COPING WITH COMPLEXITY: CHARACTERIZING HIGH AND LOW LEARNING DURING ON-LINE ACQUISITION OF A SEMINATURAL MICRO LANGUAGE

by

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DISSERTATION ABSTRACT

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Natural language is highly complex and can be challenging for some learners, yet the contribution of complexity to individual differences in language learning remains poorly understood. This poor understanding appears due to both a lack of consensus among researchers regarding what complexity is, and to on-line language research often employing low complexity, artificial grammar stimuli. This dissertation addresses the first aspect of this problem with an integrative review of complexity theories, and the second aspect with original research. A novel micro language paradigm made it possible to track learning online as participants were trained in a subset of a mini-language based on Japanese. Thirty-two adult native English speakers progressed through four phases of training to learn eight phrases, four at each of two complexity levels, while the acquisition was tracked online with dense-array EEG and frequent behavioral measures of learning. Participants first listened to a soundstream of micro language phrases to familiarize them with the phonology of the language. Next, they completed semantic training and practice. Finally, they listened to the soundstream again, now (presumably) comprehending the phrases. Participants were then divided into high and low learners based upon noun segmentation ability. Overall, findings suggested systematic differences between high and low learner responses to the simple and complex phrases. Both high and low learners were quick to develop a differential response to the noun initial and noun medial syllables, with a higher N1 response to the noun initial syllables emerging around the second minute and a later medial frontal negativity appearing to track engagement in learning. However, high learner electrophysiological response suggested a more strategic response to the noun syllables. It was speculated that the high learner response might constitute a customization of their attention to align with the information content of each syllable. In conclusion, observing learning online and using stimuli of varied complexity provided new insights into the nature of individual differences in learning. The micro language paradigm with the recall behavioral tracking method provides a new way to explore learning of sequential systems such as language.

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For babaganoosh, googoonana, batman, anehta, arfer, quin, lily, ruth, rocky and dad.

. . . but don't worry. You don't have to read it.

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CHAPTER I

INTRODUCTION

Extracting meaning from fast, complex information streams, such as language or action, is essential to understanding the world and responding to it appropriately, both in infancy and in adulthood. Individuals vary in how easily they can process such streams. In the case of spoken language, for example, there are clear individual differences in learning. These differences are evident in childhood first language acquisition (Nelson, 1981; Fenson et al., 1994) and persist into adulthood, with adults showing clear individual differences in native language attainment (Dąbrowska, 2012, 2018; Kidd et al., 2018). These individual differences are evident in adult second language learning as well (Skehan, 1991; Dörnyei & Skehan, 2003; Ehrman, Leaver & Oxford, 2003). What accounts for the fact that for some individuals, learning to process these streams proceeds seemingly effortlessly, while others experience real obstacles to learning? The goal of the dissertation will be to add insight to this question.

There are likely multiple factors that play a role in language learning difficulty. One likely contributor is how well individuals cope with complexity in streaming information. Natural language is highly complex and presents perceptual and cognitive challenges to any new learner. Understanding complexity's role in language learning seems key to understanding the individual differences in learning to process these information streams. However, the role of complexity in language learning difficulty has not yet been well characterized. This lack of characterization appears to be due both to a lack of consensus among researchers regarding what complexity is (and it may actually be multiple phenomena masquerading as one), and to the use of highly simple artificial grammar stimuli to explore the on-line process of language learning (e.g., Saffran, Newport & Aslin, 1996; Peña et al., 2002; Abla, Katahira & Okanoya, 2008). While this artificial language research has provided much insight into the mechanisms that enable language acquisition, the research fails to present learners with the degree of complexity inherent in naturalistic language learning settings; thus, findings from this body of work may offer an incomplete depiction of how learners cope with the level of complexity they face in everyday language learning.

To provide background for this topic, Chapter 1 will examine classical theories of complexity and the limitations that arise when these characterizations are applied to language learning. Chapter 2 will then review approaches to studying individual differences in language acquisition and introduce the current research, an exploratory study which aims to shed new light on language acquisition difficulty by investigating the impact of complexity on learning of a natural-based language that has been reduced in size to allow for on-line tracking of its acquisition within a single laboratory session.

Characterizing Complexity (What is Complexity?)

Addressing the question of how learners cope with complexity inherent in information to be acquired hinges upon how best to conceptualize what constitutes complexity. This in itself is not entirely straightforward; there continues to be a lack of consensus regarding how best to conceptualize complexity.

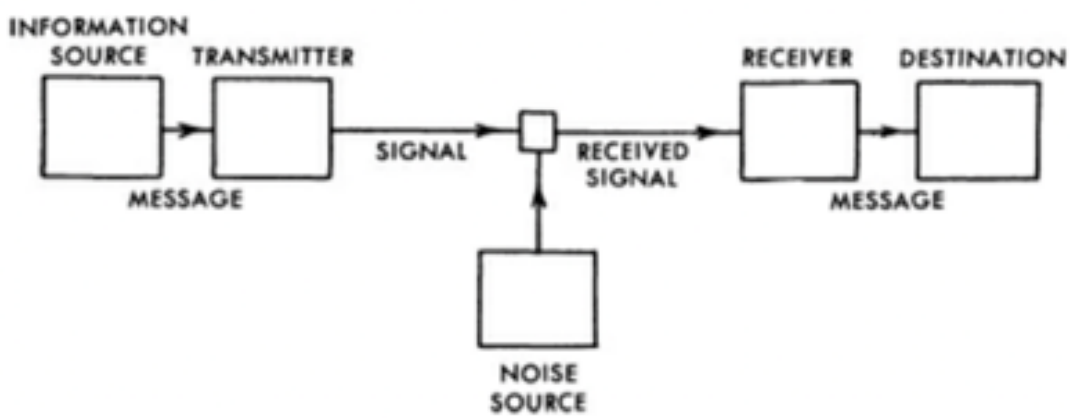
Complexity in Information Theory

Perhaps the most influential account is that proposed by Shannon (1948) in his Mathematical Theory of Communication, in which information is quantified as entropy, a measure of disorder or uncertainty in a system; and calculated in bits, or binary digits. Entropy is a measure of the system's information production, or, more precisely, the rate at which the system creates information (Shannon, 1948; Weaver, 1949). Shannon's entropy (often referred to as information entropy) therefore can be seen as a measure of information density. Within this context, the system's complexity can be thought of as the average amount of information carried by an element in the system (Grünwald & Vitányi, 2010). Expressed as a general communication model, shown in Figure 1.1, this account was also groundbreaking for its identification of the concept of channel capacity, the limitation on processing of information that is due to system constraints on maximum information flow that can pass per unit time. It was intended for engineering applications; for example, characterizing information flow and the impact of noise and channel capacity in telegraphic systems such as Morse code or audio transmission (Shannon, 1948). A principle contribution of Shannon's (1948) model to complexity research stems from its insight that information can be quantified. Thus, while not explicitly a theory of complexity, Shannon's work took a necessary first step toward characterizing the role of complexity in sequential communication systems.

Shannon's information entropy quantifies the information content of a communication system in terms of the sequence probabilities. In this view, an improbable event is considered to contain more information than a probable event. Therefore, by Shannon's account, a sequence with few elements contained within it, and with those elements repeating within a predictable pattern, would be characteristic of a low entropy system, corresponding to a low complexity system. In contrast, a sequence with many elements occurring with little repetition and consequently containing elements with low probability on average, would be a high entropy system, and likewise a high complexity system; with a random sequence considered a system of maximal complexity. As a result, information entropy captures a measure of complexity that is described mathematically in terms of system probabilities, with systems of higher average uncertainty more complex. Because prediction is important for language processing (Kuperberg & Jaeger, 2016), this prediction aspect gives Shannon's communication model particular applicability to language.

Figure 1.1

Shannon's General Communication System Model (1948)



Complexity in Language

While Shannon's general communication model was originally intended for a limited engineering application, Weaver (1949) subsequently redescribed it as an account of communication broadly defined "to include all of the procedures by which one mind may affect another" (p. 3). Indeed, there are many parallels evident between communication in the simple, encoded telegraphic systems of the 1940's, and in natural communication. For example, both telegraphic and natural communication systems (e.g., music or language) have an information source and a receiver, and both have noise intermixed with the signal during the information transfer. Additionally, both telegraphic and natural communication systems are constrained by a channel capacity. For example, telegraphic systems have a maximum rate at which messages can be sent; while natural language production and reception likewise have a processing "bottleneck" or constraint in processing due to human cognitive and attentional capacities (Christiansen & Chater, 2015). Thus, it seems reasonable that information in both system types share properties and, therefore, that information within each could be represented by the same model.

However, while Shannon's (1948) model provides a starting point for characterizing complexity in language, there are assumptions made that may limit the extent to which his communication model accurately characterizes complexity outside the anticipated application. First, the model disregards the aspects of complexity related to the system's elements themselves, the within-element (or "object") characteristics (Gruenwald & Vitanyi, 2010). An element in this context can be thought of as an individual segment that occurs/cycles within the sequence. For example, an element in language may be a single syllable, or it might be a word that occurs within the speech stream. Second, aspects of complexity related to the meaning of the communication are not factored into the model, because these semantic-conceptual aspects of communication were irrelevant in the intended engineering application. Third, Shannon's model explicitly assumes that the communication system is an ergodic process, i.e., that the probabilities in the system are stable through the entire sequence.

Language Has Complexity Between and Within Sequence Elements

Complexity in language can result from the patterns that result from relationships between elements, such as the repetitions or frequencies of syllables or words; as well as from the within-element patterns, such as the patterns of within-element detail that must be processed in order to distinguish phonemes. Therefore, both can contribute to complexity in language processing. Additionally, there is variation in the ability to track the distributional information arising from both these levels of patterning that relates to language ability (Erickson & Thiessen, 2015; Kidd & Arciuli, 2016; Kover, 2018); thus implicating variation in the ability to track both the between- and within-element information as potential contributors to the individual differences seen in language processing ability.

Between-Element Patterns Reveal Linguistic Structure. The patterns that occur between language system elements reveal the linguistic structure and rules. For example, infants and adults track the transitional probabilities occurring between elements in artificial language streams, implicitly learning the linguistic structures and rules revealed by these patterns (e.g., Saffran, Newport, Aslin, Tunick & Barrueco, 1997; Peña et al., 2002). Further, the ability to track these transitional probabilities is associated with language ability (Kahta & Shiff, 2016, 2019; Daltrozzo et al., 2017), suggesting that this ability to track such between-element information supports natural language learning as well as artificial (Erikson & Thiessen, 2015). While research investigating the individual differences in the ability to track and learn from these transitional probabilities in sequential information is sparse (as reviewed by Siegelmann & Frost, 2016), there is evidence that an inability to track these patterns in sequential information is associated with language impairment in clinical populations (e.g., Evans, Saffran, Robe-Torres, 2009). This is not surprising, because these patterns reveal both the structure of words and the syntactic structural rules of the language (for a review, see Arciuli, 2017). Because this information increases the learner's ability to predict what will come next in the language sequence, the ability to key into these patterns is fundamental to language proficiency.

Local Detail Processing and Algorithmic Complexity. In addition to the information that arises from the relationships between language sequence elements, the information held within an individual element (i.e., within words, or within syllables) can be a relevant source of complexity in human information processing. In natural sequences such as action or language, the intricacy of individual elements can have perceptual detail that must be processed with high perceptual resolution as well (e.g., Kosie & Baldwin, 2019), and this potentially contributes to information processing load. In the domain of language, infants learning their first language are faced with sounds that they must attend to in high-grain detail, in order to learn the language's phonology (Sundara et al., 2018); and their ability to discriminate these complex sounds predicts childhood language ability (Cantiani et al., 2016). Outside of early childhood, there are individual differences in phonological processing that persist (for a review, see Yu and Zellou, 2019). Therefore, the complexity of this within-element information is potentially significant in order to characterize the role of complexity in individual differences in language processing; making it important that this aspect of complexity is factored in when quantifying language complexity.

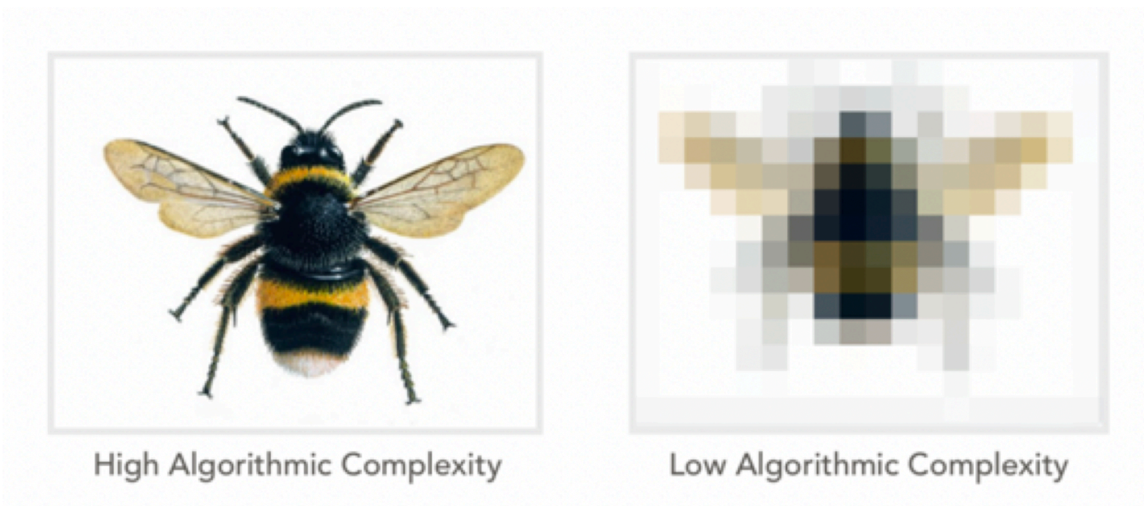
Algorithmic complexity, such as Kolmogorov Complexity (1965) factors in within-element information, making it a potentially useful measure for researching the impact of within-element complexity on perceptual processing (e.g., Meredith, 2012; Ellis et al., 2018) as well as a useful approach to defining complexity within language research (Goldsmith, 2001). This fills the gap left by Shannon's model, which did not account for the complexity due to within-element aspects. Algorithmic complexity quantifications define complexity as the length of the shortest computer program, the algorithmic length in bits, from which it is possible to reconstruct the information (Grünwald & Vitányi, 2010). For example, one sound or picture is more complex than another if its digital representation requires more bits, when the files are maximally compressed with lossless compression. This analysis provides an account of complexity that is both content/domain independent as well as observer independent. For example, it can be used to quantify complexity not only of sequences but also of any other information that can be represented digitally, such as images or procedural information; making it a highly versatile method for quantifying complexity. By this account, for a given quantity of information, lower compressibility corresponds to higher complexity; with highest complexity represented by a random sequence. Thus, algorithmic complexity, like information entropy, captures an information density aspect of system complexity. Consequently, information entropy and algorithmic complexity will often rank system complexity similarly, given equivalent complexity within the system elements; with both characterizing systems with few elements that repeat in a predictable pattern as low complexity, and systems with many unpredictable elements as high complexity.

However, algorithmic complexity, while it often coincides with information entropy measure of complexity, does not reliably correspond to subjective or intuitive ratings of complexity (Grassberger, 1986). For example, a digital image in high resolution will have higher algorithmic complexity than the same image in low resolution. However, if the difference in appearance between the two images is imperceptible, due to limitations of the human visual system, the information available to the perceiver, and therefore the complexity of the processing, may be equivalent. Furthermore, if the resolution of the image is reduced further (as shown in Figure 1.2) the algorithmic complexity will continue to decrease though the complexity subjectively will increase as the image pixelates and the image depicted becomes hard to identify. As a result, these information theory quantifications can be misleading unless their application to human perception is confirmed with assessment that factors in subjective aspects of perceptual ability. For example, one way in which researchers have measured perceptual complexity subjectively is by simply collecting participant ratings of stimulus complexity (e.g., Ellis et al., 2018). Alternatively, within the visual domain length of eye gaze and eye movements can provide a measure of an image's attentional capture (e.g., Nummenmaa, Hyönä & Calvo, 2006).

Balancing Between- and Within-Element Information. Additionally, there is evidence that the balance between the within- and between-element information processing may be a source of individual difference among learners. The balance of processing between these two types of information is atypical in some clinical populations, such as in autism spectrum disorder (ASD). Deficits in global processing ability may tilt the balance toward local processing for these individuals (Van der Hallen et al., 2015; Booth & Happé, 2018). The resulting perceptual emphasis on local features and weakness in global or contextual features could explain the deficits in learning from distributional cues seen in individuals with ASD (Scott-Van Zeeland et al., 2010). Thus, individual differences in the ability to cope with either of these two aspects of complexity has the potential to upset this balance and contribute to the individual differences seen in language ability.

Figure 1.2

Image of Honeybee with High and Low Algorithmic Complexity



Note. An illustration of mismatch between algorithmic and subjective complexity. The image on the left is higher in algorithmic complexity, while the picture on the right may be considered higher in subjective complexity.

Conceptual Complexity and Processing Meaning

As mentioned previously, aspects of complexity related to semantic and conceptual processing – complexity due to processing of meaning – are not factored into Shannon's (1948) model. Semantic-conceptual aspects of information were irrelevant to the intended engineering application, so they were excluded from Shannon's model (1948). Communication has meaning attached to it. This meaning, and therefore how informational the communication is, varies based on subjective measures of complexity. For example, the complexity due to semantic and conceptual processing may vary along with the relevance and/or surprising-ness of information (Baldi, 2002.) Thus, the processing of semantic and conceptual information will vary based on the receiver's prior knowledge. Further, other aspects of information may modulate the complexity of processing experienced by the receiver, such as the interestingness, pleasingness and beauty of information (Day, 1967; Friedenberg & Liby, 2016; Gauvrit, Soler-Toscano & Guida, 2017). For example, the words of an artfully phrased poem may be processed for longer and more deeply than standard prose. Thus, not only prior knowledge but also other receiver-dependent factors may alter how complex it is for a particular individual to process information.

Measuring Subjective Complexity. While the measurement of subjective aspects of complexity is inherently difficult, researchers have devised ways to quantify semantic/conceptual aspects of complexity in language processing. Cognitive effort during language processing can be quantified with pupillometry (Engelhardt et al., 2010; Chapman & Hallowell, 2015). The brain's electrophysiological response to language provides a measure of semantic processing, with the amplitude of the N400 component tracking word expectancy or surprising-ness of a word (Kutas & Hillyard, 1980, 1984; Kutas & Federmeier, 2011). Preferential processing of word onsets can be observed in the electrophysiological response during passive listening to native language continuous speech, with a higher amplitude N1 to a linguistic probe elicited by word onset syllables

(Astheimer & Sanders, 2009, 2012). These methods provide well-established approaches to measuring semantic and conceptual aspects language processing from the receiver's perspective.

Objective Quantification of Conceptual Complexity. However, an alternate approach is to provide an objective measure of conceptual information with mathematical models (Feldman, 2000, 2006; Aitkin & Feldman, 2006; Vigo, 2011, 2013). Such mathematical measures of conceptual complexity provide researchers a means to quantify conceptual complexity as a receiver-independent measure. For example, Boolean complexity is an analog of algorithmic complexity in that both define complexity as the size of representation at maximum compression. Conceptually reminiscent of Shannon's (1938) use of Boolean algebra to simplify systems of flip switch circuits, and a logical analog of algorithmic complexity (Feldman, 2006), Boolean complexity quantifies conceptual information as the length required to express all positive instances of a concept at maximal compression, known as the concept's "minimal formula" (for a review, see Feldman, 2003). Research indicates that concepts with higher Boolean complexity are harder to learn (Feldman, 2000; 2006), supporting the use of this mathematical modeling approach to quantify conceptual complexity. Category learning is relevant to complexity in language because learning categories can reduce complexity in processing. For example, words with certain endings may be verbs. Particular syllables may be word final and signal that the next syllable will begin a new word. These mathematical accounts pave the way for research to investigate the role of complexity in learning by providing techniques to structure experimental stimuli with strategically varied amounts of complexity and conceptual difficulty.

Complexity in Language Learning

Including semantic/conceptual and perceptual aspects of complexity provides a more complete conceptualization of complexity in language, filling a gap left by information theory accounts that model complexity as a receiver-independent characteristic of the system. However, including these subjective measures results in a model of language complexity that is no longer a characterization of the system's objective complexity, as they had been in Shannon's computation (Baldi, 2002). Instead, an account that includes subjective aspects of complexity models the complexity experienced by the receiver. If complexity depends upon probability, and if the goal is to understand the receiver's ability to cope with complexity, then the probabilities upon which to base the quantification of complexity are those experienced by the receiver, particularly when the goal is to understand the impact of complexity and the individual differences of it among learners. However, an implication of this shift concerns the stability of the probabilities. Shannon's (1948) model assumes probabilities across the sequence are stable, i.e., that the system is an ergodic process. Using probabilities to quantify complexity relies upon this assumption. For natural language processing between two expert speakers, this assumption that language probabilities are stable across time may provide a reasonable approximation. In natural language processing there will undoubtedly be some local fluctuation in predictability across the sequence. For example, we may be less able to predict what someone will say during the first words of a conversation than we are a few moments into the interaction. If someone is speaking about the weather on a cloudy day, words such as "rain" and "galoshes" will be more probable. However, on a global language system level, it is reasonable to assume that the probabilities as experienced by an expert native receiver are approximately stable. For example, from one day or week to the next, the complexity will be about the same.

Complexity in Language Learning is Dynamic

For language learning, however, the assumption that the probabilities of language are stable across time is less straightforward to assess. A primary reason for this lack of straightforwardness is that the learner's understanding of the system grows with exposure. Consequentially, their ability to predict what will occur next in the sequence is ever-increasing. For example, from the new learner's perspective upon first exposure to a new language, the probability of each element is equal during the first moments. From their perspective at first exposure, it is as though the stream is random; because no prior information has yet passed to reveal the system probabilities. They have no ability to predict what will come next. Then, as exposure continues and they track the regularities of the system, they develop the ability to predict which elements are likely to occur next in the sequence. Therefore, if the probabilities are represented (considered) as they are known to the receiver, it follows that complexity (as entropy) changes with learning., as a result of the increasing ability of the learner to predict what comes next in the sequence.

Complexity as a Learner-Based Measure

This updating of predictability that accompanies language learning needs to be factored into the conceptualization of complexity in language, in order to understand the role of complexity in language learning. The probabilities of language as they are experienced by the receiver are impacted by the informativeness and relevance to the receiver. For example, the statement that polar bears live at the North Pole is not particularly information-rich if that fact is already known to the receiver (Attneave, 1959). However, for someone who had previously believed that polar bears live only at the South Pole, this statement may be more informative, and therefore more complex to process. Thus, complexity decreases as prior knowledge increases, iteratively updating with each newly acquired bit of information. In this way, learning language lowers the complexity experienced by the learner, as their ability to predict what comes next in the language sequence increases with learning.

Regarding level of subjective complexity, it is important to note that, in some instances it is possible that learning could increase subjective complexity. This is because learning can open up new levels of interpretation. For example, a lecture in quantum mechanics in Hungarian may be more complex to process for someone who has learned Hungarian, than to someone who has not.

Complexity as Distance from Current Model. This conception of human learning as iterative updating of an internal predictive model is consistent with the prominent neuroscience theory of predictive coding, which holds that the nervous system forms predictive internal models and only processes that which violates the models' prediction, thereby maximizing efficiency by reducing redundancy in processing (for a review, refer to Huang & Rao, 2011). From this perspective, complexity in language processing would be seen to decrease as the learner's internalization of the language system probabilities increasingly aligns with the objective probabilities of the system, resulting in fewer errors in prediction. As this happens, the need to process would be minimized due to the higher accuracy of the internalized model.

Complexity as Surprise. A term used to capture this receiver-dependent aspect of complexity that varies based on prior knowledge is "surprise", a measure of information that factors in the updating to prediction that occurs as a result of learning. Conceptualizing complexity as surprise provides a characterization of complexity that captures the updating of predictability that happens with language learning. However, surprise, like complexity, is a term that is used to cover multiple constructs. For example, surprise is used to refer to the experience of novelty, uncertainty, or expectancy violation (for a review, see Munnich, Foster & Keane, 2019). Thus, multiple characterizations of surprise have been necessary to cover these multiple aspects.

A Bayesian Model of Surprise. In a recent series of studies, Baldi and Itti propose an observer-dependent Bayesian computational model of surprise. Using human participants (Baldi, 2002; Itti & Baldi, 2006) as well as neural nets (Baldi & Itti, 2010) they demonstrate that surprise attracts attention in visual scenes. By their account, the surprise ("relative entropy") contained in an event is a measure of the change from receiver's prior to posterior belief as a result of the event (Baldi, 2002). Their mathematical computation of surprise, based upon Bayes theorem, can be applied to model instable systems, in which beliefs have ongoing instability, as well as to model systems that have beliefs evolving toward a stable value (Baldi & Itti, 2010), such as language during acquisition. Thus, their Bayesian surprise model has the potential to characterize both the fluctuations that characterize natural language processing and the changes that occur with language learning.

Modeling Group and Individual Differences. The Bayesian neural net approach from Baldi and Itti (2010) demonstrates a methodology with which it would be possible to explore the impact of complexity on individual differences in language learning, applying modern machine learning methods to continue early foundational work by

Elman (1990, 1993) that applied this methodology to understand language learning and the development of language, using an early recurrent neural net. Elman's "starting small" theory (1993), holds that infants' smaller cognitive capacities lead to a more gradual rather than complex-at-start learning of the language system; and that this more gradual onset learning results in a more successful acquisition of complex systems such as language due to better network development. Elman (1993) demonstrated that this more graduated onset resulting from smaller working memory constraint made language more learnable by artificial connectionist networks. Input to the network was composed of sentences with high-complexity linguistic structure (e.g., complex sentences, clauses, number and verb agreement). When he set these networks to start with a constrained working memory that gradually increased as learning progressed, they trained successfully. However, when these networks instead started in their fully formed state, they failed when trained on the language. These findings could indicate that the cognitive limitations of childhood may be necessary for acquisition of at least some complex systems such as language (Elman, 1993). While it is important to note that subsequent research has indicated a need to qualify under what conditions "starting small" coveys an advantage (Rohde & Plaut, 1999; Westermann & Ruh, 2012; Brooks & Kempe, 2019), Elman's (1990, 1993) recurrent connectionist modeling offers an approach to fine-tuning understanding of the role of complexity in language learning.

Tracking Individual Differences in Complexity Preference. Kidd, Piantodosi and Aslin (2012) developed an information-theoretic model of surprise (as "surprisal"; Levy, 2008) to model the change to complexity during an infant sequential learning task. They measured seven-month-old infants' preference for complexity level in a visual sequential learning experiment. They tracked infants' looking time to videos that showed event sequences of visual stimuli consisting of simple patterned blocks occluding common objects (e.g., a bottle or ball). As infants watched the sequence, these common objects appeared, or did not appear, based on patterns learnable through transitional probability. Results of this experiment confirmed the researchers' prediction that infants look longer to events of medium surprising-ness. This indicated that, rather than learning passively, infants were strategically attending to information content that was of medium complexity in relation to their current knowledge state; thus supporting the researchers' "Goldilocks hypothesis," that complexity is optimal for learning when it is at a sweet spot in the middle, the level at which events are not so simple that they are uninformative, yet not so complex that they are too different from previous events to be learnable. An insight from this experiment to individual differences in language learning is that a preference for a particular complexity level may impact learning efficiency (Kidd et al., 2012).

Subsequent work by this group indicates that a similar preference for medium-level surprising-ness influences infant auditory experience as well in an auditory artificial language, suggesting that preference for particular complexity could play a role in language learning (Kidd et al., 2014). Rather than modeling complexity of the system as an ergodic process, this approach, like Baldi's (2002) computational theory of Bayesian surprise, models the complexity experienced by the processor or learner as a receiver-dependent, dynamic process. Following up on their initial analyses reported in their "Goldilocks" paper (Kidd et al., 2012), these researchers analyzed the individual differences in preference for complexity seen in these data in order to gain insight into how a preference for complexity may drive individual learning efficiency (Piantodosi, Kidd & Aslin, 2014). By tracking infants' individual learning as an on-line measure, Kidd and colleague's methodology allows for an analysis of an infant's individual complexity preference, an approach that provides insight into how infants' differences in individual complexity preference impacts infant learning.

Implications for Research

By factoring in the learner-dependent measures, these complexity-as-surprise approaches, or what could more generally be termed "experiential complexity" approaches, i.e., approaches to understanding complexity that consider the online updating of complexity experienced by the learner, are poised to provide a more accurate depiction of complexity in language learning than do models that consider only the complexity of the language system. In several ways, they highlight or reveal key direction for future research to progress knowledge on these topics.

The Importance of Factoring in the Learner

The learning-adaptive models of complexity, such as the artificial language learning work from Kidd and colleagues (2014) and those that similarly characterize complexity as surprise (e.g., Itti & Baldi, 2006), provide new methods that can be applied not only to gain insight into complexity's role in language learning, but also suggest next questions to explore complexity's contribution to the individual differences seen in language learning.

The Importance of On-Line Measurement

This research from Kidd and colleagues additionally illustrates the usefulness of on-line tracking of learning. They use an artificial language paradigm. Artificial language paradigms are frequently used to investigate questions about individual differences in language learning; and in this case they have innovatively adapted the paradigm in order to track individual infants' preference for complexity during the sequence learning task. Their findings demonstrate that additional information about the individual differences can be accessed by observing the learning as an on-line dynamic behavioral streaming measure, rather than as a post-learning outcome measure.

The Importance of Examining Learning at Multiple Complexity Levels

By tracking infants' individual learning as an on-line measure, Kidd and colleague's methodology allows for an analysis of an infant's individual complexity preference, an approach that provides insight into how infants' differences in individual complexity preference impacts infant learning. Research methodologies that employ on-line measurement, such as Kidd et al.'s (2012, 2014), have been increasingly recognized as important tools for understanding learning and individual differences in learning. As will be described in the next chapter, artificial languages combined with neuroimaging technologies make this on-line tracking of learning possible. As described above, the inclusion of multiple levels of complexity in the work with adults by Itti and Baldi (2006) as well as with infants by Piantodosi and colleagues (2014) contributed insight into how complexity can impact individual differences in learning.

CHAPTER II

ON-LINE LANGUAGE LEARNING AS A WINDOW INTO INDIVIDUAL DIFFERENCES

Researchers use natural language in studies investigating many aspects of language processing. However, natural language is not as useful for addressing research questions that investigate the initial moments of language acquisition, when the listener is first exposed to a new language. This is because the complexity of natural language makes the time course of these early learning processes as they occur in natural language too lengthy to be observed within the laboratory. Thus, to examine the processes that occur during the earliest phases of language learning, languages miniaturized for laboratory research, often referred to as "mini languages" are frequently employed. While some mini languages are natural-based languages with reduced lexicon and with such complexity that they take hours or even weeks to be learned proficiently (e.g., Mueller et al., 2005, 2006, 2007, 2009; Poulsen et al., 2011), some are artificial languages created by researchers for the purpose of laboratory language learning research. Artificial languages vary greatly in complexity, with some taking days or weeks to be learned proficiently. Other, such as “artificial grammars” (of which Kidd and colleagues’ research provided an example) are so simple that they can be learned within minutes. An example artificial grammar from Saffran and colleagues (1997) is shown in Figure 2.1. In a commonly used soundstream listening paradigm, the artificial "words" are concatenated and presented in a multi-minute continuous stream. Findings of this research reveal that listeners can segment streams of these artificial grammar syllables by implicitly tracking distributional regularities within these sequences to "statistically learn" the artificial grammar system. Naturally occurring dips in transitional probability between the artificial words cue the location of word boundaries (Saffran, Aslin and Newport, 1996; Saffran et al., 1997). Subsequently researchers have added hierarchical structures and cues in order to finetune understanding of the boundaries of human statistical learning capacities (e.g., Peña et al., 2002). This sensitivity to distributional cues in speech has been shown to be present from birth (Teinonen et al., 2009) and to continue through the lifespan (Saffran et al., 1997; Neger et al., 2015).

Figure 2.1

Example Stimuli Used for Artificial Grammar Research

Words	Nonwords
babupu	batipa
bupada	bidata
dutaba	dupitu
patubi	pubati
pidabu	tipabu
tutibu	tapuba

Note. The artificial grammar shown here is from Saffran and colleagues (1997).

Importantly, while this ability to learn linguistic systems by tracking their distributional patterns (i.e., distributional cues) was first identified in the auditory domain, subsequent research has revealed that this ability to track system distributional information crosses domains: individuals across ages are able to implicitly track non-linguistic auditory patterns (e.g., Abla et al., 2008) as well as to learn distributional properties of visual stimuli (Saffran et al., 2007; Campbell et al, 2012) and to track co-occurring events to discover boundaries in action sequences (Baldwin et al., 2008). Thus, what is learned from the study of statistical learning of artificial grammars has the potential to inform regarding how acquisition of other streamed information systems takes place.

While it is less known to what extent statistical learning abilities are recruited for the learning of natural language, the artificial grammar (statistical learning) research provides an account of early word learning: listeners implicitly track that the sound combinations within the words of the language occur together more frequently than those sounds that occur between words; by tracking these patterns of co- occurrence, listeners develop an implicit recognition of which sounds likely combine to form meaningful units of the language. For statistical learning research, artificial grammars are typically presented in a soundstream, a paradigm that will be referred to in this dissertation as the soundstream listening paradigm. The words and structures of the sequential system are acquired within a few minutes of exposure. Word-level learning is usually measured behaviorally by participants' ability to distinguish the artificial "words" from "nonwords" or "part words" on a forced-choice test. "Part words" are syllable combinations heard within the soundstream that cross word boundaries. For example, a part word could contain the final syllable of one word and the initial and medial syllable of another word, as represented by the distributional properties within the soundstream; while nonwords are groupings of syllables that did not co-occur in the soundstream (Saffran et al., 1997).

It is important to note that the structure of this forced-choice testing provides a measure of implicit learning, thus providing a glimpse of the listener's early learning, able to provide a measure of learning even before the learner is aware they have begun to acquire the linguistic system. The simplicity of artificial grammar accelerates learning so the entire acquisition can happen within a single laboratory session, increasing experimental control and easy research acquisition. Thus, even though artificial language reduces the naturalistic aspect of the research, it is widely used to explore questions about early language learning and has led to revised learning account of language acquisition.

Neural Indices of On-Line Language Learning

Adding electrophysiological recording to the soundstream listening paradigm, the entire process of artificial grammar learning can be recorded online; allowing a glimpse of the actual learning process, including the electrophysiological changes that co-occur with learning. From this research, electrophysiological indices of artificial grammar on-line learning have been identified. These electrophysiological changes are thought to track component mechanisms of on-line language learning processes.

Higher N1 to Word Initial Syllables (N1 Word Onset Negativity)

The development of higher amplitude N1 to word-initial syllables is associated with the development of soundstream segmentation (Sanders et al., 2002, 2009; Abla et al., 2008) The N1 word onset negativity has been reported in a variety of level natural language processing contexts, in addition to during artificial grammar learning. For example, Sanders and colleagues observed it in a natural language listening paradigm, with word onset syllables eliciting a higher N1 in native but interestingly not in nonnative speakers (2003a; 2003b). This negativity is seen as a higher N1 to word onset syllables. It is sometimes referred to as the word onset negativity (Sanders et al., 2002). In some artificial grammar research, a window of latency 40-200ms post syllable onset has been found to be sensitive to the increase in negativity that develops to the word initial syllable as segmentation occurs.

In the artificial grammar context, the N1 word onset negativity has been reported to emerge in paradigms during which participants receive explicit artificial word learning, including explicit word boundary instruction (e.g., Sanders et al., 2002). However, during online artificial language learning, for which segmentation must be accomplished by soundstream listening alone, it sometimes does not appear (Cunillera et al., 2009); or does appear, but with amplitude not consistently correlating with behavioral learning measures but instead showing a transitory significant correlation at the time word learning occurs (Abla et al., 2008).

The overall pattern of results appears to point to a higher level of language system expertise being required in order for the N1 component to appear. Consistent with this idea is research by Sanders and colleagues (2009). They recorded EEG during soundstream listening before and after training, with training ending not after a set exposure duration but rather after participants performed well (minimum 89% accuracy) on a behavioral measure of learning (Sanders et al., 2009). In contrast, in Cunillera et al.'s (2009) study in which the N1 word onset effect did not appear, participants scored only mean of 67.3% accuracy in a comparable post-training forced choice test for the study in which they found no significant difference in the post-training N1 amplitude develop. Instead, Cunillera et al. (2009) did not observe a change in the N1 amplitude either as learning progressed during the experiment or between conditions (syllables in language and in random streams) with no higher amplitude N1 discernable to word initial syllables at any time during their experiment.

More recently a series of natural language experiments conducted by Astheimer and Sanders suggest that this higher N1 indexes an attentional or preferential processing at times of word onsets: native speakers appear to modulate their attention temporally during speech processing, using their expert knowledge of the language system to detect moments in the soundstream at which there is a drop in transitional probability, such as word onsets, and devoting a quick burst of attention at these moments, the points in the speech stream that are most likely to be information-rich (Astheimer & Sanders, 2009; 2011). The N1 component is well documented as an attentional effect (Hillyard et al., 1998; Makeig et al., 2003). Thus, research converges to characterize the higher N1 amplitude to word initial syllables as a temporal modulation of attention to allocate more attention to the segments in the soundstream that are predicted, to be more informational.

The "Learning N400" as an Index of Word Learning

The most commonly reported component to emerge during soundstream listening is a medial frontal N400-like negativity. When adults listen to a sequence of artificial language syllables with embedded words discoverable by distributional cues, this negativity develops to word-initial syllables relative to comparator syllables and has been suggested to index word learning processes. It emerges within minutes of first exposure, appearing as a higher amplitude broadly focused medial frontal negativity to word-initial syllables relative to word-medial syllables or to syllables in a random stream (such as in an unlearnable stream of syllables used as a control) and has a latency of approximately 250-500ms after word onsets. In the context of soundstream listening, this negativity appears to track word learning and generally shows a pattern of increase in amplitude during initial minutes of exposure and then decrease in amplitude as exposure continues (e.g., De Diego-Balaguer et al., 2007; Abla et al., 2008; Cunillera et al., 2009). Cunillera and colleagues (2009) refer to this component as the "Learning N400" to differentiate it from the Semantic N400 (Kutas & Hillyard, 1980), which has a central-parietal focus and which is thought to index processing of semantic or other meaningful content (for a review, see Kutas et al., 2011). In contrast, this Learning N400 that appears during the soundstream listening task has a more anterior focus and emerges in the absence of semantic information (although detecting word boundaries through distributional cue tracking in some ways resembles learning of semantic meaning). These distinctions between the two components appear to indicate that this Learning N400 component is distinct from the Semantic N400 component that was described by Kutas and Hillyard (1980).

Conclusions

The inclusion of electrophysiological measurement in artificial grammar learning research studies has led to a better understanding of the attentional and evaluatory dynamics underlying language learning and to the individual differences in the language learning process. However, there are still unresolved questions regarding the extent to which the results from artificial language research studies may be generalized to natural language processing. First, because these very simple artificial languages can have as few as four words with each word presented over 20 times per minute, and with the artificial words typically following a strict pattern (for instance all words having three syllables and each syllable one consonant followed by one vowel) it is important to investigate to what extent the processing of these artificial grammar resembles acquisition of real language.

Second, during natural language acquisition, the learner receives a wide array of cues all put together from the onset of exposure. In the natural language immersion learning situation the listener is utilizing all of these cues in combination to learn to segment the language. Artificial language allows researchers to strategically isolate cues by eliminating others, and this allows for the teasing apart the ERP indices associated with different component language processes. However, through this process of isolating cues the learning process may no longer be the same as in natural language, because in natural language the cues may be used in combination, escalating the learning process. In order to confirm that research findings about language processing through these studies utilizing artificial language stimuli can be generalized to natural language learning, it would be very useful to observe the electrophysiological patterns that emerge during on-line learning with a language that more closely approximates the properties of natural language. Particularly given the low complexity of the artificial grammar stimuli, and considering that language learning difficulties may arise as a result of the perceptual and cognitive challenges faced by the learner due to the complexity of the natural language signal, it is important to examine the on-line process of learning with language stimuli of higher complexity.

The Micro Language Approach (Dissertation Overview)

To provide further insight into the nature of the individual differences as learners acquire a new language, as well as to increase understanding into how learners differ in their ability to cope with complexity during the initial moments of learning a new language, the exploratory research presented in this dissertation used a novel "micro language", a native-spoken natural-based language with the lexicon greatly reduced. A main goal of this work was to observe the changes that occurred during learning of the seminatural language stimuli. For the current research, adult participants progressed through four phases of training language, while dense-array EEG and frequent behavioral measures of learning were recorded, thus providing on-line electrophysiological tracking of their learning. It took about an hour of exposure to acquire the language system. For the first learning phase (*Phonological Familiarization*), participants listened to a soundstream of the micro language phrases and became familiar with the sounds and patterns of the language. For the second phase (*Semantic Mapping*), participants listened to the phrases paired with pictures to represent their meaning. Next, for the third training phase *(Semantic Use Practice)*, participants performed a simple matching task, for which they saw a picture and heard a phrase, then pressed a key to indicate whether the picture and phrase matched or mismatched, thus engaging them in the use of the language to facilitate active learning. In the fourth phase *(Comprehension Listening)* participants again listened to the micro language soundstream, now able to comprehend the phrase meanings.

Dissertation Research Strategy

The micro language strategy was to preserve features of a natural language system while minimizing the lexicon enough to conduct an on-line learning experiment using the soundstream listening paradigm; and then to extend the paradigm to include later phases of learning. The goal was not only to test for replication of the artificial grammar experiment findings with natural-language-based stimuli, but also to extend the investigation into expert learning. This approach intended to provide more insight into what the electrophysiological indices of soundstream learning, which have been identified in artificial grammar research, represent; as well as to better characterize the individual differences that exist in natural language learning processes.

The purpose of the lexicon reduction was to accelerate learning and therefore to increase the proficiency that participants reached by the end of the session. In addition to the on-line electrophysiological measurement, frequent behavioral measurements were collected, in order to provide a fine-grained picture of the co-emergence of the electrophysiological components and the language acquisition they indexed. Thus, the underlying strategy was to accelerate the brain changes in order for the electrophysiological indices of on-line learning to emerge within the one-session (four-phased) experiment, and to relate these changes to the course of language system acquisition.

Regarding the role of complexity in language learning, the micro language phrases had two levels of phrase complexity, with half of the phrases possessing high complexity and half low complexity, to make it possible to explore the impact of varying levels of complexity on learning. Therefore, this micro language approach, as a hybrid of natural miniature language and artificial grammar approaches, offered a new, exploratory glimpse into the processes of natural language learning by enabling the on-line capture of the learning processes of naturalistic language stimuli, as well as by providing the opportunity to explore the impact of complexity. The organization of the language system into two levels of phrase complexity (simple and complex) was with the intent to explore the extent to which complexity differentially impacted learners of higher and lower language learning ability. It was thought that a different pattern of individual differences might emerge at a higher level of complexity than at a lower level of complexity, thus providing additional information provided by the on-line research that uses the highly simple artificial grammars.

Micro Language Development and Seminatural Characteristics

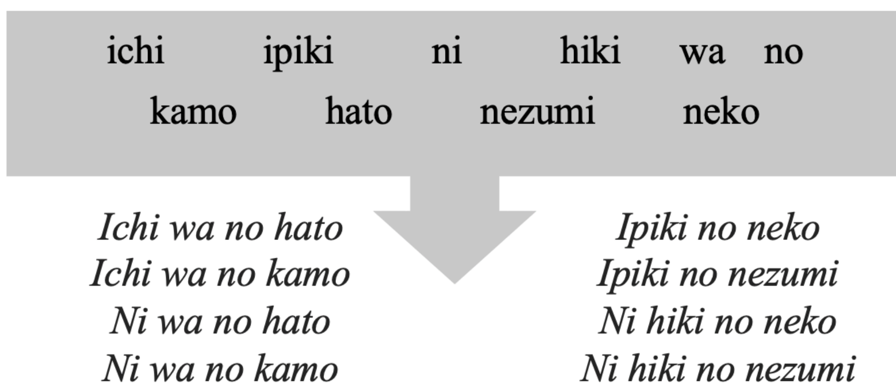
Micro Language Origins. To develop the micro language, prior empirical research using natural miniature language was reviewed in order to find a miniature language suitable for adaptation to the planned on-line soundstream micro language paradigm. The "Mini Nihongo" mini Japanese language developed by Mueller and colleagues and used in a series of (off-line) language learning experiments (2005, 2006, 2007, 2009) was selected for adaptation. The Mini Nihongo language stimuli were sentences of approximately 20-25 syllables in length. The micro language stimuli derived from Mini Nihongo were pared down to phrase stimuli of 5-7 syllables. For example, the Mini Nihongo sentence “Ichi wa no hato ga ni hiki no neko wo oikakeru tokoro desu” became “Ichi wa no hato” in the micro language. The entire micro language consisted of eight phrases, shown in Figure 2.2.

Micro Language Structure. The eight micro language phrases contained four nouns in the two categories of birds and small mammals: *hato* (pigeon), *kamo (*duck*)*, *nezumi* (rat) and *neko* (cat); two numbers, *ichi* (one) and *ni* (two); and three support words: *wa* (numeral classifier for birds), *hiki* (numeral classifier for small mammals) and *no* (a genitive particle following the numeral classifier, which translates approximately to "of" in English). In addition, *ichi* followed by *hiki* contracted to *ipiki*.

Two Levels of Complexity. These categories represented two levels of phrase complexity. It was expected that the bird phrases would be easier to learn due to their simpler structure: each phrase had “wa no” preceding the noun, and all bird phrases

Figure 2.2

Micro Language Lexicon and Phrase Structure



Note. The micro language was a pared-down version of Mueller and colleagues’ Mini Nihongo language (2005). The lexicon reduction allowed for use within an on-line soundstream listening paradigm. Bird phrases (simple phrases) are on the left; small mammal (complex) phrases are on the right.

contained only one or two syllable words. In contrast, the more difficult mammal phrases contained one, two and three-syllable words; as well as a subtle phonological distinction between the “ne” in “neko” and in “nezumi”, and the syllable “ki” occurring in two different words.

These phrases were recorded by a male native Japanese speaker, as will be described in Chapter 3. However, it is important to note that in natural Japanese, these phrases would always include a case marker. For example, the syllable "ga" added to the end of the phrase would identify the phrase as nominative (i.e., subject of a sentence). In order to minimize the linguistic structure and to have the nouns appear at the end of the phrase (to accelerate noun segmentation), the case marker was removed. Thus, these sentences, while spoken by native speaker and containing structure consistent with Japanese, should be considered *seminatural*, rather than natural language stimuli.

The micro language system's phrase structure was highly predictable, with the word denoting number always the first word in the phrase and the noun always the final word. The stark linguistic reduction and high structural regularities together were intended to accelerate learning while producing a seminatural linguistic system that was comparable in size to the artificial grammars typically used in on-line soundstream learning paradigms (e.g., Saffran et al., 1996); yet they retained natural language features, such as natural acoustic and temporal variation. Neither orthographic training nor English translations were provided to participants at any time during the session. The entire language system was intended to be learned to proficiency in about an hour of exposure.

Dissertation Research Aims and Hypotheses

The overarching goal of the current research was to better understand the contribution of complexity to the difficulty some individuals have in the acquisition of complex, natural information systems such as language. To achieve this goal, this dissertation had the following three aims.

Aim #1 was to characterize novice learning as participants listen and develop initial phonological familiarity to the new language. Analyses for this aim focused on the Soundstream Listening phase. Normative questions for this aim included whether systematic N1 and Learning N400 components emerged to word-initial syllables, and whether these components interacted with phrase complexity. Individual differences questions that this aim addressed included whether participants with different learning profiles displayed systematic differences in regard to N1 and Learning N400 components and whether such learner differences interacted with phrase complexity.

Aim #2 was to characterize the development of expertise as learners practiced a new language system. These analyses focused on the semantic use practice phase. This aim explored whether the Learning N400 component tracked surprise, a learner-based measure of complexity, as indexed by participants' semantic use practice reaction time. Reaction time provided an online (trial by trial) behavioral measure. It was expected that participants would have faster reaction times as they developed expertise with the language system.

Aim #3 was to characterize the changes that emerged between the phonological familiarization phase (Phase 1) and the comprehension phase (Phase 4). Normative questions for this aim included whether systematic N1 and Learning N400 components emerged to word-initial syllables, and whether these components interacted with phrase complexity. Individual differences questions included whether participants with different learning profiles displayed systematic differences with regard to the post-training appearance of the N1 and Learning N400 components and whether such learner differences interacted with phrase complexity.

To summarize, the first aim investigated novice learning during the initial moments of exposure to the micro language phrases before the system has been acquired. The second, exploratory aim focused on the development of expertise, as learners practiced the newly acquired language system. The third aim sought to identify to what extent differences in processing and proficiency persisted after training was complete, as participants listened to and comprehended the newly learned phrases in the post-training phase.

Analyses investigated the hypothesis that the previously identified neural indices of early language learning would appear in response to newly learned naturalistic micro language as they do in response to artificial grammar word onsets; and that the previously identified electrophysiological indices of language learning would track explicit measures of word learning. Further analyses tested the hypothesis that level of stimulus complexity would differentially impact learners' ability to acquire the micro language. The following sections describe the purpose, research questions and hypotheses for each phase of the current research.

Phase 1, Phonological Familiarization

During the phonological familiarization phase (Phase 1), participants listened to a soundstream of the micro language phrases. It was expected that they would discover the words and structures of the language during this phase, through exposure to the soundstream and the cues present in the naturalistic language stimuli. Analyses tested the hypothesis that previously identified electrophysiological indices of language learning would emerge during this phase and track participants' processes of early language learning, replicating findings in the artificial grammar research. These indices include the N1 word onset negativity (Sanders et al., 2002, 2009), represented in the current research also as a broader 40-200ms interval; and the Learning N400, a later N400-like medial frontal negativity (Cunillera et al., 2009).

As discussed previously in Chapter 2, the N1 word onset negativity has been shown to develop during artificial grammar learning paradigms as participants reach high proficiency through both on-line learning (Abla et al., 2008) and explicit word training (Sander et al., 2009) paradigms. A similar higher N1 to word onsets is seen in natural language processing, and there is evidence that it is an attentional effect (Astheimer & Sanders, 2009), with proficient listeners using their language structure expertise to anticipate points in the sequence most likely to contain higher information and preferentially processing those points in the sequence. For the N1 peak and 40-200ms interval, it was predicted that word onset syllables (represented in these analyses by the noun initial syllables) would develop a higher amplitude N1 in comparison to (noun) medial syllables. It was expected that the N1 word onset negativity would develop as participants discovered the linguistic structure and became proficient enough to anticipate when the noun onsets would occur. This higher N1 to word onset syllables is notably absent in non-native (later-acquired) natural language processing (Sanders & Neville, 2003a, 2003b). However, it is expected that the simplified structure of the micro language stimuli will increase the predictability of the syllable onsets enough to create a task that is more similar in difficulty to that of artificial grammar learning, in which this higher N1 does emerge.

The later N400-like medial frontal negativity, referred to by Cunillera and colleagues (2009) as the Learning N400 to distinguish it from the Semantic N400 component (Kutas & Hillyard, 1980), develops within initial minutes of exposure to the artificial grammar sequences. This ERP component, generally measured in the artificial grammar research as the amplitude difference between word initial and other syllables, appears to track the word discovery process, increasing as learning engages and then decreasing after word learning is accomplished. For the Learning N400 (N400-like component with medial frontal distribution), it was predicted that during the soundstream listening phase, noun onset syllables would develop higher amplitude negativity relative to noun medial syllables during the N400 time window, and that this negativity would decrease in amplitude after learning. This would replicate findings from prior on-line artificial grammar learning research that use a soundstream listening paradigm (e.g., Alba et al., 2008; Cunillera et al., 2009).

Because prior research has provided evidence that these ERP components track the word learning process, it was predicted that they would correlate with the behavioral learning measures, developing sooner and stronger with higher learning. However, it is important to note that the current research measures a more explicit behavioral measure (recall ability) than did the artificial grammar research paradigms. These artificial grammar paradigms typically measure a forced choice familiarity test which has been shown to correlate with the amplitude of the early (N1) and later (N400-like) ERP components. The explicit recall approach was adopted to collect mid-learning assessments while avoiding the presentation of language violations that could have interfered with the learning process. It was unclear whether the more explicit recall measure used in the current research would have a different association with the electrophysiological changes that accompany early learning.

Regarding the role of phrase complexity in learning, the two-tiered phrase complexity levels (simple and complex) were expected to produce examples of successful and unsuccessful language learning. Based on piloting, most participants were expected to learn the simple phrases successfully by the end of the fourth phase of the experiment; and some participants were expected to be less successful at learning the complex phrases. It was expected that high and low learners might show interesting differences in learning at these two levels of difficulty, both as measured by their behavioral learning performance and as tracked by these two ERP components; and that these differences might provide insight into why some individuals were more successful at the learning task.

Phase 2, Semantic Training. During the second phase, participants continued in their exposure to the phrases and additionally received pictorial training of semantic mappings for the phrase meanings. The primary purpose of this phase was to provide semantic training for the participants. A secondary purpose of this phase was to collect behavioral measure of learning in the form of a training log that was completed by participants upon completion of this training phase. Although EEG was recorded during semantic training, the electrophysiological data was not analyzable as event-related potentials (ERPs) due both to the small number of trials (104), and to participants verbally repeating phrases as they looked at the images that represented their meaning, creating movement artifact.

Phase 3, Semantic Use Practice. During the third phase, participants performed a simple matching task ("game") that engaged them in semantic use of the phrases. This phase had the purpose of engaging participants in active practice of the language system to develop expertise. Additionally, it had the purpose of collecting an on-line behavioral (reaction time) measure of language learning during the development of language system expertise as well as a behavioral measure of language system proficiency (task accuracy). These online behavioral measures will be used for complexity exploratory analyses.

Phase 4, Comprehension. For the fourth phase, comprehension listening, participants listened to the same soundstream they had been exposed to during the soundstream listening task. They were instructed to try to comprehend the phrases during listening. It was expected that a Semantic N400 would develop to noun onsets by this phase, reflecting that participants not only listen to the phrases but additionally process their meaning.

Regarding the N1 word onset negativity during comprehension listening, in the natural language literature, the higher N1 to word onset syllables has been observed in native but not non-native speakers (Sanders et al., 2003a, 2003b.) It was predicted that noun initial syllables would elicit a higher amplitude N1 in comparison to noun medial syllables after learning to high proficiency. A learner-type difference was expected, with a higher N1 to noun initial syllables predicted to develop in high learners and not in low learners; based on the prior findings that this effect emerges with development of expert level proficiency (e.g., Sanders et al., 2009).

The next chapter will describe the method used to acquire the data for the current research. It will include details about the structure of the micro language.

CHAPTER III

METHOD

Participants

Thirty-two adults were recruited via a study pamphlet distributed at the University of Oregon and in the surrounding community. The pamphlet described a one-session, paid language experiment with a miniature Japanese language lesson and concurrent electrophysiological recording. All participants provided written informed consent before taking part and were compensated $30. Institutional Review Boards of the University of Oregon and Electrical Geodesics, Inc. (EGI) approved the research protocol. Data from six participants were excluded from all analyses. Of these, three participants did not meet inclusion criteria (two were left handed and one was a non-native English speaker); two had data files with trial specification corruption that interfered with data processing; and one participant's data had excessive movement artifact.

The remaining 26 (13 male) participants contributed data to the analyses reported here. All were native English speakers. Participant recruitment aimed to provide a diverse sample to capture individual differences in learning. Age ranged from 20 to 76 years ($M = 29.4$, $SD = 14.5$) and years of education from 12 to 18 years ($M = 15.9$, $SD = 1.42$). Participants completed the Edinburgh Handedness Inventory to confirm right dominance. Their laterality quotient ranged from 37.5 to 100 with a mean of 80.6 and standard deviation of 16.9. Eight participants reported having at least one left handed biological parent or sibling.

Participants' prior language experience was collected through a study-specific language history inventory on which they recorded information about their prior language training and exposure (Appendix A). For this inventory, participants were asked to list all languages in which they had received training or to which they had been exposed enough that the language sounded "very familiar to you, even if you are not able to understand it. . . please include any languages to which you were exposed when you were young, even if you feel you no longer remember any of the language." These histories are summarized in Appendix B. Participants reported prior experience with 0 to 4 languages ($M = 2.04$; $SD = 1.11$), not including their English experience. Regarding age of first foreign language exposure, there was a broad range, with four participants reporting some foreign language exposure since birth; however, in none of these cases did this early exposure result in high fluency. Two participants reported no prior experience with a foreign language. Two participants reported prior watching of Japanese anime cartoons with English subtitles but with no formal Japanese training. Participants' mean length of experience with the foreign language to which they had longest exposure was 12.52 years ($SD = 11.24$).

Materials

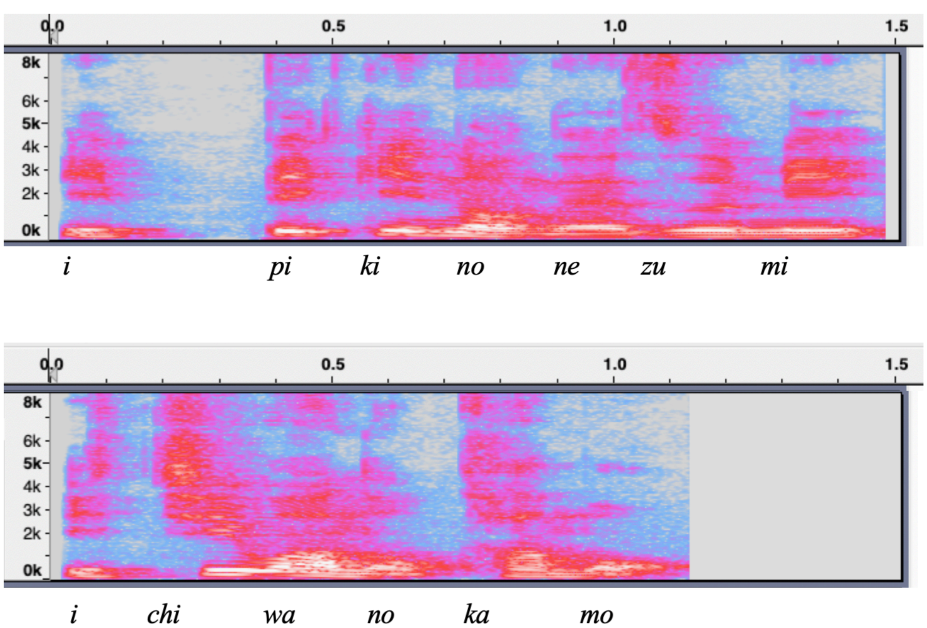
Auditory Phrase Stimuli

The auditory language stimuli used in this experiment were eight phrases drawn from a subset of the Mini Nihongo lexicon created by Mueller and colleagues (2005), as described in Chapter 2. To create language stimuli with complexity that would more closely approximate natural language, four recordings of each phrase were used in the study, yielding a total of thirty-two phrases.

Phrase Recording. These phrases were digitally recorded in Audacity at 44.1 kHz sampling rate by a male native Japanese speaker. The speaker was instructed to speak in a "normal conversational tone" and was aware that the sound files were for the purpose of adult language training. The sound files underwent noise removal in Audacity to remove static. To add natural language variation, the stimuli set included four recordings of each phrase, yielding a total of thirty-two phrase. To capture these four recordings, the native speaker recorded each phrase five times; the second through fifth recordings were used. Figure 3.1 displays two sample micro language phrases. Additional sample phrase spectrograms and oscillograms illustrating the natural variation of the micro language stimuli are included in Appendix C.

Figure 3.1

Sample Spectrograms of the Micro Language Phrase Stimuli



Note. The figure provides an example of a complex phrase (top) and simple phrase (bottom).

Phrase onset, noun initial and noun medial syllables were marked by a native Japanese speaker for later ERP stimuli-based time locking. Phrases were presented through noise-reduction earphones (Etymotic Research, Elk Grove Village, IL).

Phrase Characteristics. Phrase characteristics were compared by phrase complexity level to quantify difference in complexity between the two phrase complexity levels. Table 3.1 displays syllable-level characteristics of the auditory stimuli, including duration, intensity and pitch.

Phrase and Syllable Durations. Simple phrases had a mean duration of 1066ms (*SD* = 82ms, *range* = 159ms). Complex phrases had a mean duration 1352ms (*SD* = 119ms, *range* = 119ms).

Boolean Complexity. Boolean complexity, which quantifies conceptual information as the length required to express all positive instances of a concept at maximal compression, known as the concept's "minimal formula" (Feldman, 2003, 2006) was balanced across the two phrase complexity levels. Each phrase identified one of two possible number quantities and one of two possible animal identities for the phrase type. Thus, simple and complex phrases did not differ on Boolean complexity level.

Semantic Training Visual Stimuli

The visual stimuli used for semantic training (Phase 2) and semantic practice (Phase 3) were created in Inkscape, a vector-drawing program. Photographs of animals in right profile were outlined to create four animal shapes. All detail was then removed and a dot was added to represent the eye. The resulting silhouettes were color filled.

Table 3.1

Auditory Stimuli Syllable Characteristics: Duration, Intensity and Pitch

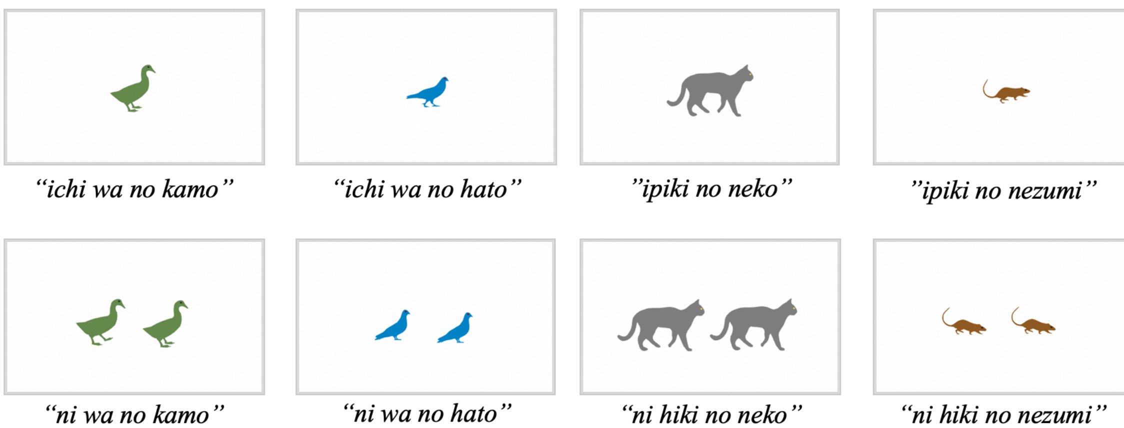
	Count	Duration (ms)		Intensity (dB)		Mean Pitch (Hz)
		Mean	SD	Mean	Max	
Simple						
i	8	145.88	14.53	59.52	70.03	138.03
ni	8	191.75	26.67	72.30	77.48	157.89
chi	8	204.50	13.06	71.40	82.12	184.26
wa	16	170.38	13.99	75.90	78.93	152.43
no	16	174.69	41.45	65.04	71.36	107.58
ha	8	282.88	22.05	61.80	75.29	130.86
to	8	170.25	30.76	66.20	72.58	140.05
ka	8	210.25	8.84	66.28	76.66	127.23
mo	8	185.38	41.66	64.78	71.85	101.53
Complex						
i	8	402.75	23.10	42.37	71.38	133.8
ni	8	162.25	26.51	72.36	77.95	163.4
pi	8	163.88	15.52	66.32	79.25	192.2
hi	8	243.50	31.20	51.23	67.91	172.5
ki	16	151.13	17.76	67.05	75.88	151.9
no	16	166.63	22.18	71.54	75.27	119.4
ne (ko)	8	229.13	19.07	67.91	76.82	122.9
ne (zumi)	8	148.50	12.80	69.04	70.71	104.8
ko	8	211.38	52.98	65.38	74.86	181.5
zu	8	232.88	21.01	68.63	73.52	114.9
mi	8	221.25	26.82	69.65	72.33	127.3

Note. Values shown represent the average of the eight or 16 syllables of each type.

Figure 3.2 shows the micro language semantic images. These images were presented on computer and were equally sized at about one inch high. They were sized as small as possible, in order to minimize eye movement artifact during electrophysiological recording, while still being easily distinguished when displayed on the computer monitor, as determined by piloting feedback.

Figure 3.2

Images Used for Semantic Mapping and Semantic Use Practice



Note. No orthographic training was provided to participants.

Logs for Phonological Familiarization (Phase 1)

During the phonological familiarization phase (Phase 1), participants filled out four listening logs (Appendix D) at evenly spaced intervals, approximately every two minutes during soundstream exposure. They wrote down, spelling phonetically, all the “words or sounds” they could recall, indicating breaks between words by placement of spaces or commas. While completing each listening log, participants were not able to refer back to their prior logs.

Logs for Training, Practice and Comprehension (Phases 2-4)

During the subsequent three phases, participants filled out four additional logs. These logs included a training log following the semantic training phase (Phase 2); two practice logs during the semantic use practice phase (Phase 3), one completed halfway through the practice and the other at phase end; and a comprehension log, completed at the end of the comprehension phase (Phase 4). A sample log, the training log, is attached as Appendix E; practice and comprehension logs were of similar format. For these logs, participants recorded, spelling phonetically, all the "words or sounds" they could recall. These logs -- unlike the listening log from phonological familiarization -- included the eight images that represented the micro language phrases, each next to a blank space on which participants recorded the phrase associated with each picture. Before completing each log, they were reminded to indicate breaks between words by placement of spaces or commas.

Procedure

All sessions were conducted in EGI's Brain Electrophysiology Lab. After providing written consent to participate, participants provided basic demographic information, then completed the Edinburgh Handedness Inventory (Oldfield, 1971); followed by the language history inventory.

Before receiving task instructions, participants were fitted with a 256-channel HydroCel Geodesic Sensor Net (Electrical Geodesics, Inc.). The sensor net application took about 10 - 20 minutes. Photogrammetry was then used to register sensor scalp locations. Medi-Tech Spandage elastic headwrap was placed over the sensor net to reduce motion artifact. Throughout the experiment participants' electroencephalogram

(EEG) was recorded and digitized at 250 Hz using a GES 300 system (Electrical Geodesics, Inc.). Channel voltages were referenced to the vertex sensor during recording. Sensor seating was adjusted at setup and midway through the experiment to maintain impedances below 100 kΩ. During adjustments, verbal interaction between the experimenter and participant was minimized to reduce English exposure during the language learning process.

After the sensor net application, brief instructions explaining the four-phased experimental format were read to participants. (Instructions are attached as Appendix F). To increase participant understanding and engagement, the experimental procedure was additionally outlined on a placard for the participant to hold and follow along with as the experimenter read the instructions (This placard has been sectioned and will be included as Figures 3.3 through 3.6). The placard included instructions both in words and in pictorial representation of the trial structure.

Phonological Familiarization (Phase 1)

The phonological familiarization phase consisted of a trial-based sound stream presentation of the micro language phrases, with each phrase constituting a trial, as depicted in Figure 3.3. Participants were instructed to close their eyes, relax and listen carefully to the sounds of the language. They were told that this learning phase was intended to familiarize them with the sounds of the language. During this phase, the eight phrases were each presented twenty times for a total presentation of 160 phrases, or trials, lasting approximately eight minutes. Stimuli were presented with E-Prime software (Psychology Software Tools, Pittsburgh, PA) with stimulus events and EEG recorded by Net Station (Electrical Geodesics, Inc.). The phrases were presented in pseudorandomized order with the same sequence for all participants. No phrase was heard twice in succession, and phrases occurred with even distribution during the presentation. The inter-trial interval was 500ms ± 200.

Figure 3.3

Trial Procedure for Phonological Familiarization (Phase 1)

Block 1: Listening (about 8 minutes)			
What you'll see or hear:	*What will appear on the monitor:* +	+ *You will hear a phrase in Mini Nihongo.*	*What will appear on the monitor:* ⇨
What you'll do:	*Keep your eyes closed and relax.*	*Listen very carefully to the sounds.*	*This signals that the experiment is about to proceed.*

Note. Participants additionally received detailed verbal task instructions, which are attached in Appendix F.

The sound stream presentation was divided into four "miniblocks" of 40 phrases, each providing approximately two minutes of exposure, followed by a pause. During these pauses, participants were provided with the listening log on which they wrote down, spelling phonetically, as many "words or sounds" as they could remember. They were reminded to indicate breaks between words by placement of spaces or commas. Participants were not permitted to review their previous listening logs as they completed the current one. No semantic or orthographic training was provided. Participants were not told that there were eight unique micro phrases in the language; however, each listening log had eight blanks. When the participant had completed the log, the experimenter collected it and resumed the soundstream presentation.

Semantic Mapping (Phase 2)

For the second phase of the experiment, which immediately followed the first, participants listened to a series of 104 of the micro language phrases in a trial-format presentation, as depicted in Figure 3.4. During the second phase, each phrase was presented along with the image representing its meaning. The goal of this phase was for participants to map the meaning of the phrases to their semantic representation.

Figure 3.4

Trial Procedure for Semantic Mapping (Phase 2)

Block 2: Training (about 12 minutes)				
What you'll see or hear:	*You will see:* +	+ *You will hear a phrase in Mini Nihongo.*	*You will see a picture in the center of the monitor:* *The picture illustrates the meaning of the phase you just heard.*	*What will appear on the monitor:* ⇨
What you'll do:	*Fixate your eyes on the "+".*	*Listen very carefully to the sounds. Keep your eyes on the "+".*	*Repeat the phrase you just heard (once as you look at the picture.*	*This signals that the experiment is about to proceed.*

Note. Participants additionally received detailed verbal task instructions, which are attached in Appendix F.

During the semantic mapping phase pre-task instructions, participants were told that the purpose of the phase was to teach them the meaning of the phrases. During this phase, participants kept their eyes open, fixated on a fixation mark on the computer monitor while listening to each phrase. Each phrase was immediately followed by an image illustrating the meaning of the phrase. Participants were instructed to repeat the phrase aloud as they looked at the image. They then pressed a response pad key to continue to the next phrase. Thus, participants were able to control the pace of phrase presentation. To facilitate learning, phrases were ordered with repetition, rather than randomly ordered. This order was fixed, i.e., all participants heard the phrases in the same order. The duration of the semantic training phase exposure was about 12 minutes with a brief pause ("break") every two to three minutes, after which participants could self-resume the experiment with a button press. At the end of the phase, participants were provided with the training log and asked to record, spelling phonetically, the phrase associated with each image in the space beside the picture, indicating word boundaries with spaces or commas. The training log displayed each semantic training picture with a space next to it in which the participant recorded the phrase corresponding to the picture. As in the phonological familiarization phase (Phase 1), no orthographic training was provided.

Semantic Use Practice (Phase 3)

For the semantic use practice phase (Phase 3), participants were told they would play a simple matching game to practice the phrases they had just learned. For each trial, participants saw a picture and then heard a micro language phrase, as shown in Figure 3.5. Their task was to decide whether the picture and the phrase matched or mismatched, and to indicate their response (yes or no) by pressing the appropriately labeled response key. They immediately received feedback on their response accuracy. For correct responses, their feedback was a green checkmark. For incorrect responses, their feedback was a red X. The feedback was small, approximately the same size as the fixation mark, and located in the same location as the fixation mark to minimize eye movement. This phase consisted of 128 trials (each of 8 phrases presented 16 times) and lasted about half an hour, with total duration of the phase depending upon how long the participant waited before pressing a key to proceed to the next trial.

Figure 3.5

Trial Procedure for Semantic Use Practice (Phase 3)

Block 3: Practice (about 12 minutes)						
What you'll see or hear:	*You will see:* *+*	*You will see a picture:*	*You will see:* *+* *and then you will hear a phrase in Mini Nihongo.*	*You will see:* *?*	*You will see:* *√ or X*	*You will see:* ⇨
What you'll do:	*Fixate your eyes on the "+".*	*Look at the picture.*	*Listen very carefully to the sounds. Keep your eyes on the "+".*	*Press **Yes** if the picture and phrase match.* *Press **No** if they don't match.*	*√ means you responded correctly.* *X means you responded incorrectly.* ***Press any key to proceed.***	*This signals that the experiment is about to proceed.*

Note. Participants additionally received detailed verbal task instructions, which are attached in Appendix F.

There were two types of practice: animal practice, which required a decision based on whether the noun in the phrase matched the animal shown in the picture; and number practice, which required a decision based on number. Due to the naturalistic word order, the number matching task required a decision based on the first word of the phrase, and the animal matching task required a decision based on the final word of the phrase. Practice types were counterbalanced such that half of the participants first listened for a noun match or mismatch, and half for a number match or mismatch. The rate of match was 50%, although participants were given no indication what the rate of match to mismatch would be.

Comprehension Listening (Phase 4)

The comprehension phase (Phase 4) was completed immediately following the semantic use practice (Phase 3), as a continuation of the four-phased session. As depicted in Figure 3.6, participants were instructed to listen to the soundstream with eyes closed, and to try to comprehend the phrases. The 160-phrase soundstream from the phonological familiarization phase (Phase 1) was again presented. The phrase sequence was identical for Phase 1 and Phase 4. However, during Phase 4 there were no mid-phase pauses during which participants wrote down the phrases. Instead, participants listened to the eight-minute soundstream in its entirety. Immediately following the soundstream presentation, the participant completed the comprehension log as the experimenter remotely measured electrode impedances.

Figure 3.6

Trial Procedure for Comprehension Listening (Phase 4)

Block 4: Comprehension (about 8 minutes)			
What you'll see or hear:	*What will appear on the monitor:* +	+ *You will hear a phrase in Mini Nihongo*	*What will appear on the monitor:* ⇨
What you'll do:	*Keep your eyes closed and relax.*	*Listen very carefully to the sounds.* ***Try to comprehend what you hear.***	*This signals that the experiment is about to proceed.*

Note. Participants additionally received detailed verbal task instructions, which are attached in Appendix F.

Post-Task Procedure

After the comprehension log was completed, photogrammetry measurements were retaken to document sensor locations at the end of the session. The experimenter then removed the geodesic sensor net and reviewed the debriefing form with the participant. Participants were provided with a copy of the consent and debriefing forms before being paid, thanked for their participation, and escorted from the lab. The entire session had a duration of under three hours.

Behavioral Data Processing

Behavioral measures for the current research included learning measures coded from the eight language logs, an on-line measure of reaction time collected during the semantic use practice, and mean task accuracy from the semantic use practice.

Language Log Measures

The following measures were coded from the logs. Listening logs collected during the phonological familiarization phase (Phase 1) were coded on syllable, word and phase level measures. For the later phases of learning (Phases 2-4), learning was assessed on the phrase level only; with the one exception that noun segmentation from the comprehension logs was coded to determine whether low learners had correctly segmented all four nouns by the end of the session.

Syllables Recalled. Syllable learning was coded as the number of the 16 micro language syllables the participant had recorded on the listening logs. A syllable was counted if its phonological representation was recorded in the listening log, despite any minor inaccuracy in phonological precision. This measure did not require correct segmentation of the syllable. Thus, it was a measure of participant recall of the sounds of the language. Syllables recalled was coded by individual miniblock and as a cumulative measure for the phonological familiarization phase.

Words Segmented. Word learning was measured by counting the number of the 10 micro language words that a participant had recorded on the listening log for each miniblock. To be counted, the word needed to be segmented correctly and to have all syllables included. Words with minor inaccuracy in phonological representation were included in the count.

Learner Type. Learner Type was a binary measure of noun segmentation. It was used as a participant grouping measure for analyses. Participants who correctly wrote down all four nouns by the end of the phonological familiarization phase (Phase 1) were classified as “high” learners; those who did not were classified as “low” learners. In other words, high learners had correctly segmented out all four nouns by the end of the phonological familiarization phase; low learners had not. Thus, rather than being a medial split of noun segmentation, this measure captured whether or not participants were able to segment the phrases. Division of participants by learner ability is standard for the soundstream listening research, with groups generally determined by accuracy on a violation-based test of word vs. nonword recognition (e.g., Abla et al., 2008). This learner type measure was intended for viewing the data and as a between-subjects factor in planned analyses. Noun segmentation was coded four times, once for each listening log from phonological familiarization. It was coded again at the end of the comprehension phase.

Weighted Noun Learning. It was noted that some participants learned to segment nouns correctly earlier than others. To quantify this difference in learning rate, a weighted noun recall measure was added whereby faster segmentation was awarded a higher noun recall score. This measure, weighted noun learning, was a continuous measure of noun segmentation and learning rate. For the weighted noun learning score, participants scored four points for each noun segmented correctly by the end of miniblock (MB) 1, three points for each noun segmented correctly by the end of MB2, two points for each noun segmented by the end of MB3, and one point for each noun segmented correctly by the end of MB4. Because the weighted noun learning measure factored in the rate of segmentation, it measured not only how many nouns the participant correctly segmented but also the amount of post-learning exposure to the noun the participant had received. This weighted noun measure intended to provide an alternative, more sensitive measure of noun segmentation than that used for the binary learner type grouping measure, for possibly inclusion in analyses.

Phrases Segmented. Phrase segmentation was measured by counting the number of the eight phrases that the participant correctly recorded for each miniblock. To be counted, all words needed to be included. Phrases segmented with only one error received one point. Phrases segmented with two errors received half point. Phrases segmented with more than two errors received no points. This measure was coded separately for each phrase complexity.

Phrases Sequenced. Some participants recalled phrase syllables in sequence, yet did not mark word boundaries. To measure this phrase sequence learning, phrases sequenced was coded. For this measure, participants received one point for each correct syllable-to-syllable sequencing recorded on their language logs. This code provided a continuous measure of phrase sound sequence learning. Phrases sequenced was coded for logs recorded during the training, practice and comprehension phases (Phases 2-4). This measure was coded separately for each phrase complexity.

Semantic Learning. Semantic learning was coded by counting the number of pictures next to which the participant wrote the correct phrase. A phrase was considered correct if enough syllables of the phrase were present that the coder judged that both halves of the phrase (i.e., a representation of the number and the noun) had been recalled. Half phrase semantic learning was counted if only the number or noun was correctly represented on the language log. This measure was coded separately for each phrase complexity.

Inter-Coder Reliability

Noun learning, learner type, weighted noun learning, phrases sequenced and semantic learning were coded by two research assistants with prior linguistics coding experience. Both were blind to the experimental hypotheses. To assess rater consistency, intraclass correlation coefficients (two-way random model) were calculated for these measures to determine inter-rater reliability (Koo & Li, 2016). These analyses will be presented in Chapter 4.

Electrophysiological Data Processing

Event-related potentials (ERPs) were created for visual review and statistical analysis. After acquisition, the EEG data were digitally filtered with a highpass frequency of 0.10 and lowpass frequency of 40Hz in Net Station 5.2 (EGI). The continuous EEG was then segmented into 752ms (188 sample) epochs, beginning 100ms before selected syllable onsets and continuing 652ms post stimulus onset, selectively maintaining separate categories as were needed for planned analyses for each phase. These data were then cleaned in MATLAB using Fully Automated Statistical Thresholding for EEG artifact Rejection (FASTER; Nolan, Whelan & Reilly, 2010). Subsequent processing was completed with Net Station 5.3 (EGI). Residual artifacts, including eye movement and eye blink, were removed using Net Station artifact rejection tools and manual inspection. The resultant ERPs were then average referenced with polar average reference effect (PARE) correction (Junghofer et al., 1999) before averaging across trials. For the phonological familiarization phase (Phase 1), difference waves (noun medial syllables subtracted from noun initial syllables) were then created in order to compare current results with prior research findings (e.g., Abla et al., 2008; Cunillera et al., 2009).

Statistics Extraction

To create the dependent measures for planned analyses of the medial frontal negativity, selected sections of the ERPs were extracted for noun initial and noun medial syllables for three time windows. This extraction was done identically for the phonological familiarization (Phase 1) and Comprehension Listening (Phase 4). The selected windows, along with the scalp locations extracted to represent them, with these locations selected due to their being the focus of the medial frontal negativity that best captured the components of interest, are shown in Figure 3.6. Of these three windows, one captured the narrow N1 peak, a second encompassed a broader window overlapping the N1 peak (40-200ms interval), and the third window represented the Learning N400. For the N1 peak measure, the window was selected using a method adapted from Abla and colleagues (2008). First, the grand mean peak latency of the noun syllables was extracted. The grand mean latency of 111.66 (SD = 19.23) was rounded to 110ms. Using 110ms as a center point and extending 50ms before and after it, a window with latency of 60 and 160ms was selected. Next, the N1 adaptive peak was extracted by selecting the negative peak within this window and calculating the mean amplitude of the 40ms window surrounding this adaptive N1 peak. The mean amplitude of a broader time window encompassing the N1 peak (40-200ms interval) was also extracted. This window was selected based upon both the use in prior research (e.g., Sanders et al., 2009) and upon confirmation by visual inspection of the grand average that this time window captured the early word onset effect present in the MINA data. For the Learning N400 measure, the mean amplitude between 300 and 500ms was extracted.

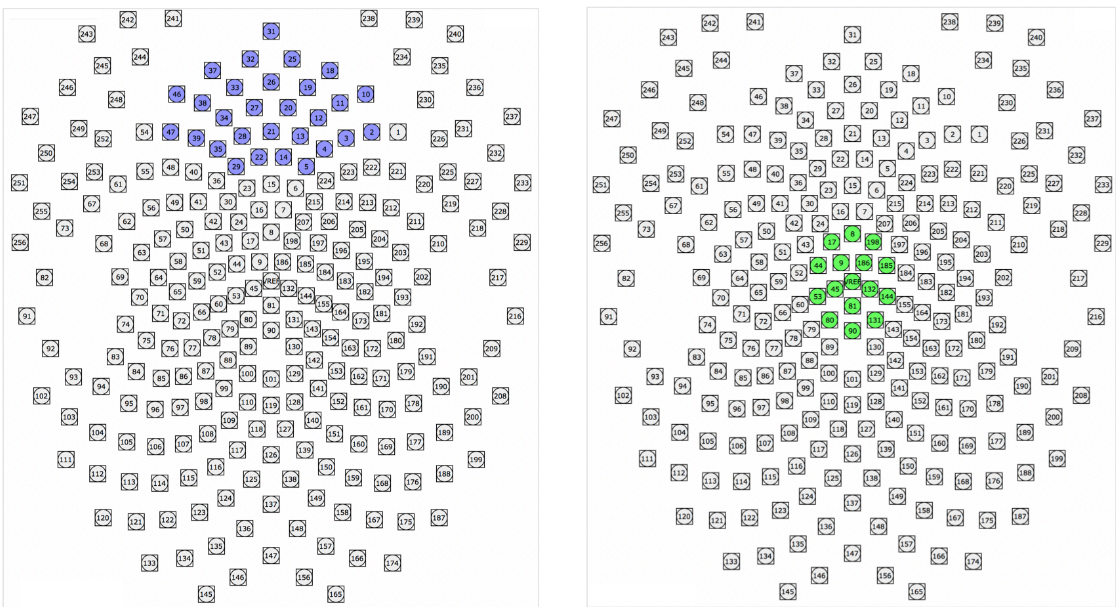
To create the dependent measure for the planned Semantic N400 analysis, the mean amplitude of electrodes surrounding the vertex (shown in Figure 3.6) were extracted for latency 300-450ms after phrase onset. This measure was taken for both phonological familiarization (Phase 1) and for comprehension listening (Phase 4) for purpose of a pre- and post-training comparison.

Outlier Handling

The extracted data was examined and appeared to have extreme value data points for multiple participants. Based on visual review of the single subject average ERPs, it appeared that these data points may have been due to high amplitude oscillations and therefore represented extreme data points rather than out-of-range noise. Because there is evidence that oscillations may entrain to noun onsets during on-line soundstream learning (e.g., Batterink & Paller, 2017), these data points possibly represented true extreme values. Consequently, an approach to handling these outliers was taken that maintained their direction while bringing them back into range and preventing them from distorting the mean. An interquartile range (IQR) multiplier approach to detecting outliers was applied with a multiplier of 2.2 (Hoaglin et al., 1987). First, the IQR for each measure was calculated, and values greater than 2.2 times the IQR from the mean were labeled as outliers. Next, these outlier values were replaced with the closest within-range value occurring for that measure (Tukey, 1962). Statistical analyses were performed on both the pre-and post-outlier handled data for comparison.

Figure 3.7

Electrodes Extracted for Statistical Analysis



Note. The electrodes used to represent the N1 word onset negativity, the 40-200ms interval, and the Learning N400 are shown on the left (blue). The electrodes used to represent the Semantic N400 are shown on the right (green).

CHAPTER IV

RESULTS

How Well Did Participants Learn the Micro Language?

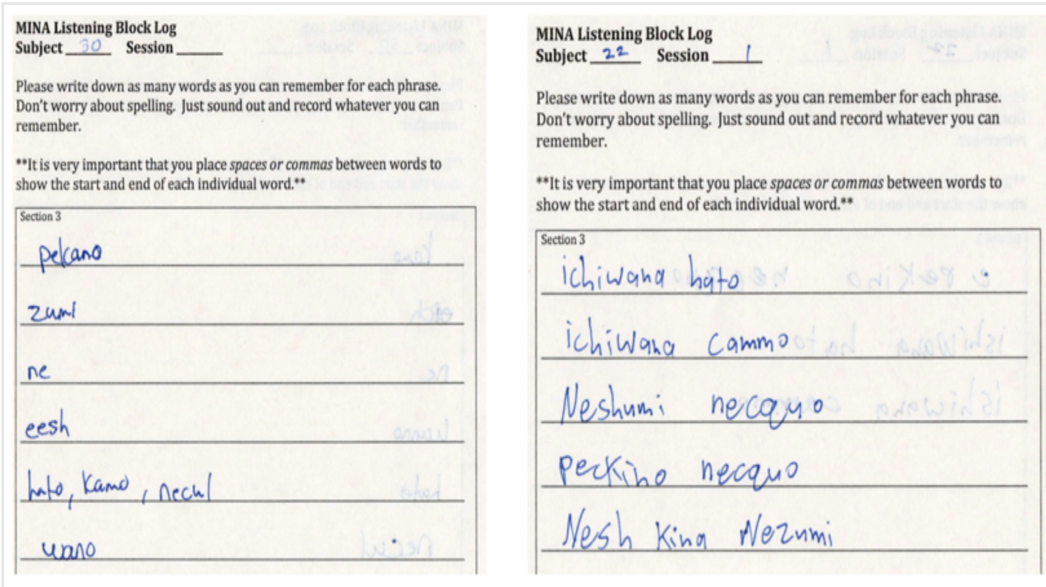
To determine how well the participants learned the micro language during the session, the four listening logs collected during the phonological familiarization (Phase 1) were analyzed to assess learning on the syllable and word level.

Language Logs

Figure 4.1 shows excerpts from the listening logs, the recall assessments collected approximately every two minutes of exposure during the phonological familiarization. The figure shows one listening log from two individual participants, each completed after about six minutes into the phrase exposure immediately following the third miniblock. While the participant whose log is on the left recorded only syllables and single words, the participant whose log is on the right showed recall that suggested learning of the micro language structure was already underway. For example, there appears to be intentional segmentation of the syllables into words and there is already organization of the syllables into the phrase sequences. (The recall "ichiwana hato" appears to be an early representation of "ichi wa no hato".) In contrast, the log on the left shows syllable and word level learning. Thus, individual differences in learning were evident already within the phonological phase. Similar differences in learning were seen for the language logs collected on the training logs, the two practice logs and on the comprehension logs.

Figure 4.1

Sample Listening Log Recall from Two Participants



Language Log Coding

As described in Chapter 3, language log entries were coded to quantify language learning on measures at the syllable, word and phrase level. Two research assistants independently coded the four listening logs for syllable and noun recall and the training, practice and comprehension logs on the phrase-level measures of phrases sequenced and semantic learning. The phrase-level measures were coded separately for each phrase complexity level. Inter-rater reliability was estimated by calculating interclass correlational coefficients (Koo & Li, 2016), using the mean rating of the two coders and testing for consistency agreement with a two-way random-effects model. The results of the inter-rater reliability coding are shown in Table 4.1. Rater reliability was excellent, ranging from .91 to .98. For other measures reported, single-coded data is reported.

Table 4.1

Interclass Correlational Coefficients and 95% Confidence Intervals for Inter-Coder Reliability on Language Log Measures Used as Mean Measure

	Interclass Corr.	95% Conf. Interval Lower B.	Upper B.	F Test with True Value 0 Value	*df*1	*df*2	Sig.
Listening Logs (Phase 1)							
Syllables Recalled By Miniblock	.93	.89	.95	13.69	103	103	.001
Simple Noun Recall Cumulative	.96	.94	.97	24.84	103	103	.001
Complex Noun Recall Cumulative	.97	.95	.98	28.64	103	103	.001
Language Logs (Phases 2-4)							
Phrases Sequenced Simple	.93	.90	.96	15.06	99	99	.001
Phrases Sequenced Complex	.91	.87	.94	11.63	99	99	.001
Semantic Learning Simple	.98	.97	.98	42.02	99	99	.001
Semantic Learning Complex	.98	.97	.99	49.14	99	99	.001
Simple Noun Recall Phase 4	.90	.77	.95	9.53	25	25	.001
Complex Noun Recall Phase 4	.91	.79	.96	10.68	25	25	.001

Syllable and Word Learning Across Phonological Familiarization

Table 4.2 shows the number of micro language syllables participants recalled after each miniblock of phonological familiarization (Phase 1), measured by the listening log for each individual miniblock.

Table 4.2

Syllables Recalled for Individual Miniblocks (MBs) Phonological Familiarization

	MB1	MB2	MB3	MB4
N	26	26	26	26
Mean	8.83	9.35	11.5	12.1
SD	1.90	2.27	2.49	2.67
Min	4.50	6.00	5.50	6.50
Max	13.5	14.0	15.0	15.0

Note. These values represent means of the double-coded data. There were 16 syllables in the micro language.

Measured cumulatively on the syllable level, participant mean syllables learned was 14.4 (*SD* = 1.10) by the end of the phase, with a mean syllable recall of 90% (min = 75%, max = 100%), indicating that participants overall had learned most of the language syllables by the end of the first phase of learning.

Word learning was lower than syllable learning. The mean word recall was 4.31 (of 10) words, indicating a mean of 43% correctly segmented words (*min* = 0%, *max* = 80%). Figure 4.2 shows the word segmentation for individual participants across the phonological familiarization phase. There was higher segmentation of the nouns, which occur as phrase-final and therefore had one word boundary exposed. This higher tendency to correctly segment nouns can be seen in Figure 4.2 at the far right of each miniblock depiction.

Figure 4.2

Words Segmented During Phonological Familiarization

Words Recorded in MB1

Index	ichi	ipiki	ni	hiki	wa	no	hato	kamo	neko	nezumi
1			x							
2	x		x							
3			x		x	x	x	x	x	x
4	x						x	x		x
5										
6	x							x	x	
7										
8	x						x	x		x
9	x						x	x		
10							x		x	
11	x						x	x	x	x
12							x	x		
13								x		x
14							x	x		
15							x	x		
16										
17							x			
18	x							x		
19			x				x	x		
20							x	x		x
21								x		x
22							x	x	x	x
23							x			
24			x				x	x		
25			x				x	x		
26			x			x		x		

Words Recorded in MB2

Index	ichi	ipiki	ni	hiki	wa	no	hato	kamo	neko	nezumi
1	x		x					x		
2	x		x				x		x	
3			x		x	x	x	x	x	x
4	x					x	x	x		x
5									x	
6	x						x	x	x	
7										
8	x						x	x		x
9	x		x				x	x		
10							x	x	x	x
11	x	x	x				x	x	x	x
12							x	x	x	
13								x		x
14			x				x	x		
15							x	x	x	x
16										
17							x	x	x	
18	x						x	x		
19		x	x				x	x		
20							x	x		x
21			x				x	x	x	x
22							x	x	x	x
23							x	x		
24			x				x	x	x	
25			x				x	x		
26						x	x	x		

Words Recorded in MB3

Index	ichi	ipiki	ni	hiki	wa	no	hato	kamo	neko	nezumi
1	x		x				x	x		
2	x		x				x	x	x	
3	x		x		x	x	x	x	x	x
4	x					x	x	x		x
5									x	
6	x		x				x	x	x	
7										
8	x		x				x	x		x
9	x						x	x	x	x
10							x	x	x	x
11	x	x	x				x	x	x	x
12							x	x	x	
13								x		x
14	x		x				x	x		
15							x	x	x	x
16										
17							x	x	x	x
18	x						x	x		x
19		x	x				x	x		
20							x	x	x	x
21	x		x				x	x	x	x
22							x	x	x	x
23							x	x	x	
24			x				x	x	x	
25			x				x	x		
26			x			x	x	x		

Words Recorded in MB4

Index	ichi	ipiki	ni	hiki	wa	no	hato	kamo	neko	nezumi
1	x		x				x	x		
2	x		x				x	x	x	
3	x		x		x	x	x	x	x	x
4	x	x				x	x	x		x
5									x	
6	x		x				x	x	x	x
7										
8	x		x				x	x		x
9	x		x				x	x	x	x
10							x	x	x	x
11	x	x	x				x	x	x	x
12							x	x	x	
13							x	x		x
14	x		x				x	x		
15							x	x	x	x
16										x
17							x	x	x	x
18	x		x			x	x	x	x	x
19		x	x				x	x		
20							x	x	x	x
21	x		x				x	x	x	x
22							x	x	x	x
23				x			x	x	x	x
24			x				x	x	x	
25			x				x	x		
26			x			x	x	x		

Noun Learning from Session Beginning to Ending

Participants had a mean recall of 3.04 (*SD* = 1.11) of the four nouns. Individual differences were noted not only in the number of nouns learned by the end of the phase, but also in the learning rate. As can be seen in Figure 4.2, three participants had already learned (correctly recorded with correct segmentation) all four nouns within two minutes exposure. In contrast, 14 participants still had not learned all four nouns by the end of the phase. To test how noun learning developed over the entire session, noun learning was assessed from the comprehension listening logs. Mean noun learning on the comprehension log was 3.35 nouns (*SD* = 1.21). This mean was reduced due to two participants who did not designate word boundaries on their logs. However, even with these two outliers excluded, mean noun learning at the end of the session was only 3.63 nouns (*SD* = 0.73).

Weighted Noun Learning

As described in Chapter 3 and given this diverse timeline of noun learning among participants, an additional measure, weighted noun learning, was devised in order to capture noun learning rate combined with noun learning success. The weighted noun measure corresponded to the number of trials for which a participant heard a noun they had previously recorded on a listening log; making it a suitable measure for correlational analysis with the 300 to 500ms ERP amplitude, which has been suggested to index the recognition of a possible word in the soundstream (Cunillera et al., 2009). Scores on weighted noun segmentation ranged from 0 to 16 (*M* = 10.20, *SD* = 4.26).

Phrase-Level Learning Across the Session (Phases 1-4)

Two measures of phrase learning were coded: phrases sequenced and phrase segmented. The phrases sequenced measure counted the number of syllables which the participant recorded in sequence. The phrases segmented measure counted the number of phrases for which the participant recorded the sounds in sequence with correct segmentation. Half point was counted for phrases segmented with one error. As shown in Table 4.3 below, participants mean phrases segmented was low. Additionally, phrases segmented did not show increase with exposure across the four phases of the session.

Table 4.3

Phrases Segmented Across the Entire Session

	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**
Mean	1.04	0.75	0.69	0.89
Median	1.00	0.00	0.00	0.00
SD	0.86	0.98	1.02	1.07
Minimum	0.00	0.00	0.00	0.00
Maximum	2.00	3.50	3.50	3.00

Note. Participants received half-phrase score for a phrase that was learned with one error and received no score for phrases recalled with two or more errors. Phase 3 data shown here is from the second half of the semantic use practice phase.

Simple and Complex Phrase Learning Comparison (Phases 2-4)

The micro language two-tiered phrase complexity levels (simple and complex) were expected to produce examples of successful and unsuccessful language learning. Based on piloting, it was expected that participants would be more successful at learning the simple phrases than the complex phrases. Because the phrases segmented measure had not increased with exposure (thus indicating the measure was not capturing participant phrase-level learning), the phrases sequenced measure was used for this comparison. To allow for clear comparison of simple and complex phrase learning, the phrased sequenced scores were first transformed to proportion of total possible correctly sequenced syllables to standardize the scores. This was necessary because there were 18 total possible sequenced syllables possible for the simple phrases and 22 for the complex phrases. These proportion scores were then compared to determine whether participants showed systematic differences in ability to learn phrases of the two complexity levels across the second, third and fourth phase. For this measurement, both of the semantic use (Phase 3) practice logs were included. Although these logs were completed during the same phase, the semantic use practice phase was quite long; thus, including two logs from this phase most equally spaced the assessments.

As expected, participants overall showed higher learning of the simple phrases than complex phrases. At the end of the session, participant recall of the simple phrase sequences (M = 0.92, SD = 0.18) was higher than for the complex phrases (M = 0.84, SD = 0.23).

Did High and Low Learners Differ in Their Language Recall?

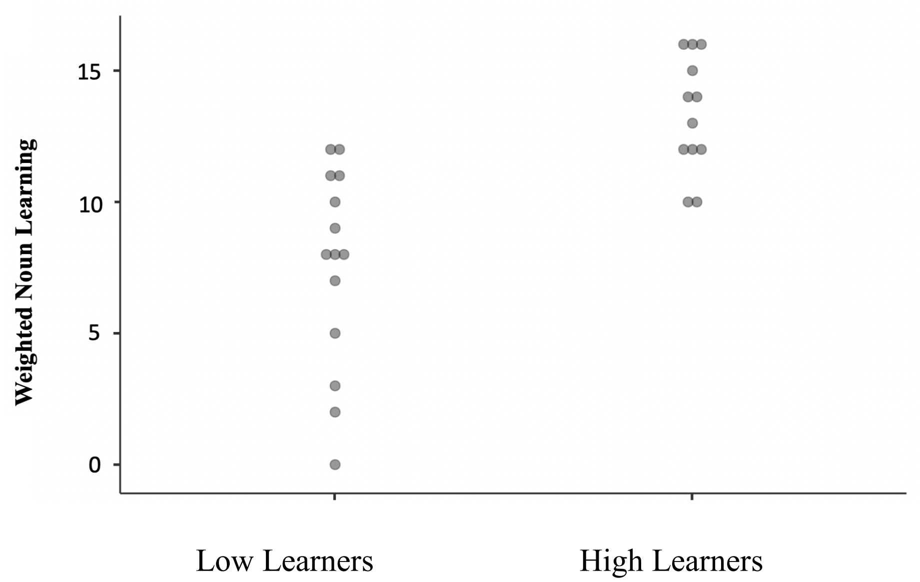
As planned, noun learning was used to group participants into two learner types. Of the 26 participants, 12 correctly segmented the four nouns by the end of the phonological familiarization phase. These participants were categorized as high learners. The 14 participants having not correctly segmented all four nouns by the end of the phase were categorized as low learners.

Learner Type Comparison of Weighted Noun Learning

Low and high learners were next compared on weighted noun learning. Low learners ranged from 0 to 12 (M = 7.57, SD = 3.80), and high learners from 10 to 16 (M = 13.3, SD = 2.19). The weighted noun scores are plotted in Figure 4.3. Most high learners outperformed most low learners on weighted noun learning, indicating that they learned more nouns and learned nouns faster. However, there was notable overlap in weighted noun scores between the two group. This was due to some low learners learning fewer nouns but learning them earlier during the phonological familiarization.

Figure 4.3

Weighted Noun Learning Scores for Low and High Learners During Phonological Familiarization Phase (Phase 1)

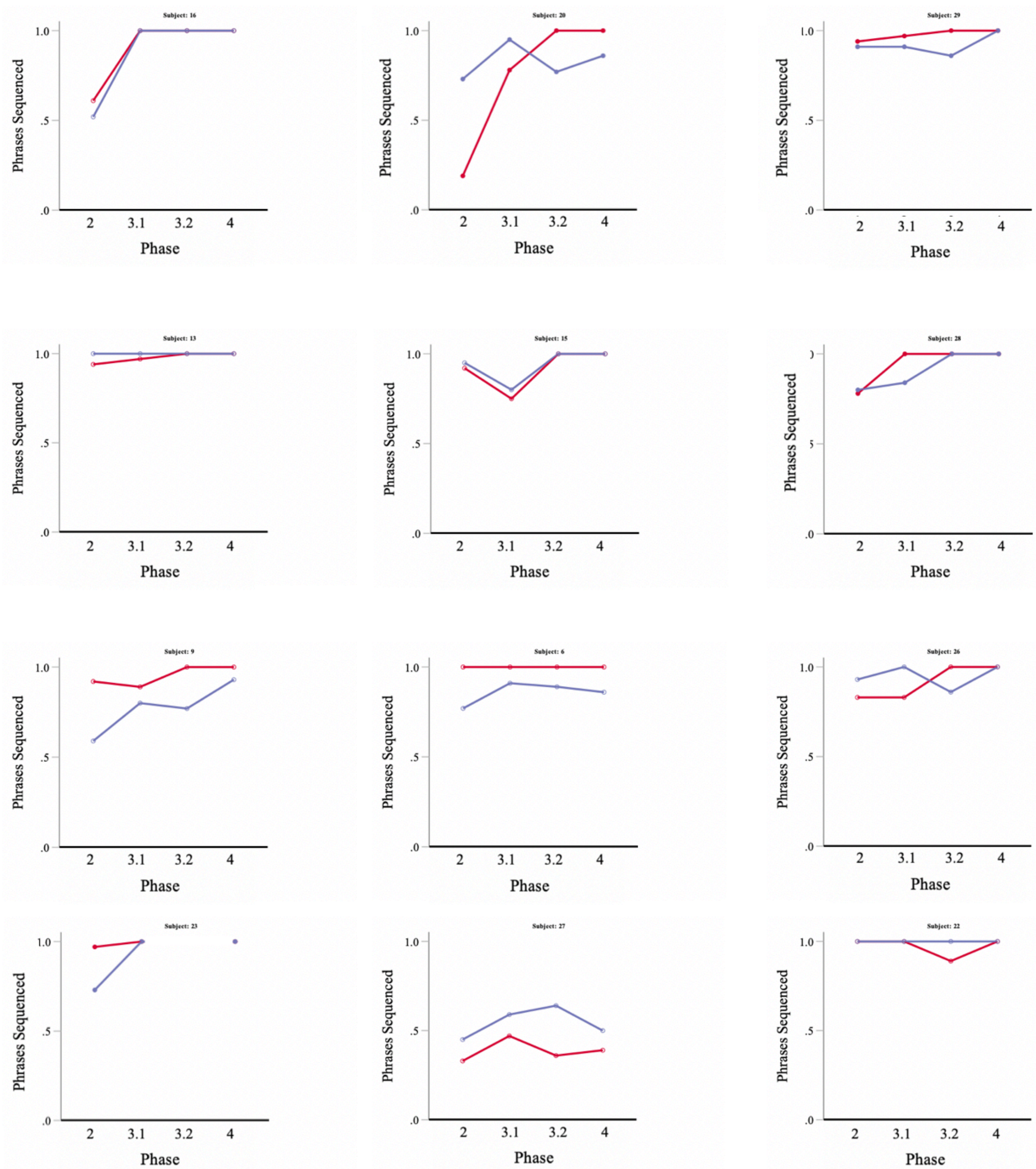


Individual Differences in Phrase Learning

To compare phrase sequence recall for low and high learners with increase in exposure across the later phases, the proportion of simple and complex phrases correctly sequenced was plotted for individual participants.

Figure 4.4

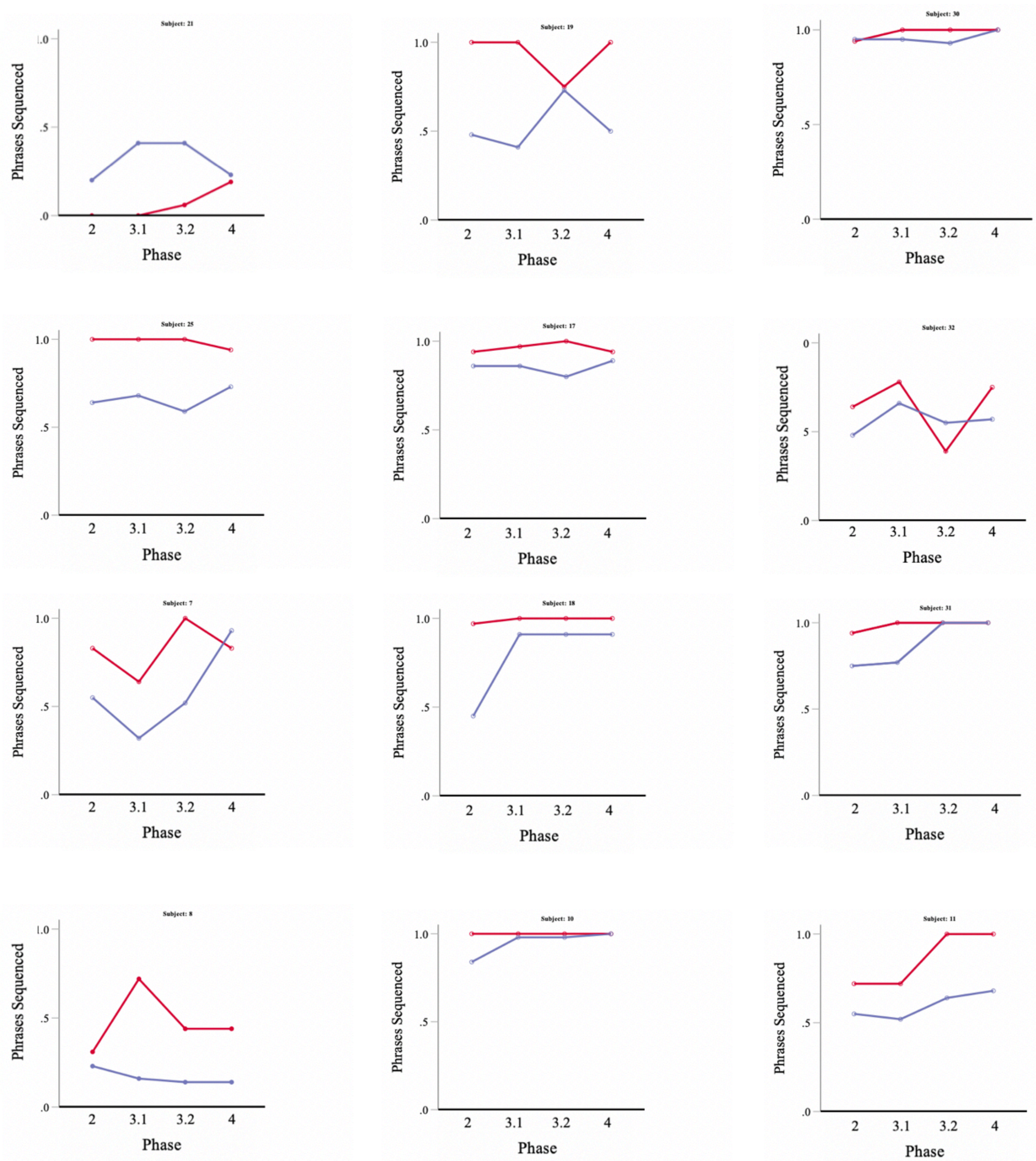
Proportion of Phrases Sequenced for 12 Individual High Learners (Phases 2-4)



Note. Red lines represent simple phrases. Blue lines represent complex phrases. A score of 1.0 represents a perfect score, i.e., all phrase sequences correctly represented on the language log. Subject 23 (bottom left) did not complete their second practice log.

Figure 4.5

Proportion of Phrases Sequenced for 12 Individual Low Learners (Phases 2-4)



Note. Red lines represent simple phrases. Blue lines represent complex phrases. A score of 1.0 represents a perfect score, i.e., all phrase sequences correctly represented on the language log.

Phonological Familiarization ERP Results

Analyses for the phonological familiarization phase (Phase 1) aimed to characterize the electrophysiological changes that accompanied early learning of the natural-based micro language as participants listened to the phrase soundstream and developed initial phonological familiarity to the new language.

Normative analyses were conducted to test the hypotheses that a) previously reported indices of early online language learning would emerge during acquisition of the naturalistic micro language and correlate with behavioral measures of learning, replicating findings from artificial grammar research; and that b) development of these neural indices would systematically differ with phrase complexity, reflecting differences in learning of the two phrase complexity types (simple and complex). For these analyses, behavioral learning was first assessed to characterize learning. Next, electrophysiological analyses examined the electrophysiological changes that accompanied learning. These analyses focused on the electrophysiological response to noun syllables.

Individual differences analyses addressed the hypotheses that a) participants with different learning profiles would display systematic differences in regard to the development of these ERP components, indexing systematic differences in their early language learning, as evidenced in their behaviorally measured learning; and b) these learner-type differences would interact with phrase complexity.

For these analyses, mixed measure ANOVAs were used to determine the effects of the within-subjects variables of syllable position (initial or medial), exposure time (miniblock 1, 2, 3 or 4), and phrase complexity (simple or complex); and the between-subjects variable of learner type (low or high) on the ERP amplitude to noun syllables for three post-syllable-onset time intervals: the mean amplitude during the three intervals of interest: the N1 peak, the 40-200ms interval, and the Learning N400. For each of these three intervals, selected medial frontal electrodes were used to represent the measure. Details of the statistics extractions to create these measures are described in Chapter 3.

To test for replication with prior research findings, these ANOVAs were additionally calculated with the difference between noun syllables (noun initial minus medial noun syllable) as the dependent variable. When indicated by sphericity assumption violation, significance values were adjusted using Greenhouse-Geisser estimates and denoted by $p_{G\text{-}G}$. Observed power was also calculated.

These results will be presented in a question-and-answer format. First, questions of normative learning will be addressed. Next, questions of complexity will be addressed. Finally, questions pertaining to the learner-type differences will be addressed.

Comparison of Noun Initial and Noun Medial Syllables During Phonological Familiarization

The topographic plot in Figure 4.6 shows the average referenced ERPs to noun initial syllables (blue) and noun medial syllables (black) for all participants during the phonological familiarization phase. As seen in the figure, noun initial syllables were followed by an extended negative deflection across medial frontal electrode locations. The difference between noun initial and medial syllables was evident beginning in the interval of the early word onset negativity (40-200ms after syllable onset), with noun initial syllables eliciting a more negative response. Approximately 110ms after the

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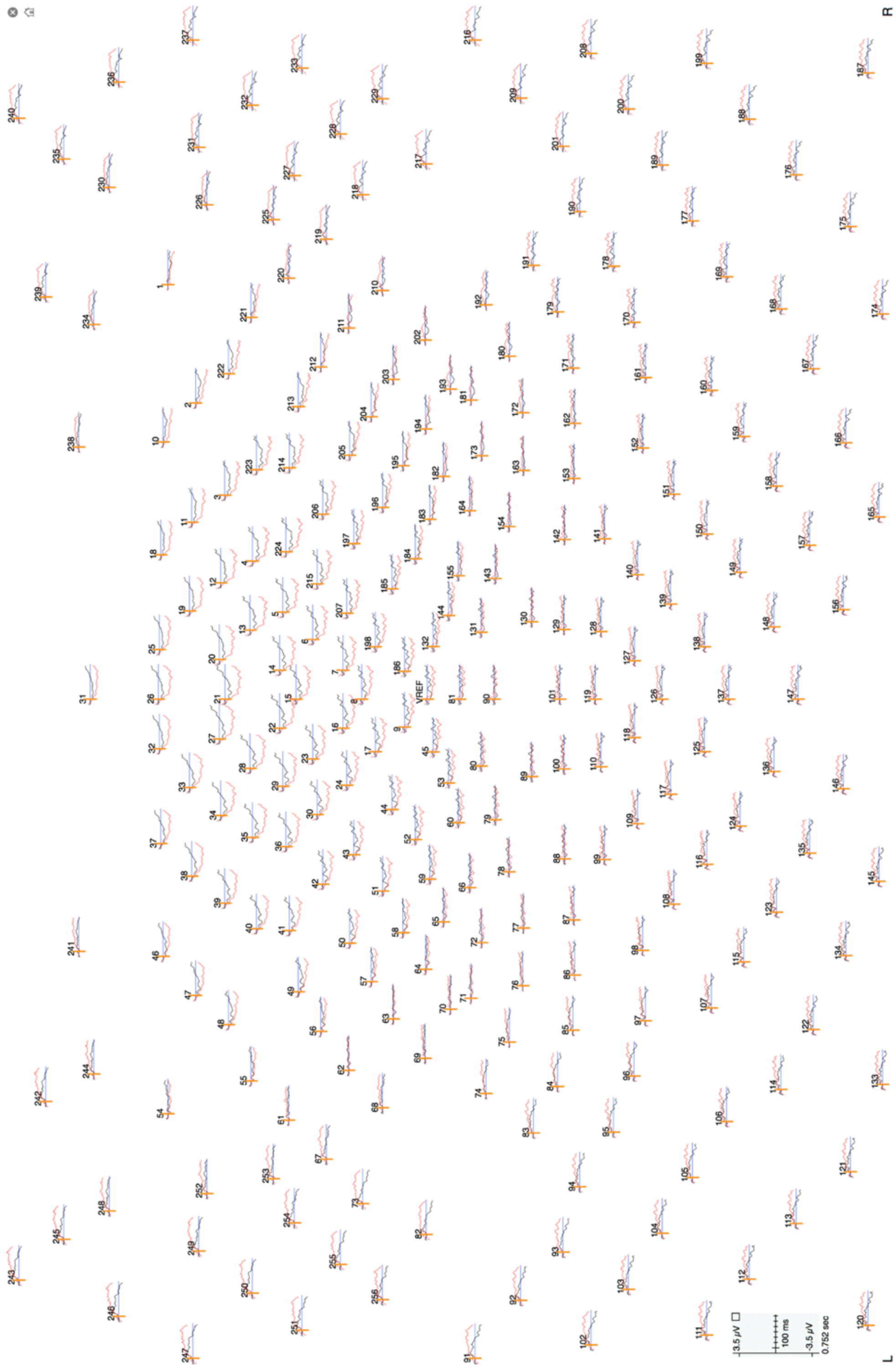
Figure 4.6

Topographical Plot of ERPs for Noun Initial (Red) and Medial (Blue) Syllables During Phonological Familiarization



Note. The grand average plot includes 100ms baseline and 650ms post-syllable onset. The data has been average referenced.

syllable onset, there was a low-amplitude N1 peak. The relative negativity of noun initial syllables continued until the end of the epoch, 650ms post-syllable onset.

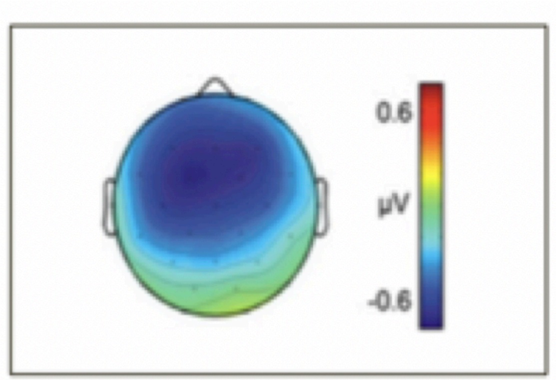
Results of the mixed measures ANOVAs revealed that the syllable position effect was significant: Overall during the phonological familiarization phase, noun initial syllables elicited significantly higher amplitude negativity at the N1 peak, $F(1,24) = 8.92$, $p = .006$, $\eta_p^2 = .27$, $pw = .82$. This effect was also significant during the broader 40-200ms interval, $F(1,24) = 8.38$, $p = .008$, $\eta_p^2 = .26$, $pw = .79$.

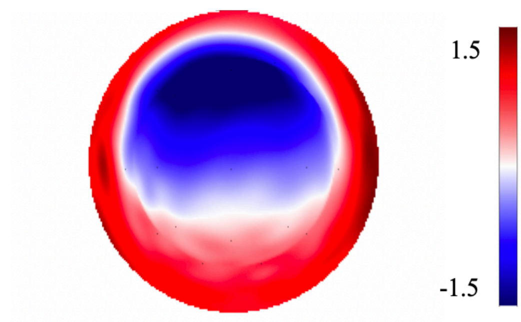
Noun initial syllables were significantly more negative than noun medial syllables in the 300 to 500ms interval, $F(1,24) = 22.64$, $p < .001$, $\eta p2 = .49$, $pw > .99$. The topography of the negativity (300-500ms post syllable onset) appeared anterior to that of the N400-like component described in the artificial grammar research as an index of early word learning, labeled the Learning N400 by Cunillera and colleagues (2009). To compare the topography of the current medial frontal negativity with the Learning N400, data from the current research was reprocessed to match its processing. Figure 4.7 shows the topographic map of the Learning N400 elicited by Cunillera and colleague's (2009) artificial grammar stimuli and the medial frontal negativity seen during phonological familiarization to the micro language noun syllables. For this comparison, data from the current research was mastoid average referenced and down sampled from 256 to 32 channel spatial resolution. Both maps show a difference wave to isolate the negativity that is due to the syllable's word initial position.

As evident in Figure 4.6, the ERPs to the midstream-occurring noun syllables, both noun initial and noun medial, were notably low in amplitude, at least in these initial moments of time to the new language. This was in contrast to the high amplitude auditory

Figure 4.7

Medial Frontal Negativity During Learning of Artificial Grammar and Seminatural Micro Language



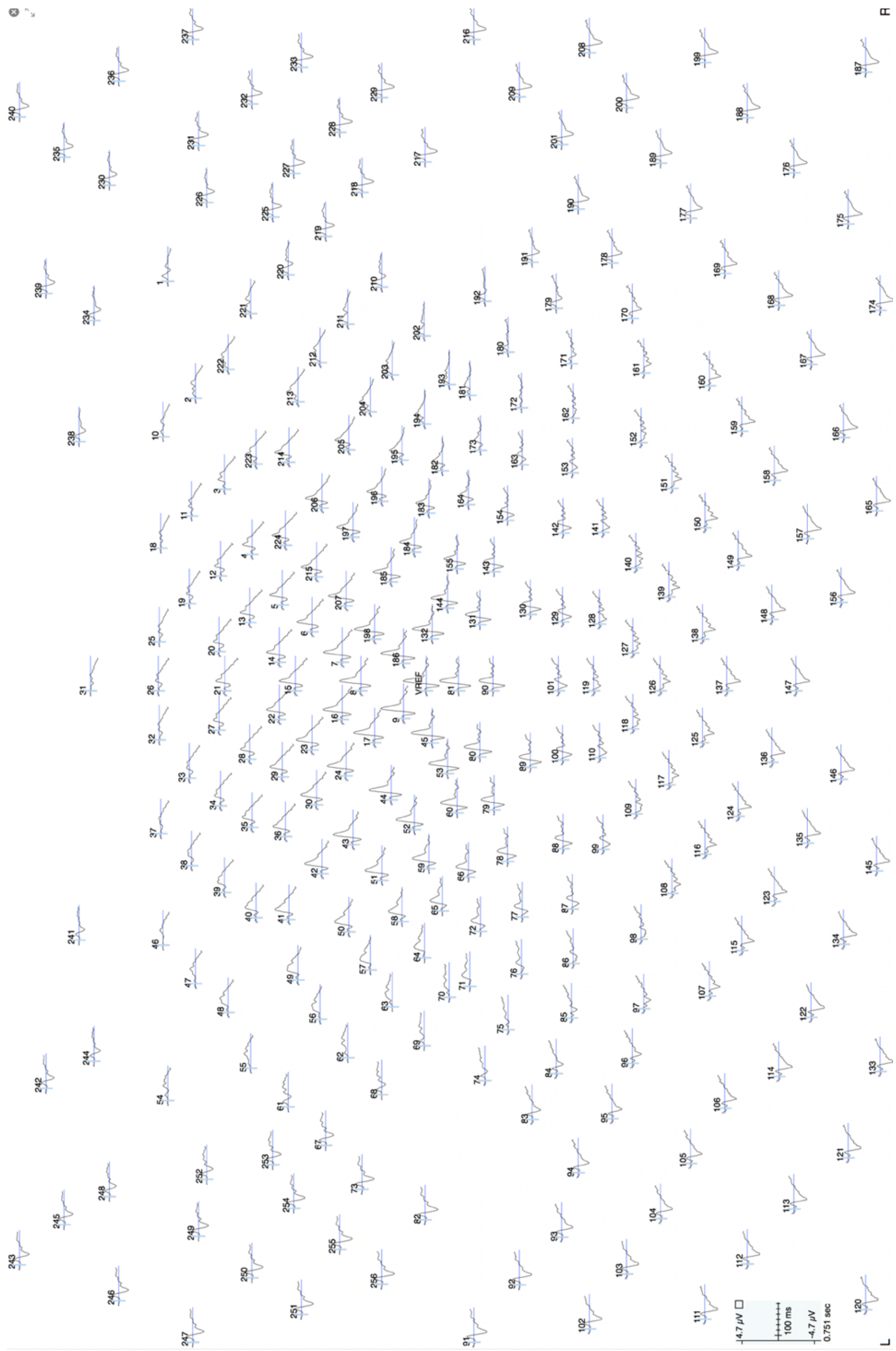


Note. Topography comparison of Cunillera et al.'s (2009) and the micro language medial frontal negativity at 400ms. Both data are processed with average mastoid referencing. The micro language data is shown from 350 to 450ms.

ERPs with well-defined P50, N1 and P2 components, elicited by the micro language phrase onset syllables, which are shown in Figure 4.8. This difference in ERP component amplitude was despite a comparable number of trials contributing to the noun onset and phrase onset ERPs. The appearance of low amplitude ERP components to the micro language midstream syllables was also in contrast to the ERP components elicited by artificial grammar words, with each artificial language syllable followed by an auditory ERP with clearly defined components including a P50, N1 and P2 (e.g., Cunillera et al., 2009).

Figure 4.8

Topographical Plot of Grand Average ERPs for Phrase Onset Syllables During Phonological Familiarization



Note. The plot includes 100ms baseline and 650ms post-syllable onset. The data shown here are average referenced.

Time Course of Noun Onset Negativity

Questions addressed by time course analyses included a) whether noun initial syllables elicited a higher amplitude negativity from the onset of soundstream listening, or whether the relative negativity developed with exposure; and b) whether the word onset negativity followed the previously reported pattern of development. Specifically, whether the early word onset negativity, represented as the interval surrounding the N1 peak or a broader 40 to 200ms interval, increased with increasing proficiency (Abla et al., 2008; Sanders et al., 2009); and whether the later relative negativity (300 to 500ms interval) increased and then decreased but with noun initial syllables remaining significantly more negative than noun medial syllables for the duration of the phonological familiarization phase (Cunillera et al., 2009).

Were Noun Onsets More Negative from the Start of Exposure, or Did This Effect Develop?

In the artificial grammar learning context, the cues to segmental structure are revealed through sequence transitional probabilities, and the structure is learned with no additional cues to word boundaries available. Thus, in the artificial grammar learning context, exposure is the only route to word onset detection. As a result, the word onset negativity develops with exposure. However, within the natural-based micro language context, it was not clear to what extent the relative negativity to word onsets developed with exposure. In the micro language, as in natural language, there are prosodic cues, some available from the onset of exposure (e.g., word onset stress cues), as well as acoustic characteristics of syllables, that could elicit the higher negativity to micro language noun initial syllables. Therefore, in the current context, there was the possibility that the word onset negativity to the micro language noun onsets could represent something other than learning. Therefore, it was important to examine whether the word onset negativity was present in the micro language data from the onset of exposure, or whether it developed with exposure.

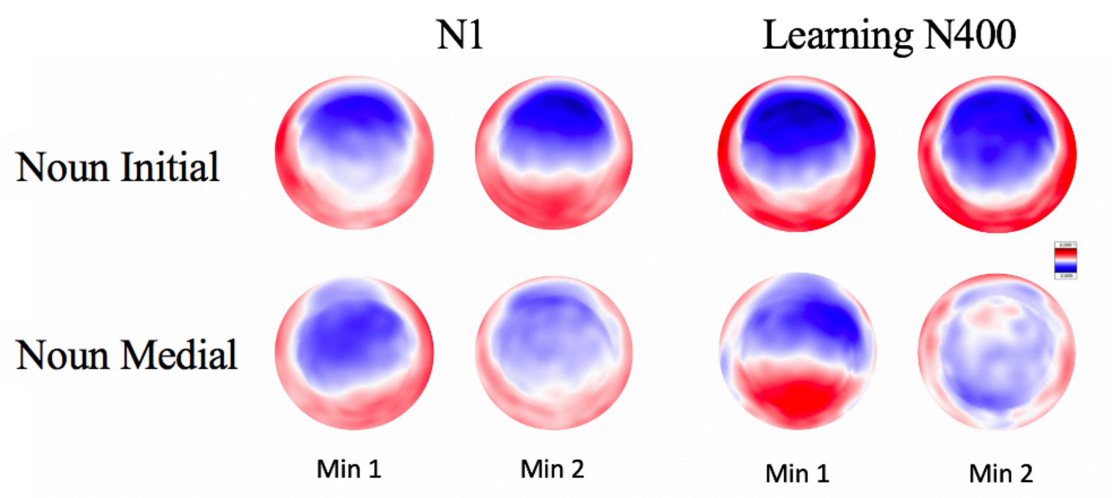
Paired-samples t-tests (two-tailed) were conducted to compare the amplitude of response elicited by the noun syllables during miniblock 1. Results indicated that noun initial syllables elicited significantly more negative response during the 40 to 200ms interval, $t(25) = -2.99$, $p = .006$; at the N1 peak, $t(25) = -2.23$, $p = .035$; and during the 300 to 500ms interval after syllable onset, $t(25) = -3.44$, $p = .002$. Thus, during the initial two minutes of exposure, the noun initial syllables already elicited greater negativity.

Next, in order to determine whether noun initial syllables elicited significantly more negative response than noun medial syllables in the *first* minute of exposure, the first miniblock was divided in half in order to compare the negativity elicited by the noun initial and noun medial syllables in the first minute. The grand average topographic map (Figure 4.9) shows the comparison of noun initial and noun medial syllables during the first and second minutes of exposure. A paired samples t-test (two-tailed) was conducted to determine whether there was a significant difference in N1 amplitude for noun initial and noun medial syllables during the first minute of phonological familiarization. Results indicated that there was no significant difference during the first minute, $t(25) = -0.33$, $p = .74$. Similarly, for the Learning N400, a paired sample t-test (two-tailed) was conducted to test whether there was a difference in mean amplitude response to the noun initial and noun medial syllables during the first minute of phonological familiarization.

indicated that there was no significant difference during the first minute of exposure, $t(25) = -1.93$, $p = .065$.

Figure 4.9

Comparison of Noun Initial and Noun Medial Syllable Response During First and Second Minute of Phonological Familiarization



Note. This figure shows the first miniblock, broken down into minute 1 and minute 2. The N1 component (left) is represented here by the 100ms interval surrounding the N1 peak (60 -160ms). The Learning N400 (right) is represented by the 100ms interval surrounding the component's midpoint (350-450ms).

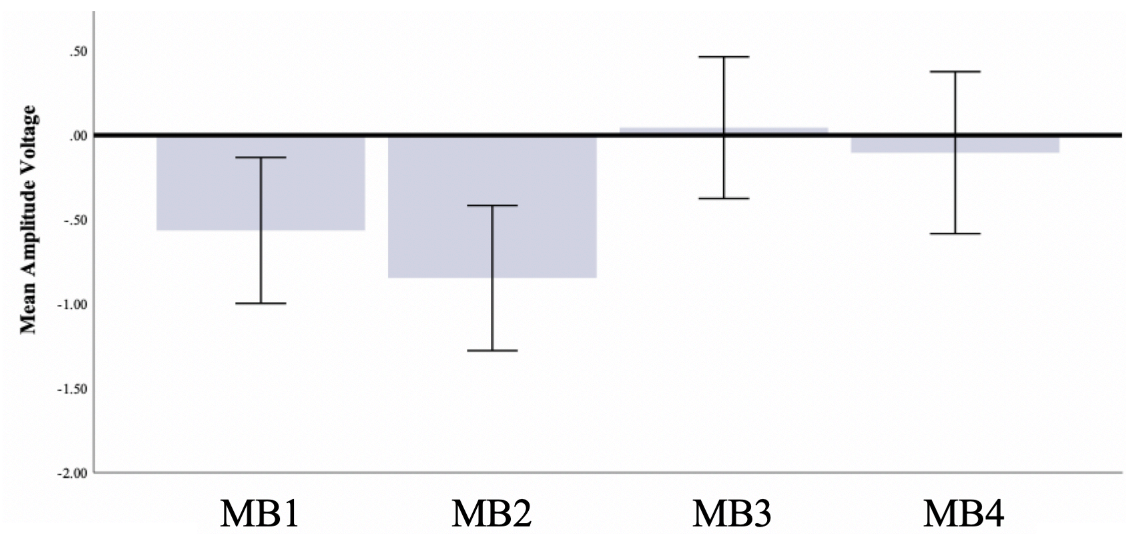
For both the early and late component the mean negativity of the noun initial syllable increased from the first to second minute; while for the noun medial syllable, the negativity decreased from first to second minute. In this grand average topographic map, there is a pattern of increasing negativity to the noun initial syllable and decreasing negativity to the noun medial syllable, suggesting a strengthening of the word onset negativity effect during the initial two minutes of soundstream exposure.

Syllable Differences Across the Miniblocks

Figure 4.10 shows the early word onset negativity (40 to 200ms interval) as it develops with exposure across the four miniblocks of the phonological familiarization phase. The figure shows the difference between syllables as a bar chart of the syllable difference means. Noun initial syllables had greater mean negativity for the first half of the phase than did noun medial syllables. The mean difference between syllables was highest in the second miniblock. There was then a decline in the greater negativity of the noun initial syllable for the second half of the phase.

Figure 4.10

Time Course of the Early Word Onset Negativity (40 to 200ms Interval) Across the Four Miniblocks.



Note. The figure graphs the difference between syllables as a bar chart of the syllable difference means. Error bars are 95% confidence intervals.

Planned mixed measures ANOVAs with syllable difference as dependent variable (noun initial minus noun medial syllable) revealed that the amplitude of word onset negativity changed significantly across the four miniblocks for the 40 to 200ms interval,

$F(2.73, 65.60) = 4.26$, $p_{G\text{-}G} = .010$, $\eta_p^2 = .15$, $pw = .82$; and at the N1 peak, $F(2.79, 67.00) = 4.85$, $p_{G\text{-}G} = .005$, $\eta_p^2 = .17$, $pw = .87$. Pairwise comparisons showed miniblock 2 was significantly more negative than miniblock 4 during the 40 to 200 interval, $p = .029$. At the N1 peak, miniblock 2 was significantly more negative than miniblock 3, $p = 0.28$. The corresponding mixed measures ANOVA for the Learning N400 (300-500ms) was not significant ($p_{G\text{-}G} = .080$), indicating no significant differences in syllable difference across the four miniblocks in the later interval.

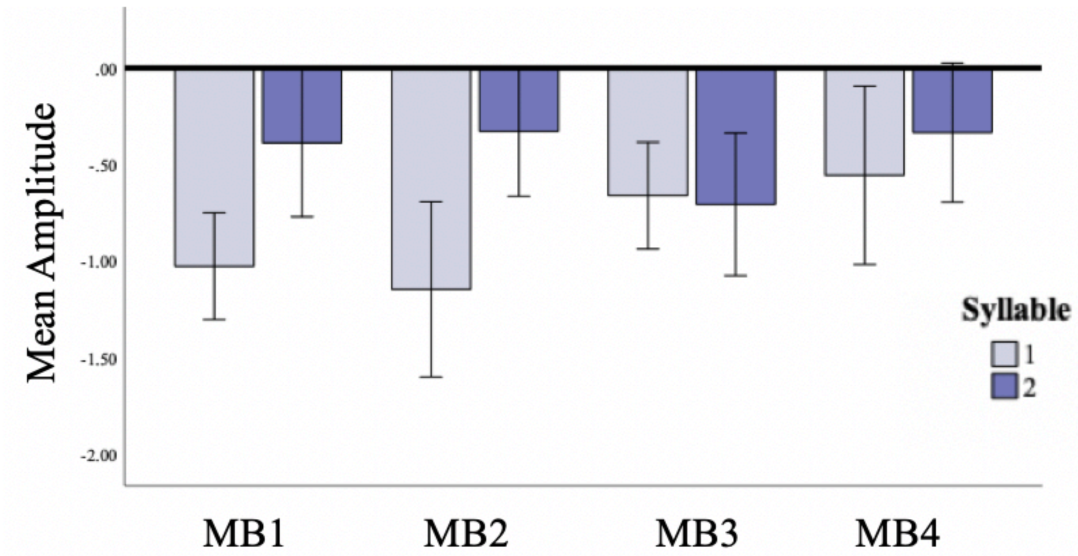
However, from these analyses with syllable difference as the dependent variable, it is unclear whether the difference between the initial and medial syllable decreased due to the noun initial syllable becoming less negative, or to the noun medial syllable becoming more positive. Similarly, it is unclear whether a stable syllable difference was due to stability of both noun initial and noun medial syllable measure, or whether it was due to noun initial and medial syllable increasing or decreasing simultaneously. To distinguish among these possibilities requires analysis of the syllable dynamics by examining the change in amplitude for each individual syllable, rather than for the syllable difference. Therefore, individual syllable amplitude for each interval was used as the dependent measure for the next analyses.

Individual Syllable Dynamics Across the Miniblocks

Figure 4.11 shows the syllable dynamics across the four miniblocks for the 40 to 200ms interval, with syllables represented as individual syllable mean amplitudes, rather than as syllable difference. From this figure, it can be seen that the mean amplitude of response elicited by noun initial syllables decreased in the second half of the phase (miniblocks 3 and 4). In contrast, the mean amplitude of response elicited by noun medial syllables was stable for the first, second and fourth miniblocks. In the third miniblock, noun medial syllables response increased in negativity, even surpassing mean amplitude of first syllable amplitude for the third miniblock.

Figure 4.11

Syllable Dynamics Across the Four Miniblocks for the 40 to 200ms Interval.



Note. This figure shows the syllable position (noun initial or medial) x exposure time (miniblock 1,2,3,4) interaction as individual syllable mean amplitudes. Error bars show 95% confidence levels.

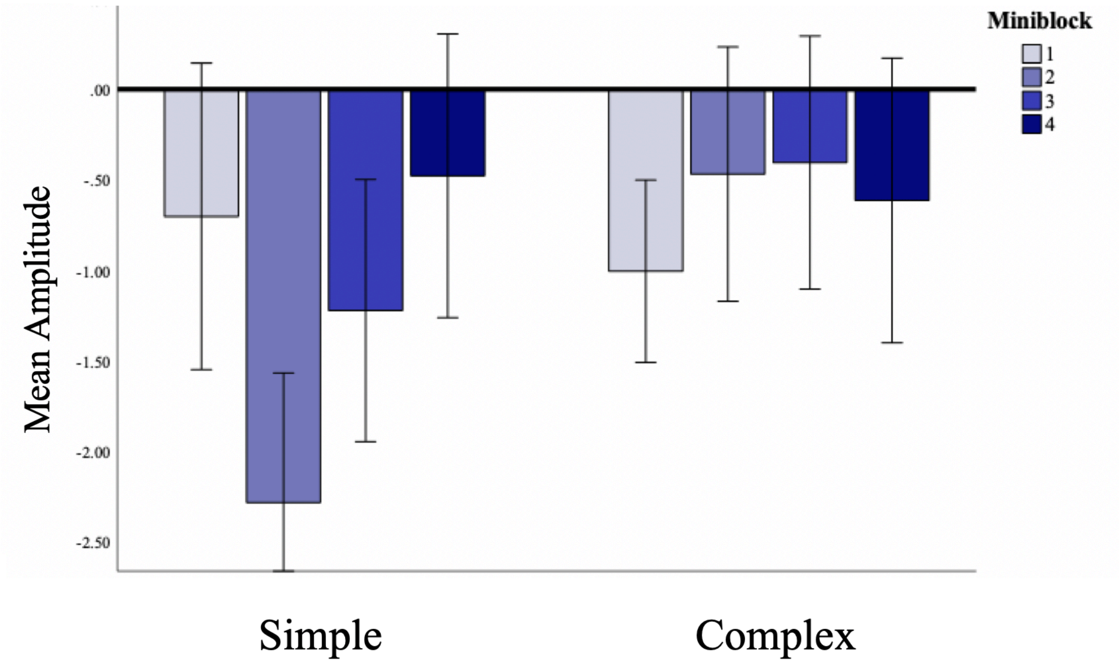
The mixed measures ANOVA revealed a significant interaction of syllable position (noun initial, noun medial) and time (miniblock 1, 2, 3, 4) for the 40 to 200ms interval, $F(2.78, 66.77) = 3.53$, $p_{G\text{-}G} = .022$, $\eta_p^2 = .128$, $pw = .74$; indicating that the syllable difference varied across the miniblocks during this interval. There was no significant interaction of syllable and miniblock for the N1 peak interval ($p_{G\text{-}G} = .069$) or for the 300 to 500ms interval ($p_{G\text{-}G}$ = .080), indicating the syllable difference overall did not change significantly across the four miniblocks for these intervals. However, to interpret these results correctly, it was necessary to consider them in the context of significant higher order interactions with both phrase complexity and learner type, factors collapsed within the previous comparisons. The next analyses explored these interactions.

Divergent Pattern of Syllable Difference Across the Miniblocks for Simple and Complex Phrases for the Learning N400 (300 to 500ms)

Previous results from artificial grammar research has shown an increase and then decrease in relative negativity during the N400 window, and it had been predicted that there would be a similar pattern of word onset negativity in the 300 to 500ms interval, with the syllable difference increasing and then decreasing across the miniblocks during phonological familiarization. The mixed measures ANOVA with the 300 to 500ms interval syllable difference showed a significant interaction of miniblock and phrase complexity; indicating that participants overall showed a different pattern of response to the simple and complex phrases across the four miniblocks, $F(2.60, 62.38) = 5.63$, $p = .003$, $\eta_p^2 = .19$, $pw = .90$. A bar chart of the interaction is displayed in Figure 4.12. As can be seen from this figure, the mean amplitude of the syllable difference revealed the expected (replicating artificial grammar research) pattern of mean increase then decrease for the simple noun syllables but not for the complex nouns. The complex noun mean amplitudes diverged from the expected pattern in the second miniblock. This interaction was not significant during the 40 to 200ms. interval ($p_{G\text{-}G}$ = .28) or at the N1 peak interval ($p_{G\text{-}G}$ = .77).

Figure 4.12

Syllable Difference for Nouns of Simple and Complex Phrases Across the Four Miniblocks for the Learning N400 (300-500ms)



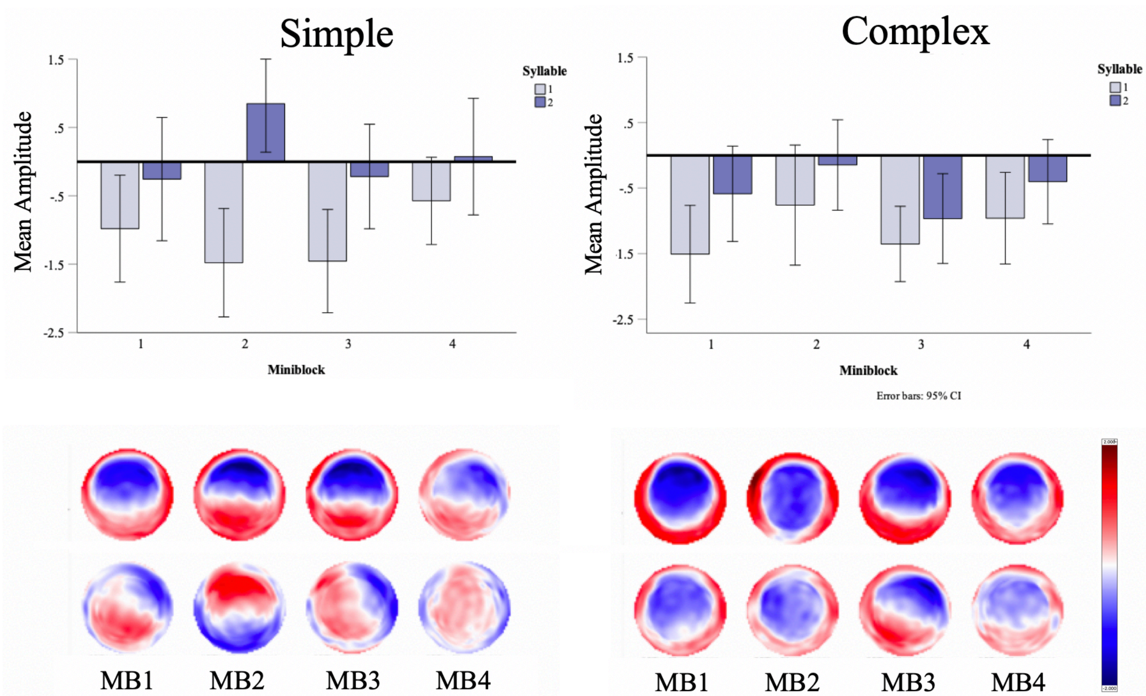
Note. The dependent variable is the syllable difference of selected medial frontal electrodes. Error bars show 95% confidence levels.

Syllable Dynamics Across the Miniblocks for Simple and Complex Phrases (300 to 500ms)

To understand this interaction, the syllable dynamics for this effect were next examined. The three-way interaction of syllable, miniblock and phrase complexity was significant for the 300 to 500ms interval, F (2.57, 61.58) = 3.63, $p_{G\text{-}G}$ = .023, η_p^2 = .13, pw = .72. As can be seen in Figure 4.13, the simple condition syllables revealed a pattern of medial frontal negativity increase and subsequent decrease to the noun initial syllable. Noun syllables in the complex condition, in contrast, elicited a negativity for both syllables. This interaction was not significant during the 40 to 200ms interval ($p = .34$) or at the N1 peak ($p = .42$).

Figure 4.13

Syllable Dynamics for Simple and Complex Nouns Across the Four Miniblocks (300-500ms)



Note. The top row of topomaps are the noun initial syllables, and the bottom row are noun medial syllables. The scale for the topomaps is -2 to 2. Error bars are the 95% confidence intervals. The bar chart shows the mean amplitude of selected medial frontal electrodes.

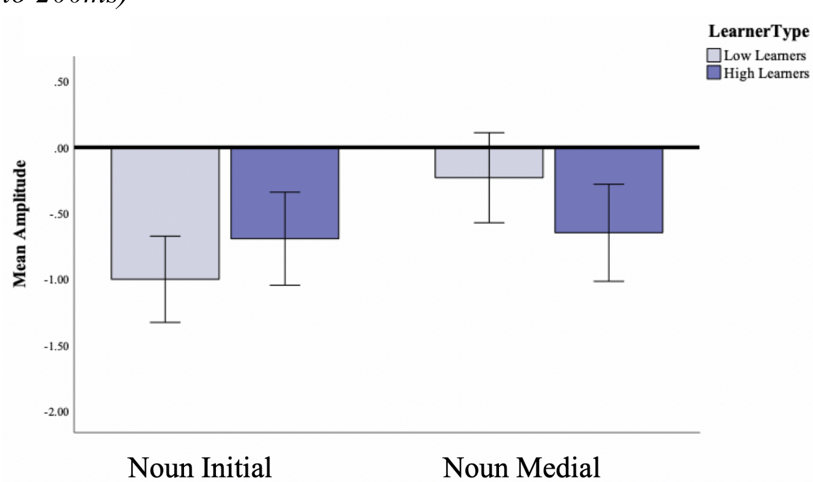
Did High and Low Learners Differ in Their Response to Nouns in Simple and Complex Phrases?

As mentioned previously, it was expected that high and low learners might show interesting differences in learning at the two levels of phrase complexity, and that the neural indices of online language learning might provide insight into the nature of differences in approach to coping with the complex task of learning a new language, as well as why some individuals were more successful at the task.

Results of planned mixed measures ANOVAs indicated that the learner types differed significantly in their electrophysiological response to the noun syllables. There was a significant interaction of syllable and learner type in the 40 to 200ms interval, $F(1, 24) = 6.62$, $p = .017$, $\eta_p^2 = .22$, $pw = .69$; and at the N1 peak, $F(1,24) = 7.77$, $p = .010$, $\eta_p^2 = .25$, $pw = .76$. Low learners overall had higher mean negativity to noun initial than to noun medial syllables, while the difference between noun initial and noun medial syllables was not significant for high learners. Mean amplitude to noun medial syllables was greater for high learners than for low learners. This interaction is shown in Figure 4.14.

Figure 4.14

High and Low Learner Mean Amplitude for Noun Initial and Noun Medial Syllables (40 to 200ms)

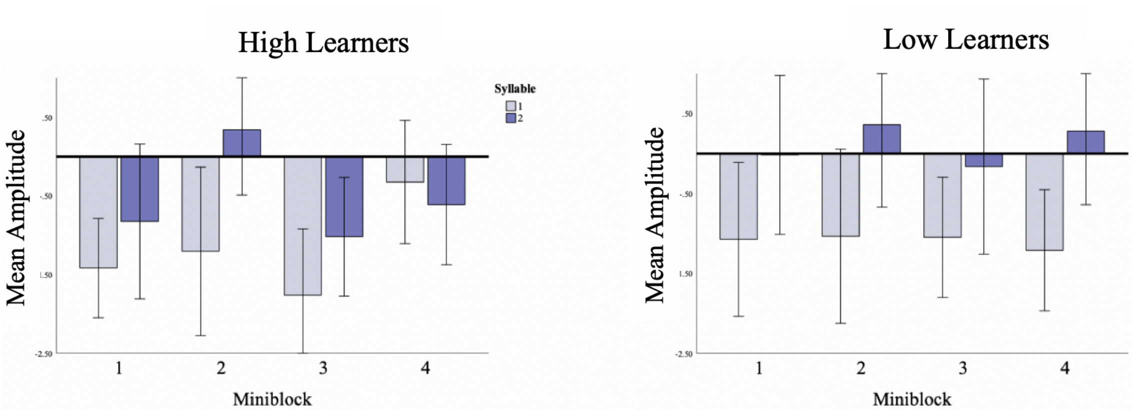


Note. Error bars are the 95% confidence intervals. The bar chart shows the mean amplitude of selected medial frontal electrodes.

For the 300 to 500ms interval, there was a significant three-way interaction of syllable, miniblock and learner type, $F(2.61, 62.72) = 3.69$, $p_{G\text{-}G} = .021$, $\eta_p^2 = .13$, $pw = .74$. Follow-up repeated measure ANOVAs (syllable x phrase complexity) conducted separately for each learner type revealed that high learners showed a significant syllable x miniblock interaction, $F(2.06, 22.69) = 7.76$, $p_{G\text{-}G} = .003$, $\eta_p^2 = .41$, $pw = .92$; while low learners did not ($p_{G\text{-}G} = .53$). Both the significant high learner interaction and non-significant low learner interaction are shown in Figure 4.15.

Figure 4.15

Interaction of Syllable, Miniblock and Learner Type for the Learning N400 (300 to 500ms)



Connecting Neurophysiology and Behavior During Phonological Familiarization

An important question was whether the amplitude of the word onset negativity correlate with behavioral measures of learning. It was predicted that weighted noun learning would correlate with the amplitude of the syllable difference (word onset negativity). Pearson's correlation coefficient (two-tailed) was calculated to determine the correlation of the weighted noun learning and the syllable difference (noun initial minus noun medial syllable). For this analysis, the correlation of weighted noun learning and the syllable difference (noun initial minus noun medial) was tested for each phrase complexity, miniblock and neural index (N1, 40-200ms and Learning N400) separately. Results indicated that, for participants overall, there were no significant correlations between weighted noun learning and the syllable difference measures for any miniblock or phrase complexity level for any of the three time intervals analyzed.

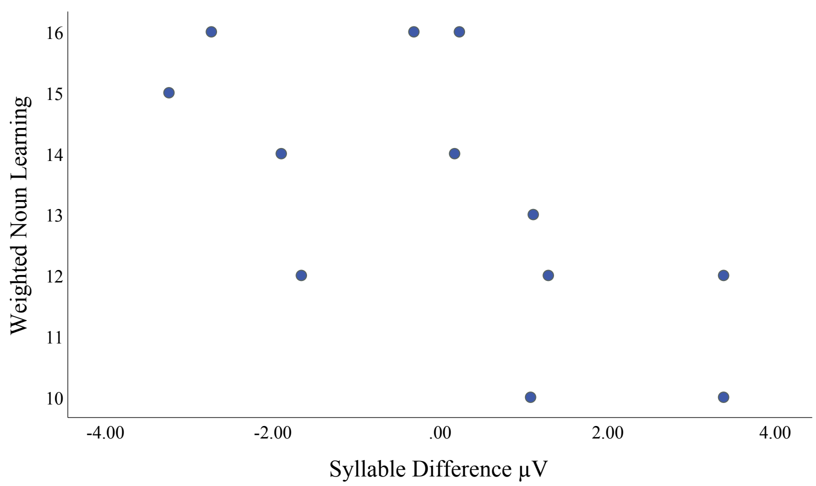
Next, this correlational analysis (two-tailed) was repeated separately for high and low learners. For low learners there were no significant correlations between weighted noun learning and the syllable difference for any of the conditions, with each phrase complexity, miniblock and time interval separately tested. For high learners, weighted noun learning correlated negatively with the amplitude of the simple noun syllable difference in response during the 40 to 200ms interval, $r(10) = -.64$, $p = .025$; and during the N1 peak interval, $r(10) = -.65$, $p = .023$. The scatterplot in Figure 4.16 displays the significant correlation. No other significant correlations were found between weighted noun learning and the syllable difference for any conditions, with each level of phrase complexity, miniblock and each time interval separately tested.

Semantic Use Practice Exploratory Analysis (Phase 3)

During the third phase, participants performed a simple matching task (“game”) that engaged them in semantic use of the phrases. This phase had the purpose of engaging the participants in practice of the language system to develop expertise. Additionally, it had the purpose of collecting an on-line behavioral measure of language learning during the development of expertise (collected as reaction time) as well as a behavioral measure of language system proficiency (task accuracy). Thus, the task was not structured for

Figure 4.16

High Learners' Correlation of Weighted Noun Learning and Simple Noun Syllable Difference in Miniblock 3 (40-200ms)



Note. Syllable difference is the difference between noun initial and noun medial syllables for selected medial frontal electrodes.

ERP analysis. Participants were engaged in a motor task. Additionally, for the semantic mapping task, they had been instructed to voice the phrases during each trial. This was intended to facilitate their development of proficiency. These factors resulted in data with low signal to noise ratio. Due to the high motion artifact, the data were not successfully cleaned with FASTER (Nolan et al., 2010). Therefore, Net Station was used to review datafiles. Three participants, two high learners (Participants A and B) and one low learner (Participant C), were selected for single-trial analysis based on their high number of good trials and the fact that they had all completed the practice task with the same order, which made comparison among the datafiles possible. Learner characteristics for the three selected participants are shown in Table 4.4.

Table 4.4

Learner Characteristics for Three Participants Selected for Single-Trial Analysis for Semantic Use Practice

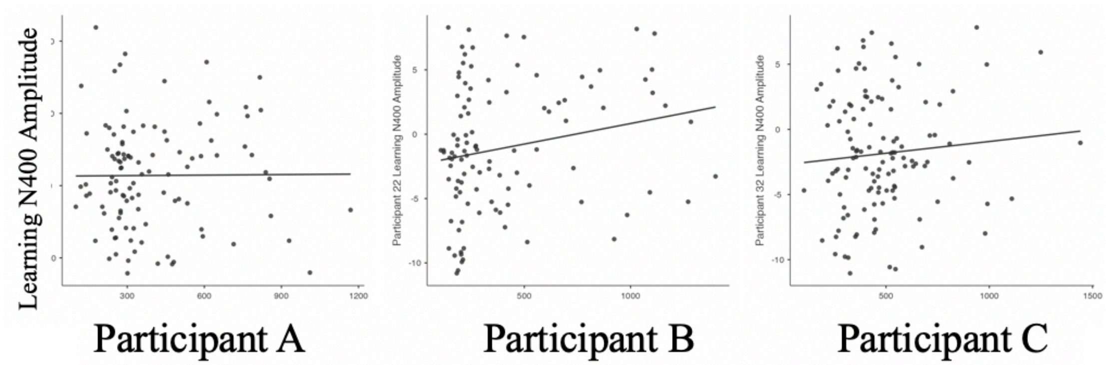
Participant	Mean RT *(SD)*	Accuracy	Noun Learning	
			Learner Type	Weighted
A	378ms (261ms)	93%	High	16
B	533ms (556ms)	96%	High	12
C	475ms (226ms)	90%	Low	7

Note. For practice task accuracy, only five participants of 26 scored below 90% correct; three scored below 80%.

Behavioral and electrophysiological measures from these three participants were then used for exploratory analyses to test the exploratory hypothesis that the amplitude of the Learning N400 would track a subjective aspect of complexity (or "experiential complexity"). It was reasoned that, if the amplitude of the Learning N400 component tracked a subjective measure of complexity, then the amplitude would decrease with exposure as learning increase; and that the amplitude of the negativity would correlate with reaction time, a measure that has been shown to be associated with task complexity (e.g., Tun and Lachman 2008). In order to test this hypothesis, the amplitude of the Learning N400 component was extracted for each of the 128 semantic use practice trials for the noun initial syllable. Scatter plots for these correlational analyses are shown in Figure 4.17. Reaction times below 100ms and above 1500ms were removed, as were extreme points for the Learning N400 measure. Next, Spearman's rank order correlation coefficient was calculated to test the relationship between each participant's reaction time and their Learning N400 measure. For Participant A, the correlation between the Learning N400 amplitude and reaction time was not significant, $r_s(106) = 0.028$, $p = .77$. For Participant B, there was a significant positive weak correlation between the Learning N400 amplitude and reaction time, $r_s(102) = 0.23$, $p = .022$. Participant C, the correlation between the Learning N400 amplitude and reaction time was not significant, $r_s(118) = 0.059$, $p = .52$. Thus, for one of three participants, there was a significant, though weak, correlation between the amplitude of the Learning N400 and the reaction time measure.

Figure 4.17

Scatterplots Showing the Relationship Between Semantic Use Practice Learning N400 Amplitude and Reaction Time



Comprehension Listening (Phase 4)

Analyses for the comprehension phase aimed to characterize the extent to which the previously reported indices of early language learning continued to index participant language processing in the post-training phase, as participants listened to and presumably now comprehended the micro language phrases.

These analyses followed two lines of questioning. The first line sought to characterize post-training processing and to determine the extent to which learner-type differences in processing and proficiency persisted after micro language training was complete. The second line of questioning examined the electrophysiological changes that occurred with the increase in micro language expertise over the course of acquisition, in order to distinguish which of these components had been transitorily present during the course of learning, indexing the mechanisms of learning, then attenuating after training; and which ERP components were still present or increasing post training.

Hypotheses tested included that a) participants with different learning profiles would continue to display systematic differences in regard to the previously identified neural indices of language learning during the comprehension listening phase; and that b) electrophysiological indices associated with higher-proficiency processing would develop from the phonological familiarization phase to the comprehension listening phase. For these hypotheses, the following specific predictions were made.

First, it was predicted that noun initial syllables would elicit a higher amplitude N1 compared to noun medial syllables during comprehension listening. A learner-type difference was predicted for this N1 effect, such that the higher N1 to word initial syllables would develop in high learners and would be absent or weaker in low learners, based on the prior findings that it emerges only with development of high-level proficiency (Sanders et al., 2003; Abla et al., 2008; Sanders et al., 2009). Because this higher N1 to word initial syllables is observed in native speaker natural language processing, it was expected to persist post training.

Second, regarding the Learning N400, it was unclear what the post-training course of the component would be. For artificial grammar, the relative negativity of onset syllables decreases in amplitude but the difference between word initial and word medial syllables is reported to remain significant after learning (e.g., Cunillera et al., 2009). Therefore, it was possible that this pattern would also be seen during the micro language acquisition, with early increase of the medial frontal negativity during word learning, then decrease but not disappearance of the negativity post learning. However, because these prior studies only record on-line acquisition process for several minutes, whether the noun onsets would still elicit this medial frontal negativity after an hour -- and after semantic training has taken place -- was uncertain.

Finally, it was predicted that a Semantic N400 would be observed during comprehension listening, reflecting that participants were not only listening but additionally evaluating meaning. This Semantic N400 was expected to have a topography posterior to that of the medial frontal component of overlapping latency seen in the phonological familiarization (pre-training) phase. Because the Semantic N400 is thought to index the processing of meaning, a question of interest was to what syllable a Semantic N400 component would emerge: whether it would be elicited by the phrase onset or by the noun onset — or alternatively, by both phase and noun onsets, or even by a noun medial syllable.

To address questions pertaining to the comprehension listening phase alone, mixed measure ANOVAs were used to test the effects of the within-subjects variables of syllable position (noun initial or medial) and phrase complexity (simple or complex), and the between-subjects variable of learner type (low or high) on the ERP amplitude for the N1 peak interval, extracted as the mean amplitude of a 40ms interval surrounding the adaptive N1 peak and the Learning N400, extracted as the mean amplitude for the interval 300 to 500ms after syllable onset.

To address questions pertaining to pre- and post-training effects, mixed measure ANOVAs were used to test the effects of the within-subjects variables of training (pre- or post-training), syllable position (noun initial or medial) and phrase complexity (simple or complex), and the between-subjects variable of learner type (low or high) on the ERP amplitude for two dependent measures: the N1 peak interval, extracted as the mean amplitude of a 40ms interval surrounding the adaptive N1 peak; and the Learning N400, extracted as the mean amplitude for the interval 300 to 500ms after syllable onset. For the N1 and Learning N400, the same medial frontal locations used for the phonological familiarization (Phase 1) analyses represented the effects. Details of these dependent measures are provided in Chapter 3.

To test whether the Semantic N400 emerged from pre-training to post-training, a mixed measure ANOVA was used to test the effects of the within-subjects variables of training and the between subjects variable of learner type (low or high) on the amplitude of the Semantic N400, extracted as the mean amplitude for the interval 350-500ms. The Semantic N400 was represented by selected channels surrounding Cz, as described in Chapter 3.

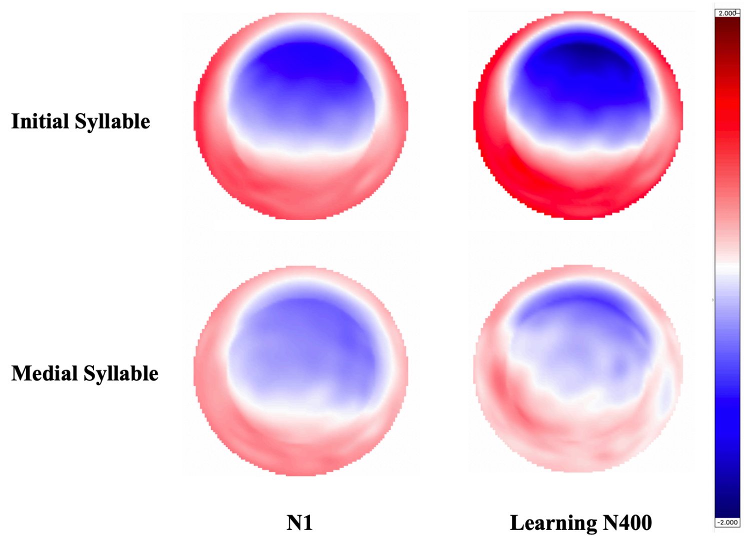
As for the prior results, these results will be presented in a question-and-answer format. First, questions of normative learning will be addressed. Next, questions of complexity will be addressed. Finally, questions pertaining to the learner-type differences will be addressed.

Did Noun Initial Syllables Elicit Greater Negativity Than Noun Medial Syllables During Comprehension Listening?

Figure 4.18 shows a grand average comparison of noun initial and medial syllables during the time of the N1 and the Learning N400. As apparent in the figure, for participants overall, noun initial syllables elicited higher mean medial frontal negativity than did noun medial syllables during both intervals.

Figure 4.18

Syllable Position Effect During Comprehension Listening



Note. For the adaptive N1 peak, an 85-135ms latency represents the 50ms interval surrounding the N1 Peak at 111ms. The Learning N400 was represented here by a window of 100ms surrounding the center point of the Learning N400. All participants are included (n = 26). Data for these topographical maps are average referenced for 256 channels.

Results of the mixed measures ANOVA for the comprehension phase indicated that for all participants together, this syllable position effect was significant for the N1 Peak interval, $F(1,24) = 11.40$, $p = .002$, $\eta_p^2 = .32$, $pw = .90$; noun initial syllables elicited higher negativity.

For the Learning 300 to 500ms interval, results of the mixed ANOVA indicated that noun initial syllables elicited significantly higher amplitude negativity than noun medial syllables for the selected medial frontal locations, $F(1,24) = 14.16$, $p = .001$, $\eta_p^2 =.37$, $pw = .95$; suggesting the continuation of the Learning N400 component into the post-training phase. Analyses later in this chapter will revisit this component and compare its characteristics in the phonological familiarization (pre-training) phase and in the comprehension listening (post-training) phase.

Did N1 Amplitude Differ by Phrase Complexity During Comprehension Listening?

Next, analyses examined how the syllable position effect differed for the two complexity levels (simple and complex). The amplitude of response to simple and complex noun syllables overall (collapsing noun initial and medial syllables together) was compared to determine whether participants showed systematic differences in their response to noun syllables of the two complexity levels during comprehension listening. Overall, with noun initial and medial syllables collapsed together, complex phrase noun syllables elicited higher amplitude response at the N1 peak, $F(1,24) = 5.92$, $p = .023$, $\eta_p^2 = .20$, $pw = .65$; indicating that the negativity elicited by complex phrase noun syllables was greater overall compared to the negativity elicited by simple phrase noun syllables, collapsing across the syllable position factor. This main effect of phrase complexity was significant also in the 40 to 200ms interval, $F(1,24) = 4.96$, $p = .036$, $\eta_p^2 = .17$, $pw = .57$. This effect was not significant in the 300 to 500ms interval ($p = .085$).

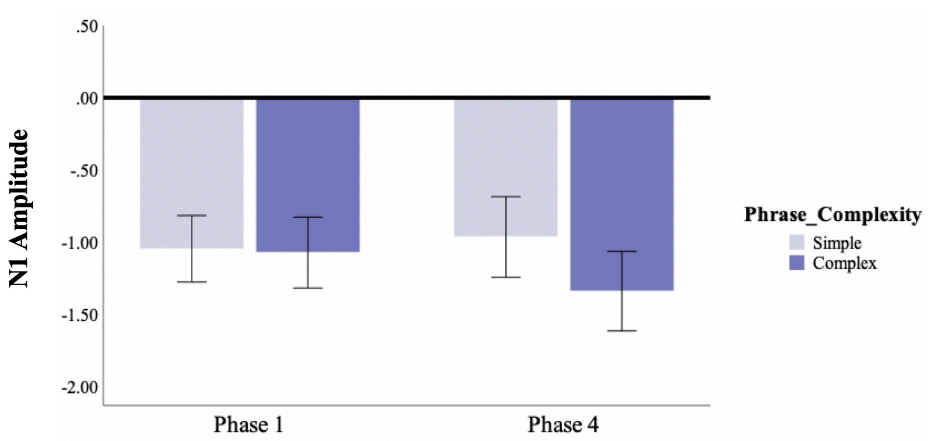
From Pre- to Post-Training: Did the Higher N1 to Complex Noun Syllables Develop, or Was it Present from the Onset of Listening?

An interesting question was whether the higher amplitude NI response seen to complex syllables during comprehension listening was a learning effect. Another possibility was that acoustic differences in the natural language stimuli may have led to the effect. If so, the higher negativity would likely be present from the onset of exposure; because acoustic differences (such as language stresses) as would presumably be available from the onset of exposure.

Figure 4.19 shows the mean amplitude of the N1 component for simple and complex phrase syllables during phonological familiarization (Phase 1) and during comprehension listening (Phase 4). As evident in the figure, their mean N1 amplitude was similar during phonological familiarization. However, by the (post training) comprehension listening, complex phrase nouns elicited higher mean N1 amplitude. This effect was significant, $F(1, 24) = 5.96$, $p = .022$, $\eta_p^2 = .20$, $pw = .65$.

Figure 4.19

Mean Amplitude of the N1 for Noun Syllables of Simple and Complex Phrases During Phonological Familiarization (Phase 1) and Comprehension Listening (Phase 4)

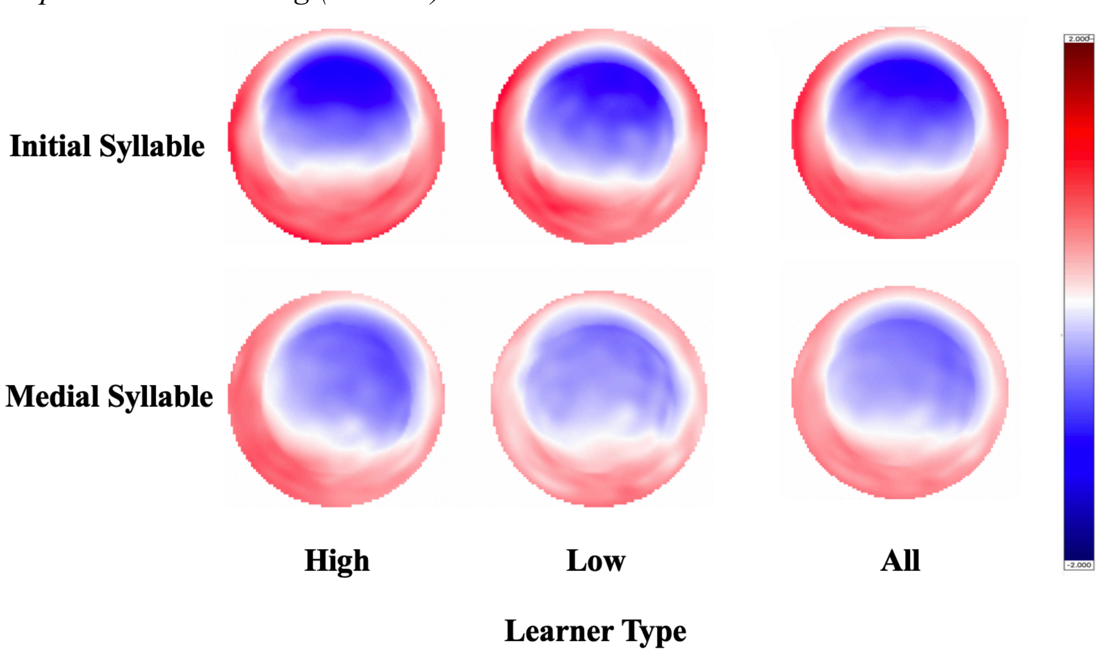


Did High and Low Learners Differ in Their Response to Nouns Initial and Noun Medial Syllables During Comprehension Listening?

Figure 4.20 shows topographic maps of the N1 mean amplitude response to noun initial and medial syllables for high learners, low learners, and for both learner types combined. It had been predicted that for high learners, noun initial syllables would elicit a higher amplitude N1 in comparison to noun medial syllables in the group of high learners, replicating prior research (e.g., Sanders et al., 2002, 2009). This effect was expected to be weaker or absent for low learners, because the higher N1 is reported to develop only at high proficiency. However, as shown in Figure 4.20, both high and low learners had higher mean N1 for noun initial syllables than for noun medial syllables.

Figure 4.20

Mean N1 Peak Amplitude to Noun Initial and Noun Medial Syllables During Comprehension Listening (Phase 4)



Note. These topographic maps show the mean amplitude from 85 to 135ms post syllable onset, a 50ms interval surrounding the mean N1 peak amplitude of 111ms.

Follow-up repeated measures ANOVA (syllable position x phrase complexity) were conducted separately for high and low learners in order to examine the effects of syllable position and phrase complexity on the amplitude of the ERP during the N1 peak, 40-200ms and 300-500ms interval; For each of these three dependent measure, the same medial frontal array of electrodes selected for the mixed measures model were used. Results of the repeated measures ANOVA supported the prediction: noun initial syllables elicited significantly higher N1 than did noun medial syllables for the group of high learners, $F(1, 11) = 7.86$, $p = .017$, $\eta_p^2 = .42$, $pw = .72$. While the low learners showed a higher mean N1 response to noun initial syllables (as visible in Figure 4.20), the syllable position effect did not reach significance for them ($p = .077$).

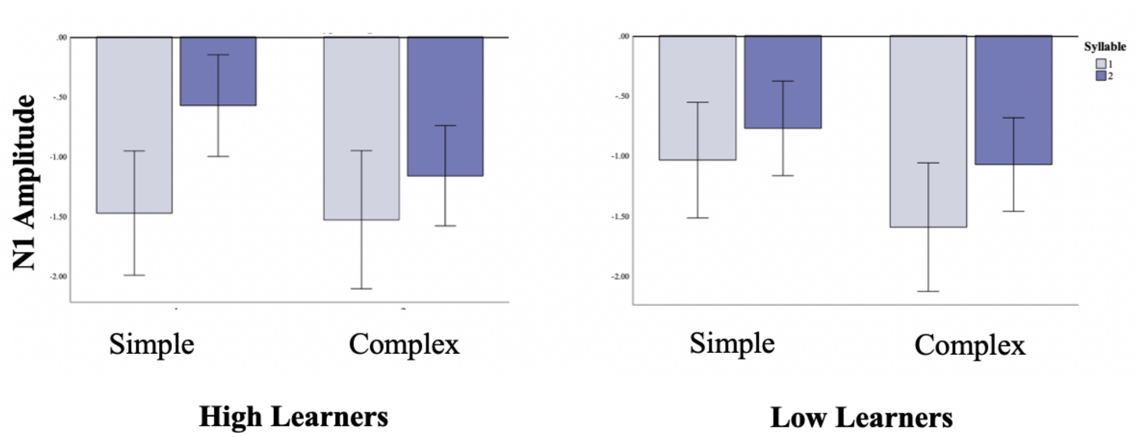
For the later 300 to 500ms interval, noun initial syllables elicited higher medial frontal negativity than noun medial syllables for both high learners, $F(1, 11) = 7.95$, $p = .017$, $\eta_p^2 = .42$, $pw = .73$; and for low learners, $F(1, 13) = 6.11$, $p = .028$, $\eta_p^2 = .32$, $pw = .63$.

Did High and Low Learners Differ in Their Response to Noun Syllables of Simple and Complex Phrases During Comprehension Listening?

Figure 4.21 shows the mean N1 amplitude of syllable response (noun initial or medial) for each phrase complexity, separately for high learners and low learners. As shown in the figure, high learners had a different pattern of response to simple noun syllables compared to complex noun syllables. Specifically, high learner mean response to the noun initial and medial syllables showed greater difference in N1 amplitude for the simple condition than for the complex condition. This syllable position by phrase complexity interaction was significant for the high learners, $F(1,11) = 6.05$, $p = .032$, $\eta_p^2 = .36$, $pw = .61$. In contrast, the syllable position by phrase complexity interaction was not significant for the low learners ($p = .42$). The low learners responded with higher N1 to the noun initial than to the noun medial syllables, but with similar difference between noun initial and medial syllables for the simple and complex conditions.

Figure 4.21

Mean N1 Amplitude Elicited by Noun Initial and Noun Medial Syllables for High and Low Learners During Comprehension Listening

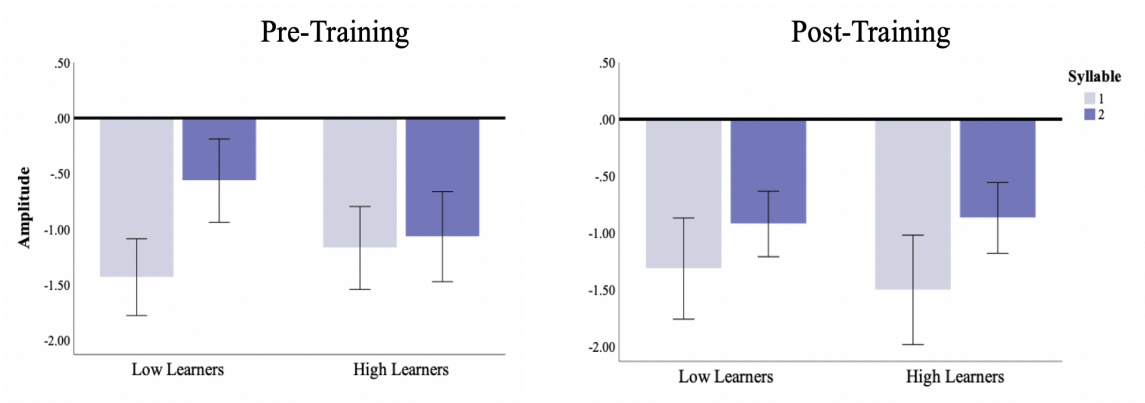


How Did High and Low Learner Response to Noun Syllables Change with Training?

To determine the effects of training on the development of the N1 and Learning N400, the results of the four-way ANOVA (training x syllable position x phrase complexity x learner type) were examined. The three-way interaction of training, syllable and learner type was significant, $F(1, 24) = 6.07$, $p = .021$, $\eta_p^2 = .20$, $pw = .66$. Figure 4.22 shows this interaction. No other interactions with training were significant for this analysis.

Figure 4.22

The Effect of Training on N1 Amplitude for Noun Initial and Noun Medial Syllables for High and Low Learners

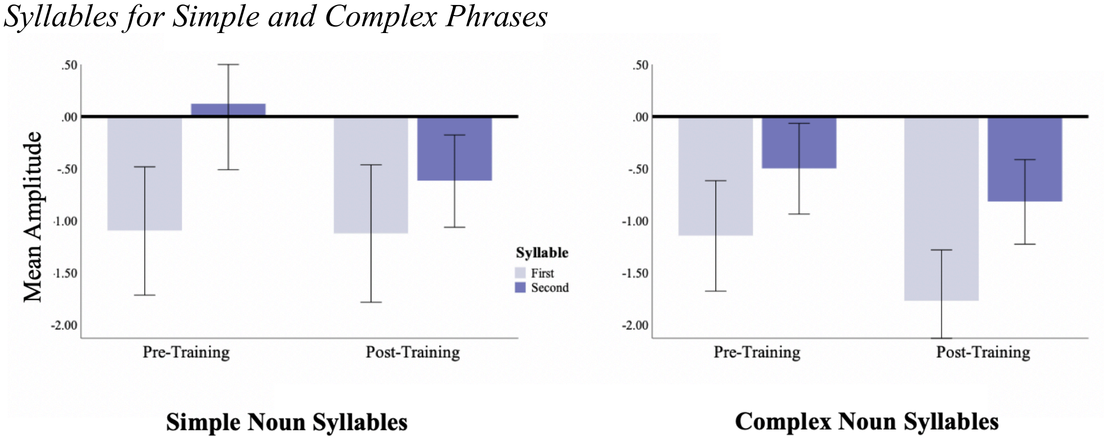


Note. This figure collapses across phrase complexity. Error bars represent 95% confidence intervals.

Regarding the effects of training on the Learning N400 amplitude, there was a significant three-way interaction of training, syllable position and phrase complexity, . This interaction is shown in Figure 4.23. No other effects of training were significant for this analysis.

Figure 4.23

The Effect of Training on Learning N400 Amplitude for Noun Initial and Noun Medial Syllables for Simple and Complex Phrases

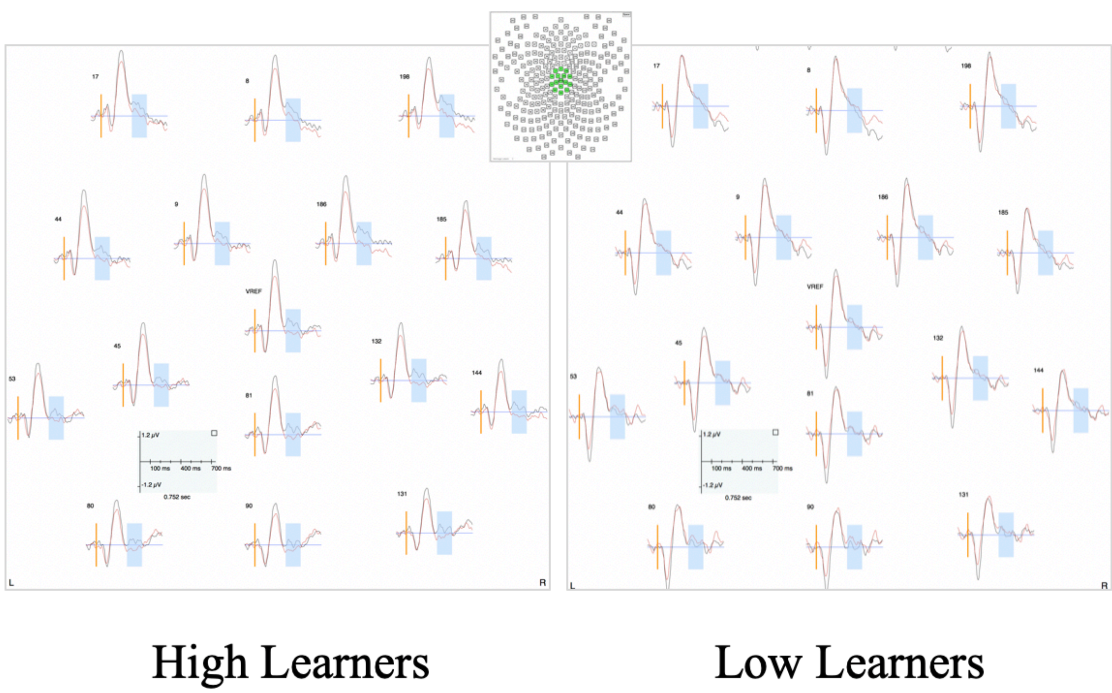


Did a Semantic N400 Component Emerge to Noun or Number Onsets from Pre- to Post-Training?

No Semantic N400 appeared to emerge to the noun initial or noun medial syllables. However, a comparison of the ERPs to phrase onset syllables for phonological familiarization (pre-training) and comprehension (post-training) phases revealed a Semantic N400-like negativity in the high learner grand average topographic plot. This comparison is shown in Figure 4.24. This negativity was not seen in the grand average topographic plot for the low learners. ANOVA results indicated that this interaction of training and learner type was not significant ($p_{G\text{-}G}$ = .12)

Figure 4.24

Centro-Parietal Negativity to Phrase Onsets at Latency 300-450ms for High and Low Learners



Note. The blue highlight shows the ERP segment extracted for statistical analysis. The inset shows the plotted scalp locations in green.

Supplementary Analyses for Comprehension Phase

The two practice orders (noun practice first and number practice first) in the semantic use practice (Phase 3) had been counterbalanced in order to observe both the noun and number practice tasks during the level of expertise reached during the first and second half of the practice task. To test whether the practice order resulted in systematic carryover effects in participant electrophysiological response during comprehension listening (Phase 4), the following supplementary analyses were conducted. First, the number of high learners and low learners in each practice order were counted. Of the 12 high learners, six completed the number practice first, and six completed the noun practice first. Of the 14 low learners, six completed the number practice first, and eight completed the noun practice first. Thus, high and low learners were approximately balanced across the two practice orders. Next, to test whether the order of practice task impacted the ERP response to noun syllables in the comprehension listening phase (Phase 4), separate ANOVAs were conducted to test for differences in the N1 peak amplitude and the Learning N400 (300-500ms). No significant effects of practice order were found for the N1 amplitude ($p > .43$) or for the Learning N400 ($p > .57$). Thus, no significant carryover effects were detected.

CHAPTER V

DISCUSSION

This dissertation research aimed to provide insight into why some individuals have a more difficult experience acquiring a new language. Specifically, the current research investigated the problem of complexity in learning with an exploratory study using seminatural language stimuli within an on-line learning paradigm. The goal was to observe how the neural indices of on-line language learning appeared over time as participants developed expertise in processing the seminatural micro language phrases. This problem was approached by examining differences in learning that were apparent during the initial moments of exposure to the new micro language.

While individual differences in electrophysiological response during on-line artificial grammar acquisition have been explored, the contribution of complexity to these individual differences is under-researched. The sparsity of research addressing this problem is due to the simplicity of the artificial grammar stimuli used for on-line language learning research, combined with the challenge of on-line recording of higher complexity natural language stimuli.

Summary and Interpretation

For the present research, the micro language made it possible to measure electrophysiological and behavioral changes during initial moments of natural-based language acquisition as adult participants progressed from initial exposure through to post-acquisition comprehension listening. These findings provide an on-line glimpse into processing during the initial moments of exposure to a new, native-spoken, natural-based language system. Grouping participants by behavioral performance revealed interesting electrophysiological differences in participant response to language stimuli of higher and lower complexity as learners experienced greater and lesser success in learning to cope with the complexity of the new language system.

The Micro Language Was Learnable Within the Soundstream Listening Paradigm

During the phonological familiarization phase, participant recall, measured by the four listening logs, indicated that the micro language stimuli were learnable within the soundstream listening paradigm. These logs revealed that at the end of the phonological familiarization phase, participants were able to recall most of the micro language sounds at the syllable level. As shown in Table 4.2, participants on average recalled about 14 of the 16 syllables. Word-level recall was somewhat lower than syllable recall. This can be seen in Figure 4.2. Participants on average had correctly segmented slightly under half the micro language words by the end of this first phase. Word segmentation requires both the preliminary step of learning the word-component sounds and the additional task of discovering the word boundaries; thus, this lower word learning compared to syllable learning was consistent with expected results. Phrase-level segmentation during this initial phase was relatively low, in comparison to syllable- and word-level recall; and it did not progress with continued exposure across the phrases, as shown in Table 4.3. This result may indicate that the lack of word order variation did not provide the cues needed for participants to parse the phrases. (An exception was the nouns, for which distributional cues to parsing were available.) Thus, these behavioral measures overall indicated that the micro language stimuli were generally learnable within the soundstream listening paradigm.

Almost half of the participants had learned all four nouns with correct segmentation by the end of the phonological familiarization phase. As planned, participants were divided into learner-type groups based upon their ability to recall all four nouns with correct segmentation by the end of this first phase. “High learners” had successfully segmented all four nouns by the end of the phonological familiarization. “Low learners” had been unsuccessful in segmenting all four nouns correctly.

High and Low Learners Overlapped in Weighted Noun Learning

In addition to learner type, weighted noun learning, a binary measure of noun learning, was scored. Weighted noun learning was a continuous measure that incorporated both segmentation success and rate of segmentation. The weighted noun learning measure corresponded to the number of trials during which the participant heard a noun after having recalled it on a language log. Thus, it was an appropriate measure to use to test whether there was a relationship between noun learning and the ERP components that are associated with word discovery, such as the N1 and the Learning N400 (Sanders et al., 2002, 2009; Abla et al., 2008; Cunillera et al., 2009).

Interestingly, there was substantial overlap in weighted noun learning and learner-type scores, as shown in Figure 4.3. This overlap resulted due to some participants segmenting most of the nouns quickly, but failing to segment all nouns correctly by the end of the phase. This overlap could suggest that there are important differences between these two measures of noun learning; and that they therefore should not be considered a binary and continuous measure of the same underlying variable. An inspection of individual participants on the measure of phrase sequencing, which tracked the ability to recall the phrase syllables in correct order (see Figures 4.4 and 4.5), revealed that some low learners appeared to *become* better learners after receiving semantic training. Thus, the high and low learner division by noun segmentation may not have captured an ideal division of ability beyond the initial phase of learning.

During Phonological Familiarization, Negativity Developed to Noun Onsets

A comparison of the ERPs to noun initial and noun medial syllables revealed an extended, broad-focused, medial frontal negativity in response to the micro language noun onset syllables. Overall, across the initial eight minutes of language exposure, noun onset syllables elicited significantly higher negativity than noun medial syllables during both the N1 and later Learning N400 time intervals.

Low-Amplitude ERP Components Elicited by Midstream Syllables

The ERP components elicited by phrase-midstream syllables were notably low in amplitude, as can be seen in the topographical plot in Figure 4.6. The low amplitude of these components was in contrast to those elicited by the mid-soundstream artificial grammar syllables. Cunillera and colleagues' findings (2009) suggested that each syllable in the artificial grammar soundstream was processed as an individual auditory event: each syllable was followed by its own related potential with its own lower-amplitude yet well-defined P50, N1 and P2. In contrast, the seminatural micro language midstream syllables did not elicit these clear auditory ERP components.

Multiple factors likely contributed to this different appearance of the ERPs to the seminatural compared to artificial language syllable onsets. First, artificial syllables have abrupt onsets, in contrast to the more continuous, coarticulated stream of natural language which has onsets that blend together. Second, in the artificial grammars there are typically uniform length of syllables (and even of phonemes; e.g., Cunillera et al., 2009).

This temporal uniformity results in a time-locking of the ERP not only to the initial syllable but also to subsequent syllables in the stream. In contrast, natural language has varied length of syllables, which results in the first syllable being time-locked to the ERP start and subsequent syllable onsets being temporally smeared. Appendix A shows this variation in syllable lengths in sample micro language phrases. Although there was temporal variation across the phrases, it was possible to align noun syllable onsets with some precision for the individual syllable ERPs. Despite the low amplitude of these midstream ERP components, the changes in the electrophysiological response to the micro language with continued exposure and with learning coincided with prior research and were consistent with predicted results.

N1 Word Onset Negativity Emerged Earlier than Expected

Close examination of the N1 component across the eight minutes of phonological familiarization, as shown in Figures 4.9 and 4.10, revealed that a greater early (40 - 200ms) negativity to noun initial syllables began to emerge already in the second minute of exposure to the phrases. This effect was significant as well for the N1 component. While it had been predicted that a higher N1 to noun initial syllables (compared to noun medial syllables) would emerge as participants became familiar with the phrase structure, it was not expected that it would be observed so early into the exposure. That this effect was observed already in the second minute of exposure was in contrast to prior results from both natural language research and artificial language research. In natural language, the higher N1 to word onset syllables is observed during native language processing (Sanders & Neville, 2003a) but not during non-native language processing (Sanders & Neville, 2003b). In the context of artificial grammar learning, this early word onset negativity has been reported to develop when the stimuli are learned to a high-level accuracy, as measured on behavioral test (Abla et al., 2008); as well as to be seen in response to artificial word onsets after word boundaries have been explicitly taught until participants have reached a higher level of expertise (Sanders et al., 2002, 2009). In all of these contexts, the higher N1 developed with high system proficiency, which made its appearance to the micro language stimuli at a point of low proficiency unexpected.

A possible explanation for why the higher N1 to noun initial syllables may have emerged so early (appearing already by the second minute) in the course of micro language exposure is that it may have been in response to a higher acoustic salience of noun initial syllables. For example, the word initial syllables may have been slightly louder or more abrupt; correlates of word-initial acoustic salience like this are common in naturalistic speech, such as the stimuli used for the present research. If this acoustic salience explanation is correct, then the higher N1 to word initial syllables -- at least upon its first appearance -- may not have indicated learning but rather a response to this higher salience of noun initial syllables. In support of this explanation is that the low learners displayed significantly higher N1 response to noun onsets compared to noun medial syllables across the phase; while the high learners did not. High learners, in contrast, showed no significant difference in N1 amplitude in response to noun initial and noun medial syllables during phonological familiarization overall. The stronger appearance in low learners supports the idea that this premature appearance of the higher N1 to word initial syllables could have represented a response to acoustic salience rather than a learning effect, because a learning effect presumably would have developed earlier in the group of high learners than in the group of low learners.

Were High Learners Strategic Attenders?

Instead, the pattern of high learner N1 response suggested that high learners may have adjusted their N1 response to the noun syllables as they learned the phrases over the phonological familiarization phase. For the simple phrases, they showed higher mean N1 response to noun initial than noun medial syllables; while for the complex phrases, they showed a more balanced N1 response to noun initial and noun medial syllables. This effect was apparent also for the broader 40-200ms window, and is displayed in Figure 4.13. In fact, collapsing the N1 amplitude across the entire phonological familiarization phase, the high learners had a higher N1 response to noun *medial* than to noun initial syllables for complex phrases. (This development of higher amplitude N1 to noun medial syllables was the reason high learners did not have a significantly higher amplitude N1 for noun initial syllables across the phase.) The N1 component is well documented to be an attentional effect (Hillyard et al., 1998; Makeig et al., 2003). Thus, this apparent customization of high learner N1 response by phrase type could possibly index a customization of attentional strategy for each phrase type. There is evidence that native speakers temporally modulate their attentional response on a fine-grained level while processing their native language, enabling them to selectively focus their processing on the more relevant moments in the speech sequence; and that the N1 amplitude indexes this modulation (Astheimer & Sanders, 2009; 2011). Thus, in native language this customization of attentional allocation is standard processing. It is possible that the high learners were showing this effect already within their micro language processing, leading to the pattern of N1 amplitude seen.

It is unclear why the low learners did not show the same pattern of N1 amplitude change seen in the high learners' results. One possibility is that the low learners may have been less sensitive to the distributional cues in the language. The high learners may have been able to adjust their attentional allocation to emphasize the more informational moments of the language stream, as revealed by the distributional cues present in the micro language phrases, while the low learners may have responded instead based solely on the acoustic salience of the syllables, which may have been similar across the phrase complexity types. In support of this explanation is the fact that both high and low learners started out the phase with higher response to the noun initial syllables in both phrase types; the high learners subsequently adjusted their N1 response to align with the syllable transitional probabilities about four minutes into exposure.

However, another possibility is that the high learners had more flexibility in allocating their attention. It is possible that high learners had superior executive control, enabling them to modulate their attention to select the individual syllables that they had identified as most relevant for highlighted processing. One speculative interpretation of this finding, the investigation of which would be a fascinating topic for future research, is that the synthesis of these two abilities – the sensitivity to distributional cues, along with the ability to adaptively modify attention -- could act to identify the higher information segments of the phrase sequence for the high learners, enabling their facilitation in learning the phrases by lessening the amount of extraneous information they processed.

The Learning N400 During Phonological Familiarization

The topography of the medial frontal negativity elicited by the micro language stimuli focused anterior to what has been reported for the Learning N400 component in the artificial grammar literature. This is evident from the comparison shown in Figure 4.7. However, when the data were re-referenced and spatially down-sampled to match prior processing used for artificial grammar research (e.g., Cunillera et al., 2009), a visual comparison revealed quite similar topography of the responses to the artificial and seminatural language stimuli during soundstream listening. Thus, it appeared that the Learning N400 component that has been found to emerge during learning of artificial grammars emerged also during learning of the natural-based micro language stimuli. Source estimation analysis of the medial frontal negativity elicited by the micro language could determine the extent to which this component shares underlying activation with Cunillera and colleagues' Learning N400; their fMRI replication of the soundstream listening paradigm indicated that artificial grammar soundstream learning was associated with activity in the superior temporal gyrus and superior ventral region of premotor cortex (2009).

Dividing the eight minutes of exposure into the four two-minute miniblocks revealed that the Learning N400 response to the noun syllables showed variation with exposure time and phrase complexity; with participants overall showing a significantly different pattern of response for simple and complex phrases across the four miniblocks, as shown in Figure 4.11. For the simple phrases, there was an initial increase and then decrease in the relative negativity of the onset syllable as learning progressed. This pattern of syllable response for the simple phrases replicated the pattern of syllable response reported for this component in the artificial grammar research (Cunillera et al., 2009). For the complex phrases, however, the relative negativity of the noun onset syllables instead showed an inverted "U" pattern, somewhat opposite the simple phrase findings.

Time Course of the Learning N400: Learner-Type Comparisons

In order to understand learner-type differences, high and low learner responses to noun initial and noun medial syllables were compared across the miniblocks separately for the simple and complex phrases, again for the Learning N400 component. This comparison is shown in Figure 4.12. For the simple phrases, high learners showed increasing negativity to noun initial syllables across the first three miniblocks, followed by a steep decrease in mean negativity during the fourth miniblock. This finding was consistent with predictions. The post-learning decrease in negativity showed replication of artificial grammar findings (e.g., Cunillera et al., 2009) as well. The high learners appeared to recognize the relative importance of the noun initial syllables early in the phase and to engage their processing with increasing focus on the first syllables through the third miniblock. Then, once learning had been accomplished, they decreased this focused engagement. In contrast, for the simple phrases, the low learners had no significant changes in their Learning N400 across the miniblocks. Their means showed an increasing negativity to noun initial syllables – quite similar to the high learners – for the first half of the phase. However, they then diverged from the high learners in the third miniblock. Rather than continuing to increase in their negativity, they showed a decrease in negativity for the second half of the phase. One speculative interpretation of this finding is that, while the high learners were able to progress in their system knowledge, successfully extracting the distributional information midway through the phase, the low learners were somehow unable to extract the distributional information. They may have instead relied solely on the acoustic cues that pointed to the noun initial syllable, which would have resulted in their missing the importance (i.e., higher surprise, assuming initial noun syllables are difficult to differentiate) of the noun medial syllable in the complex condition.

Interestingly, it was during the third miniblock, when the high learners appeared to intensify their engagement in processing of the noun initial syllables, that these high learners had a significant correlation of the amplitude of their N1 to simple noun initial syllables, and their weighted noun learning score. One possible explanation for this result is that it might indicate that by the third miniblock, the high learners had not only keyed into the importance of the noun initial syllables, but that they additionally had developed enough knowledge of the simple-phrase structure to anticipate the onset of noun-initial syllables. The low learners did not show a significant correlation with the weighted noun measure. It is possible that the low learners had not yet reached high enough system proficiency by the end of the phase to develop this relationship.

For the complex phrases, high learners appeared to more evenly distribute their focus between the noun initial and noun medial syllables than they did for the simple phrases. Thus, they appeared to be customizing their response to the simple and complex phrases; similar as they had appeared to do for the earlier N1 component. In contrast, low learners showed a similar Learning N400 response to complex phrases as they had shown to simple phrases. While low learners showed a clear distinction between their response to the noun initial and noun medial syllables (at least in the group means), the low learners did not appear to customize their response to the two phrase complexity types. Instead, overall, they appeared to be processing both simple and complex phrases as would be appropriate for the simple phrases, i.e., they appeared to focus their processing on the noun initial syllables, either not recognizing that there was information to extract from the complex noun medial syllables, or perhaps being unable to modulate their processing depth to customize their approach to processing the two phrase types. Analysis of these data on an individual level could help to resolve the question of whether some of the low learners did show a customization of response for the simple and complex phrases. Particularly given that some low learners outperformed some high learners on the weighted noun learning measure, this would be an interesting question to investigate. It is possible that some low learners showed differential N1 response to the simple and complex phrases.

It had been expected that learners would focus on the complex noun initial syllables in order to make the fine-tuned discrimination between the two acoustically similar complex noun initial syllables. However, the higher amplitude of the noun medial syllable for the high learners appears to suggest that they instead focused on *both* noun syllables for the complex phrases. Therefore, while this pattern of customized response from the high learners -- i.e., their more equal processing of the two noun syllables for the complex phrases, and focus on noun initial syllables for the simple phrases – was incidental, it is an intriguing finding because it demonstrates how these indices of learning appear to reveal fine-tuned differences in processing of the language. It is possible that this apparent higher ability to recognize and implement a customized response may be an example of a subtle difference that provides some learners with a means to both capitalize on more of what is discovered to be important in the speech stream and to de-emphasize what is found to be extraneous.

Indices of On-Line Learning During Comprehension Listening

For the comprehension listening phase, participants listened to the same soundstream they had heard during phonological familiarization, thus providing a pre-post design for comparison of participant processing before and after they had received semantic training and practice. The expectation was that participants would now hear *and comprehend* the phrases during this final phase. ERP analyses for this phase examined the post-acquisition appearance of the neural indices that had been tracked during initial phonological familiarization, in order to determine the degree to which these components persisted post training versus the degree to which they had been transitorily present during the course of learning and then attenuated after acquisition. For comprehension phase (i.e., post-training) analyses, high and low learners were again compared, with participants still divided into the groups based on their noun segmentation success during phonological familiarization (i.e., pre-training). Thus, these analyses tested whether the learner-type differences seen during the initial moments of exposure persisted into the post-training comprehension phase.

N1 Word Onset Negativity Continued into Post-Training Comprehension Listening

During the comprehension phase, for participants overall, noun initial syllables continued to elicit significantly higher-amplitude N1 response than did the noun medial syllables, as shown in Figure 4.17. This word onset negativity had been observed prior to training during the phonological familiarization, and it had been predicted that it would persist into the comprehension listening. The higher N1 to word onset syllables is observed during expert-level processing of streamed information in a variety of contexts. For example, it is observed during both native language processing (Sanders & Neville, 2003a; Astheimer & Sanders, 2009), and with system high proficiency during artificial grammar learning (Abla et al., 2008, Sanders et al., 2009).

Interestingly, in the present research, complex noun syllables developed a significantly higher N1 amplitude overall (collapsing noun initial and medial syllables together) compared to simple noun syllables over the course of the session. Figure 4.18 shows this effect. This increase in N1 amplitude for complex phrase nouns was not predicted; however, it was consistent with the understanding of this N1 component as an index of selective attention (Hillyard et al., 1998; Makeig et al., 2003; Astheimer & Sanders, 2009). In the current research, a possible interpretation would be that the higher N1 to noun syllables from complex phrases indicated that participants had begun to allocate more attention to the noun syllables in the complex phrases. This would be a reasonable post-learning shift in attentional allocation; due to the higher difficulty of processing the acoustically subtle distinction between the complex noun initial syllables, as well as the higher challenge of processing the complex phrases overall.

High and Low Learner Pattern of N1 Amplitude Differed Post-Training

The pattern of N1 response to noun syllables for high and low learners was compared to determine whether differences seen during phonological familiarization persisted post-training, or whether those differences had been transitory during learning. Comparisons, as shown in Figure 2.20, revealed that high and low learners continued to differ in their pattern of N1 response to the noun syllables of simple and complex phrases. Specifically, for simple phrases, high learners showed higher amplitude response to the noun initial than to the noun medial syllables; while for complex phrases, they showed more balanced response to noun initial and noun medial syllables. Low learners also demonstrated the ability to discriminate between noun initial and noun medial syllables, showing higher N1 to the noun initial than to the noun medial syllables (although, as previously noted, this effect could in part be due to response to acoustic cues). However, low learners did not differ in their N1 response to simple and complex phrases. Instead, low learner N1 amplitude did not appear to differentiate between simple and complex phrases. Thus, the high learners continued to show an apparent customization of their N1 for the two phrase complexities.

High Learner N1 Amplitude Shifted Toward Alignment with Information Content

As was speculated during the phonological phase, the high learner differential response to the simple and complex phrases could be interpreted as a customization of their attentional response to the two phrase types. Interestingly, in the post-training comprehension listening phase, the mean N1 amplitude of high learners appeared to shift toward what could be interpreted as an alignment with the information content of the syllables. Specifically, for the simple phrases, the N1 amplitude for the noun initial syllable increased from pre- to post-training. This can be seen in Figure 4.21. This simple phrase noun initial syllable was less predictable and therefore more informational. In contrast, the N1 amplitude for the noun medial syllable decreased from pre- to post-training. This simple phrase noun medial syllable was highly predictable and therefore less informational; for a learner who had acquired the system, this syllable was 100% predictable upon hearing the noun initial syllable. Thus, it added no additional between-syllable information; although it would contain within-syllable information, such as related to the micro language phonetic variation. For the complex phases, the N1 amplitude for the two noun syllables was similar; and this possibly aligned with the more balanced information content of the two noun syllables in the complex phrases.

Did High Learner N1 Amplitude Reveal Noun Syllable Information Content as a Learner-Based Measure?

If this post-acquisition N1 response to the micro language noun syllables indexed the attention high learners allocated to the noun syllables, then one speculative interpretation of their pattern of response would be that the N1 amplitude during comprehension listening revealed the high learners' weighting of their attention to the information content of each noun syllable within the micro language system. From this perspective, the N1 amplitude of the high learners during comprehension listening could be revealing the high learners' internalized understanding of the micro language system probabilities. In other words, the high learner post-learning N1 amplitude could be providing a learner-based measure of the information contained within each syllable.

Low Learners Could Be Slow Distributional Cue Learners

Low learners did not demonstrate this shifting toward alignment of their noun syllable N1 amplitudes to match system probabilities. Instead, the means of the low learners showed a shift in the opposite direction for the simple phrases over the course of acquisition. One possible explanation for this is that the low learner higher N1 for noun initial syllables was driven by syllable salience during phonological familiarization; and then, by the post-training comprehension phase, these low learners are beginning to incorporate distributional information but are still early in the process of discovering distributional information of the system. In support of this speculative interpretation is the similarity of the high learner's N1 response to simple phrase syllables during the phonological familiarization, to the low learner's N1 response to simple phrase syllable during the comprehension phase. Additionally, there is some evidence in the artificial grammar literature that the amount of time needed to learn words in an artificial grammar varies greatly among individuals (Sanders et al., 2009). This broad range of time to learn words could also be true for the natural-based micro language. In the current research, some participants had correctly segmented all four nouns within the initial moments of acquisition while others had not learned all four nouns by the end of the session, as measured by their language log recall. Thus, it is reasonable to consider that some high learners were at the same point in proficiency during the first phase of exposure as some low learners were at the fourth. If so, the post-training differences seen between the high and low learners may have been due to a difference in system proficiency, rather than demonstrating a difference in how they approach processing the language stimuli.

The Learning N400 Persisted into Comprehension Listening

The Learning N400 component continued into the comprehension phase, as shown in Figure 4.17. For participants overall, noun initial syllables continued to elicit significantly higher-amplitude negativity than did the noun medial syllables during the latency of this component (300-500ms post syllable onset). No significant differences between the high and low learners remained in the Learning N400 during Comprehension Listening.

The amplitude of the Learning N400 for the noun initial syllables did not decrease with training. In fact, for the complex condition it *increased* with training. An increase in Learning N400 amplitude for the complex phrase noun initial syllables was observed in both the high and low learners. The effect appeared stronger for the high learners, although there was no significant learner type interaction. One explanation for this increase could be that participants had increased their evaluation of the noun initial syllables for the complex phrases. It could be that the challenge of on-line learning of the complex phrases led some participants to rely on both syllables of complex nouns during phonological familiarization; and that later, after acquiring the system, they shifted to learning the fine-tuned phonological distinction between the noun initial syllables.

This word onset negativity had been observed prior to training during the phonological familiarization, and it had been predicted that it would persist into the comprehension listening. Thus, this finding supported predictions. In the context of on-line artificial grammar learning, the Learning N400 component appears to index engagement in the learning process, and it attenuates when learning -- specifically word segmentation, in the artificial grammar learning context -- is accomplished. In the current research, high learners had shown the attenuation of this component already in the initial phonological familiarization phase. While its continuation into the post-training comprehension phase was predicted, this prediction had been somewhat tentative; particularly given the lack of prior research investigating this component's development within the context of on-line natural language learning. Participants in the current research were still only one or two hours into exposure to the micro language, and their behavioral measures indicated that their learning – including segmentation -- was not yet complete. The finding that it continued into the comprehension listening is consistent with the idea that this component indexes the active engagement in learning.

Summary and Interpretation Conclusions

Overall, results of this exploratory research suggested systematic differences between the high and low learner responses to the simple and complex phrases. Both high and low learners were quick to develop a differential response to the noun initial and noun medial syllables, with a higher N1 response to the noun initial syllables emerging around the second minute. However, high learner electrophysiological response suggested a more systematic response to the noun syllables, perhaps constituting a customization of their attention to align with the information content of each syllable.

Limitations

The current research sought to explore the role of complexity in individual differences in on-line process of seminatural language learning. The results show an intriguing first glimpse into this under-explored topic. However, it is important to be aware of the following limitations while considering the implications of the results, particularly given the exploratory nature of the research.

Limitations Related to the Sequential Stimuli

Language by nature is a fast, streamed signal. Thus, the study of its naturalistic processing requires the study of the response to the sequential signal. As mentioned in Chapter 2, event-related potentials are often used to track the neural mechanisms of language processing because ERPs provides a direct measure of neural activity with high temporal resolution. However, the sequenced presentation inherent to language results in multiple events being temporally related to each other. In the case of the micro language phrases in the current research, the sequential phrase structure created a situation in which the ERP to midstream syllables (such as the noun syllables) was temporally related to not only the syllable of interest but also to the syllables that preceded it in the phrase.

Consequently, it cannot be assumed that the ERP components following a given syllable represented a response elicited solely by that syllable. Instead, the ERP time-locked to the syllable represented a combination of the response elicited by that syllable *and* the neural response of the preceding syllables. For example, the Learning N400 (300-500ms latency) of noun initial syllables overlapped, temporally and spatially, with the N1 of noun medial syllables. One example of how this could have impacted the results is that this overlap could have increased the negativity of the noun initial syllable during the 300-500ms interval; because the N1 to the noun medial syllable co-occurred and overlapped with it during this interval, increasing its negative deflection.

Additionally, the sequential structure of the stimuli opened the possibility that changes in processing due to phrase-level response could have altered the response to an individual syllable. For example, as mentioned in Chapter 3, some participants appeared to synchronize their alpha with the syllable onsets, which appeared to amplifying their N1 to noun syllables. This appeared to result in outlying voltage values for some participants, and more so for low learners; engendering a significant Levene's Test for some conditions during the initial two minutes of the session. This inequality of error variance must be considered when interpreting the N1 ANOVA results; however, Levene's test was not significant for the 40-200ms latency ANOVA, providing a means to confirm this violation did not impact the findings.

Still another issue that could have influenced the relative amplitudes of the noun initial and noun medial syllable negativities (whether computed as a difference measure or examined by individual syllables) was the continuous nature of the soundstream and the fact that the baseline period for the second syllable was not independent of the first syllable processing negativity.

It is important to note, however, that these limitations resulting from the use of ERPs with sequential stimuli were present as well for the on-line artificial grammar research. The use of ERPs within the soundstream listening paradigm to investigate on-line language learning is well-established. Replication of artificial grammar studies using ERP, fMRI and NIRS together converge to form the current understanding of the processes underlying on-line language processing. The current findings align with prior results, while adding the additional information regarding the pattern of individual differences at differing levels of complexity, as well as demonstrating that electrophysiological changes seen in on-line acquisition learning of a natural-based language resemble those seen during artificial grammar learning, while revealing some intriguing differences, such as the faster development of the higher N1 to noun onsets, as well as the overall lower amplitude ERPs elicited by the midstream syllable onsets.

Limitations Due to the Natural-Based Language Stimuli

In addition to being sequentially presented, the micro language phrases were composed of native-spoken utterances, and were derived from natural language. The lack of controlled and defined characteristic of natural-based language, and consequently of the seminatural stimuli derived from it, limited what conclusions could be drawn from the results in a few important ways. First, it was not possible to determine to what extent participants relied on each type of cue to discover the word boundaries, due to the presence of multiple, overlaid cues in the micro language phrases. An important consequence of the use of natural-spoken language stimuli was that it was not possible to disentangle the extent to which the differences seen in the pattern of ERP response to noun syllables was due to acoustic properties or to learning. In contrast, artificial grammars using synthetic stimuli are intentionally constructed with well-defined and balanced characteristics. Thus, the impact of each individual cue may be studied in isolation, in order to understand its individual impact; as well as in combination with other cues, in order to understand how the cues operate in unison to enable learning. (For example, in a soundstream listening paradigm, Pena and colleagues (2002) presented participants with a soundstream of artificial grammar syllables with artificial "words" and higher structural rules embedded and demonstrated that higher level structures were not learnable by the distributional cues alone; participants only acquired them when the prosodic pause cues were added.) As a secondary means to ensure that unintended higher salience of a particular artificial grammar element does not impact results, artificial grammar system elements additionally can employ counterbalancing, with language elements reorganized such that each element is used across categories. For example, a syllable can be positioned in one rendition of the grammar as word initial, and in another rendition as word medial), allowing for a counterbalance. Natural-derived language does not allow this flexibility. Thus, replication is required to ensure that results of the current research generalize.

Second, to enhance the natural language variation of the micro language, multiple recordings of each phrase had been included in the language stimuli, as described in Chapter 2. This variation was intentional and served to preserve the natural features of the language. However, this variation introduced the possibility that the natural variation of the speech sounds could result in a temporal smearing of the ERPs to syllables upon trial averaging, a step in the ERP data processing. To maximize the alignment of the phrase onsets, each syllable onset was marked by a native Japanese speaker. These markings were then reviewed by a native English speaker (the experimenter), and it was confirmed that these markings aligned with sound perception for a native English speaker as well. While syllable onsets were aligned with care, it is possible that residual smearing due to the natural language variation, particularly in the length of the syllables, could have contributed to the overall lower-amplitude ERPs seen to the micro language midstream syllables. This limits the extent to which this lower amplitude of ERP components to the phrase midstream syllable can be concluded to result from a difference in how natural language streams are processed, in comparison to artificial grammar streams.

Limitations Related to Learner Differences

Additionally, individual differences among the participants limit the extent to which conclusions can be drawn from the findings of the present research. For example, within the micro language soundstream paradigm, it was not possible to determine whether observed differences in electrophysiological response were due to participant level of system expertise, or whether they were due to differences in participant capacities, such as their ability to focus their attention. The recall measures of the language logs provided a guide to understanding how to tease the learning approach apart from the system proficiency. However, the inability to distinguish learner type differences due to system proficiency (i.e., the high learners being farther along in their learning) from those due to underlying differences, such as in cognitive capacities or executive control ability, was still a limitation.

Similarly, for the complexity factor, it was not possible to determine whether the differences seen between processing of the simple and complex phrases were due to differences in participant proficiency with the simple and complex phrases, or whether they were due to a difference in participant approach to processing the phrases. However, the high learners demonstrated greater difference in how they processed the simple and complex phrases. This would seem to indicate that the differences seen in processing of the simple and complex phrases were not due to lack of system proficiency but rather to the development of high system proficiency, with these high learners developing the ability to predict and flexibly allocate their attention to align with the information content in the phrases.

Second, it was possible that some participants were not able to make the subtle phonological distinction between the two noun initial syllables of the complex phrases. Some participants' orthographic representation on the language logs indicated they distinguished the two "ne" sounds, such as by their representing these two syllables differently (e.g., "ne" and "na"). However, other participants did not represent these two syllables differently on their language logs; thus, it was unclear whether they made this phonological distinction. It could be that participants who readily made the distinction between these two syllables were more efficient from the onset of listening, more quickly processing each sound and therefore advantaged in their discovery of the underlying phrasal structures, possibly leading to their being high learners. The possibility that some participants would not be able to make this distinction had not been foreseen, thus no post-training assessment on the ability to distinguish the two sounds was performed.

Limitation Related to Complexity

As described in Chapter 1, complexity is multifaceted, and different types of complexity may have different impacts on human perception and subsequently on learning. Thus, the generalizability of the current findings to other types of linguistic complexity are unknown and require further research to characterize more precisely the impact that various types of complexity have on individual differences in language processing.

Limitations Summary

In summary, the natural-based language stimuli used for the current research aimed to enhance ecological validity and therefore the generalizability of the findings to natural language processing. However, these same characteristics that enhanced the ecological validity simultaneously introduced a number of limitations that must be considered when interpreting the results. As for all exploratory work, further research is needed to establish the extent to which these findings replicate across stimuli and populations.

Broader Implications

Implication for Varied Complexity in On-Line Learning Stimuli

The current research has several implications for research in learning and complexity. One implication of the current research is that examining learning with multi-tiered complexity can provide additional insight into individual differences in learning. Importantly, when the data initially were analyzed, the high and low learner differences in N1 amplitude became evident only when the data were split by phrase complexity. This finding demonstrates the importance of including -- and analyzing separately -- stimuli of varied complexity, in order to develop an accurate understanding of the individual differences in on-line learning; as well as to understand the impact of complexity on those individual differences. In the natural learning situation, individuals face varying levels of complexity. Thus, including stimuli of varied complexity has potential to develop a more accurate characterization of how the individual differences in learning exist in the natural learning setting and to bring better ecological validity to the research.

Implications of the N1 Amplitude Tracking Subjective Complexity During On-Line Learning

A question of the current research was whether it would be possible to track a subjective measure of complexity by measuring the electrophysiological response to individual syllables during the on-line learning process. Specifically, it was thought that one of the indices of on-learning, such as the Learning N400 or possibly the N1, could be used for this purpose. In the context of this question, subjective complexity could be considered to be the relative amount of processing that the individual allocated to a given syllable, with syllables the individual expects to be more informational receiving higher allocation. It was thought that, as individuals gained knowledge of the system, they would begin to preferentially process the most informational syllables, such as the noun onsets and the complex phrase noun second syllables.

Previous research has provided preliminary evidence that the Semantic N400 component may provide this type of measurement during language processing. It is well established that semantic evaluation is related to the amplitude of this component (for a review, see Kutas & Federmeier, 2011). More direct evidence that this component tracks information extraction was provided by Frank and colleagues (2015) who found that the amplitude of the N400 response to words was related to word surprisal. However, a speculative interpretation of the current research findings was that during the earliest moments of language acquisition, as the initial knowledge of system probabilities develops, the N1 amplitude should be considered a potential tracker of information content. Prior research has indicated that the amplitude of this N1 component appears to track a heightening of attention at word onsets (Astheimer & Sanders, 2009, 2011). In the current research, the N1 amplitude to syllable onsets appeared to track the information content of each syllable.

The current research was exploratory and requires replication. However, the current research findings that implicate the N1 as a tracker of expectancy (i.e., expectation of the amount of information in the upcoming system element) were in line with prior results from Abla and colleagues (2008). They found that both the N1 and a medial frontal N400-like component (Learning N400) were associated with the transitional probability of the syllables (which, in their artificial language, were tones), although in their research the association was transitory. An advantage of using the N1, rather than the N400, to track an individual's information extraction is that it would allow tracking of complexity without presentation of a system violation. For some questions of on-line early learning, violations may not work within the research paradigm.

Implication of the Learning N400 Component Monitoring Engagement in Learning

The association of the Learning N400 component with on-line learning is robust and has been observed during auditory acquisition of a wide variety of sequential systems of artificial and now seminatural information. Previous research has suggested that this component indexes the learning process itself (Cunillera et al., 2009). Particularly of interest is its disengagement post-learning, which in the current research was seen for the high learners already in the phonological familiarization phase. This has the potential to allow experimenters a means to track when the learning process is completed, or when the listener has disengaged from learning.

In the current research however, low learners were shown to have Learning N400 negativity similar to high learners; suggesting that, rather than the learning itself being indexed, this component may index the engagement in learning. It is possible that it tracks the processing, the attempt to learn whether or not the learning is successful. If this is the case, an implication is that this component — as a robust and fast-developing ERP component — could be used to gauge on-line engagement in learning, as well as to track disengagement from (or lack of engagement in) learning.

One possible application therefore could be for tracking on-line engagement in auditory learning in children -- and, in particular, for non-verbal, motor-limited children. Most children provide feedback regarding the level of complexity they need. This begins in infancy, with infants looking away or crying when overstimulated. In toddlerhood, there is evidence that caregivers implicitly track their child's course of language development on a fine-grained level and provide input at a level of complexity customized to their current state of proficiency (Roy et al., 2015). For children who do not have the motor control to provide feedback to the caregiver, it may be less possible for caregivers to titrate complexity to optimal level. Children with disorders such as cerebral palsy that impact their ability to give motor response may therefore not receive such customized complexity input from their caregivers, leading to their potentially receiving input that is either too simple or too complex to optimally engage their learning. For these children, tracking medial frontal negativity in response to stimuli of varied complexity could be used in lieu of motor feedback to assess the extent to which auditory input is hitting the sweet spot of complexity that they require for optimal learning.

Future Directions

Analyzing data from the current research with event-related potentials of scalp data was a reasonable first step, in order to show the similarity of results with these seminatural language stimuli to the artificial grammar work done with ERP analysis. However, an important next step for the current dataset is to analyze by source rather than by scalp. Particularly with the multiple components of interest that overlap temporally and spatially, a technique such as independent components analysis could be used to separate them in order to disentangle the underlying neural mechanisms and how they differ for individual learners.

The oscillatory dynamics during the phonological familiarization phase are intriguing. Some participants appear to have synchronization of alpha oscillations with the noun onset syllables. It is possible that the case marker "no" syllable that occurs prior to each noun onset (in both simple and complex phrases) cues them to the upcoming noun onset and that this resets their oscillation, similar to how a beat gesture can modulate oscillations during natural speech processing (Biau et al., 2015)

Prior research has established the importance of understanding oscillatory dynamics in order to understand language processing (for a review, see Hauk et al., 2017). It is possible that the ability to entrain to the new language during the earliest moments of exposure could facilitate learning.

While this research had the strength that multiple stages of learning were recorded with a single set of participants progressing through the entire acquisition, enabling a glimpse at processing across learning phases in the same individuals, a weakness was the lack of broader assessments collected. To improve the interpretability of results, future research could include additional measurements in order to provide more clarity on unresolved questions. For example, while the high learners in the current research appeared to be allocating their attention more strategically than the low learners, it was unclear whether the low learners had lower language system proficiency, or whether they were less able to flexibly allocate attentional focus. Assessments of executive control could provide more insight on this question. Cognitive measurements could provide additional insight as well. For example, it would be interesting to see whether participants with higher verbal working memory are more likely to be high learners at an on-line auditory-based learning task. Finally, future research that examines on-line learning of natural-based language could include language assessment. First, a post-test to assess participant phoneme discrimination could be collected. In the current research, for example, it was unclear whether participants were relying on the noun medial syllable of the complex phrases because they could not distinguish between the noun initial syllables of these phrases, or whether they were being strategic; i.e., whether it was less effort to shift attention to the noun medial syllable rather than making the discrimination between the two noun initial syllables that had a subtle distinction. An assessment could resolve such uncertainty. Second, a native language proficiency assessment could have provided another measure of high and low language learning ability. Given the overlapping learner ability measures in the current research, such an assessment could have provided an additional measure of learner ability. One consideration however is that the current research had a session that lasted 2-3 hours, due to the length of experimental setup and learning task. Additional measurements may therefore require a second session to avoid overtaxing participant attention.

Conclusion

This dissertation investigated why some individuals have a more difficult experience acquiring a new language; specifically, how complexity impacts the individual differences seen in language learning difficulty. How complexity impacts individual differences in learning of new systems such as language is not well understood, and a key to understanding these differences may lie in the on-line processes during the early stages of system acquisition. A novel micro language paradigm made it possible to track learning of a miniaturized subset of natural language with the lexicon reduced to accelerate acquisition, enabling the investigation of earliest moments of natural-based language online.

For the current research, high learner electrophysiological response suggested a more systematic response to the language stimuli than did the response of low learners. It was speculated that the high learner response to the language could constitute a customization of their attention to align with the information content of each syllable. However, this finding will need to be replicated.

In conclusion, stimuli of varied complexity added insight to individual differences in learning. While it is important to note that the current work is exploratory and future research will be required to follow up on these initial findings, the micro language paradigm provides a new way to explore on-line learning of sequential systems such as language. All in all, these findings open new possibilities for understanding the impact of complexity on individual differences in learning.

APPENDIX A

LANGUAGE HISTORY INVENTORY

Please list all languages in which you have received training or to which you have been exposed enough that the language sounds very familiar to you, even if you are not able to understand it. Additionally please include any languages to which you were exposed when you were young, even if you feel you no longer remember any of the language.

Language	Age of First Exposure	Years of Exposure	Please give details about your exposure to the language. For instance did your grandparents speak the language to you, or were you enrolled in a foreign exchange program? How well can you understand and speak the language? Can you identify the language when you hear it?

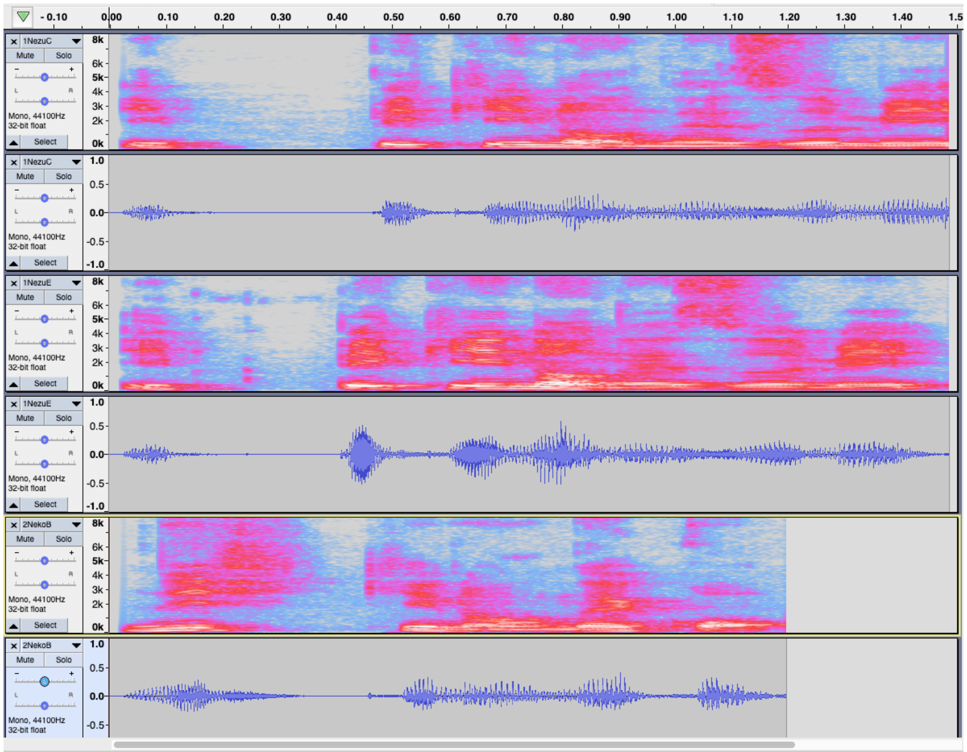
APPENDIX B

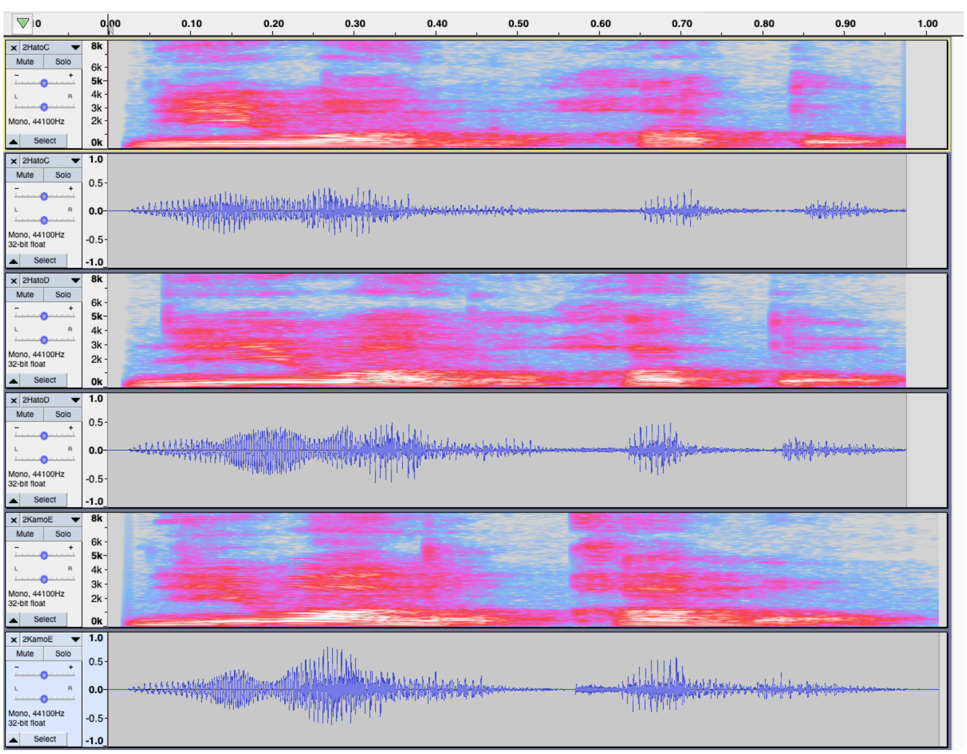
PARTICIPANT LANGUAGE HISTORIES

Participant Index	Language	Age at First Exposure (Years)	Years of Exposure	Description of Exposure
1	Spanish	7	3	worked alongside native Spanish speakers, can speak and understand basic Spanish
	Dutch	0	35	parents are native Dutch speakers, spoke some Dutch around the house growing up, visited Holland 3 times and had Dutch speaking visitors growing up
2	Spanish	0	43	It was spoken around me growing up (in CA), and as an adult I used it at work. I can speak it with some fluency.
	Dutch	0	43	I recognize it, and I can understand it. I have limited fluency.
3	Hebrew	2 or 3	11	Hebrew school, Bat Mitzvah, Jewish Preschool
	French	14	8	high school language class, visited France, French friends, semi-fluent
	Spanish	2 or 3	20	live in CA with high rate of Spanish speakers, been to Mexico
	Japanese	10	12	watch TV shows in Japanese with English subtitles
4	Spanish	10	<1	class at local college
	German	15	2	high school class
5	Spanish	16	3 or 4	learned it in high school, can tell when people speak it but don't understand it
6	French	17	3	took intro to French in high school for 1yr and 2yrs in college, best friend is fluent
	Spanish	5	15	attended school with a large population of Spanish speaking students, live in a community where many people spoke Spanish often, best friend growing up had Spanish speaking parents
7	Korean	0	22	father's native tongue and mother speaks fairly well, studied wen 12 and have studied 1 year at university, still very beginner
	French	7	15	had a French speaking sitter but did not pick up much, looked through books and listened to tapes, studied for 4 years in high school, but not since
	Spanish	0	22	grew up in a mostly Spanish speaking neighborhood and have Spanish speaking family friends, studied 2 years in middle school, but don't know much at all
	Arabic	20	2	studied 2 years in university
8	Polish	0	4	lived on Polish army camp in England
	Spanish	44	1	worked with a group of Mexicans on training
	Latin	15	2	took Latin in high school
9	Spanish	13	13	Took classes in middle school, high school, and college, and can understand Spanish very well and speak it fairly well
10	Estonian	0	22	grandparents on mom's side immigrated, mom's side of family uses Estonian frequently, I understand it alright, but I'm not fluent
	German	15	7	studied in high school, U of O, studied abroad in Vienna, was nearly fluent when leaving Europe but not quite as good now
	Spanish	22	<1	started studying Spanish this summer just for interest, only know the basics
11	Spanish	5	16	I was in Spanish classes for most of my elementary and high school years, from California so I hear it a lot, don't speak it very well though
12	Spanish	13	4	studied in middle and high school, can identify it
13	None		N/A	
14	Spanish	14	20	took in high school and 3 years in college, used in work
	French	19	1	college level course
	Italian	20	1	college level course
15	German	7	15	lived in Germany for some time (8yrs), speak German at my father's house
	Hungarian	11	11	stepmother is Hungarian, spoken in our home with my kid brothers
	Spanish	16	2	took classes in high school
16	Spanish	15	<1	10th grade class - can identify but don't understand
17	Spanish	5	5	1yr in elementary school, grades 8-11 in high school, good at reading but poor at listening, moderate speaking. I can identify it when heard
	German	18	<1	2 mo. in Germany, no formal study of the language, but I know lots of words and recognize when heard
	Japanese	18	<1	I have watched an anime series with subtitles three times and would recognize 5-10 words and be able to identify the langauge
18	Spanish	7	15	can understand and speak some, not fluent though, took classes on and off
19	Spanish	2	20	babysitter spoke it to me, not fluent but I can understand and speak a lot
	Hebrew	5	17	went to day school, can recognize language, but no longer speak it
20	Portugese	20	1	UO Class. Alright, very basic. Can identify the langauge when I hear it.
	Spanish	15	2	High school class, not very well, only a few phrases. Can identify the langauge when I hear it.
21	None		N/A	
22	French	8	21	I began learning French (just a little) in 2nd grade, then took French classes in high school and college. I am not fluent but very familiar.
	Spanish	3	26	I grew up in a community with a large Spanish speaking population, though I don't speak it myself.
23	German	1	2 or 3	lived in Germany for a few years and my parents spoke random German phrases. I can sometimes recognize it.
	Spanish	16	2	1 year in high school, 2 terms in college
	Hebrew	14	6	My dad is/has been learning it and my family sometimes sings or prays in Hebrew.
24	Spanish	15	2	high school course, 2 terms in college, listening - poor, speaking - poor
	Dari	22	2	NALT project, listening - poor, speaking - poor
	French	25	1	Rosetta Stone and Friends, listening - very poor, speaking - very poor
25	Spanish	12	8	Heard Spanish throughout grade school. Took 2 years of Spanish in high school.
26	Spanish	13	6	took Sanish 4 years in high school and can understand well and identify, 2 years in college, speak poorly
	Lithuanian	21	2	worked with native speakers for 2 years, cannot speak or understand but can recognize it
	French	20	1.5	worked with native speakers for 2 years, cannot speak or understand but can recognize it

APPENDIX C

SAMPLE MICRO LANGUAGE SPECTROGRAMS AND OSCILLOGRAMS





APPENDIX D

LISTENING LOGS

MINA Listening Block Log
Subject ______ Session ______

Please write down as many words as you can remember for each phrase. Don't worry about spelling. Just sound out and record whatever you can remember.

It is very important that you place *spaces or commas* between words to show the start and end of each individual word.

Section 1

MINA Listening Block Log
Subject ______ Session ______

Please write down as many words as you can remember for each phrase. Don't worry about spelling. Just sound out and record whatever you can remember.

It is very important that you place *spaces or commas* between words to show the start and end of each individual word.

Section 2

MINA Listening Block Log
Subject ______ Session ______

Please write down as many words as you can remember for each phrase. Don't worry about spelling. Just sound out and record whatever you can remember.

It is very important that you place *spaces or commas* between words to show the start and end of each individual word.

Section 3

MINA Listening Block Log
Subject ______ Session ______

Please write down as many words as you can remember for each phrase. Don't worry about spelling. Just sound out and record whatever you can remember.

It is very important that you place *spaces or commas* between words to show the start and end of each individual word.

Section 4

APPENDIX E

TRAINING LOG

Please write down as many words as you can remember for each phrase. Don't worry about spelling. Just sound out and record whatever you can remember.

It is very important that you place *spaces or commas* between words to show the start and end of each individual word.

APPENDIX F

PARTICIPANT VERBAL INSTRUCTIONS

For this experiment we will be recording your brainwaves while you receive a lesson in Mini Nihongo. Mini Nihongo is Japanese, but with the lexicon restricted to make it possible for you to acquire it very quickly.

The experiment will have four sections. For the first section, the Listening Block of the experiment, you will listen to a stream of Mini Nihongo phrases, spoken by a native Japanese speaker, to familiarize you with the sounds of the language. During the second section of the experiment, the Training Block, you will hear phrases and see pictures that illustrate their meaning, and you will repeat the phrases while looking at the pictures. For the third section, the Practice Block, you will perform a simple matching game to practice your understanding of the language. The final block, the Comprehension Block, will have the same format as the first block; with the important distinction that you now will be listening *and comprehending* what you hear.

During the experiment, is important that you find a comfortable sitting position so you are able to relax and minimize your movements during the recording; because any movement -- including shifts in posture, facial muscle tension, eye blinks and eye movements – will interfere with the recording of your brainwaves. To help you stay comfortable, you will have a break every two to four minutes throughout the experiment.

Block 1: Listening Block

For this section of the experiment you will hear a series of phrases in Mini Nihongo. Your task will be to relax with your eyes closed while listening very carefully to the phrases. The purpose of this block is to familiarize you with the sounds of the language.

The listening block will last about eight minutes. You will have a break every two minutes. During each break the experimenter will check on you and ask you to fill out a section of a questionnaire to track your learning.

Do you have any questions?

Block 2: Training Block

For this section of the experiment you will again hear a series of phrases in Mini Nihongo. However during this block each phrase will be followed by a picture illustrating its meaning. The purpose of this block is to teach you the meaning of the phrases.

Please keep your eyes fixated on the plus sign in the center of the screen as you listen carefully to each phrase. When the picture appears, try to repeat the phrase you just heard while you look at the picture.

After you have repeated the phrase, press any key on the response pad to continue to the next phrase. If you do not press a response key, the experiment will proceed to the next phrase automatically after a brief pause.

The training block will last about eight minutes. It will be divided into four two minute sections, and you will have a break between sections. You will be able to restart the experiment after these breaks by pressing a response key. The experimenter will not visit you during these breaks, and there will be no questionnaire to fill out for this block.

Do you have any questions?

Block 3: Practice Block

For this section of the experiment you will play a simple matching game to practice the Mini Nihongo phases you just learned.

For each trial of the game, a picture will appear briefly on the computer screen. Then plus sign will appear in the center of the screen. Focus your eyes on the plus sign. You will then hear a phrase in Mini Nihongo.

A question mark will replace the plus sign. Your task will be to decide whether the picture and the phrase match. Press the **YES** key is they match. Press the **NO** key if they don't match.

You will immediately receive feedback on the accuracy of your response. You will see a green check mark if you responded correctly. You will see a red X if you responded incorrectly.

The practice block will last about 12 minutes. It will be divided into four three minute sections, and you will have a break between sections. You will be able to restart the experiment after these breaks by pressing a response key. The experimenter will not visit you during these breaks, and there will be no questionnaire to fill out for this block.

<u>Odd numbered subjects</u>: For the first two sections, you will practice the Mini Nihongo *animals*. Any mismatch will be of *animal*. For the third and fourth sections you will practice the Mini Nihongo *numbers*. Any mismatch will be of *number*.

<u>Even numbered subjects</u>: For the first two sections you will practice the Mini Nihongo *numbers*. Any mismatch will be of *number*. For the third and fourth sections you will practice the Mini Nihongo *animals*. Any mismatch will be of *animal*.

Do you have any questions?

Block 4: Comprehension Block

For this section of the experiment you will again hear a series of phrases in Mini Nihongo. Your task will be to relax with your eyes closed while listening very carefully to the phrases. The purpose of this block is to record your brainwaves as you listen to *and understand* Mini Nihongo. As you listen to the phrases, try to comprehend what you hear.

The listening block will last about eight minutes. You will have a break every two minutes. Every two minutes, the experiment will pause. You will need to press a response key in order to proceed. After you have completed all four two-minute sections of this block, the experimenter will check on you and ask you to fill out a section of a questionnaire to track your learning.

Do you have any questions?

REFERENCES CITED

Abla, D., Katahira, K., & Okanoya, K. (2008). On-line assessment of statistical learning by event-related potentials. *Journal of Cognitive Neuroscience*, 20(6), 952-964.

Aitkin, C. D., & Feldman, J. (2006). Subjective complexity of categories defined over three-valued features. In *Proceedings of the Annual Meeting of the Cognitive Science Society* (Vol. 28, No. 28).

Alvarez, G. A., & Cavanagh, P. (2004). The capacity of visual short-term memory is set both by visual information load and by number of objects. *Psychological science*, 15(2), 106-111.

Arciuli, J. (2017). The multi-component nature of statistical learning. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *372*(1711), 20160058.

Astheimer, L. B., & Sanders, L. D. (2009). Listeners modulate temporally selective attention during natural speech processing. *Biological Psychology*, 80(1), 23–34.

Astheimer, L. B., & Sanders, L. D. (2011). Predictability affects early perceptual processing of word onsets in continuous speech. Neuropsychologia, 49(12), 3512-3516.

Astheimer, L. B., & Sanders, L. D. (2012). Temporally selective attention supports speech processing in 3- to 5-year-old children. *Developmental Cognitive Neuroscience*, 2(1), 120–128.

Attneave, F. (1959). *Applications of information theory to psychology: A summary of basic concepts, methods, and results*. New York: Holt, Rinehart & Winston.

Baldi, P. (2002). A computational theory of surprise. In *Information, Coding and Mathematics* (pp. 1-25). Springer, Boston, MA.

Baldi, P., & Itti, L. (2010). Of bits and wows: A Bayesian theory of surprise with applications to attention. *Neural Networks*, 23(5), 649-666.

Baldwin, D., Andersson, A., Saffran, J., & Meyer, M. (2008). Segmenting dynamic human action via statistical structure. *Cognition*, *106*(3), 1382-1407.

Biau, E., Torralba, M., Fuentemilla, L., de Diego Balaguer, R., & Soto-Faraco, S. (2015). Speaker's hand gestures modulate speech perception through phase resetting of ongoing neural oscillations. *Cortex*, *68*, 76-85.

Booth, R. D. L., & Happé, F. G. E. (2018). Evidence of Reduced Global Processing in Autism Spectrum Disorder. *Journal of Autism and Developmental Disorders*, 48(4), 1397–1408.

Brooks, P. J., & Kempe, V. (2019). More is more in language learning: Reconsidering the less-is-more hypothesis. *Language Learning*, *69*, 13-41.

Cantiani, C., Riva, V., Piazza, C., Bettoni, R., Molteni, M., Choudhury, N., ... & Benasich, A. A. (2016). Auditory discrimination predicts linguistic outcome in Italian infants with and without familial risk for language learning impairment. *Developmental Cognitive Neuroscience*, 20, 23-34.

Campbell, K. L., Zimerman, S., Healey, M. K., Lee, M., & Hasher, L. (2012). Age differences in visual statistical learning. *Psychology and Aging*, *27*(3), 650.

Chapman, L. R., & Hallowell, B. (2015). A novel pupillometric method for indexing word difficulty in individuals with and without aphasia. *Journal of Speech, Language, and Hearing Research*, 58(5), 1508-1520.

Christiansen, M. H., & Chater, N. (2015). The Now-or-Never bottleneck: A fundamental constraint on language. *Behavioral and Brain Sciences*, *39*(2016).

Cunillera, T., Camara, E., Toro, J. M., Marco-Pallares, J., Sebastian-Galles, N., Ortiz, H., & Rodriguez-Fornells, A. (2009). Time course and functional neuroanatomy of speech segmentation in adults. *NeuroImage*, 48(3), 541-553.

Cunillera, T., Toro, J. M., Sebastián-Gallés, N., & Rodríguez-Fornells, A. (2006). The effects of stress and statistical cues on continuous speech segmentation: an event-related brain potential study. *Brain Research*, 1123(1), 168-178.

Dąbrowska, E. (2012). Different speakers, different grammars: Individual differences in native language attainment. *Linguistic Approaches to Bilingualism*, *2*(3), 219-253.

Dąbrowska, E. (2018). Experience, aptitude and individual differences in native language ultimate attainment. *Cognition*, *178*, 222-235.

Daltrozzo, J., Emerson, S. N., Deocampo, J., Singh, S., Freggens, M., Branum-Martin, L., & Conway, C. M. (2017). Visual statistical learning is related to natural language ability in adults: An ERP study. *Brain and Language*, 166, 40-51.

Day, H. (1967). Evaluations of subjective complexity, pleasingness and interestingness for a series of random polygons varying in complexity. *Perception & Psychophysics*, 2(7), 281–286.

De Diego Balaguer, R., Toro, J. M., Rodriguez-Fornells, A., & Bachoud-Lévi, A.-C. (2007). Different neurophysiological mechanisms underlying word and rule extraction from speech. *PloS One*, 2(11), e1175.

Dörnyei, Z. & Skehan, P. (2003). Individual differences in second language learning. In: C. J. Doughty and M.H. Long, (Eds), *The Handbook of Second Language Acquisition* (pp. 589– 630). Malden, MA: Blackwell.

Ehrman, M. E., Leaver, B. L., & Oxford, R. L. (2003). A brief overview of individual differences in second language learning. *System*, 31(3), 313-330.

Ellis, C. T., & Turk-Browne, N. B. (2019). Complexity can facilitate visual and auditory perception. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(9), 1271.

Elman, J. L. (1990). Finding structure in time. *Cognitive Science*, *14*(2), 179-211.

Elman, J. L. (1993). Learning and development in neural networks: The importance of starting small. *Cognition*, *48*(1), 71-99.

Engelhardt, P. E., Ferreira, F., & Patsenko, E. G. (2010). Pupillometry reveals processing load during spoken language comprehension. *Quarterly Journal of Experimental Psychology*, 63(4), 639–645.

Erickson, L. C., & Thiessen, E. D. (2015). Statistical learning of language: Theory, validity, and predictions of a statistical learning account of language acquisition. *Developmental Review*, 37, 66–108.

Evans, J. L., Saffran, J. R., & Robe-Torres, K. (2009). Statistical learning in children with specific language impairment. *Journal of Speech, Language, and Hearing Research,* 52, 321–335.

Feldman, J. (2000). Minimization of Boolean complexity in human concept learning. *Nature*, 407(6804), 630–633.

Feldman, J. (2003). The Simplicity Principle in Human Concept Learning. *Current Directions in Psychological Science,* 12(6), 227–232.

Feldman, J. (2006). An algebra of human concept learning. *Journal of Mathematical Psychology*, 50(4), 339-368.

Fenson, L., Dale, P., Reznick, J., Bates, E., Thal, D., Pethick, S., . . . Stiles, J. (1994). Variability in Early Communicative Development. *Monographs of the Society for Research in Child Development*, 59(5), i-185.

Frank, S. L., Otten, L. J., Galli, G., & Vigliocco, G. (2015). The ERP response to the amount of information conveyed by words in sentences. *Brain and Language*, *140*, 1-11.

Friedenberg, J., & Liby, B. (2016). Perceived beauty of random texture patterns: A preference for complexity. *Acta Psychologica*, 168, 41–49.

Gauvrit, N., Soler-Toscano, F., & Guida, A. (2017). A preference for some types of complexity comment on “perceived beauty of random texture patterns: A preference for complexity.” *Acta Psychologica*, 174, 48–53.

Goldsmith, J. (2001). Unsupervised learning of the morphology of a natural language. *Computational Linguistics*, *27*(2), 153-198.

Grassberger, P. (1986). Toward a quantitative theory of self-generated complexity. *International Journal of Theoretical Physics*, 25(9), 907–938.

Gruenwald, P., & Vitanyi, P. (2010). Shannon Information and Kolmogorov Complexity. arXiv:cs/0410002, 1–51.

Hauk, O., Giraud, A. L., & Clarke, A. (2017). Brain oscillations in language comprehension. *Language, Cognition and Neuroscience*, *32*(5), 533–535.

Hillyard, S. A., & Anllo-Vento, L. (1998). Event-related brain potentials in the study of visual selective attention. *Proceedings of the National Academy of Sciences*, *95*(3), 781-787.

Hoaglin, D. C., & Iglewicz, B. (1987). Fine-tuning some resistant rules for outlier labeling. *Journal of the American Statistical Association*, *82*(400), 1147-1149.

Itti, L., & Baldi, P. F. (2006). Bayesian surprise attracts human attention. In *Advances in Neural Information Processing Systems* (pp. 547-554).

Junghöfer, M., Elbert, T., Tucker, D. M., & Braun, C. (1999). The polar average reference effect: a bias in estimating the head surface integral in EEG recording. *Clinical Neurophysiology*, *110*(6), 1149-1155.

Kahta, S., & Schiff, R. (2016). Implicit learning deficits among adults with developmental dyslexia. *Annals of Dyslexia*, 66(2), 235-250.

Kahta, S., & Schiff, R. (2019). Deficits in statistical leaning of auditory sequences among adults with dyslexia. *Dyslexia*, 25(2), 142-157.

Karuza, E. a, Emberson, L. L., & Aslin, R. N. (2014). Combining fMRI and behavioral measures to examine the process of human learning. *Neurobiology of Learning and Memory*, *109C*, 193–206.

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2012). The Goldilocks effect: Human infants allocate attention to visual sequences that are neither too simple nor too complex. *PloS One*, 7(5), e36399.

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2014). The Goldilocks effect in infant auditory attention. *Child Development*, 85(5), 1795-1804.

Kidd, E., & Arciuli, J. (2016). Individual differences in statistical learning predict children's comprehension of syntax. *Child Development*, 87(1), 184-193.

Kidd, E., Donnelly, S., & Christiansen, M. H. (2018). Individual differences in language acquisition and processing. *Trends in Cognitive Sciences*, *22*(2), 154-169.

Kolmogorov, A. N. (1965). Three approaches to the quantitative definition of information. *Problems of Information Transmission*, 1(1), 1-11.

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine*, *15*(2), 155-163.

Kosie, J. E., & Baldwin, D. (2019). Attentional profiles linked to event segmentation are robust to missing information. *Cognitive Research: Principles and Implications*, *4*(1), 8.

Kover, S. T. (2018). Distributional cues to language learning in children with intellectual disabilities. *Language, Speech, and Hearing Services in Schools*, *49*(3S), 653-667.

Kuperberg, G. R., & Jaeger, T. F. (2016). What do we mean by prediction in language comprehension?. *Language, Cognition and Neuroscience*, *31*(1), 32-59.

Kutas, M., & Federmeier, K. D. (2011). Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). *Annual Review of Psychology*, 62, 621–647.

Kutas, M., & Hillyard, S. A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science*, 207(4427), 203-205.

Kutas, M., & Hillyard, S. A. (1984). Brain potentials during reading reflect word expectancy and semantic association. *Nature*, 307(5947), 161.

Levy, R. (2008). Expectation-based syntactic comprehension. *Cognition*, *106*(3), 1126-1177.

Meredith, David (2015) Music Analysis and Point-Set Compression, *Journal of New Music Research*, 44:3, 245-270.

Mueller, J. L. (2006). L2 in a nutshell: The investigation of second language processing in the miniature language model. *Language Learning*, *56*(SUPPL. 1), 235–270.

Mueller, J. L. (2009). The influence of lexical familiarity on ERP responses during sentence comprehension in language learners. In *Second Language Research* (Vol. 25, Issue 1).

Mueller, J. L., Hirotani, M., & Friederici, A. D. (2007). ERP evidence for different strategies in the processing of case markers in native speakers and non-native learners. *BMC Neuroscience*, *8*(1), 1–16.

Mueller, J. L., Girgsdies, S., & Friederici, A. D. (2008). The impact of semantic-free second-language training on ERPs during case processing. *Neuroscience Letters*, 443(2), 77–81.

Mueller, J. L., Hahne, A., Fujii, Y., & Friederici, A. D. (2005). Native and nonnative speakers' processing of a miniature version of Japanese as revealed by ERPs. *Journal of Cognitive Neuroscience*, 17(8), 1229- 1244.

Munnich, E. L., Foster, M. I., & Keane, M. T. (2019). Editors' Introduction and Review: An Appraisal of Surprise: Tracing the Threads That Stitch It Together. *Topics in Cognitive Science*, *11*(1), 37-4

Mueller, J. L., Girgsdies, S., & Friederici, A. D. (2008). The impact of semantic-free second-language training on ERPs during case processing. *Neuroscience Letters*, *443*(2), 77–81.

Neger, T. M., Rietveld, T., & Janse, E. (2015). Adult age effects in auditory statistical learning. In *18th International Congress of Phonetic Sciences (ICPhS 2015)*. International Phonetic Association.

Nelson, K. (1981). Individual differences in language development: Implications for development and language. *Developmental Psychology*, 17(2), 170.

Nolan, H., Whelan, R., & Reilly, R. B. (2010). FASTER: fully automated statistical thresholding for EEG artifact rejection. *Journal of Neuroscience Methods*, *192*(1), 152-162.

Nummenmaa, L., Hyönä, J., & Calvo, M. G. (2006). Eye movement assessment of selective attentional capture by emotional pictures. *Emotion*, 6(2), 257.

Oldfield, R. C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, *9*(1), 97-113

Peña, M., Bonatti, L. L., Nespor, M., & Mehler, J. (2002). Signal-driven computations in speech processing. *Science*, 298 (5593), 604–7.

Piantadosi, S. T., Kidd, C., & Aslin, R. (2014). Rich analysis and rational models: Inferring individual behavior from infant looking data. *Developmental Science*, *17*(3), 321-337.

Poulsen, C., Luu, P., Davey, C., Tucker, D., & Nelson, J. (2011, July). From sound to meaning: changes in EEG source-localized brain activity with foreign-language training. In *International Conference on Foundations of Augmented Cognition* (pp. 203-211). Springer, Berlin, Heidelberg.

Rohde, D. L., & Plaut, D. C. (1999). Language acquisition in the absence of explicit negative evidence: How important is starting small?. *Cognition*, *72*(1), 67-109.

Roy, B. C., Frank, M. C., DeCamp, P., Miller, M., & Roy, D. (2015). Predicting the birth of a spoken word. *Proceedings of the National Academy of Sciences*, *112*(41), 12663-12668.

Saffran, J. R., Newport, E. L., & Aslin, R. N. (1996). Word Segmentation : The Role of Distributional Cues. *Journal of Memory and Language*, 621(35), 606–621.

Saffran, J. R., Newport, E. L., Aslin, R. N., Tunick, R. A., & Barrueco, S. (1997). Incidental Language Learning: Listening (and Learning) out of the Corner of Your Ear. *Psychological Science*, 8(2), 101–105.

Saffran, J. R., Pollak, S. D., Seibel, R. L., & Shkolnik, A. (2007). Dog is a dog is a dog: Infant rule learning is not specific to language. *Cognition*, *105*(3), 669-680.

Sanders, L. D., Ameral, V., & Sayles, K. (2009). Event-related potentials index segmentation of nonsense sounds. *Neuropsychologia*, 47(4), 1183–6.

Sanders, L. D., & Neville, H. J. (2003a). An ERP study of continuous speech processing. I. Segmentation, semantics, and syntax in native speakers. *Cognitive Brain Research,* 15(3), 228–40.

Sanders, L. D., & Neville, H. J. (2003b). An ERP study of continuous speech processing. II. Segmentation, semantics, and syntax in non- native speakers. *Cognitive Brain Research*, 15(3), 214– 27.

Sanders, L. D., Newport, E. L., & Neville, H. J. (2002). Segmenting nonsense: an event-related potential index of perceived onsets in continuous speech. *Natural Neuroscience*, 5 (7), 700-703.

Scott-Van Zeeland, A., McNealy, K., Wang, A. T., Sigman, M., Bookheimer, S. Y., Dapretto, M., … Dapretto, M. (2010). No neural evidence of statistical learning during exposure to artificial languages in children with autism spectrum disorders. *Biological Psychiatry*, 68(4), 345–351.

Shannon, C.E. (1938). A symbolic analysis of relay and switching circuits. *Transactions of the American Institute of Electrical Engineers*, Vol. 57, 713–723.

Shannon, C. E. (1948). A mathematical theory of communication. *Bell System Technical Journal*, 27(3), 379-423.

Siegelman, N., & Frost, R. (2015). Statistical learning as an individual ability: Theoretical perspectives and empirical evidence. *Journal of Memory and Language*, 81, 105-120.

Skehan, P. (1991). Individual differences in second language learning. *Studies in Second Language Acquisition*, 13(2), 275-298.

Sundara, M., Ngon, C., Skoruppa, K., Feldman, N. H., Onario, G. M., Morgan, J. L., & Peperkamp, S. (2018). Young infants' discrimination of subtle phonetic contrasts. *Cognition*, 178, 57-66.

Teinonen, T., Fellman, V., Näätänen, R., Alku, P., & Huotilainen, M. (2009). Statistical language learning in neonates revealed by event-related brain potentials. *BMC Neuroscience*, *10*(1), 1-8.

Tun, P. A., & Lachman, M. E. (2008). Age differences in reaction time and attention in a national telephone sample of adults: education, sex, and task complexity matter. *Developmental Psychology*, *44*(5), 1421.

Tukey, J. W. (1962). The future of data analysis. *The Annals of Mathematical Statistics*, *33*(1), 1-67.

Van Der Hallen, R., Evers, K., Brewaeys, K., Van Den Noortgate, W., & Wagemans, J. (2015). Global processing takes time: A meta-analysis on local-global visual processing in ASD. *Psychological Bulletin*, 141(3), 549–573.

Vigo, R. (2011). Representational information: A new general notion and measure of information. *Information Sciences*, 181(21), 4847–4859.

Vigo, R. (2013). The GIST of concepts. *Cognition*, 129(1), 138–162.

Weaver, W. (1949). Recent contributions to the mathematical theory of communication. *The Mathematical Theory of Communication*, 1, 1-12.

Westermann, G., & Ruh, N. (2012). A neuroconstructivist model of past tense development and processing. *Psychological Review*, *119*(3), 649.

Yu, A. C. L., & Zellou, G. (2019). Individual Differences in Language Processing: Phonology. *Annual Review of Linguistics*, 5(1), 131–150.