants were asked to press a key when they believed they figured out a category or the category order, and to do this as many times as they thought necessary throughout the exposure phase. This procedure ensured that the effort group was paying attention and actively trying to determine the language structures.

3.2.3.4 Statistical Learning Test Phase

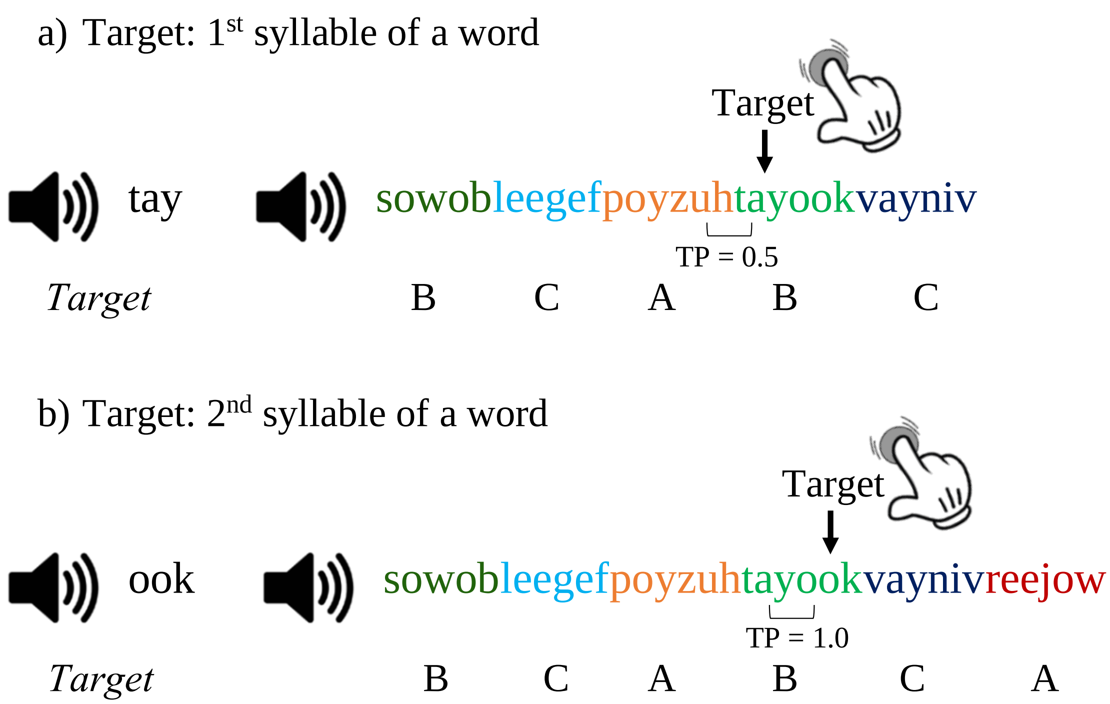
Testing Word Segmentation via Target Detection of Familiar Syllables. Following the exposure phase, participants from both learning groups completed the same test phase comprised of two target detection tasks. The first task assessed word segmentation learning by measuring RT to detecting the syllables presented in the exposure phase (familiar syllables). Here, participants completed 60 trials: 30 where the target was the first syllable of a word and 30 where it was the second syllable. As depicted in Figure 3.2, each trial began with an auditorily presented target syllable followed by a short pause and then a short speech stream ranging from 10 to 20 syllables. Participants' task was to press the space bar when they heard that target syllable in the speech stream. They were asked to respond as quickly and accurately as possible. Each of the 12 syllables from the exposure phase acted as the target five times, each time appearing in a different position within the trial (varying from syllable position seven to 16). To ensure a target never appeared in the same position, each of the six words in the exposure stream acted as the first word of a test trial 10 times. Thus, the trial did not necessarily start with a Category A word, but always followed the same category order (e.g., [A → B → C…] or [B → C → A…] or [C → A → B…]). The target syllable was never presented within the first three words of the test stream. The trial ended three or four syllables following the target presentation, depending on whether the target was the first or second syllable of a word, respectively. Trial order was randomized across participants.

RTs of key responses were measured from the onset of the target syllable presentation. To measure word segmentation learning, the average RT of detecting first-syllable targets was compared to second-syllable targets. Due to differences in TPs of syllables within words (TP = 1.0) and between words (TP = 0.5), second-syllable targets were more predictable than first-syllable targets.

This target detection task was adapted from Batterink, Reber, Neville, et al. (2015). However, the language used here is distinct from their design in two important ways: First, the words in the present design are disyllabic rather than trisyllabic, and therefore, word-final targets only have one within-word "cue" syllable as opposed to two. Thus, the predictability distinction between first and second syllable target conditions may not be as prominent as previous comparisons of first and third syllable target conditions. Secondly, the between-word TP in this language (TP = 0.5) was greater than that used in previous studies (TP = 0.33), making the distinction between the target conditions (0.5 vs. 1.0) less apparent than previous studies (0.33 vs. 1.0). Despite these differences, it was expected that if participants learned the statistical regularities of the language, second-syllable targets should elicit faster mean RT than first-syllable targets.

Figure 3.2

Examples of Familiar Target Detection Trials Measuring Word Segmentation



Note. Examples of target detection trials for a) first-syllable targets (e.g., “tay”) with a TP of 0.5 with the preceding “cue” syllable (e.g., a “tay” target may follow either “zuh” or “jow”), and b) second-syllable targets (e.g., “ook”) which have a TP of 1.0 with the preceding “cue” syllable (e.g., “tay”).

Testing Grammar Generalization via Target Detection of Unfamiliar Syllables. Immediately following the familiar syllable detection task, participants completed a second target detection task designed to assess grammar generalization using unfamiliar syllables that did not appear in the exposure phase (see Figure 3.3). For this task, 32 novel syllables not used in the training language were created. Twenty of these made up 10 words that contained syllable targets that either followed or violated the rule structure of the trained language, and the remaining 12 syllables were used in filler words (see Table 3.3). Just as in the familiar target detection task, participants completed 60 target detection trials. This time, the target was always a second syllable of either a Category B or Category C word since these syllables are phonologically unique in their consonant and vowel compositions (Category B = VC; Category C = CVC). The two test conditions differed based on whether the word containing the target syllable appeared in a legal (grammatical) position (e.g., …A → B → $\boldsymbol{C_{target}}$…) or an illegal (ungrammatical) position (e.g., …A → $\boldsymbol{C_{target}}$ → B…) within the trial stream. Each of the 10 targets appeared in three different legal and three different illegal positions within the stream, varying in positions 8, 10, 12, 14, 16, or 18. Trial order was randomized across participants.

If participants learned the three underlying grammatical categories (2nd syllable: C-V, V-C, or C-V-C) and their presentation order (Category A → B → C), faster RT should be exhibited for targets in legal positions compared to those in illegal positions since the illegal-positioned targets were presented earlier in the stream than would be predicted based on the learned pattern. As all of the syllables were novel, RT differences would only occur if participants had abstracted the grammatical rules of the exposed language.

Table 3.3

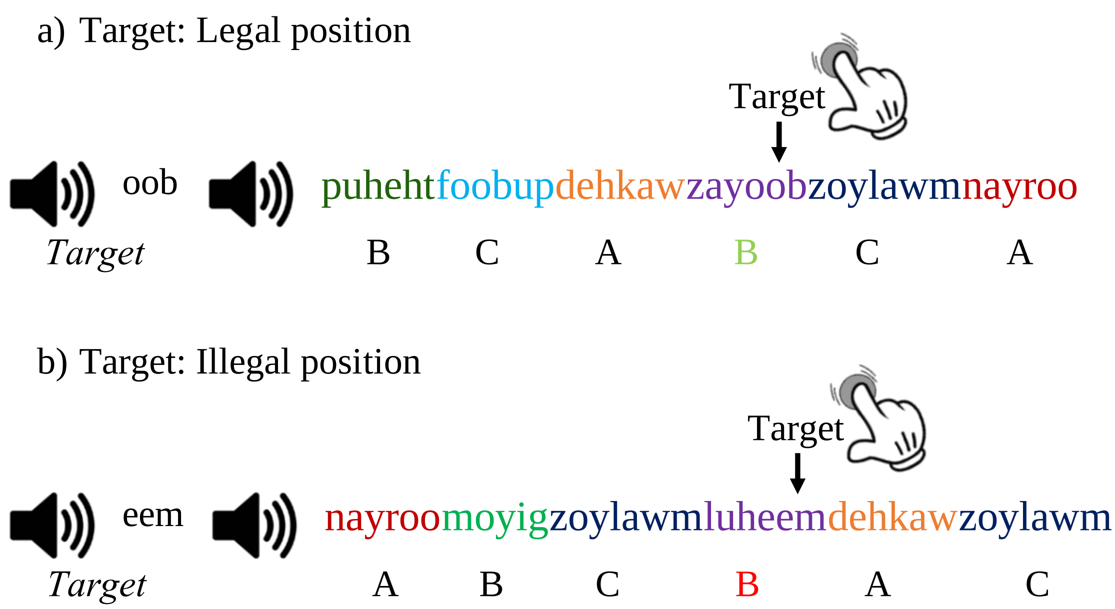
Unfamiliar Syllables From the Grammar Generalization Target Detection Task

	Category A			Category B			Category C		
	C-V	-	**C-V**	C-V	-	**V-C**	C-V	-	**C-V-C**
Fillers	d-eh /dɛ/	-	k-aw /kɑ/	m-oy /mɔɪ/	-	i-g /ɪg/	f-oo /fu/	-	b-u-p /bʌp/
	n-ay /neɪ/	-	r-oo /ɹu/	p-uh /pʌ/	-	eh-t /ɛt/	z-oy /zɔɪ/	-	l-aw-m /lɑm/
Words containing second-syllable targets				z-ay /zeɪ/	-	oo-b* /ub/	s-eh /sɛ/	-	r-oi-t* /ɹɔɪt/
				f-aw /fɑ/	-	ay-n* /eɪn/	g-uh /gʌ/	-	p-ee-f* /pif/
				l-uh /lʌ/	-	ee-m* /im/	r-auw /ɹaʊ/	-	j-uh-n* /ʤʌn/
				b-aw /bɑ/	-	oi-k* /ɔɪk/	t-uh /tʌ/	-	m-eh-p* /mɛp/
				v-oy /vɔɪ/	-	au-p* /aʊp/	d-aw /dɑ/	-	t-oo-g* /tug/

Note. * = target syllable. Each of the 10 novel second-syllable targets acted as the target six times. Target words never acted as fillers and vice versa. Phonetic pronunciation is presented in IPA notation beneath each syllable.

Figure 3.3

Examples of Unfamiliar Target Detection Trials Measuring Grammar Generalization



Note. Examples of grammar generalization test trials where a Category B target is presented in a) a legal (grammatical) position and b) an illegal (ungrammatical) position.

3.2.4 Data Analyses

Mean RT differences between the target conditions were calculated independently for familiar and unfamiliar target detection tests and compared between the two language versions to ensure that learning outcomes of the two languages were comparable, and that data from both versions can be combined (see Appendix E). The three target detection tasks (baseline, word segmentation, and grammar generalization) were analysed separately. Mean baseline RT differences between passive and effortful learning groups were analyzed using an independent t-test to ensure comparable baseline detection speeds between experimental groups. To examine the effect of effort (learning group) on word segmentation ability (familiar target detection task), a two-way 2 (passive vs. effort group) x 2 (1st syllable vs. 2nd syllable) mixed analysis of variance (ANOVA) was conducted, with learning group as the between-subject variable and target condition as the within-subject variable. If directing effort towards learning the language facilitates word segmentation, an interaction was expected to emerge between the familiar test target conditions and learning group. To examine the effect of effort on grammatical generalization using unfamiliar targets, a two-way 2 (passive vs. effort group) x 2 (legal vs. illegal target position) mixed ANOVA was conducted, again with target condition as the within-subject variable and learning group as the between-subject variable. If effort negatively interferes with category learning, an interaction between the unfamiliar test target conditions and learning group was expected to emerge. MATLAB (The MathWorks Inc., 2021) and R Statistical Software (v.4.0.2; R Core Team, 2020; R packages psych, ggplot2, tidyr, dplyr; Revelle, 2020; Wickham, 2016, 2020; Wickham et al., 2020) were used for data wrangling and plot visualizations, and mixed ANOVAS were conducted using JASP (v.0.17; JASP Team, 2023).

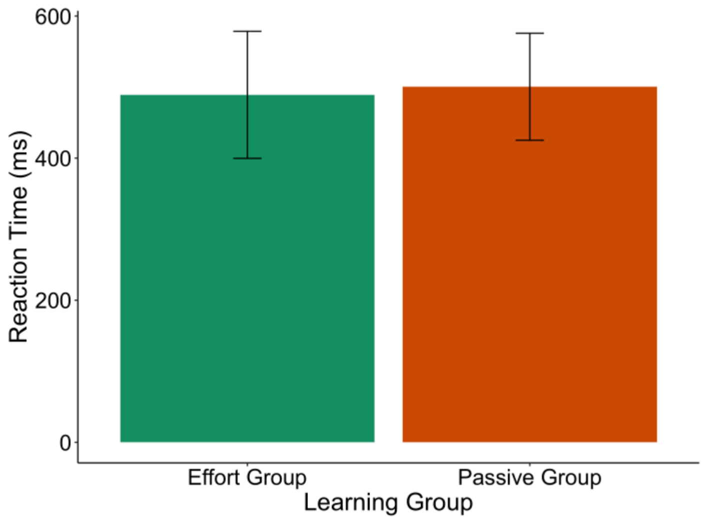
3.3 Results

3.3.1 Baseline Reaction Times

On average, participants detected 95.58% of targets in the baseline target detection task. Figure 3.4 illustrates baseline RT for both learning groups. An independent t-test confirmed that there were no significant differences in baseline RTs between the effortful learning group and the passive listening group ($t(118) = -0.75$, $p = .452$).

Figure 3.4

Mean Baseline RT for Effort and Passive Learning Groups



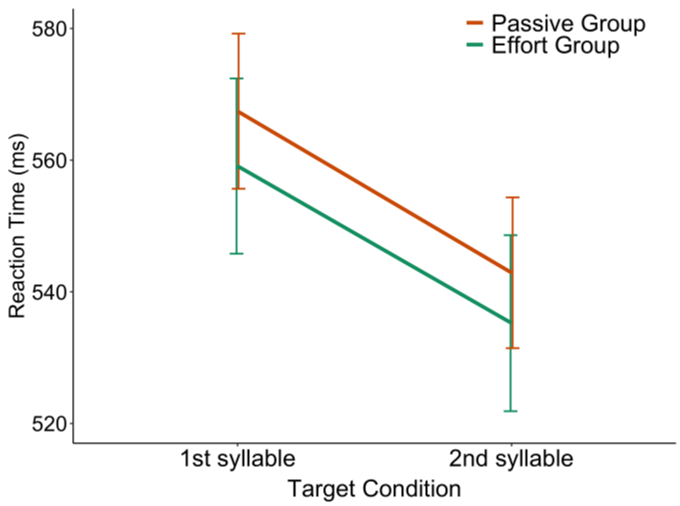
Note. Error bars represent standard deviation (SD). No significant differences in RTs between effort and passive learning groups were found.

3.3.2 Familiar Target Detection Task (Word Segmentation)

For the target detection task of familiar syllables, participants detected an average of 87.92% of first-syllable targets and 89.14% of second-syllable targets. Figure 3.5 illustrates each group's RT differences between first- and second-syllable target conditions. As predicted, a two-way 2 (1st syllable vs. 2nd syllable) x 2 (passive vs. effort group) mixed ANOVA revealed a significant main effect of target condition ($F(1, 118) = 35.46$, $p < .001$, $\eta^2_p = .231$). Across both learning groups, RTs were faster for second-syllable targets compared to first-syllable targets. This suggests that participants successfully learned to segment the words from the exposure phase and were faster to respond to the predictable targets (within-word TP = 1.0) compared to the less predictable targets (between-word TP = 0.5). Just like baseline RT, there was no main effect of learning group ($F(1, 118) = 0.22$, $p = .643$), revealing that there were no differences in RT between groups across both target conditions. Contrary to predictions, there was no significant interaction between learning group and target condition ($F(1, 118) = .007$, $p = .934$). Therefore, effortfully trying to learn did not lead to a greater difference between detecting first- and second-syllable targets.

Figure 3.5

RT Differences Between First- versus Second-Syllable Familiar Targets in Passive versus Effortful Learning Groups



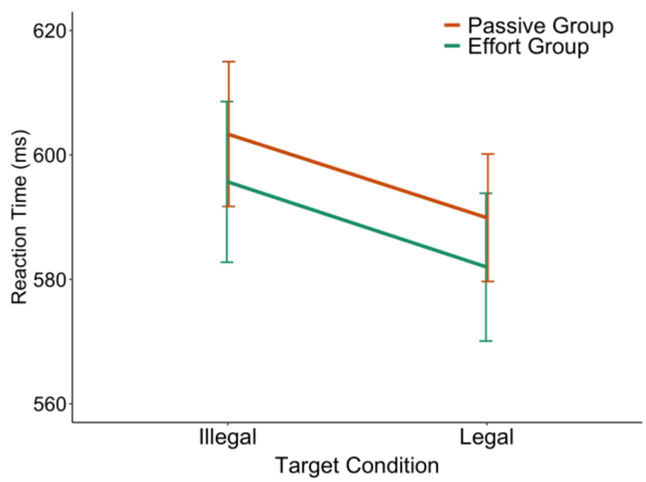
Note. Error bars represent standard error (SE). There was a significant main effect of target condition, no main effect of learning group, and no interaction between target condition and learning group.

3.3.3 Unfamiliar Target Detection Task (Grammar Generalization)

On the target detection task of novel unfamiliar syllables, participants detected an average of 88.36% of targets in legal positions and 89.83% of targets in illegal positions. Figure 3.6 illustrates each group's RT differences between targets in legal (grammatical) versus illegal (ungrammatical) positions in the stream. As predicted, a two-way 2 (legal vs. illegal) x 2 (passive vs. effortful learning) mixed ANOVA revealed a significant main effect of target condition ($F(1, 118) = 12.04$, $p < .001$, $\eta^2_p = .093$). Across both learning groups, RTs were faster for targets in legal positions compared to those in illegal positions, demonstrating that participants learned the underlying grammatical structure of the language and generalized their learning to novel syllables. As expected, there was no main effect of learning group ($F(1, 118) = 0.24$, $p = .628$), revealing that there were no differences in RT between groups across target conditions. Unlike predicted, there was no interaction between learning group and target condition ($F(1, 118) = .001$, $p = .975$). Thus, effortfully trying to learn did not interfere with grammar learning.

Figure 3.6

RT Differences Between Unfamiliar Targets in Legal versus Illegal Second-Syllable Positions in Passive versus Effortful Learning Groups



Note. Error bars represent standard error (SE). There was a significant main effect of target condition, no main effect of learning group, and no interaction between target condition and learning group.

3.4 Discussion

The primary objective of this study was to investigate the impact of intentional / effortful learning on implicit knowledge acquired from second language (L2) learning. Importantly, I sought to develop and validate a more suitable assessment of implicit knowledge of learned grammatical sequences. Specifically, following language exposure under either effortful or passive learning conditions, participants completed speeded syllable detection tasks with familiar and unfamiliar targets as indirect measures of implicit word and grammar learning outcomes, respectively.

Consistent with the first research question, the findings revealed that speeded syllable detection tasks can successfully capture the learning of both words and grammatical patterns. Particularly, across both learning groups, significant RT differences between target conditions with varying levels of predictability were observed for both familiar and unfamiliar target detection tasks, indicative of successful statistical learning related to word segmentation and grammar generalization. However, the findings further revealed that neither of these effects were modulated by the effortful learning manipulation, as reflected by null interactions between learning group and target conditions. Thus, directing effort towards language learning neither facilitated nor hindered implicit word or category learning outcomes. I will now address these findings in more detail and discuss them in relation to existing theories and empirical work.

3.4.1 The Utility of Implicit Target Detection Tasks as Assessments of Word Segmentation and Grammar Generalization

Regarding word segmentation, using a novel language design, I replicated previous findings demonstrating the utility of speeded syllable detection tasks as covert measures of word learning. Specifically, when tracking familiar target syllables learned from the exposure phase, learners responded significantly faster to second-syllable targets compared to less predictable first-syllable targets. Notably, the absence of acoustic or contextual cues between word boundaries indicate that adults can use acquired knowledge of transitional probabilities (TP) to predict upcoming syllables. The words and target conditions differed from typical statistical language learning studies in two key aspects. First, the words here comprised two syllables instead of the customary three, resulting in a single syllable rather than two serving as a cue for word-final targets. Secondly, the TP cue difference between the target conditions in the present study ($TP_{initial\_syllable} = 0.5$ vs. $TP_{final\_syllable} = 1.0$) was smaller than in previous designs (e.g., $TP_{initial\_syllable} = 0.33$ vs. $TP_{final\_syllable} = 1.0$). Despite the relatively subtle differences present in this language paradigm, where the less-predictable word-initial syllables retained 50% predictability based on the preceding cue, these findings demonstrated that adults can nevertheless pick up on these subtle distinctions, resulting in slower RT for the less predictable targets than for predictable word-final targets.

However, it is worth considering that the deterministic quality of the cues between the target conditions may have influenced the observed RT differences. That is, differences in RT may be driven by the distinction of whether the target is 100% predictable or not. This idea comes from statistical language learning paradigms that have typically used trisyllabic words, oftentimes reporting differences between first- and third-syllable targets, but not between first- and second-syllable targets (e.g., Batterink, Reber, Neville, et al., 2015; Batterink, Reber, & Paller, 2015). Importantly, the languages used in those studies recycled syllables across words, resulting in some syllables only serving as 100% reliable cues when presented in pairs. In those instances, word-final syllable targets had deterministic disyllabic cues whereas second-syllable targets had less reliable probabilistic cues. Consequently, a possible explanation for why RT differences between first- and second-syllable targets were observed here but not in previous work may be attributed to the deterministic predictability of the second-syllable targets based on the preceding 100% reliable cue. This theory aligns with findings from Finn et al. (2014) wherein comparable performance was observed when making explicit decisions between words and nonwords (TP differences of 1.0 vs. 0) versus words and part-words (TP of 1.0 vs. 0.5 or 0.33). In other words, a greater difference in TP between conditions did not facilitate word segmentation. Although EEG findings have indicated that subtle probabilistic differences are detected on a neural level (Batterink, Reber, Neville, et al., 2015), adults may rely more on the deterministic quality of the TP to successfully complete the statistical learning tasks. Future research can explore this hypothesis by comparing statistical learning tasks with and without deterministic cues in the language, such as by comparing outcomes from the present design with a language where all TP values are below 1.0. A language absent of deterministic cues may prompt adults to shift reliance to more subtle probabilistic TP information to successfully learn the statistical regularities of the language.

Novel to this study was the use of speeded syllable detection tasks to quantify implicit learning of grammatical categories and their order presentation. While learned words can be stored implicitly or explicitly, assessing RT in detecting novel untrained syllables differing only in the apparent grammaticality of their position within a speech stream allowed us to target true implicit generalization of these learned patterns. As predicted, participants exhibited faster RT when detecting targets presented in grammatical positions compared to ungrammatical positions within the stream, indicating that learners were able to extract the underlying grammatical patterns from the exposure phase and generalize their knowledge in a manner that enabled them to predict novel untrained syllables based solely on their phonological structure. Note that each target appeared in an equal number of legal and illegal positions. Therefore, the observed differences in detection speed cannot be attributed to inherent acoustic differences between syllables, nor could the differences be attributed to learning the TP within words. Rather, the targets were being conditioned not by the preceding syllable, but the phonological structure (serving as a *category* cue) of the preceding word. Therefore, the observed differences in detection speed between target conditions solely reflect learners' knowledge of whether the position of these syllables adhered to or violated the grammatical rules of the learned language. In summary, this study successfully demonstrated the utility of implicit measures as assessments not only for word learning, but grammatical generalization to sequences extended beyond the exposed words. These findings highlight this measure's suitability for evaluating grammar learning, particularly when explicit or verbalizable knowledge of grammatical information may be limited. By avoiding engagement of executive decision-making processes that explicit tasks tend to rely on, target detection tasks may also be more suitable for investigating developmental differences in language learning, especially when it comes to implicit grammatical pattern learning in which children's linguistic advantage may lie.

3.4.2 Effortful Learning Does Not Influence Implicit Word or Grammar Learning Outcomes

Drawing upon the interference hypothesis, it was hypothesized that directing effort towards learning would differentially affect word (through facilitation) and grammar (through interference) learning outcomes. As such, interactions between the target conditions and the learning groups were expected, such that the effort group would exhibit greater RT differences between target conditions for the familiar target detection task, and vice versa for the unfamiliar target detection task. Contrary to these predictions, the learning group manipulation had no effect on learning either language component. That is, exerting effort towards learning the language neither facilitated nor interfered with word segmentation or grammar generalization, respectively. Note that the effort group exhibited marginally, although not statistically significantly, faster detection speed across all the target conditions. This difference was also reflected in a non-significant difference between groups in target detection of random, unpredictable syllables, as measured in the baseline phase. However, note that a learning effect would emerge as a significant *interaction* between group and target condition, which was not the case for either target detection task. Instead, the findings align with a number of studies that have reported comparable behavioural learning outcomes between implicit or incidental and explicit or intentional learning groups (Batterink & Neville, 2013; Morgan-Short et al., 2012; Ruiz et al., 2018). Nevertheless, prior evidence suggests that learning manipulations may have a greater impact on neural processing of grammatical structures, with implicit language immersion settings resulting in neural signatures more closely resembling those of native speakers, and this difference was not reflected by behavioural measures (Morgan-Short et al., 2012).

I offer several speculations regarding the discrepancies between these findings and those employing explicit measures (e.g., Finn et al., 2014). First, it may be the case that effort particularly affects explicit, but not implicit recall of the language. Indeed, there is evidence that not only are both explicit and implicit knowledge acquired through statistical learning, but that the two are uncorrelated (Batterink, Reber, Neville, et al., 2015; Bertels et al., 2013; Kim et al., 2009; Moreau et al., 2022; Smalle et al., 2022). Therefore, it is plausible that effort differentially influences the two memory systems. However, variability across the literature suggests that the answer may not be so straightforward. For example, Batterink, Reber, & Paller (2015) reported no effect of instruction condition when measured through either explicit 2AFC or implicit RT-based tasks. On the other hand, explicitly presenting each word in isolation prior to the exposure phase resulted in both better explicit and implicit recall of the language (Batterink, Reber, Neville, et al., 2015). Furthermore, inducing cognitive fatigue particularly enhanced recognition accuracy for words that participants rated as having low confidence in remembering, thereby particularly affecting implicit rather than explicit knowledge (Smalle et al., 2022). Additionally, while some have found that neural inhibition of PFC regions enhances sequence learning (Ambrus et al., 2020; Galea et al., 2010; Smalle et al., 2017, 2022; Uddén et al., 2008), others have found no effects (e.g., Savic et al., 2017). Given the variations in manipulations and language structures employed across these studies, multiple factors may contribute to these discrepancies. Future work should directly examine the factors contributing to the observed variability, with a specific focus on identifying robust learning manipulations to improve sequence learning outcomes. Such work has important pedagogical implications for the development of more effective teaching strategies in formal education settings.

3.5 Conclusion

To the best of my knowledge, this is the first study to use speeded target detection tasks to measure both word segmentation of familiar words and grammar generalization of a novel language. To summarize, the findings outlined here suggest that effort neither helped nor hindered word or grammar learning, at least in terms of implicit representations formed following language exposure. This suggests that interference effects from higher-order processes on grammatical learning may be more nuanced, and potentially depend on task modality. However, using a novel language, this study replicated the finding that implicit measures of recall can be used to identify statistical learning of encoded words, even when there are less apparent differences between target conditions. Moreover, and novel to this study, it was demonstrated that adults could rely on non-adjacent statistical regularities to learn grammatical patterns and generalize this learning to novel sequences. Importantly, these learning outcomes can be reliably assessed using implicit target detection tasks. I highlight the utility and importance of using tasks that better target implicit recall of various language components. In the next chapter, I extend the use of these target detection tasks to explore individual differences in implicit word and grammar learning, particularly as they relate to domain-general cognitive skills.

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Chapter 4: Mind the Gap: Individual Differences in Implicit Word and Grammar Learning in Relation to Domain-General Cognition

4.1 Introduction

While there is a substantial body of literature exploring how bilingualism impacts higher-order domain-general cognitive skills (e.g., Bialystok, 1999; Costa et al., 2008, 2009; Morton & Harper, 2007; Paap & Greenberg, 2013; Ware et al., 2020), the inverse relationship - how domain-general skills influence second language (L2) learning ability - has received less attention. Language learning and processing involve a diverse set of cognitive mechanisms such as explicit and implicit memory processes (Archibald, 2017; Baddeley, 2003; Ullman, 2004, 2016) and inhibitory and cognitive control (Berninger et al., 2017; Hussey et al., 2017; Kapa & Colombo, 2014). Thus, the question arises whether and how individual differences in these mechanisms are related to variance in language learning outcomes. Moreover, various cognitive processes may have varying influences on learning distinct language components, such as novel lexical items and grammatical structures. Thus, this study aimed to explore the relationships between various higher-order cognitive functions and novel word and grammatical pattern learning using a version of the statistical learning task employed in Chapter 3.

Executive Function (EF) is an umbrella term used to describe the higher-order cognitive functions that control other cognitive mechanisms and behaviours. EF processes typically include cognitive, attentional, and inhibitory control, monitoring and switching behaviours, working memory, planning, organizing, strategic thinking, and problem solving (Baggetta & Alexander, 2016; Rabbitt, 1997; Stuss & Benson, 1984). The Prefrontal Cortex (PFC) is the primary neural region responsible for regulating EF processes (Fuster, 1991; Panikratova et al., 2020; Stuss & Benson, 1984). Notably, PFC development continues into young adulthood and this delayed maturation is thought to contribute to adults' advanced complex thinking and reasoning skills (Casey et al., 2008; Finn et al., 2016). However, recent theories have emerged suggesting that PFC and EF development may come at a cost to certain aspects of learning, particularly those involving procedural memory processes (Nozari & Thompson-Schill, 2013; Thompson-Schill et al., 2009) including grammatical pattern and sequence learning (Smalle et al., 2017, 2022; Uddén et al., 2008). Indeed, in comparison to children, adults tend to have less success in learning the grammatical components of language including morphology and syntax and are more likely to make grammatical errors in speech (Mayberry & Lock, 2003; Newport, 1990). Accordingly, these invertedly changing linguistic and non-linguistic processes may be interrelated.

To recap, empirical support for this theory comes from transcranial magnetic stimulation (TMS) studies demonstrating that temporary inhibition of PFC regions responsible for mediating EF processes, somewhat counterintuitively, results in improved sequence learning (Ambrus et al., 2020; Galea et al., 2010; Smalle et al., 2017, 2022; Uddén et al., 2008). Statistical learning has also been found to be negatively correlated with functional connectivity in anterior brain regions, with this negative association increasing across learning (Tóth et al., 2017). Moreover, inducing cognitive fatigue prior to sequence learning, and thus dampening reliance on EF processes, has been found to improve sequence learning outcomes (Borragán et al., 2016; Cochran et al., 1999; Smalle et al., 2021, 2022). Notably, this inverse relationship seems to be particularly pronounced when it comes to implicit, but not explicit, knowledge and learning. For instance, engaging in a working memory task weakened explicit learning, but improved implicit category learning (Filoteo et al., 2010). Overall, there is converging evidence to suggest that domain-general cognitive processes such as working memory, attention, and cognitive control directly interfere with optimal procedural learning and processing.

4.1.1 Individual Differences in Language and Sequence Learning

Consistent with the idea of an interference effect, individual differences in EF skills and higher-order processing in general are expected to be associated with variance in implicit language learning abilities. Yet, the literature surrounding individual differences in EF and language learning is quite variable and as such, is not as straightforward to interpret. Some studies have found that select cognitive skills are negatively related to certain aspects of language learning (Galea et al., 2010; Smalle et al., 2017), while others have reported a positive relationship (e.g., Festman et al., 2010), and yet others have found no relationship (e.g., Grey et al., 2015). Select higher-order cognitive processes have been grouped together under the EF "umbrella" for theoretical purposes as they may be interrelated and governed by shared frontal lobe regions (Baggetta & Alexander, 2016; Stuss & Benson, 1984). However, this grouping is slightly problematic as the observed inconsistencies across the literature may be attributed to differential effects that different EF processes (or sub-processes) have on distinct components of learning. For instance, intuitively, inhibitory control is likely to aid language learning by allowing learners to inhibit phonological and grammatical patterns from their first language (L1) when learning novel words or grammatical rules. In contrast, explicit reasoning processes may impede complex grammatical pattern learning, especially amid exceptions and inconsistencies to the rules. Grouping the mechanisms that potentially play opposing facilitatory and interfering roles on sequence learning may therefore cancel out any effects or distort the picture. I next discuss the literature in greater detail, highlighting converging and conflicting evidence.

When assessing EF as a single unit, combined performance on the digit span task, the Wisconsin Card sorting task, and the semantic fluency task negatively correlated with implicit sequence learning as measured by a Hebb repetition task (Smalle et al., 2017). Notably, this negative effect was not found in a group who underwent temporary dorsolateral PFC (DLPFC) disruption prior to completing the sequence learning task. However, there is evidence that domain-general cognitive skills are positively related to language learning and processing in both monolinguals and bilinguals (Festman et al., 2010; Mercier et al., 2014; Pivneva et al., 2012).

Cognitive and inhibitory control are two central EF processes referring to the abilities to regulate thoughts, emotions, goals, and behaviour (Braver, 2012), and supressing automatic responses and prior knowledge (Luque & Morgan-Short, 2021; Miyake et al., 2000). Intuitively, both of these processes should help L2 learners inhibit conflicting patterns and representations from their L1. Accordingly, a number of studies have found a positive relationship between cognitive control and L2 learning skills (e.g., Bartolotti et al., 2011; Kapa & Colombo, 2014; Levy et al., 2007; Linck et al., 2009). Similarly, performance on the Culture Fair Intelligence Test (CFIT, Cattell, 1973), a measure of abstract logical and analytical reasoning skills, positively mediated grammar learning (Brooks et al., 2006; Kempe et al., 2010; Kempe & Brooks, 2008). Performance on the Attention Network Test (ANT) (Fan et al., 2002), a measure of alerting, orienting, and executive control, predicted artificial language learning such that those with better inhibitory control skills (lower ANT scores) were better language learners (Kapa & Colombo, 2014). Conversely, Linck & Weiss (2015) found no relationship between cognitive control and L2 learning. Importantly, it may be the case that distinct tasks necessitate engagement of individual sub-components of cognitive control that may further play differential roles on language learning. For instance, performance on complex cognitive control tasks involving reactive and proactive control significantly predicted proficiency in intermediate L2 learners of Spanish, whereas general cognitive control abilities, as measured by the Flanker task (Eriksen & Eriksen, 1974), did not (Luque & Morgan-Short, 2021).

Various memory processes are also likely to contribute to L2 learning abilities. In line with the theory that explicit memory processes may interfere with implicit grammar learning in adults (Ullman, 2016), declarative recall of a learned sequence was found to be negatively correlated with procedural skill learning on a serial reaction time (SRT) task (Galea et al., 2010). Working memory (WM), referring to the ability to actively hold and manipulate information in mind, is another key memory function critical for language learning and processing (Atkins & Baddeley, 1998; Baddeley, 2003; Miyake et al., 2000). WM is involved in temporarily remembering numbers such as phone numbers, computing mental math, following a set of instructions, or holding onto and manipulating information during reasoning or problem-solving tasks. Related to WM, but more specific to short-term *storage* of linguistic information, is phonological short-term memory (PSTM) (Wagner & Torgesen, 1987), oftentimes measured by nonword repetition tasks. WM and PSTM are thought to play a vital role in both explicit and implicit learning processes as they are required for learning and manipulating words as well as extrapolating grammatical patterns and rules (Baddeley, 2012).

Findings on the relationships between L2 word and grammar learning and PSTM and WM are somewhat variable. For example, some have found that WM was positively related to statistical learning outcomes (Misyak & Christiansen, 2012) and implicit grammatical sequence learning (Kapa & Colombo, 2014; Karpicke & Pisoni, 2004). However, Misyak and Christiansen (2012) reported that performance on the forward digit span task was only positively correlated with statistical learning of adjacent, but not non-adjacent dependencies. Further, Grey et al. (2015) reported no relationship between PSTM (as measured through a nonword repetition task) and morphosyntactic learning. Backward digit span scores have been found to be correlated with L2 reading, production, comprehension skills, and vocabulary (Kormos & Sáfár, 2008). Likewise, performance on a reading span task was associated with incidental grammar learning in both productive and receptive sentence tasks (Robinson, 2002). However, those with a specific working memory impairment were found to have a deficit in explicit word and nonword learning, but not implicit sequence learning (Archibald & Joanisse, 2013). Moreover, PSTM and WM were found to have independent relationships with novel word learning, and WM was more strongly associated with grammar learning than was PSTM (Martin & Ellis, 2012). Likewise, in a meta-analysis, Linck et al. (2014) reported that L2 comprehension and production were only weakly associated with WM measures, but more so than with PSTM, and especially when WM tests included linguistic (e.g., words) rather than non-linguistic stimuli (e.g., numbers).

The literature surrounding the relationship between language learning and general intelligence (e.g., as measured by the intelligence quotient (IQ)) also paints an inconsistent picture. For example, Reber et al. (1991) reported a significant relationship between IQ as measured by the Wechsler Adult Intelligence Scale-Revised (WAIS-R, Wechsler, 1981) and performance on an explicit problem solving task, but not with implicit artificial grammar learning. On the other hand, Robinson (2005) found a negative relationship between IQ and implicit learning. Furthermore, Archibald & Joanisse (2013) reported a positive relationship between nonverbal intelligence and explicit learning of nonwords, but no relation with implicit Hebbian sequence learning. However, it is important to note that IQ tests are not intended to be measures of EF. In fact, only a few EF skills have been found to be correlated with IQ (Ardila et al., 2000; Welsh et al., 1991). Nevertheless, as IQ tests typically assess verbal comprehension, perceptual reasoning, processing speed, and working memory abilities, understanding the relationship between IQ and L2 learning can provide insight into the domain-specificity nature of language learning and processing.

The variability observed across the literature regarding the relationships between language learning and domain-general cognition may be mediated by factors such as the achieved level of language proficiency or amount of experience or time learning the novel language. For example, Morgan-Short et al. (2014) reported that combined performance on the paired associate task and a continuous verbal memory task predicted early but not later grammatical learning. On the other hand, procedural planning efficiency improvement over time (assessed using the Tower of London test (Shallice, 1982)) and the Weather Prediction Task (Knowlton et al., 1994) assessing probabilistic procedural memory, predicted later but not early grammatical learning outcomes. Similarly, Hamrick (2015) reported inverse relationships between explicit and implicit memory systems on performance on immediate versus delayed language recognition tasks. Specifically, performance on the paired associate task, a measure of explicit memory skills, predicted performance only on immediate, but not delayed recognition of language. In contrast, a modified SRT task predicted delayed, but not immediate language performance. Thus, declarative memory may play a bigger role in early language recall, whereas long-term consolidation and recall may be more dependent on procedural memory processes.

Overall, this broad body of literature presents conflicting evidence regarding whether EF and general cognition aid, interfere, or have no relationship with language learning. Inconsistencies are observed even within sub-components of EF such as cognitive control or working memory skills. Measures of these functions may be affected by task-related differences as well as other factors such as experimental design (e.g., delay of measurement after learning) or language proficiency achieved. Likewise, as language learning is an intricate process, the variability observed across the literature may arise from inherent differences in the artificial languages and tasks used to measure the learning outcomes.

4.1.2 The Present Study

As it is difficult to draw conclusions across multiple studies using various language learning models and tasks, the goal of this study was to explore the relationships between domain-general cognitive functions and distinct aspects of language learning. Specifically, given the uncertainty surrounding the relationship between domain-general cognition and language learning abilities, I pose the research question: *Are individual differences in select higher-order cognitive abilities associated with implicit 1) novel word learning, and 2) grammatical generalization outcomes*? To address this question, I used a subset of validated (Hampshire et al., 2012; Honarmand et al., 2019; Sternin et al., 2019) cognitive tasks from the Creyos Online Cognitive Assessment Platform (creyos.com), an online tool targeting short-term and working memory, attention, inhibition, grammatical and deductive reasoning, strategic thinking, and planning skills. I then examined whether performance on these tasks were related to performance on a modified statistical language learning task. As further described in the following methods section, the statistical learning paradigm was adapted from Chapter 3, this time, using only one language version for all participants, and the exposure protocol from the passive learning group. As a brief recap, participants passively listened to a speech stream of novel syllables which followed phonologically-defined grammatical patterns. Language learning was assessed using speeded syllable detection tasks targeting implicit recall of words and grammatical patterns. Support for the interference hypothesis would emerge as negative relationships between grammar learning outcomes and select cognitive processes such as explicit memory, deductive reasoning, strategy, and planning skills, with the intuition that increased performance in these processes may interfere with optimal procedural sequence learning.

4.2 Methods

4.2.1 Participants

Participants were recruited through the Prolific online recruitment platform (www.prolific.co). Participants were required to be 18 years of age or older, native monolingual English speakers, with the absence of any diagnosed learning or neurological impairments, and with normal hearing and normal or corrected-to-normal vision. These criteria were set using Prolific's demographic filters and verified through a demographic and language background questionnaire (Appendix C). One hundred and seventeen participants completed the study. Of these, seventeen participants were excluded for the following reasons: missing over 35% of test trial responses (14), reporting high proficiency in a language other than English (1), and experiencing technical difficulties (2). Recruitment was continuous until an a-priori target sample of 100 participants was met. This final sample ranged in ages 19-71 (M = 39.5, SD = 14.07). Forty-seven participants self-identified as female, 52 as male, and one as non-binary. All study procedures were approved by the University of Western Ontario Non-Medical Research Ethics Board (Appendix D).

4.2.2 Procedure

Both the cognitive test battery and statistical language learning task were completed online. After signing up for the study through Prolific, participants read a letter of information, provided informed consent, and completed a general demographics and language history questionnaire (Appendix C) through the Qualtrics survey platform. Each participant was then directed to a custom auto-registered link to complete an online cognitive test battery (Creyos Research, https://creyos.com). Instructions and practice trials were provided prior to each task. Upon completing the cognitive test battery, participants were directed to the language learning experiment through the Pavlovia online experiment platform (https://pavlovia.org). The language learning experiment consisted of an audio check, target detection practice trials, a three-minute baseline target detection task, an eight-minute language exposure phase, and a test phase comprised of two 10-minute target detection tasks. Optional breaks were provided between each phase.

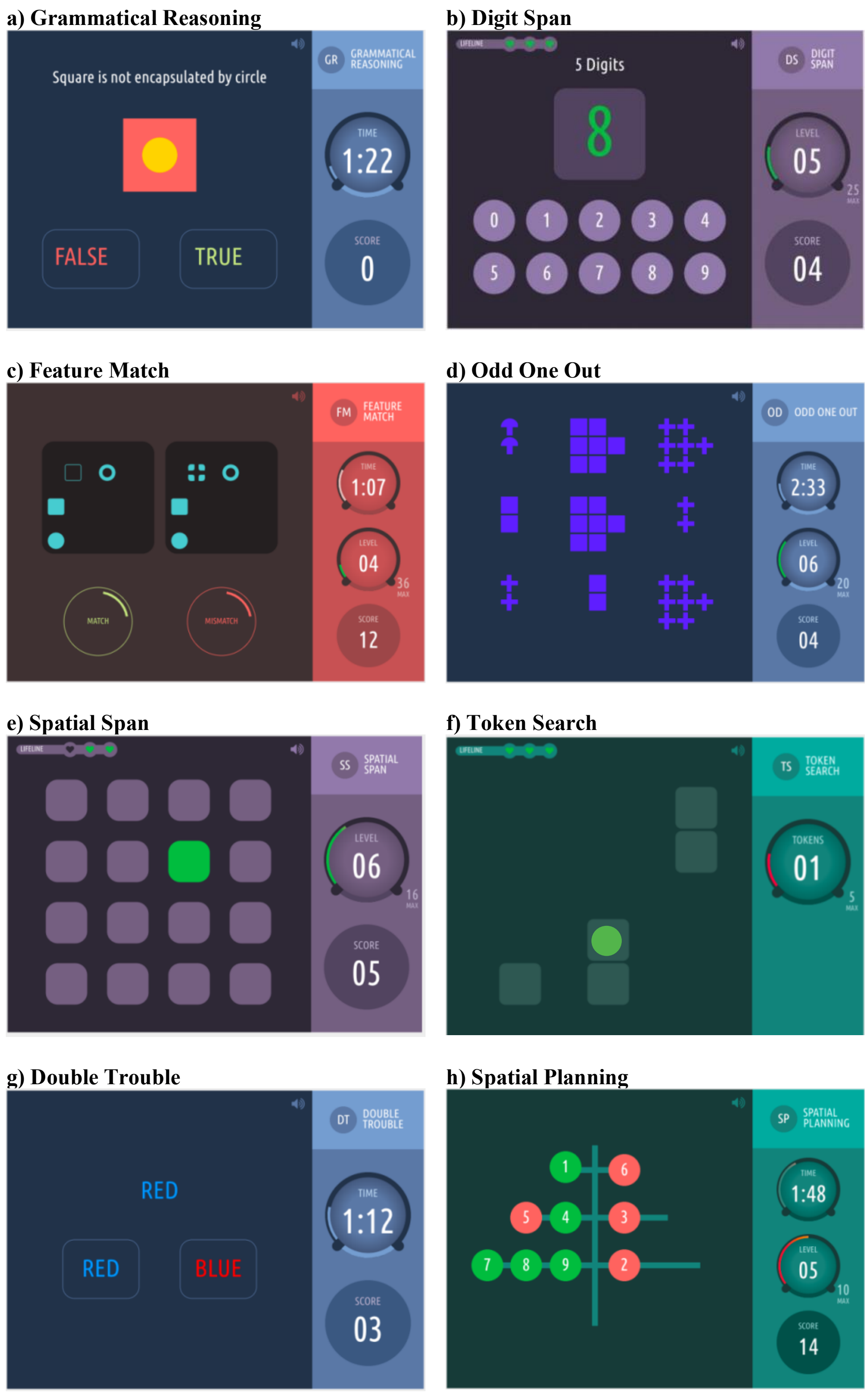
4.2.3 Stimuli

4.2.3.1 Cognitive Test Battery

Participants completed a customized subset of Creyos tasks comprised of the following eight cognitive tests in the following fixed order: Grammatical Reasoning, Digit Span, Feature Match, Odd One Out, Spatial Span, Token Search, Double Trouble, and Spatial Planning. As further described below, these tasks are short computer tests designed to assess a variety of cognitive abilities including verbal skills, short term and working memory, attention, planning, and reasoning / decision-making. Each task began with written instructions and two or three practice rounds with feedback provided. Figure 4.1 illustrates example trials for each task.

Figure 4.1

Cognitive Battery Task Example Trials



The Grammatical Reasoning task was designed to measure verbal reasoning ability and was adapted from Baddeley's three minute grammatical reasoning task (Baddeley, 1968). Each trial consisted of two overlapping shapes presented on the screen with a short sentence describing the relationship between the shapes written above the figures (see Figure 4.1a). Participants were required to make true or false decisions regarding whether the statement was an accurate description of the shapes. Feedback was provided following each trial response with either a green checkmark or red X appearing on the screen. Participants were given 90 seconds to complete as many trials as possible. A countdown clock along with the participants' score for that task were visible on the screen throughout the task. The final score was measured as the number of trials answered correctly subtracted by the number answered incorrectly.

The Digit Span task was designed to measure short-term memory and was adapted from the verbal working memory task from the WAIS-R test (Wechsler, 1981). Each trial displayed a box with single digits presented one after the other. The digits 0 to 9 were displayed under the box (see Figure 4.1b). Following sequence presentation, participants used their mouse to click on the digits under the box in the same order as the sequence shown. The first trial consisted of a 4-digit sequence. Following either a correct or incorrect sequence repetition response, the difficulty of the next trial either increased or decreased by one number, respectively. The task ended once three incorrect responses were made. The number of incorrect responses made was presented on the top of the screen, along with the current level, and the highest level reached. The final score was calculated as the average level completed.

The Feature Match task was designed to measure attention and was adapted from Treisman and Gelade's (1980) feature search task. Each trial depicted two squares appearing side by side containing filled-in and hollow shapes presented in various arrangements (see Figure 4.1c). Half the trials included identical arrangements while the other half differed by a single shape. Using a mouse response, participants made match versus mismatch decisions regarding whether the two boxes were identical. The first trial began with three shapes in each box. The difficulty of the following trial increased in difficulty by one shape following a correct response and decreased in difficulty following an incorrect response. Participants were given 90 seconds to complete as many trials while minimizing as many errors as possible. A countdown clock along with the current level and the participant's updated score for that task were visible on the screen throughout the task. The score was calculated as the difference between the sum of the difficulties of correct response trials minus the sum of the difficulties of incorrect response trials. Difficulty was determined based on the number of shapes in the grid. Thus, following each trial, the score increased or decreased proportionately to the number of shapes present for that level.

The Odd One Out task was designed to measure deductive reasoning skills and was adapted from a subset of the Culture Fair Intelligence Task (CFIT, Cattell, 1973). Each trial consisted of nine patterns with the following features: types of shapes, colours of shapes, and number of shapes (see Figure 4.1d). The patterns were related to each other based on various rules pertaining to the three features, with one of the nine patterns not following the rules. Participants' task was to click on the pattern that did not belong. Feedback was provided following each trial response with either a green checkmark or red X appearing on the screen. The difficulty of the following trial either increased or decreased following a correct or incorrect response, respectively. Participants were given three minutes to complete as many trials while trying to make as few errors as possible. A countdown clock, along with the current level and updated score for that task, were presented on the screen throughout the task. The score was calculated as the difference between the number of correct response trials completed and the number of incorrect responses.

The Spatial Span task was designed to measure spatial short-term memory and was adapted from the Corsi Block Tapping Task (Corsi, 1972). Sixteen squares were displayed on the screen in a 4x4 arrangement. A sequence of squares then flashed green in a random order (see figure 4.1e). Following sequence presentation, participants clicked on the squares in the order of the sequence shown. The task began with a 4-square sequence trial, and trial difficulties increased or decreased in difficulty following a correct or incorrect sequence repetition response, respectively. The task ended once three incorrect responses were made. The number of incorrect responses made was presented on the top of the screen along with the current level and the highest level reached. The final score was the average level correctly completed, calculated as the number of the difficulty of trials correctly completed, divided by the numbers of levels completed.

The Token Search task was based on a strategic search behaviour task (Collins et al., 1998) designed to measure visual working memory. Each trial consisted of a random arrangement of squares presented on the screen with one green circle "token" hidden in one square at a time (see Figure 4.1f). For each round within a trial, participants' task was to click on the boxes one at a time until they found the token without clicking on the same square twice within a trial. Once a token was found, it was then hidden in another square that did not previously contain a token in that trial. Participants must then continue searching for the token while avoiding squares in which tokens were already found. The trial ended once the tokens have been found in each square, or once an error was made (either clicking on the same square twice within a round or clicking on a square that previously contained a token within that trial). The subsequent trial's difficulty either increased or decreased by one square depending on whether an error was made. The task ended once three errors were made. The number of errors made was presented on the screen along with the highest level reached. The final score was calculated as the average level successfully completed.

The Double Trouble task is a variant of the Stroop Task (Stroop, 1935) designed to measure attention and response inhibition. For each trial, three words spelling out "RED" or "BLUE" were written in red or blue ink colours, although not necessarily written in the same colour ink that they spelled. The word on the top of the screen acted as the target with two descriptor words below it (see Figure 4.1g). Participants' task was to click on one of the two descriptor words that described the colour that the target word was written in. There were three possible word-colour mappings: 1) Congruent (all words were written in the colour they spelled out), 2) incongruent (the target word was written in a different colour than it spelled, whereas the descriptor words were written in the same colour they spelled), and 3) double-incongruent (none of the words were written in the colours they spelled out). Participants must therefore match the correct descriptor word to the target ink colour while both ignoring the spelling of the target word and the ink colours of the descriptor words. Participants were given 90 seconds to complete as many trials while making as few errors as possible. A countdown clock along with an updated score were presented on the screen throughout the task. The score was calculated as the difference between the number of correct and incorrect responses.

The Spatial Planning task was adapted from the Tower of London Task (Shallice, 1982) designed to measure reasoning and efficient planning skills, with numbers as opposed to colours in this version. Each trial consists of a tree-shaped figure containing numbered circles (see Figure 4.1h). In as few moves as possible, participants' task was to arrange the circles in numerical order. The difficulty of each subsequent trial was increased upon successful completion of each trial. Participants were given three minutes to solve as many problems in as few moves as possible. If a participant made more than twice the number of moves required to solve the problem, the trial was aborted and a new trial of the same difficulty was restarted. Moves made in aborted trials did not count towards the final score. A countdown clock along with the current level and updated score for that task were presented on the screen. The final score was calculated as the total number of moves made subtracted from twice the minimum number of moves required for all completed trials.

4.2.3.2 Statistical Learning Stimuli

Following completion of the cognitive test battery, participants completed a statistical language learning task adapted from the study detailed in Chapter 3. All participants were exposed to the same language (from Chapter 3, Language Version 2) to ensure individual differences did not emerge as a result of inherent differences in the language, although it was established in Chapter 3 that learning effects were robust irrespective of the language version being learned (see Appendix E). Likewise, all participants completed the task under the same learning condition, equivalent to the passive learning group protocol described in Chapter 3. To recap, the artificial language consisted of disyllabic nonsense words that followed English phonotactic constraints. The words belonged to three phonologically-defined categories (A, B, or C) differing on the pattern of vowels (V) and consonants (C) of the second syllable (C-V, V-C, or C-V-C), and presented in a predefined grammatical order: Category A → Category B → Category C → repeat. Therefore, the transitional probability (TP) between syllables within-words was 1.0 whereas the between-word TP was 0.5, and the between-category TP was 1.0. Table 4.1 depicts the exposed words from the artificial language. Each syllable was generated using Google Cloud's Text-To-Speech Application Programming Interface (API) using a female American accent. In a given speech stream, syllables were divided by 40 ms silent gaps with no acoustic cues between word boundaries. The mean syllable length was 346 ms.

Table 4.1

The Artificial Language

Category A			Category B			Category C		
C-V	-	C-V	C-V	-	V-C	C-V	-	C-V-C
d-eh /dɛ /	-	k-aw /kɑ /	z-ay /zeɪ/	-	oo-b /ub/	s-eh /sɛ/	-	r-oi-t /ɹɔɪt/
n-ay /neɪ/	-	r-oo /ɹu/	f-aw /fɑ/	-	ay-n /eɪn/	g-uh /gʌ/	-	p-ee-f /pif/

Note. Phonetic pronunciation is presented in International Phonetic Alphabet (IPA) notation beneath each syllable.

4.2.3.2.1 Baseline Test Phase. Participants first completed 30 target detection trials measuring baseline reaction times (RT) to unpredictable syllables (see Table 4.2). Syllables from the baseline target detection test were not used in the rest of the experiment but were composed of the same consonant-vowel combinations from the artificial language, presented in a randomized order ensuring equal predictability between all syllables. Trials varied between 7 to 11 syllables in length, with the target appearing in five possible positions with at least three filler syllables appearing prior to the target.

Table 4.2

Syllables Used in Baseline Target Detection Task

Phonological Structure	Target Syllable	IPA
C-V	loy	/lɔɪ/
	feh	/fɛ/
	tauw	/taʊ/
	ruh	/rʌ/
V-C	eeb	/ib/
	auwf	/aʊf/
	oov	/uv/
	ayb	/eɪb/
C-V-C	meep	/mip/
	nuk	/nʌk/
	layf	/leɪf/
	reg	/rɛg/

4.2.3.2.2 Statistical Learning Exposure Phase. Following the baseline target detection phase, participants were exposed to an eight minute speech stream presented through computer speakers or headphones. The exposure stream was composed of six words presented in Category A, B, and C triplets, each presented 100 times. A→B→C sequences were counterbalanced to ensure the same sequence was never presented twice in a row. Figure 4.2 depicts a short example of the exposure speech stream. No information about the language was provided prior to the exposure phase. To replicate incidental learning conditions during language exposure but in an online setting, participants completed a simple irrelevant visual detection task (pressing a key upon seeing a circle appear on the screen amid other distractor shapes) while listening to the language sounds in the background.

Figure 4.2

Example of Exposure Speech Stream Segment

dehkawzayoobsehroitnayroozayoobguhpeef…

A B C A B C

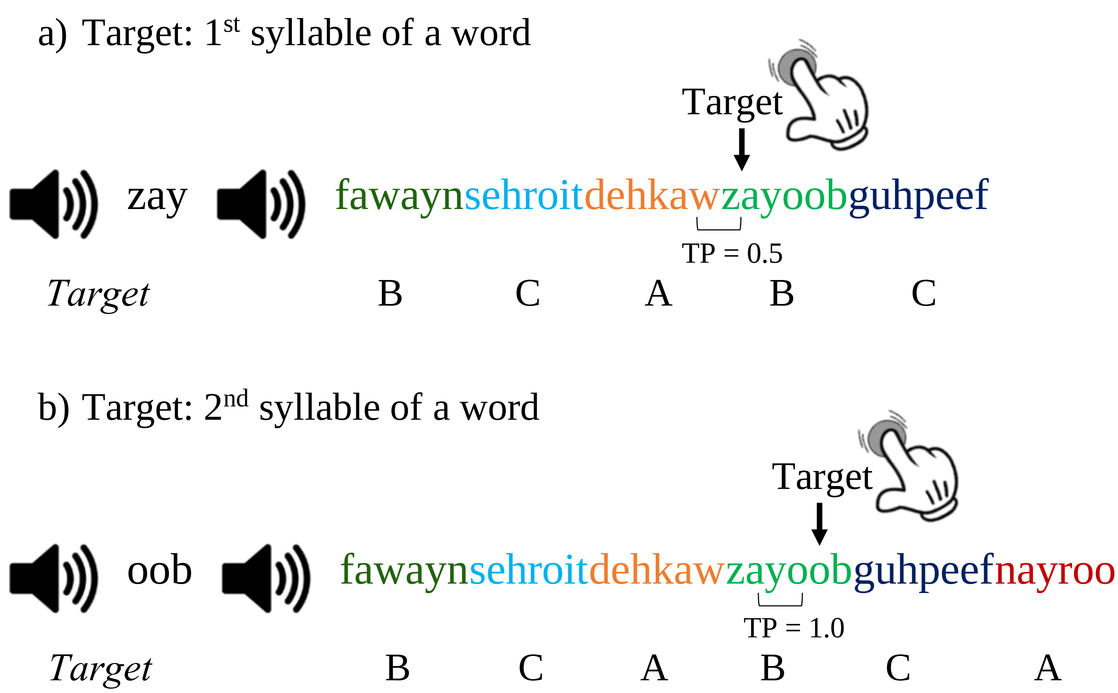
4.2.3.2.3 Statistical Learning Test Phase. Following the eight-minute exposure stream, participants completed two target detection tasks, the first with familiar syllables, and the second with unfamiliar syllables, aimed to assess word segmentation and grammar generalization, respectively.

Testing Word Segmentation via Target Detection of Familiar Syllables. The first target detection task consisted of listening for a target syllable embedded within fragments of the exposure phase speech stream. This task was originally adapted from Batterink et al. (2015), which compared RT to target syllables varying in TP predictability. Participants completed 60 target detection trials with two possible target conditions: 1st syllable versus 2nd syllable of a word. Each syllable appeared as the target five times, varying in five possible positions within the trial. The trials began with any of the 12 words, and therefore a trial did not necessarily begin with a Category-A word.

Trial order was randomized across participants. RT for each trial was measured from the onset of the target syllable presentation. Figure 4.3 illustrates an example of the target detection trials for each target condition.

Figure 4.3

Examples of Familiar Target Detection Trials Measuring Word Segmentation



Note. Examples of target detection trials with a a) first-syllable target (e.g., “zay”, TP with preceding syllable = 0.5) and b) second-syllable target (e.g., “ook”, TP with preceding syllable = 1.0). Participants first heard the target syllable in isolation before being presented with a short speech stream consisting of words from the familiarization phase presented in grammatical order, 10 to 20 syllables in duration. As quickly and accurately as possible, participants were required to make a key response upon hearing the target syllable in the speech stream.

Testing Grammar Generalization via Target Detection of Unfamiliar Syllables*.** The second target detection task assessed grammar generalization by testing target detection of unfamiliar syllables that were not previously exposed in the experiment but were composed of the same phonological compositions and grammatical patterns as the exposed language (see Table 4.3). This time, the target was always the second syllable of a Category B or Category C word but varied in whether the word containing the target appeared in a legal (grammatical) position (e.g., …A → B → ***C*target*…) or an illegal (ungrammatical) position (e.g., …A → ***C****target* → B…). Category A targets were not included since their second syllables share the same composition (C-V) as first syllables and are thus not uniquely predictable the way that Category B and C second syllables are. 10 different target syllables were included, each appearing in three legal and three illegal positions within the stream (60 trials total). Trial order was randomized across participants. Figure 4.4 illustrates examples of the unfamiliar target detection trials for each target condition.

Table 4.3

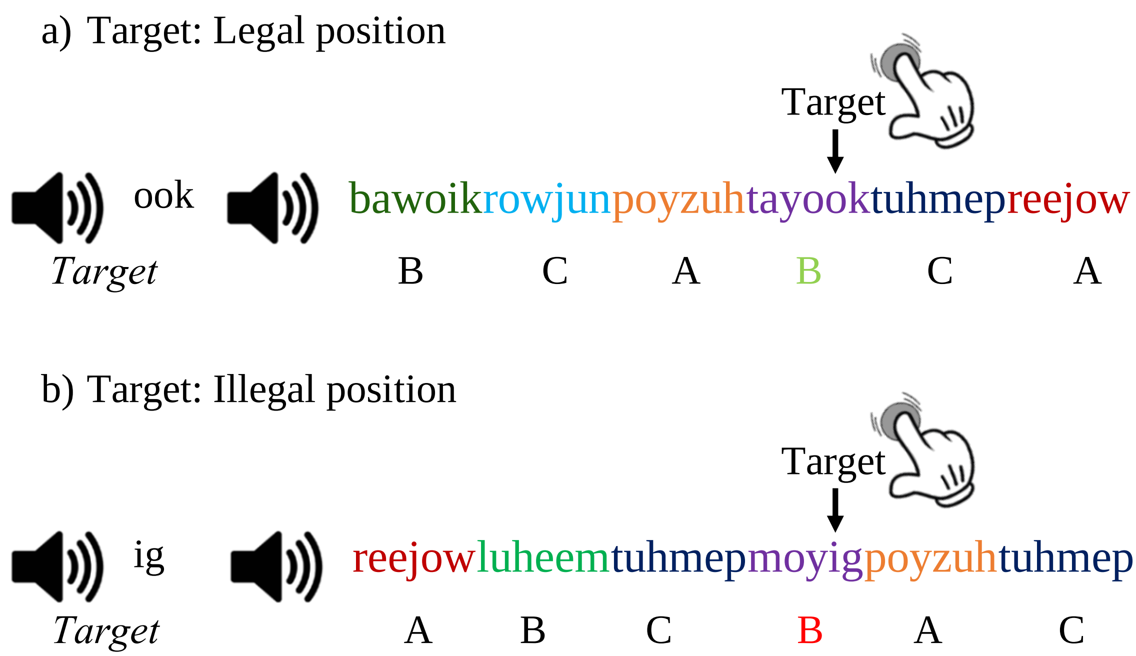
Unfamiliar Syllables Used in the Grammar Generalization Target Detection Task

	Category A			Category B			Category C		
	C-V	-	C-V	C-V	-	V-C	C-V	-	C-V-C
Fillers	p-oy /pɔɪ/	-	z-uh /zʌ/	l-uh /lʌ/	-	ee-m /im/	r-ow /ɹaʊ/	-	j-u-n /ʤʌn/
	r-ee /ɹi/	-	j-ow /ʤaʊ/	b-aw /bɑ/	-	oi-k /ɔɪk/	t-uh /tʌ/	-	m-e-p /mɛp/
Words containing second-syllable targets				t-ay /teɪ/	-	oo-k* /uk/	l-ee /li/	-	g-e-f* /gɛf/
				s-ow /saʊ/	-	o-b* /ɑb/	v-ay /veɪ/	-	n-i-v* /nɪv/
				m-oy /mɔɪ/	-	i-g* /ɪg/	f-oo /fu/	-	b-u-p* /bʌp/
				p-uh /pʌ/	-	eh-t* /ɛt/	z-oy /zɔɪ/	-	l-aw-m* /lɑm/
				v-aw /vɑ/	-	au-d* /aʊd/	d-ee /di/	-	k-oo-t* /kut/

Note. * = target syllable. The unfamiliar target detection task was comprised of 32 novel syllables. 20 syllables contained a 2nd syllable target*, and the remaining 12 syllables acted as fillers. Words containing target syllables never acted as fillers. Phonetic pronunciation is presented in IPA notation beneath each syllable.

Figure 4.4

Examples of Unfamiliar Target Detection Trials Measuring Grammar Generalization



Note. Like the familiar target detection task, participants heard the target syllable in isolation followed by a short speech stream containing the target, this time, composed of novel syllables not from the exposure phase. The targets varied in positions 8, 10, 12, 14, 16, or 18 within the trial, with the same target never appearing in the same position twice. a) Example of a target detection trial with the target in a legal position (e.g., Category B "ook" following a Category A word). b) Example of a target detection trial with the target in an illegal position (e.g., Category B "ig" following a Category C word).

4.2.4 Data Analyses

4.2.4.1 Statistical Learning

Only responses following target presentations were included in analyses. Subject-wise mean RTs were calculated for each target condition (familiar 1st syllable, familiar second syllable, unfamiliar illegal position, unfamiliar legal position). Responses over 2.5 SD from subject-wise means per condition were marked as outliers and removed from analyses. Two-tailed paired t-tests were conducted between target conditions for familiar trials (1st vs. 2nd syllable position) and unfamiliar trials (legal vs. illegal target position) separately. Analyses were performed using MATLAB (v.R2021b; The MathWorks Inc., 2021) and plots were created using R Statistical Software (packages: dplyr, ggplot2, ggsignif, psych, readxl, tidyr; Ahlmann-Eltze & Patil, 2021; R Core Team, 2022; Revelle, 2020; Wickham, 2016, 2020; Wickham et al., 2020; Wickham & Bryan, 2023).

4.2.4.2 Correlations Between Cognitive Test Battery and Statistical Learning

To normalize data and account for variance in baseline RT across participants, following Batterink and Paller (2019), subject-wise priming effects were computed for each target detection task, calculated as the RT difference between target condition means divided by the mean RT of the less predictable condition (familiar priming effect = $(RT_{S1} – RT_{S2}) / RT_{S1}$; unfamiliar priming effect = $(RT_{Illegal} – RT_{Legal}) / RT_{Illegal}$). Task scores for each cognitive test were automatically computed and provided by Creyos. Scores for the untimed memory tests (Digit Span, Spatial Span, Token Search) were calculated as the average difficulty level correctly completed. Scores for the timed tests (Grammatical Reasoning, Odd One Out, and Double Trouble tasks) were calculated as the difference between correct and incorrect responses, with the exceptions of the Feature Match score, which was calculated as the difference in the sum of the difficulties between successful and unsuccessful trials, and the Spatial Planning score, which was incrementally added per trial, calculated as the number of moves required to complete the trial multiplied by two, subtracted by the number of moves made. Pearson correlations were performed between each cognitive task score with each RT priming effect (familiar priming effect, and unfamiliar priming effect). Cases with incomplete observations were excluded pairwise. All correlations and plots were executed using R Statistical Software (v.4.2.2 R Core Team, 2022; packages: ggplot2, readxl; Wickham, 2016; Wickham & Bryan, 2023).

4.2.4.3 Exploratory Analyses

Exploratory Pearson correlations were conducted to examine the relationships between the following variables: priming effects of familiar and unfamiliar targets, intercorrelations between all cognitive tasks, age and all cognitive scores, and age and statistical learning priming effects. Independent t-tests were conducted to explore gender differences between all the tasks.

4.3 Results

4.3.1 Cognitive Test Performance

Table 4.4 provides descriptive statistics of the scores for each of the eight Creyos tasks in the cognitive test battery. 1.75% of the scores were excluded from analyses after being flagged as “invalid” by Creyos’ Validity Indicator (see Appendix F), signifying unusual performance related to the number of attempts, scores, errors made, or time taken to complete the task.

Table 4.4

Descriptive Statistics of Raw Creyos Scores

	valid (n)	*M*	*SD*	min.	max.
Grammatical Reasoning	99	19.41	5.97	6.00	34.00
Digit Span	98	5.59	0.84	3.70	8.10
Feature Match	99	117.89	32.22	50.00	210.00
Odd One Out	98	9.31	3.75	-3.00	18.00
Spatial Span	100	4.89	0.66	3.00	6.30
Token Search	100	6.05	0.87	3.00	8.00
Double Trouble	95	23.17	17.13	-5.00	61.00
Spatial Planning	97	21.94	10.91	4.00	56.00

4.3.2 Statistical Learning Target Detection Performance

4.3.2.1 Familiar Target Detection Task Assessing Word Segmentation

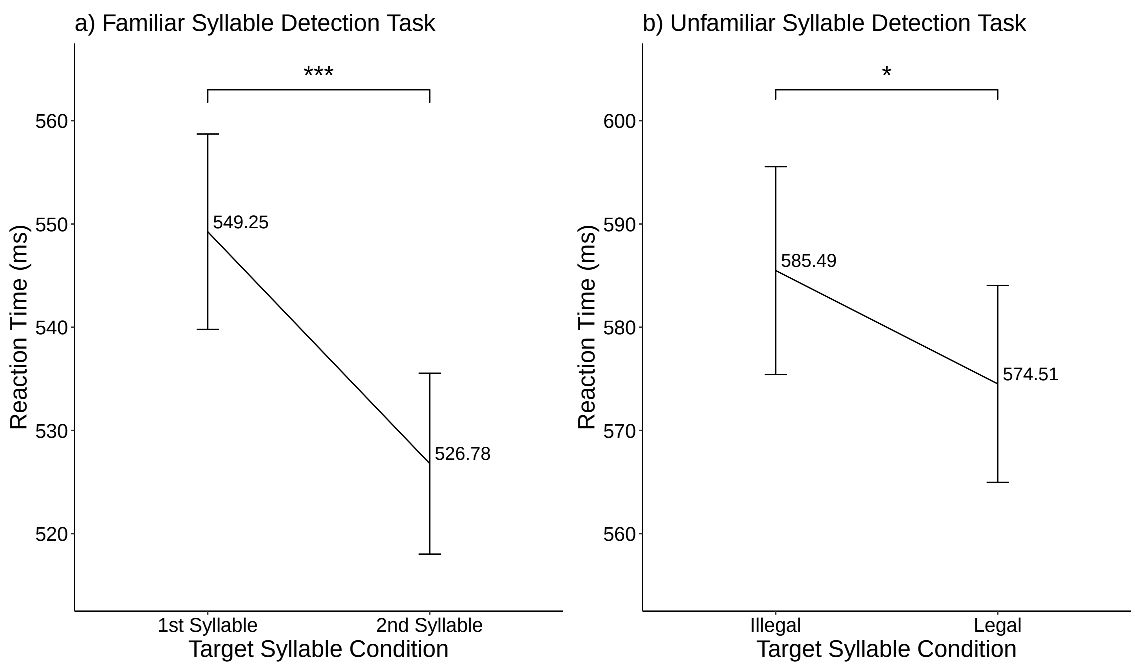
On average, participants detected 82.9% of first-syllable targets and 85.93% of second-syllable targets for the familiar target detection task. As illustrated in Figure 4.5a, a paired t-test revealed a significant difference in RT between target conditions ($t(99) = 5.00$, $p < .001$, $d = .50$), with participants exhibiting faster RT for second-syllable than first-syllable targets, with a medium effect size. These findings indicate that participants successfully learned to segment the exposed words based on differences in transitional probabilities (TP) of syllables within (1.0) versus between (0.5) words.

4.3.2.2 Unfamiliar Target Detection Task Assessing Grammar Generalization

On average, participants detected 87.53% of illegal targets and 86.1% of legal targets for the unfamiliar target detection task. As illustrated in Figure 4.5b, a paired t-test revealed a significant difference in RT between target conditions ($t(99) = 2.59$, $p = .011$, *d* = .259), with faster RT for targets in legal compared to illegal positions, demonstrating successful learning and generalization of grammatical categories and order presentation.

Figure 4.5

Reaction Time Differences Between Target Conditions for Familiar and Unfamiliar Target Detection Tasks



* p < .05, *** p < .001.

Note. Reaction Time differences between a) first- vs. second-syllable familiar targets (word segmentation), and b) illegal vs. legal unfamiliar targets (grammar generalization).

4.3.3 Correlations Between Statistical Learning and Cognitive Tests

Pearson correlations were completed to determine the relationships between each statistical learning measure (familiar and unfamiliar target detection tasks) and cognitive task. Accounting for multiple comparisons for each of the statistical learning analyses, a Benjamini-Hochberg procedure was used to control for the false discovery rate of 0.05. As displayed in Table 4.5 and Figure 4.6, there were no significant correlations between any of the cognitive tasks with either the familiar or unfamiliar statistical learning priming effects. Similar results were found when conducting the correlation analyses using raw RT difference means between target conditions (see Appendix G). Thus, contrary to predictions, statistical learning success of both words and grammatical patterns were not associated with performance in domain-general cognitive measures such as short-term memory, attention, inhibition, or reasoning abilities.

Table 4.5

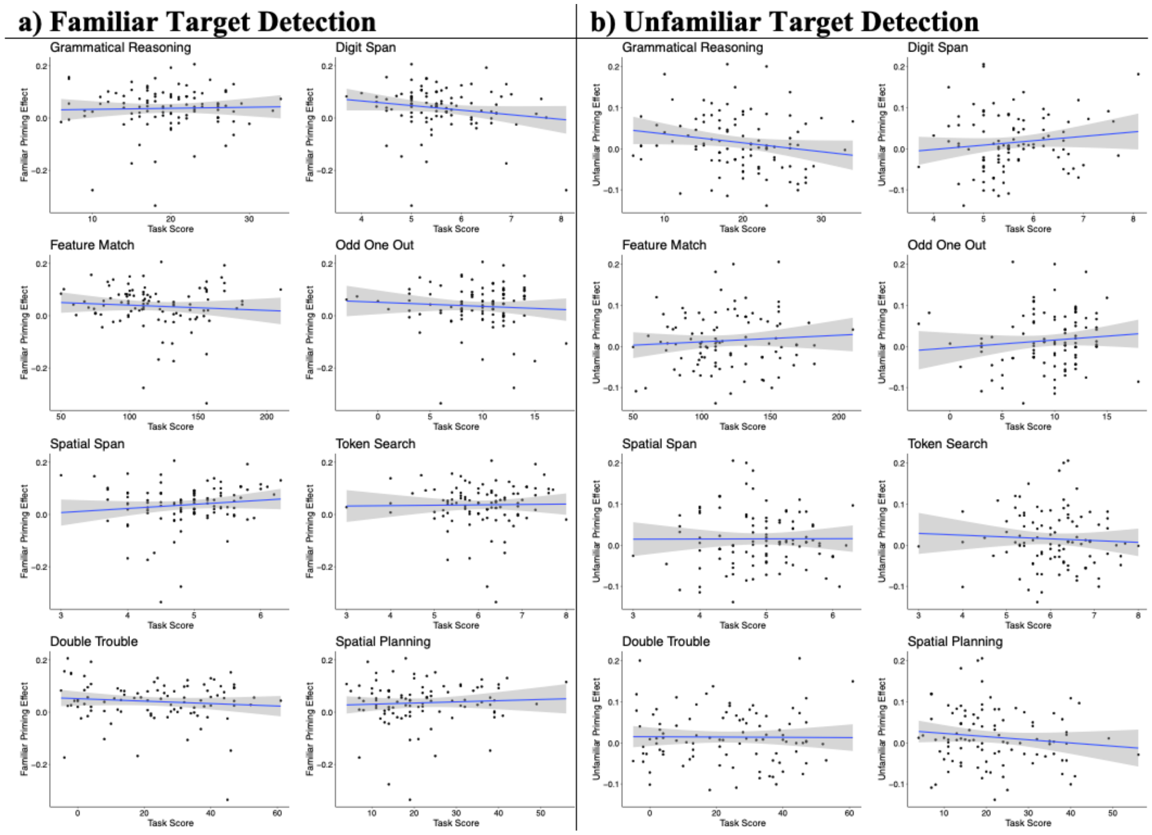
Correlations Between Statistical Learning of Words (Familiar Priming Effect) and Grammatical Patterns (Unfamiliar Priming Effect) with Cognitive Test Performance

Priming Effect		Grammatical Reasoning	Digit Span	Feature Match	Odd One Out	Spatial Span	Token Search	Double Trouble	Spatial Planning
Familiar	*r*	.03	-.18	-.08	-.07	.13	.02	-.10	.06
	p	.773	.084	.447	.494	.216	.878	.323	.568
	p (FDR)	.878	.672	.757	.757	.757	.878	.757	.757
Unfamiliar	*r*	-.19	.13	.08	.11	.004	-.06	.01	-.13
	p	.062	.203	.445	.301	.971	.582	.928	.223
	p (FDR)	.496	.595	.712	.602	.971	.776	.971	.595

Note. FDR = Benjamini-Hochberg False Discovery Rate adjustment.

Figure 4.6

Linear Relationships Between Statistical Learning Tasks and Cognitive Tasks



Note. Scatter plots with linear model trend lines depicting relationships between Creyos cognitive task performance and statistical learning priming effects of a) word segmentation, as measured through familiar target detection, and b) grammar generalization, as measured through unfamiliar target detection.

4.3.4 Exploratory Analyses

4.3.4.1 Inter-Task Correlations

Exploratory Pearson correlations were conducted to explore the relationships between the individual cognitive test battery tasks, as well as between the two statistical learning measures. As depicted in Table 4.6, performance on most of the tasks were significantly positively correlated with one another, with the exceptions of Digit Span, which was not significantly correlated with any other task, and Odd One Out, which was only significantly correlated with Token Search and Grammatical Reasoning. Interestingly, in terms of the two statistical learning measures, performance on the familiar and unfamiliar target detection tasks were not significantly correlated with one another $r(98) = -16$, $p = .110$, suggesting that statistical learning of word segmentation and grammar generalization may involve distinct processes or be constrained by domain-specific learning mechanisms.

Table 4.6

Correlation Matrix of Creyos Cognitive Tasks

Task		1	2	3	4	5	6	7
1. Grammatical	*r*	—						
Reasoning	*p*	—						
2. Digit Span	*r*	.197	—					
	p	.053	—					
3. Feature	*r*	.310**	.062	—				
Match	*p*	.002	.547	—				
4. Odd One Out	*r*	.226*	.101	.114	—			
	p	.026	.328	.263	—			
5. Spatial Span	*r*	.275**	.122	.311**	.109	—		
	p	.006	.233	.002	.287	—		
6. Token Search	*r*	.288**	.140	.326***	.266**	.420***	—	
	p	.004	.169	<.001	.008	<.001	—	
7. Double	*r*	.346***	.148	.374***	.044	.361***	.238*	—
Trouble	*p*	<.001	.156	<.001	.672	<.001	.020	—
8. Spatial	*r*	.410***	-.024	.340***	.057	.459***	.317**	.326**
Planning	*p*	<.001	.816	<.001	.581	<.001	.002	.002

* p < .05. ** p < .01. *** p < .001.

A further exploratory analysis was conducted to assess whether average RT across all target detection tasks and conditions were associated with any of the cognitive measures. Note that the average RT across all conditions is not a measure of language or sequence learning, but rather, more representative of a domain-general process reflecting processing speed and attention. Overall mean RT was calculated across the baseline task and both target conditions from each of the familiar and unfamiliar target detection tests. As depicted in Table 4.7, Pearson correlations revealed a significant correlation between mean RT and performance on the Digit Span task, such that higher digit spans were associated with faster RT. Likewise, baseline RT was significantly negatively correlated with performance on the digit span task ($r(96) = -.27$, $p = .008$).

Table 4.7

Pearson Correlations Between Performance on Each Cognitive Task and Mean Target Detection RT

Task	n	*r*	*p*
Grammatical Reasoning	99	-.09	.402
Digit Span	98	-.28**	.006
Feature Match	99	-.03	.743
Odd One Out	98	-.01	.916
Spatial Span	100	.01	.919
Token Search	100	.01	.957
Double Trouble	95	-.08	.416
Spatial Planning	97	-.08	.466

* p < .05. ** p < .01. *** p < .001.

Note. Correlations are displayed pairwise. Mean Target Detection RT was calculated as the average RT across all target detection trials including all conditions from the familiar and unfamiliar target detection tasks and the baseline target detection task.

4.3.4.2 Age and Gender Effects

A further exploratory Pearson correlation analysis was conducted to explore the relationship between age and performance on each cognitive and statistical learning task. As depicted in Table 4.8, age was significantly negatively correlated with over half of the cognitive tasks (Grammatical Reasoning, Feature Match, Spatial Span, Double Trouble, and Spatial Planning). Interestingly, age was not significantly correlated with either statistical learning of words or grammar, but the non-significant relations were reversed such that age had a positive non-significant relationship with performance on the familiar target detection task, but a negative non-significant relationship with the unfamiliar target detection task. Likewise, age was not significantly correlated with overall mean RT across all target detection conditions. Independent t-tests between self-identified male and female genders on all tasks revealed no effect of gender on any cognitive task or statistical learning measure (see Table 4.9).

Figure 4.7 provides a visual summary of all of the correlations in the present study, as depicted by a heatmap matrix of all continuous variables, including age, cognitive task scores, performance on each target detection condition across all tasks, statistical learning priming effects, baseline RT, and overall mean RT.

Table 4.8

Pearson Correlations Between Age and All Tasks

Task	**n**	**Pearson's *r***	***p***
Grammatical Reasoning	99	-.27**	.007
Digit Span	98	.04	.664
Feature Match	99	-.40***	<.001
Odd One Out	98	-.11	.301
Spatial Span	100	-.30**	.003
Token Search	100	-.14	.155
Double Trouble	95	-.33**	.001
Spatial Planning	97	-.44***	<.001
Familiar Priming Effect	100	.15	.126
Unfamiliar Priming Effect	100	-.12	.249
Mean Target Detection RT	100	.12	.240

* $p < .05$. ** $p < .01$. *** $p < .001$.

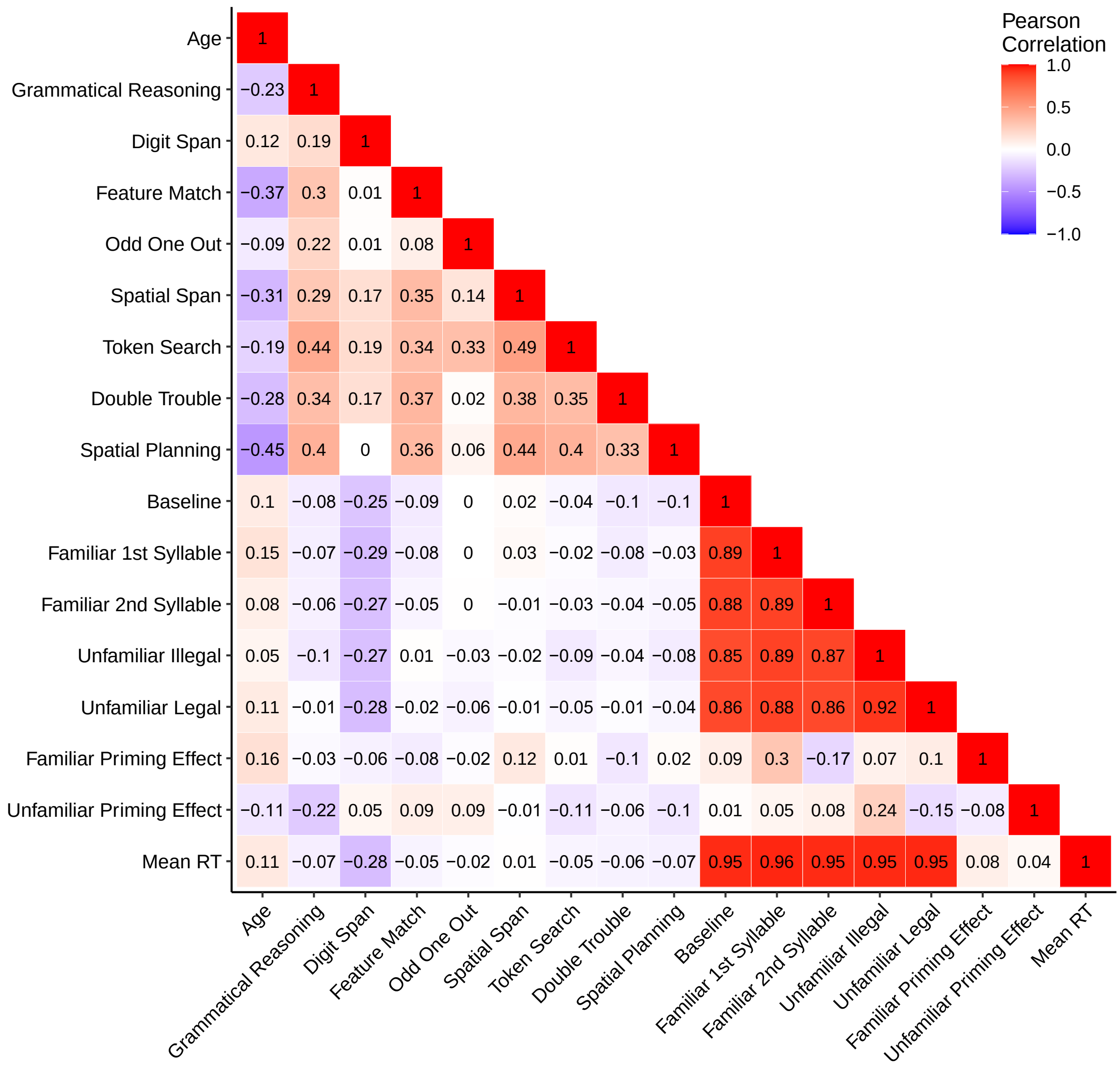
Table 4.9

Independent T-Tests Between Gender and All Tasks

Task	***t***	***df***	***p***	**Cohen's *d***
Grammatical Reasoning	-0.34	96	.738	-0.07
Digit Span	-1.24	95	.218	-0.25
Feature Match	-0.53	96	.595	-0.11
Odd One Out	0.19	95	.854	0.04
Spatial Span	-0.44	97	.664	-0.09
Token Search	0.51	97	.610	0.10
Double Trouble	-1.69	92	.095	-0.35
Spatial Planning	-0.88	94	.381	-0.18
Familiar Priming Effect	1.27	97	.208	0.26
Unfamiliar Priming Effect	0.13	97	.901	0.03
Mean Target Detection RT	-1.11	97	.269	-0.22

Figure 4.7

Heatmap Correlation Matrix



Note. Heatmap depicts correlation matrix of all continuous variables (age, performance on each cognitive task, mean RT for each target detection condition, statistical learning priming effects, baseline RT, and mean RT across all target detection tasks). Blue denotes negative correlations and red denotes positive correlations.

4.4 Discussion

This study explored the relationships between individual differences in domain-general higher-order cognitive processes and word and grammar learning abilities. Participants completed a battery of validated cognitive tests assessing short-term and working memory, grammatical and deductive reasoning skills, attentional and inhibitory control, strategic thinking, and planning. Following this, they took part in a modified statistical language learning test of incidental word and grammar learning. Speeded syllable detection tasks using familiar and unfamiliar syllables were used by comparing RT to targets with varying degrees of predictability as indirect measures of implicit word-segmentation and grammar generalization learning outcomes.

In contrast to previous findings that have demonstrated associations between domain-general cognitive processes and sequence or language learning (e.g., Archibald & Joanisse, 2013; Bartolotti et al., 2011; Galea et al., 2010; Kapa & Colombo, 2014; Levy et al., 2007; Linck et al., 2009; Smalle et al., 2017), the findings here indicate a lack of significant correlations between any of the cognitive tasks and implicit knowledge of the learned words and grammatical patterns. Rather, these findings corroborate select research (e.g., Grey et al., 2015; Linck & Weiss, 2015; Reber et al., 1991) suggesting that language learning abilities, specifically statistical learning here, operate independently of domain-general cognitive skills. For instance, Grey et al. (2015) reported similar findings in terms of a lack of relationship between phonological working memory and incidental learning of morphosyntactic regularities of a semi-artificial language. Comparable findings (or lack thereof) were also reported between language learning and general cognitive control abilities (Linck & Weiss, 2015; Luque & Morgan-Short, 2021). Overall, the mixed findings across the literature collectively suggest heterogenous relationships between distinct linguistic and non-linguistic processes that may be moderated by a diverse set of factors. I further discuss these findings in greater detail and highlight factors that may contribute to these inconsistencies.

4.4.1 Statistical Learning of Words and Grammatical Patterns are not Related to Domain-General Cognition

Findings from this study do not provide support for a negative relationship between domain-general cognitive processes and implicit grammatical sequence learning. One possible explanation could be attributed to an unintended enhancement of implicit learning within the experimental design of this study. Smalle et al. (2017) reported a negative correlation between implicit learning of a Hebb Repetition sequence and a composite measure of EF processes, but only in a control group learning without any neural manipulation. Notably, this negative relationship was erased in an experimental group who underwent inhibitory TMS prior to learning, resulting in enhanced sequence learning compared to the control group. Their findings suggest that under typical learning conditions, adults' EF processes may hinder implicit sequence learning, but such interference can be temporarily mitigated by dampening activity in the neural regions governing EF. Similar facilitatory effects have been observed when inducing cognitive fatigue or limiting attentional resources prior to language learning (e.g., Cochran et al., 1999; Smalle et al., 2021, 2022). Considering this rationale, it is plausible that administering the cognitive test battery prior to the statistical learning tasks in the present study induced cognitive fatigue, thereby reducing engagement of EF resources during language learning. Indeed, learners demonstrated successful acquisition related to both word segmentation and grammar generalization, with medium to large effect sizes. It is plausible that a negative relationship may be more likely to emerge when grammar attainment is poor. Due to constraints imposed by the task platforms used in the present study, it was not possible to reverse the task order. Nevertheless, it would be interesting to examine whether language learning effects and their relationships with domain-general cognitive skills would differ when the task order is reversed.

An additional key factor that may have contributed to the absence of significant relationships between cognitive performance and language learning may be the type of knowledge assessed by the target detection tasks employed in the present study. Importantly, the speeded syllable detection tasks are primarily implicit measures of learning. It is plausible that associations between language learning and domain-general cognitive performance would emerge when explicit tasks such as the two-alternative forced choice test (2AFC) are employed. These explicit tasks are dependent on decision-making processes that are argued to particularly target explicit language knowledge (Batterink et al., 2015; Reber et al., 1991). Moreover, previous research has indicated that performance on implicit and explicit measures of statistical learning are uncorrelated (Batterink et al., 2015; Bertels et al., 2013; Kim et al., 2009; Moreau et al., 2022; Smalle et al., 2022), suggesting that the two types of tasks capture distinct forms of knowledge or underlying processes. Aligning with this idea, Reber et al. (1991) reported that IQ scores were strongly correlated with performance on an explicit problem-solving task, but not with an implicit artificial grammar learning task. In the context of language research, speeded syllable detection tasks have primarily been compared to explicit tasks in regard to word-segmentation, with limited exploration of their relationship pertaining to grammar generalization. Future investigations should incorporate the implicit paradigm from the present study alongside explicit tasks such as the 2AFC to compare implicit and explicit grammatical knowledge, and further assess whether individual differences in EF processes are differentially associated with implicit and explicit measures of grammar learning.

Another factor that may contribute to the heterogeneity observed in the literature is the level of language proficiency attained by learners. Luque and Morgan-Short (2021) suggested that EF processes may not be related to early stages of novel language learning due to learners not yet having sufficient experience in controlling the two languages. Associations between language learning and inhibitory control in particular might only emerge when proficiency in the new language reaches a higher level, requiring learners to effectively inhibit their knowledge of the first language (L1). An avenue for future research may be to therefore explore whether proficiency moderates the relationship between language learning and domain-general processes.

4.4.2 Autonomy of Grammatical Sub-Domains

I would next like to highlight a particularly interesting finding, namely the lack of relationship observed between the Grammatical Reasoning task and grammatical statistical learning. While it may be expected that the two grammar tests would be related to one another, this finding highlights an important notion that performance on distinct tasks can vary even when measuring seemingly related concepts. However, while both tasks are measures of grammatical knowledge, I posit that they target 1) different grammatical components and 2) distinct forms of processing. Specifically, the Grammatical Reasoning task taps into the syntax-semantic interface and assesses syntactical reasoning specific to comprehending passive versus active voices and negation (e.g., understanding differences between "square does not contain circle" versus "square is not contained by circle"). On the other hand, the grammatical patterns in the statistical language learning task better represent more abstract grammatical category and order learning in the absence of semantic representations. Consequently, the findings outlined here suggest that these two sub-domains of grammar may operate autonomously.

Second, the Grammatical Reasoning task requires participants to make explicit reasoning judgements regarding grammatical sentences that accurately or inaccurately describe visual information. This task necessitates engagement of higher-order reasoning and decision-making processes and is more aligned with what Suzuki (2017) described as "automatized explicit knowledge", distinct from implicit knowledge due to the amount of awareness of the grammatical rules. In contrast, the speeded syllable detection task used in the statistical learning portion of this study solely targeted implicit grammar knowledge, which was ensured through several means. First, incidental learning was promoted by redirecting participants' attention to a visual side-task during exposure and by ensuring that the grammatical patterns were too complex to be explicitly discerned or verbalized within the given timeframe. Any acquired grammatical knowledge was based on implicit learning of transitional probabilities between non-adjacent regularities, specifically, the phonological compositions of every other syllable. Additionally, the learning measure itself was computed as differences in RT to syllables in grammatical versus ungrammatical positions, which relied on predictability properties of the syllables, thus avoiding engagement of explicit decision-making processes. Further, as the stimuli consisted of novel syllables not presented in the exposure phase, participants could not rely on explicit recall of learned sequences as is possible for the word-segmentation condition. Thus, just as implicit and explicit measures of word-segmentation have been found to be uncorrelated (Batterink et al., 2015; Bertels et al., 2013; Kim et al., 2009; Moreau et al., 2022; Smalle et al., 2022), the present findings demonstrate that automatized explicit grammatical knowledge is unrelated to implicit statistical learning of grammatical sequences.

4.4.3 Exploratory Correlations

In this section, I shift focus to some exploratory analyses. Of particular interest was the observation that although participants demonstrated successful statistical learning of both word segmentation and grammar generalization, the priming / learning effects of these two language components did not correlate with one another. This finding is particularly interesting because it demonstrates that even in the absence of semantic associations, when both word and grammar components rely on statistical learning of probabilistic regularities, performance on the two are nonetheless uncorrelated. One key difference between the conditions was that learning to segment the words depended on TPs between adjacent syllables whereas the ordering of grammatical categories was contingent upon TPs between every other syllable. Accordingly, it may be the case that individual differences in statistical learning based on adjacent regularities are not related to those based on non-adjacent regularities. However, other differences between the two tests, such as the use of familiar or unfamiliar targets, or the difference in TPs between the conditions, could have also contributed to differential learning outcomes. In any case, the findings suggest that a good word learner does not necessarily make a good grammatical pattern learner, such that statistical learning skills do not transfer across distinct linguistic components. This notion aligns with theories positing that statistical learning is governed by modality-specific constraints (Frost et al., 2015), along with empirical research demonstrating limited transfer of statistical learning skills across domains, such as the visual and auditory domains (Conway & Christiansen, 2009; Emberson et al., 2011).

In terms of intercorrelations between the tasks comprising the cognitive test battery, it is not surprising that performance on most of the tasks were significantly and positively correlated with one another. This suggests that while each task may be designed to assess distinct higher-order processes, these functions may rely on shared cognitive resources or be influenced or moderated by an overarching mechanism. However, there were two exceptions to this pattern. First, deductive reasoning skills, as assessed by the Odd One Out task, was only related to the Token Search task, which primarily measures visual working memory and strategic thinking skills. Similarly, performance on the Digit Span task was not related to any other task in the test battery. This finding indicates that PSTM operates independently of other cognitive processes, including visual and spatial short term memory assessed by the Token Search and Spatial Span tasks. These findings are in line with Baddeley and Hitch's (1974) model of working memory, which distinguishes between distinct phonological and visuo-spatial systems. Interestingly, performance on the Digit Span task was also the only task that significantly correlated with overall mean RT to targets across all conditions of the speeded syllable detection tasks. Thus, target detection of syllables and PSTM may be moderated by a common underlying factor.

Lastly, as age-related effects are typically exhibited in language learning and cognitive performance, I explored whether age was correlated with any of the cognitive or language tasks. Interestingly, age was not significantly correlated with statistical learning of either words or grammatical patterns. Given that this study only included adult participants, it is likely that age effects would emerge when including younger age groups. For instance, Janacsek et al. (2012) reported a rapid decline in implicit probabilistic sequence learning skills after the age of 12. On the other hand, regarding the cognitive battery tasks, negative correlations between age and the Grammatical Reasoning, Feature Match, Spatial Span, Double Trouble, and Spatial Planning tasks were observed. Thus, performance on tasks assessing explicit grammatical reasoning, attention, inhibition, spatial short-term memory, and planning decline across adulthood. On the other hand, age was not associated with verbal or visual working memory, deductive reasoning, or strategic thinking skills. Previous research suggests that most EF processes including inhibitory control, working memory, and planning abilities tend to improve across adolescence and decline in mid- to older adulthood (Ferguson et al., 2021), with the decline specifically related to neural changes in the DLPFC (MacPherson et al., 2002). However, consistent with Hartshorne and Germine (2015), the findings of the present study highlight the heterogeneous nature of age-related changes across adulthood.

4.5 Conclusion

This study investigated the relationships between domain-general cognitive processes and implicit learning outcomes of novel L2 words and grammatical patterns. The findings revealed that performance on various cognitive tasks were not related to individual differences in statistical learning of words or grammatical patterns, as measured by speeded syllable detection tasks. This may suggest the distinctiveness and autonomy of implicit language learning from domain-general cognitive processes. However, the considerable heterogeneity in findings across the literature indicate that the relationship between the two is more complex and is plausibly influenced by various interacting factors such as task demands, proficiency levels achieved, and experimental task designs. Notably, statistical learning of word segmentation was also unrelated to that of grammatical generalization, suggesting that the two language components may be learned independently. Remarkably, this was the case even though successful acquisition of both words and grammatical patterns relied on similar incidental probabilistic learning processes, and when learning outcomes were measured using similar implicit target detection tasks. Thus, while statistical learning was once believed to be a domain-general mechanism, I demonstrate here that this may not necessarily be the case, or in the very least, it may be subject to domain-specific (or even sub-domain specific) constraints.

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Chapter 5: General Discussion

Despite the extensive body of research surrounding the cognitive and neural mechanisms that underly second language (L2) learning (e.g., Bartolotti et al., 2017; Bialystok & Hakuta, 1999; Birdsong, 2006, 2014; DeKeyser, 2005, 2009; Li et al., 2014; Morgan-Short et al., 2015; Perani & Abutalebi, 2005; Ullman, 2001; Yang et al., 2015), our current understanding of the challenges adults face in acquiring grammatical components of language while excelling in other cognitive domains such as attention, decision-making, and reasoning skills, remains limited. The intriguing paradoxical relationship observed between procedural learning and higher-order cognitive functioning has prompted theories positing a causal competitive relationship between the two (Finn et al., 2014; Nozari & Thompson-Schill, 2013; Smalle et al., 2021; Thompson-Schill et al., 2009). Thus, the primary objective of my doctoral dissertation was to examine the differences between vocabulary and grammar learning and contribute to the limited empirical work surrounding the interference hypothesis. To recap, the interference hypothesis is an emerging theory in the field of cognitive development, proposing that adults' increased reliance on later-developing higher-order cognitive functions interferes with implicit sequence learning processes involved in optimal grammar acquisition (Ambrus et al., 2020; Finn et al., 2014; Smalle et al., 2017, 2021). Over the course of three experiments, I 1) examined the cortical substrates that support the initial stages of language learning (Chapter 2, Training Phase), 2) compared cognitive and neural differences between novel explicit word and implicit morphological processing (Chapter 2, Test Phase), 3) investigated the influence of directed effort towards learning an L2 on implicit representations of novel words and grammatical patterns (Chapter 3), and 4) explored whether individual differences in implicit L2 word and grammar learning outcomes were associated with domain-general cognitive skills (Chapter 4). In this chapter, I provide a concise overview of the findings, draw connections between them, and offer insights into future avenues of research that stem from this work. I end this dissertation with some discussion of the theoretical, methodological, and practical implications of this research, with a specific focus on enhancing experimental, and ultimately, pedagogical approaches to language learning.

5.1 Summary of Key Findings

To deepen our understanding of the intricate process of L2 learning, I began this dissertation by examining the cortical correlates involved in learning and processing a novel artificial language. Specifically, in Chapter 2, I used functional Near-Infrared Spectroscopy (fNIRS) alongside an artificial language inspired by the Declarative / Procedural Model (Ullman, 2001, 2004, 2016) to investigate 1) the cortical regions governing the language *learning* process, and 2) the differential neural mechanisms implicated in explicit word and implicit grammar processing following the learning period. My findings revealed that while adults attained higher proficiency outcomes in novel vocabulary words than in the underlying grammatical patterns of the language, the cortical regions involved in processing these two distinct language components exhibited comparable patterns of activation. I discussed possible reasons for this discrepancy, highlighting that the behavioural differences observed in learning distinct language components likely arise from additional factors such as the nature in which the language is initially learned, or the involvement of more subcortical regions (e.g., medial temporal lobe, cerebellum, and basal ganglia regions) (Burianova & Grady, 2007; Mochizuki-Kawai, 2008; Ullman & Pierpont, 2005).

In contrast to the test phase data, significant and widespread cortical changes were evident throughout the learning phase in the temporal (temporal pole, middle temporal gyri, and superior temporal gyri), parietal (supramarginal gyrus, subcentral gyrus, and precuneus), occipital (occipitotemporal and visual cortex), and frontal (frontopolar cortex, dorsolateral prefrontal cortex, inferior frontal gyrus, premotor cortex, and orbitofrontal cortex) lobes. These findings indicate that the initial stages of language learning engage in an extensive network of cortical regions, likely tapping into a complex network of linguistic and non-linguistic cognitive processes. This was especially evident in select temporal lobe regions known to govern semantic memory (Binder et al., 2009; Burianova & Grady, 2007; Noppeney & Price, 2002) and the frontal lobe known to be involved in higher-order executive functions (Domenech & Koechlin, 2015; Filoteo et al., 2010; Frey & Petrides, 2002). Interestingly, the observed pattern of activation suggests that cognitive demands placed on temporal, parietal, occipital, and select frontal areas (namely frontopolar cortex and dorsolateral prefrontal cortex) decrease across learning, and thus become more efficient with increased exposure to language patterns. However, in contrast to this trend, other frontal lobe regions (the left inferior frontal gyrus / Broca's area, left dorsolateral prefrontal cortex, left premotor cortex, and right orbitofrontal cortex) exhibited the opposite pattern of activation, suggesting that these distinct areas may play a larger role in recalling or reconsolidating previously learned word-forms and grammatical patterns. Taken together, the distinct patterns observed from various neural regions may speak to the differential influence of higher-order cognitive functions on the process of language learning.

To further explore whether the nature in which we learn influences novel implicit word and/or grammatical proficiency success, in Chapter 3, I shifted focus to investigate the interference hypothesis, which suggests that greater engagement in more developed higher-order cognitive processes may interfere with implicit grammar learning (Finn et al., 2014; Galea et al., 2010; Nozari & Thompson-Schill, 2013; Smalle et al., 2017; Thompson-Schill et al., 2009). I used a modified statistical language learning paradigm with a grammatical component to examine whether directing effort towards learning words and grammatical categories (thereby promoting engagement of complex attentional and learning processes) impacts word or grammar learning outcomes. Importantly, I addressed this question using speeded syllable detection tasks to capture implicit representations of the language while minimizing learners' engagement in higher-order decision-making processes. Interestingly, while successful word and grammar learning were observed for learners under both effortful and passive learning conditions, directing effort towards learning did not significantly affect word or grammar learning outcomes. These findings diverge from those of a study that employed explicit decision-making tests (Finn et al., 2014) and demonstrated word facilitation and grammar interference effects following effortful learning. As discussed in Chapter 3, several experimental distinctions between the two studies necessitate further research to unravel these contradictory outcomes. It is plausible that directing effort towards learning may have a greater impact on explicit rather than implicit knowledge of the learned language, although the interference hypothesis would suggest otherwise, positing that explicit processes particularly interfere with implicit knowledge (e.g., Smalle et al., 2022).

Consistent with this line of reasoning, variability in language learning abilities should correspond to individual differences in higher-order cognitive functioning. Specifically, according to the interference hypothesis, implicit grammatical sequence learning should have a negative relationship with reasoning, attentional and explicit cognitive control skills within individual learners. To explore this idea, in Chapter 4, I addressed whether individual differences in domain-general higher-order cognitive processes were associated with word or grammar learning abilities. Using the passive exposure protocol of the statistical learning paradigm employed in Chapter 3, along with a comprehensive cognitive test battery, I probed for possible connections between domain-general skills and statistical language learning, asking whether better (or worse) grammar learning corresponds to specific cognitive profiles. Contrary to the predictions derived from the interference hypothesis, none of the cognitive measures exhibited significant correlations with either word or grammar learning. Interestingly, implicit word and grammar learning outcomes were also found to be uncorrelated with one another, suggesting that the two processes may operate independently, even when relying on presumably shared statistical learning mechanisms. This observation is in line with the existing literature highlighting the distinct operation of statistical learning across diverse domains (Conway & Christiansen, 2005, 2009; Emberson et al., 2011, 2019), emphasizing here that successful or efficient word learning does not necessitate effective grammar learning, and vice versa.

Collectively, the three studies presented in this dissertation reinforce the long-standing notion that word and grammar learning involve discrete processes, yielding divergent learning outcomes, even within the context of simplified artificial languages. However, the underlying origins of these observed differences remain unclear. While the data from the training phase presented in Chapter 2 revealed the involvement of a wide-ranging network of cortical regions during the initial language *learning* process, findings from the test phase, along with the results of Chapters 3 and 4, collectively indicate that the disparities in word and grammar learning outcomes are not mirrored by differential engagement of cortical regions (Chapter 2), nor is learning success affected by (Chapter 3) or related to (Chapter 4) domain-general cognitive mechanisms. Despite the appeal of the interference hypothesis, which is logically situated from a clear inverse relationship observed between the developmental progression of higher-order cognitive functions and the decline in grammar learning skills, the findings presented here do not support this theory, at least in terms of implicit representations of language structures. The differences observed in natural L2 word and grammar learning likely stem from a complex interplay of factors including, but not limited to, neural plasticity (Birdsong, 2018; Callan et al., 2003; Galván, 2010; Li et al., 2014; Zhang & Wang, 2007), influence from subcortical substrates (Bradley et al., 2013; Burgaleta et al., 2016; Krizman et al., 2012; Liu et al., 2020), and external influences such as prior knowledge (Zion et al., 2019) and cross-linguistic similarities (Ringbom, 2006; Ringbom & Jarvis, 2009). In the following section, I highlight some important methodological implications of this research and propose avenues for future investigations to advance our understanding of the intricate complexities of L2 learning.

5.2 Implications and Future Directions

A crucial avenue for future research is to better understand developmental differences in learning distinct linguistic components. While extensive research exists on the developmental trajectory of language learning and processing (e.g., Berl et al., 2014; DeKeyser, 2013; Finn et al., 2016; Gómez & Maye, 2005; McLaughlin, 1977; Raviv & Arnon, 2018; Van Heugten et al., 2015), the literature directly comparing word and grammar learning outcomes across ages remains limited. My research lays the foundation for such investigations by employing two key approaches. First, fNIRS provides significant advantages for examining the neural substrates of language learning in children. This non-invasive technique ensures participant comfort during prolonged experimental sessions (a crucial factor for ensuring sufficient exposure to language patterns), overcomes limitations associated with more restrictive and noisy imaging methods such as fMRI, and is less susceptible to motion artifacts, which are commonly encountered in younger participants (Abtahi et al., 2017; Pinti et al., 2020; Quaresima et al., 2012; Soltanlou et al., 2018; Wilcox & Biondi, 2015). Moreover, unlike other widely used techniques such as fMRI and EEG, fNIRS permits speech-related responses including oral reading, word repetition, and verbal output (e.g., Sugiura et al., 2011; Walsh et al., 2017; Wan et al., 2018), thus providing a unique avenue for investigating language learning and processing across development.

Second, the target detection tasks presented in Chapters 3 and 4 hold significant promise in assessing implicit learning outcomes in children. These tasks have the advantage of not requiring explicit decision-making procedures, thereby potentially avoiding the inadvertent engagement of higher-order cognitive functions in which adults may have an advantage. Notably, speeded target detection tasks within the statistical language learning domain have recently been successfully employed with children between the ages of 8 and 12 years to investigate developmental differences in word segmentation ability (Moreau et al., 2022). Although the authors did not uncover a statistical learning advantage in children with regard to word learning, I speculate that developmental differences may emerge when examining grammar generalization in particular, as this is the area that adults tend to struggle with the most (DeKeyser, 2005, and as demonstrated in Chapter 2). While the present research did not reveal a facilitative or interfering effect of effort on word or grammar learning, respectively, with certain design modifications as outlined in Chapter 3, this approach can be used across age groups to determine whether age mediates any potential effects of higher-order engagement on language learning.

Indeed, I would like to highlight the demonstrated utility of speeded target detection tasks in capturing implicit representations formed through exposure to a novel language. Notably, Chapters 3 and 4 demonstrated the successful application of implicit speeded target detection tasks as indirect measures of not just word segmentation, but also implicit grammatical knowledge through the comparison of reaction time to novel untrained syllables in grammatical and ungrammatical positions. The findings that adults were able to predict novel syllables in previously unheard sequences based solely on the phonological compositions of the targets is remarkable in and of itself. This finding highlights our impressive capacity to rapidly learn and generalize complex patterns from limited brief exposures, utilizing this acquired knowledge unconsciously yet in a somewhat top-down manner to predict elements within our environment. Moving forward, this method should be employed in future research to investigate implicit representations of language and non-linguistic patterns across diverse populations encompassing various ages and learning abilities.

It is worth noting that, for a considerable period, statistical learning was primarily believed to be an implicit process, evident from successful learning occurring after passive exposure to statistically-defined sequences (Christiansen, 2019; Kim et al., 2009; Perruchet & Pacton, 2006). However, more recent empirical work has demonstrated that both implicit and explicit representations are formed following statistical learning, arguably independently of one another (Batterink et al., 2015; Moreau et al., 2022; Smalle et al., 2022). Consequently, I believe it is important for future research to integrate both explicit and implicit measures of learning in order to gain a more comprehensive understanding of the diverse representations formed through pattern exposure. I propose that incorporating both types of measures (e.g., explicit two-alternative forced choice and implicit target detection) within the framework of these three studies may yield crucial insights into the subtle constraints on word and grammar learning. In particular, the word-object association task used in Chapter 2 may be considered an explicit task because it requires participants to make overt decisions on presented word-object pairings. Although grammar learning was assessed using novel untrained words and objects, the inclusion of a more implicit task may have unveiled more nuanced neural differences that better align with the behavioral disparities observed between word and grammar learning. Future investigations can integrate fNIRS with statistical learning paradigms encompassing both explicit and implicit tasks. Likewise, as discussed in Chapters 3 and 4, I speculate that the inclusion of explicit measures alongside the target detection tasks in the statistical learning studies would unveil differences in the influence of effort on word or grammar learning, as well as the relationship between statistical learning and domain-general cognition.

Additionally, I would like to briefly highlight the importance of incorporating multiple language components, particularly within the context of artificial languages. Often, research in this field focuses solely on word or grammar learning in isolation, disregarding the fact that natural languages are learned through simultaneous and inseparable exposure to both grammatical patterns and novel words. Examining either one independently may lead to an incomplete understanding of the intricate process by which language is naturally acquired. Consequently, our understanding of the different mechanisms that govern these language components would inevitably rely upon inferences drawn from disparate studies employing distinct methodologies.

A further implication of this research is its contribution to enhancing our understanding of the neural underpinnings of the initial language learning process. Language *learning* itself is oftentimes overlooked as the focus tends to be on measuring learning outcomes and recall post-learning. However, by comparing neural engagement between identical learning blocks (Chapter 2, training phase) that differed only in the amount of language exposure received, I was able to isolate the neural processes specifically involved in the learning process while cancelling out neural responses related to more fundamental visual or auditory information processes. For instance, while significant changes over time in select occipital lobe areas were observed, it can be inferred that these differences are likely attributable to object or word *recognition* rather than fundamental visual or auditory processing. To gain deeper insights into the age-related differences observed in language learning, future research should shift some of its focus towards the learning phase itself, as the way we initially learn and encode various types of information may uncover the key to understanding such differences.

Overall, forming a comprehensive understanding of the mechanisms governing L2 learning holds significant importance for shaping educational policies and informing pedagogical practices including the development of effective language teaching methods, curriculum designs, and assessment strategies, ultimately enhancing educational outcomes for foreign language learners (DaSilva Iddings & Rose, 2012; Hu & Gao, 2021). For instance, the explicit nature in which grammatical rules are often taught in instructional settings may be a possible factor contributing to poor language outcomes following L2 learning programs (e.g., formal obligatory French education in select Canadian provinces). This is especially important in our contemporary globalized and multilingual society, wherein immigrant and refugee experiences are influenced by language barriers that can affect social integration and inclusion, successful career development, and participation in the social, economic, and civic aspects of their new communities (Ding & Hargraves, 2009; Huot et al., 2020; Isphording & Otten, 2014; Simich et al., 2005).

5.3 Concluding Remarks

In this dissertation, I have addressed some factors that may contribute to the longstanding disparities observed in natural L2 learning, focusing on the differential outcomes of word and grammar learning in adults. Despite providing empirical evidence supporting the notion that adults face particular challenges in grammar learning, while demonstrating strengths in word learning, the underlying factors driving these language learning differences are likely multifaceted. While the findings of this study do not offer conclusive support for the hypothesis that domain-general cognitive functions interfere with grammar learning, it would be premature to dismiss this idea entirely. Drawing upon the pioneering encoding specificity paradigm in memory research (Thomson & Tulving, 1970; Tulving & Thomson, 1973), it is evident that the initial manner in which information is learned and encoded plays a crucial role in subsequent memory recall processes. Applying this idea to the linguistic domain may provide the key to understanding age-related differences observed in natural L2 learning.

By addressing the important avenues for future research discussed here, along with applying the methodological implications derived from the three studies presented in this dissertation, we can form a better understanding of interference effects and the contexts in which they may emerge. This would have significant theoretical implications for our understanding of L2 learning and cognitive development, but also for improving the education system. Gaining a comprehensive understanding of the most effective learning mechanisms tailored to distinct types of material is crucial for optimizing pedagogical approaches in order to improve language learning attainment in our increasingly globalized and multilingual society.

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Appendices

Appendix A: Chapter 2 Behavioural Group Ethics Approval

Western Research

Date: 18 April 2018

To: Prof. Marc Joanisse

Project ID: 111390

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

Dear Prof. Marc Joanisse

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

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

Documents Approved:

Document Name	Document Type	Document Date	Document Version
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 under the IRB registration number IRB 00000941.

Appendix B: Chapter 2 fNIRS Group Ethics Approval

Western Research

Date: 19 October 2018

To: Prof. Marc Joanisse

Project ID: 112643

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

Dear Prof. Marc Joanisse

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

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

Documents Approved:

Document Name	Document Type	Document Date	Document Version
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 under the IRB registration number IRB 00000941.

Appendix C: Demographics Background and Language History Questionnaire

Section 1: General Information

Gender: __________________

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

1. Is English the first language you learned (circle one)? Y N
If no, please list which language(s) you learned at birth:

2. 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:

Very little	Poorly	Good	Very Good	Perfectly
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	1	2	1	1

Comments:

3. For each of the languages listed in Question 2, please indicate the primary method of learning, such as from family members, formal education, while visiting a foreign country, through a tutor, or immersion-type course, etc.

E.g., English = from family members; French = university course.

Appendix D: Chapters 3 and 4 Ethics Approval

Date: 23 May 2019

To: Prof. Marc Joanisse

Project ID: 113955

Study Title: Real-time processing of language in first- and second-language users

Short Title: Investigating language processing in real time

Application Type: NMREB Initial Application

Review Type: Delegated

Full Board Reporting Date: 07/Jun/2019

Date Approval Issued: 23/May/2019 15:49

REB Approval Expiry Date: 23/May/2020

Dear Prof. Marc Joanisse

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

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

Documents Approved:

Document Name	Document Type	Document Date	Document Version
2.5 pre-screening and demographic questionnaire	Paper Survey	21/May/2019	1
3.1.10f SONA	Recruitment Materials	23/May/2019	1
3.1.2b Poster_ad	Recruitment Materials	21/May/2019	1
3.1.5f Telephone script	Recruitment Materials	23/May/2019	1
3.1.6f Email Script	Recruitment Materials	23/May/2019	1
3.1.7b Facebook_ad	Recruitment Materials	21/May/2019	1
4.3 LOI_Consent	Written Consent/Assent	21/May/2019	1
Experiment Sample Polysemy	Other Data Collection Instruments	03/Apr/2019	1

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

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

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

Sincerely,

Katelyn Harris, Research Ethics Officer on behalf of Dr. Randal Graham, NMREB Chair

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

Appendix E: Chapter 3 Comparisons between Language Versions A and B

Supplementary Table 1

Independent T-Tests Between Language Version A and B for Familiar and Unfamiliar Target Detection Tasks

	t	*df*	*p*	Cohen's *d*
Familiar Target detection	-1.648	118	0.102	-0.301
Unfamiliar target detection	0.392	118	0.695	0.072

Note. For each test, difference scores in RT were calculated between target conditions (Familiar = 2nd syllable – 1st syllable target; Unfamiliar = ungrammatical – grammatical target position) and compared using an independent t-test between language versions. No significant differences were found in learning between language versions for either familiar or unfamiliar target detection tests.

Appendix F: Creyos Scores Validity Indicator

Supplementary Table 2

Creyos Score Validity Parameters

Feature	Spatial Span	Token Search	Odd One Out	Spatial Planning	Grammatical Reasoning	Digit Span	Feature Match	Double Trouble
Number of attempts	> 0	> 0	≥ 11; ≤ 39	> 0	> 0	> 0	≥ 11; ≤ 39	> 0
Number correct	≥ 0; ≤8	≥ 1; ≤ 13	≥ 7; ≤ 34	≥ 0; ≤ 19	≥ 5; ≤ 46	≥ 0; ≤ 11	≥ 9; ≤ 33	≥ 9; ≤ 109
Number of errors	= 3	= 3	≥ 0; ≤ 16	≥ 0; ≤4	≥ 0; ≤ 10	= 3	≥ 0; ≤ 9	≥ 0; ≤ 37
Duration (seconds)	≥ 39; ≤ 180	≥ 24; ≤ 751	≥ 179.5; ≤ 180.5	≥ 179.5; ≤ 180.5	≥ 89.5; ≤ 90.5	≥ 40; ≤ 362	≥ 89.5; ≤ 90.5	≥ 89.5; ≤ 90.5
Max score	≥ 0; ≤9	≥ 2; ≤ 14	______	______	______	≥ 0; ≤ 12	______	______
Average Score	≥ 0; ≤ 6.9	≥ 2.0; ≤ 9.4	______	______	______	≥ 0; ≤ 8.4	______	______
Final Score	______	______	≥ -3; ≤ 37	≥ 0; ≤ 136	≥ -1; ≤ 46	______	≥ 6; ≤ 289	≥ -6; ≤ 107
Correct Score	______	______	______	______	______	______	≥ 24; ≤ 323	______
Max Level	______	______	≥ 8; ≤ 20	______	______	______	≥ 4; ≤ 17	______

Note. This table was recreated with permission from Creyos. Values outside of these parameters render the score for that task as invalid. Invalid scores were excluded from analyses. Validity conditions for each task were calculated based on Creyos's normative database. 99% of scores in the database fall within the bounds of these parameters.

Appendix G: Correlations Between Cognitive Tests and Raw Mean RT Differences

Supplementary Table 3

Correlations Between Raw RT Difference Means and Cognitive Tests

RT mean differences		Grammatical Reasoning	Digit Span	Feature Match	Odd One Out	Spatial Span	Token Search	Double Trouble	Spatial Planning
Familiar (2^{nd} - 1^{st} syllable)	*r*	.010	-.196	-.071	-.057	.101	.018	-.109	.051
	p	.918	.053	.483	.576	.317	.862	.293	.621
Unfamiliar (illegal - legal target)	*r*	-.180	.097	.070	.090	-.017	-.051	-.021	-.120
	p	.075	.343	.491	.376	.865	.617	.843	.241

Curriculum Vitae

Leah Brainin

Post-Secondary Education

2019 – 2023	University of Western Ontario London, Ontario, Canada Ph.D. Psychology
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 Exchange Program

Honours and Awards

2021 – 2022	Ontario Graduate Scholarship (OGS)
2020 – 2021	Ontario Graduate Scholarship (OGS)
2019 – 2020	Ontario Graduate Scholarship (OGS)
2019	Award for Best Oral Presentation: Western Research Forum
2018	Reva Gerstein Fellowship for Master’s Study in Psychology
2017	Canada Graduate Scholarship-Masters (CGS-M)
2017	Arthur B. McDonald Prize for Academic Excellence
2017	Woodsworth Leadership Scholarship
2016	Undergraduate Travel Award
2016	The Global Undergraduate Awards: Psychology Category
2016	The Global Undergraduate Awards: 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

Publications

Parks, K. M., Moreau, C. N., Hannah, K. E., Brainin, L., & Joanisse, M. F. (2021). The task matters: A scoping review on reading comprehension abilities in ADHD. *Journal of Attention Disorders, 26*(10), 1304-1324.

Manuscripts Under Review & In Preparation for Publication

Parks, K. M., Hannah, K. E., Moreau, C. N., Brainin, L., & Joanisse, M. F. Language abilities in children and adolescents in DLD and ADHD: A scoping review. *Under review at Journal of Communication Disorders*.

Moreau, C. N., Parks, K. M., Brainin, L., & Joanisse, M. F. A systematic review and meta-analysis of multimedia learning: Multimodal input improves second language learning. *Under review at Language Learning*.

Brainin, L., Stubbs, K., Joanisse, M.F. Shedding light on language learning: An fNIRS investigation of explicit vocabulary and implicit morphology learning. *In prep*.

Brainin, L., Finn, A. S, Hudson Kam, K. L., Joanisse, M. F. The impact of effort on implicit word and grammar learning. *In prep*.

Brainin L., & Joanisse, M. F. Statistical learning of words and grammatical patterns are not related to domain-general cognitive processes. *In prep*.

Brainin L., Moreau, C. N., Parks, K. M., & Joanisse, M. F. The Cognitive Trajectory of Reading Disorder: A Scoping Review of Longitudinal Studies. *In prep*.

Moreau, C. N., Brainin, L., & Joanisse, M. F. A systematic review of neural entrainment in language and reading disorders. *In prep*.

Conference Presentations

Brainin, L., Samy, G., & Joanisse, M. F., (2022). The Role of Effort in Novel Word and Grammar Learning. *Ensuring Full Literacy Annual Meeting*. Toronto, Canada. [Poster].

Brainin, L., Samy, G., & Joanisse, M. F., (2022). Too Smart for Their Own Good: The Role of Effort in Novel Word and Grammar Learning. *Interdisciplinary Advances in Statistical Learning*. San Sebastian, Spain. [Poster].

Brainin, L. Stubbs, K., & Joanisse, M. F., (2021). Shedding Light on Language Learning: Neural Correlates of Vocabulary and Grammar Learning and Processing. *Society of fNIRS Conference*. International (virtual). [Oral Presentation].

Brainin, L. (2020). Examining the neural correlates of language learning using fNIRS (2020). *Western Interdisciplinary Student Symposium for Language Research (WISSLR)*. London, Canada. [Oral presentation].

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 (CSBBCS).* Waterloo, Canada. [Poster].

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].

Brainin, L., & Joanisse, M. F. (2019). Enhanced explicit vocabulary learning compared to implicit grammar learning in adults. *The Lake Ontario Visionary Establishment (LOVE) annual meeting*. Niagara Falls, Canada. [Poster].

Brainin, L. (2016). An integrated model of language production and comprehension. *The Undergraduate Awards Global Summit*. Dublin, Ireland. [Oral Presentation].

Related Experience

2023 – Present	Research Communications & Knowledge Mobilization Coordinator
2021 – 2023	Ensuring Full Literacy Knowledge Mobilization Committee
2017 – 2023	Graduate Teaching Assistant
2019 – 2022	Undergraduate Thesis Co-supervisor
2017 – 2022	Western Undergraduate Psychology Journal (WUPJ) Editor
2020 – 2021	fNIRS Journal Club Leader
2019 – 2021	Psychology Colloquium Committee Organizer
2020	Global Undergraduate Awards Judge – Psychology Panel
2018, 2019	CIHR Canadian National Brain Bee Organizer
2018	Inspiring Diversity in STEM Conference volunteer
2016	Research Assistant