UNIVERSITY OF CALIFORNIA SAN DIEGO

SAN DIEGO STATE UNIVERSITY

# Brain-Behavior Investigations of Lexical Representation Development and Lexical-Semantic Processing in Individuals With and Without Communication Disorders

A Dissertation submitted in partial satisfaction of the requirements
for the degree Doctor of Philosophy

in

Language and Communicative Disorders

by

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2024

The Dissertation of Ashlie Hope Pankonin is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

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# DEDICATION

I dedicate this dissertation to the countless people who supported me and my sanity throughout this insane endeavor, especially my husband, Mr. Dr. Ashlie Pankonin (AKA Colin "Lord of the Ping" Kenley); my family; and my coaches (athletic and otherwise). I would not have made it to this point without everyone who supported me through the ups and downs of graduate school, drying my tears, celebrating my wins with me, and always encouraging me to keep going no matter where the path might take me.

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ACKNOWLEDGEMENTS

It is impossible to articulate how grateful I am to my endlessly patient and supportive mentors whom I have had the pleasure to learn from over these past five years. I owe a huge thank you to Dr. Alyson D. Abel for her unwavering faith in me, holistic guidance, and for being an example of how to have both a fulfilling and intellectually stimulating career *and* a rich and rewarding life outside of the office. You have helped me to grow in ways I never would have imagined, and I will be forever thankful for that. I would also be remiss if I did not acknowledge all the compassion, encouragement, and support Dr. JoAnn P. Silkes has provided me. The development of my writing and theoretical knowledge is largely a result of you, and I cannot thank you enough for always being so understanding and taking a genuine interest in my well-being and extracurricular involvements.

No number of years of weightlifting would equip me to bear the weight of this endeavor on my own, and there are so many others to thank for helping lighten the load. Thank you to my committee members, Drs. Phillip Holcomb, Seana Coulson, and Sarah Creel; my unofficial mentors, Drs. Irina Potapova and Jörg Matt; my JDP and clinical colleagues and supervisors; the members of the Language Learning Lab; and so many more. It would take a list longer than this dissertation to acknowledge everyone that has played an invaluable role in earning my Ph.D.

Chapter 2, in full, has been submitted for publication of the material as it may appear in *Psychology of Language and Communication*. This chapter is coauthored with Drs. Julie M. Schneider and Alyson D. Abel. The dissertation author was the primary researcher and author of this paper.

Chapter 3, in full, is currently being prepared for submission for publication of the material. This chapter is coauthored with Dr. JoAnn P. Silkes. The dissertation author and co-author contributed equally to the research and authorship of this material.

Chapter 4, in full, is currently being prepared for submission for publication of the material. This chapter is coauthored with Dr. Alyson D. Abel. The dissertation author was the primary researcher and author of this material.

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Schneider, R., Pankonin, A., Schachner, A., & Barner, D. (2021). Starting small: Exploring the origins of successor function knowledge. *Developmental Science, 24*(4), e13091. https://doi.org/10.1111/desc.13091. PMID: 33527570.

Pankonin, A., & Meyers, R. (2017). Teachers' use of positive and negative feedback: Implications for student behavior. *NYU Applied Psychology Online Publication of Undergraduate Studies, 8*(1), 27-34. https://issuu.com/nyu_applied_psych_opus/docs/opusspring17__1_

ABSTRACT OF THE DISSERTATION

Brain-Behavior Investigations of Lexical Representation Development and Lexical-Semantic Processing in Individuals With and Without Communication Disorders

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The fast pace and relative ease at which individuals with typical language acquire and use words belie the complexity and vulnerability of lexical representation development (i.e., word learning) and lexical-semantic processing. Lexical-semantic processing impairments are

common in both developmental and acquired communication disorders and, even in those without such disorders, various factors can influence the abstraction, encoding, and access of lexical information. Understanding the factors that influence lexical representation development and lexical-semantic processing and how these processes might be altered in individuals with communication disorders is crucial for advancing research and supporting clinical populations.

This dissertation presents three studies that integrate behavioral and neural approaches to investigate lexical representation development and lexical-semantic processing in individuals with and without language-based communication disorders. Chapter 2 explores how deducing a novel noun or verb's meaning from an incidental context influences later recognition of the word form in adults with typical language, revealing neural differences in encoding and accessing lexical information based on word class even when behavioral differences are absent. Chapter 3 uses a priming paradigm and event-related potentials (ERPs) to examine how the time course of an implicit mechanism underlying lexical and semantic processing, automatic spreading activation, differs between people with post-stroke aphasia (PWA) and neurologically unimpaired older adults. Chapter 4 applies a similar approach to children with developmental language disorder (DLD), investigating the potential link between the time course of spreading activation and (lexical-)semantic abilities in children with DLD and children with typical language development. Chapters 3 and 4 reveal atypical time courses of spreading activation in PWA and children with DLD, with PWA showing abnormally slow activation decay and children with DLD exhibiting atypically rapid activation decay. These chapters also show that PWA additionally struggle to integrate implicitly and explicitly processed information, and children with DLD display broader semantic processing impairments beyond lexical-semantic difficulties.

Altogether, these findings highlight how both lexical features and neurological differences affect lexical representation development and lexical-semantic processing, and—critically—exemplify the importance of considering underlying, implicit processes. They further suggest that interventions that target both the brain and behavior will lead to the greatest gains.

# INTRODUCTION

On the surface, acquiring, understanding, and using words—a fundamental unit of language—might appear to be a relatively fast-paced and straightforward process simple enough that even infants can do it. Indeed, children typically begin producing words within their first year of life, and comprehend language even before that (Samuelson & McMurray, 2017). However, in reality, the process is complex, multifaceted, and mediated by several factors (Bolger et al., 2008; Dumay et al., 2004; Frishkoff et al., 2008; Fukkink et al., 2001; Gaskell & Dumay, 2003; Jenkins & Dixon, 1983; Leach & Samuel, 2007; Schwanenflugel et al., 1997; Sternberg & Powell, 1983; Swanborn & de Glopper, 1999). The complexity of this process is, in part, due to the multiple components of information comprising the mental representation of a word (i.e., a lexical representation). At a minimum, some amount of information about word form (e.g., phonology, orthography), grammatical features (i.e., syntax), and word meaning (i.e., semantics; Leach & Samuel, 2007; Storkel, 2011) must be first encoded in long-term memory and then simultaneously activated when the word is accessed again later in order to process or produce the word. A word's lexical representation is incomplete without information from all of the domains, and information from each domain is critically important to correctly using and/or understanding a word (Leach & Samuel, 2007; Storkel, 2011).

To further complicate the process, in most cases, this information must be obtained incidentally, or gleaned from context rather than through explicit instruction (Beck et al., 1983; Nagy et al., 1985; Nagy & Herman, 1987; Sternberg, 1987). That is, the relevant lexical information must be abstracted from the surrounding environment, be that linguistic, such as the sentence in which the word is embedded, or otherwise, such as the observable actions or features that co-occur with the production of the word. A single encounter with a word can be enough to

abstract and encode some information, but the lexical representation is unlikely to be complete after such limited exposure (e.g., Abel et al., 2018; Borovsky et al., 2012; Frishkoff et al., 2008; Oetting et al., 1995; Perfetti et al., 2005; Storkel, 2011). Consequently, multiple encounters are often necessary to further develop the lexical representation via elaboration, refinement, and integration of the information, both with regard to mapping the information for a single word together and to making connections with existing information for other words (Abel et al., 2018; Storkel, 2011). As a lexical representation develops, the memory traces for the encoded information are strengthened, thus facilitating lexical access (Durso & Shore, 1991; Frishkoff et al., 2008, 2009; Leach & Samuel, 2007; Storkel, 2011).

The extent to which any encounter with a word supports its lexical representation development depends on a range of factors that influence the abstraction and encoding of lexical information. For instance, numerous studies have found that participants are more accurate at deducing the meanings of words encountered in sentences with high semantic constraint, where the context strongly suggests one particular meaning (e.g., *blicket* in *The blicket barks* is likely "dog"), than of words encountered in sentences with low semantic constraint, which allow for multiple potential interpretations of the word's meaning (e.g., *blicket* in *The blicket runs* could mean many things; Abel et al., 2018; Bolger et al., 2008; Daneman & Green, 1986; Frishkoff et al., 2008, 2010, 2011; Shore & Kempe, 1999). There is substantive literature demonstrating that word class is another factor that impacts success in discerning a word's meaning, with verbs' meanings being more difficult to identify than nouns' (e.g., Behrend, 2014; Gentner & Boroditsky, 2001; Gillette et al., 1999). These are only two factors of many that can affect the extent to which lexical information is abstracted, but they demonstrate the vulnerability of lexical representation development, specifically regarding semantic information.

While abstracting information is a critical step in developing representations, it is of little use if that information is not subsequently encoded and cannot be accessed later. As such, understanding how various factors influence those steps of lexical-semantic processing are equally important. It is here that we encounter gaps in the literature. We know that factors including what information (e.g., word form, semantics) is provided and other lexical features like word class can impact how well lexical information is encoded and/or accessed. Specifically, when the word is a noun rather than a verb, or when both form and semantic information are explicitly provided as opposed to when only form information is available, encoding and lexical access are facilitated as reflected by measures of better recognition (e.g., Balass et al., 2010; Earles & Kersten, 2017; Reynolds & Flagg, 1976; Takashima et al., 2014, 2017). However, what is less clear is how these factors affect encoding and access in more naturalistic language contexts (i.e., incidental contexts), especially at the neural level.

Behavioral measures of lexical knowledge and lexical-semantic processing provide valuable insight into robust, conscious processes and the language behavior resulting from more subtle unconscious processes. More sensitive measures, like electroencephalography (EEG), are required to discover the nuances of processes that fall outside of our conscious awareness and control, though. As such, using a combined brain-behavior approach allows for the most comprehensive understanding and complementary insights. Thus, to address one gap in the literature, **Chapter 2** describes a study in which my co-authors and I examine the effect of encoding form and semantic information from an incidental context on later explicit and implicit recognition of novel nouns and verbs in typical, college-aged adults. This study demonstrates the utility of a combined brain-behavior approach, considering both behavioral demonstrations and neural indicators (i.e., mismatch negativity [MMN] and N400 event-related potential [ERP]

effects) of lexical representation development and lexical-semantic processing. We found that, while explicitly identifying incidental semantic information did not enhance later behavioral recognition of novel nouns or verbs, neural measures showed different types of lexical information were encoded and accessed based on word class, showing variations in lexical representation development for nouns and verbs.

Impairments to the mechanisms underlying lexical-semantic processing can also greatly impact one's ability to abstract, encode, and access lexical and semantic information. In fact, lexical-semantic processing deficits are found in both acquired and developmental language disorders (e.g., Roth et al., 2006; Sheng & McGregor, 2010). Deficits in processing any lexical or semantic information hinders processing of all other downstream language, including higher-level language, like discourse. Consequently, to best support individuals with communication disorders, it is critical we have a detailed understanding of their lexical-semantic processing impairments and, ideally, the underlying causes of the impairments.

One language disorder in which lexical-semantic processing deficits have been consistently documented is aphasia. Aphasia is an acquired language disorder that typically results from a stroke in the left hemisphere of the brain and is characterized by deficits of varying severity in speaking, listening, reading, and writing. Lexical retrieval impairment, or anomia, is a ubiquitous symptom of aphasia, and, thus, is often the focus of aphasia treatments (Benson, 1988; Goodglass & Wingfield, 1997; Nickels, 2002; Raymer, 2005; Raymer & Roitsch, 2023). However, the mechanism responsible for anomia is not well understood, which prevents treatments from being maximally effective. Because aphasia can be transient and highly variable from moment to moment (e.g., Chu et al., 2014; Galletta & Goral, 2018; Kimura et al., 2003; Tseng et al., 1993), it is unlikely anomia is due to lost or destroyed linguistic representations, but

instead due to impaired access to them. This impaired access could be because the time course of the implicit, cognitive-linguistic mechanism underlying lexical and semantic processing, automatic spreading activation, is altered. Spreading activation is fundamental to lexical access and retrieval. If activation starts spreading between elements in the lexical-semantic network after a delay or spreads and/or decays too quickly or too slowly, thus remaining maintained for an atypically short or long duration, it is possible that not all the necessary information or too much information to access the correct lexical representation will be active. **Chapter 3** details a study where my co-author and I investigate the possibility that alterations in the time course of spreading activation might account for anomia. I introduce an experimental priming paradigm with varied prime-target intervals and masked and visible primes and describe its use with PWA and neurologically healthy older adults. This study also employs a multimodal approach and evaluates both behavioral priming effects and N400 ERP priming effects, which reflect semantic processing and when that processing is facilitated by priming (Holcomb, 1988; Kiefer, 2002; Kiefer & Spitzer, 2000; Kutas & Federmeier, 2011; Kutas & Hillyard, 1984). Our findings suggested that anomia in PWA is linked to atypically slowly decaying activation and an inability to integrate explicit and implicit information as effectively as typical older adults.

Another language disorder in which lexical-semantic processing is commonly impaired is developmental language disorder (DLD). Developmental language disorder is language impairment that cannot be attributed to other conditions, such as intellectual disability or traumatic brain injury, and has no identified biomedical causes (Leonard, 2014; Tomblin, 2011). It is characterized by deficits in one or more domains of language that impact an individual's ability to understand and/or produce written and/or spoken language. Although aphasia and DLD have entirely different etiologies, the two disorders share a common symptom of lexical-

semantic deficits. Lexical-semantic deficits in DLD include difficulty processing semantic information and semantic representations that are less developed and/or more difficult to access than in individuals with typical language development (e.g., Alt et al., 2004; Botting & Adams, 2005; Drljan & Vuković, 2019; Gray, 2004; Hung & Sun, 2022; Mainela-Arnold et al., 2010; McGregor et al., 2013; Sheng & McGregor, 2010; Velez & Schwartz, 2010). While research on the lexical-semantic deficits in individuals with DLD has described the deficits and their impact, why children with DLD experience these lexical-semantic deficits is still unknown. Like for PWA, an alteration in the time course of spreading activation has been suggested as an explanation for these deficits, although there is little consensus on the nature of the alteration (e.g., Borovsky et al., 2013; Helenius et al., 2009, 2014; McMurray et al., 2014; Pizzioli & Schelstraete, 2011; Velez & Schwartz, 2010). In **Chapter 4**, I present a study that aims to clarify how the time course of automatic spreading activation for both lexical-semantic (i.e., word meaning) and semantic (i.e., object meaning) processing in children with DLD is altered compared to their typical peers and how individual differences in that timing are related to lexical-semantic abilities. I use a similar priming paradigm as in Chapter 3 but include additional behavioral assessments of language and cognition to explore how patterns of brain signals to repetitions of masked primes after different delays relate to the observable language behavior. This study suggested that children with DLD experience accelerated decay of activation which disrupts both lexical-semantic and semantic processing, as well as showed that differences in spreading activation timing might be related to general language abilities rather than exclusively semantic skills.

Across these three studies, this dissertation strives to highlight how various factors influence the way lexical and semantic information is encoded, accessed, and more generally

processed. I conclude this dissertation in **Chapter 5** with a discussion of the findings from all three studies, focusing on the importance of considering underlying, implicit processes even when they are not observably reflected in behavior. I ultimately aim for this research to bolster our understanding of how implicit mechanisms of lexical-semantic processing underlie language behavior, as well as for it to contribute to the theoretical foundation for developing more efficacious interventions for individuals with lexical-semantic processing deficits.

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# Chapter 2 : WORD WARS: THE ROLE OF FORM AND SEMANTIC ENCODING IN IMPLICIT AND EXPLICIT RECOGNITION OF NOUNS AND VERBS


## Abstract

Encoding word form and semantic information is critical for integrating new words into the lexicon. Factors like encoding context and word class impact the memory trace and, thus, recognition of new words. This study investigated how encoding form and semantic information from an incidental context influences later explicit and implicit recognition of novel nouns and verbs. Over two experiments (Noun: $n = 31$; Verb: $n = 23$), we found that although explicit semantic encoding did not facilitate behavioral recognition, neural measures (mismatch negativity [MMN], N400) revealed distinct implicit processing patterns for each word class. The MMN results indicated word form encoding for nouns but not verbs, while N400 findings showed more effortful processing for nouns with encoded meanings and that all previously encountered verbs had encoded meanings. Our findings provide insights into the mechanisms underlying word learning, specifically those driving word recognition and how lexical representation development differs across word classes.

## Introduction

An individual's vocabulary size increases throughout their lifetime and is estimated to reach over 17,000 words in adulthood (Goulden et al., 1990; Zechmeister et al., 1995). Each word is stored in long-term memory (e.g., the lexicon) as a lexical representation consisting of information pertaining to the word's phonological and/or orthographic form, syntactic features (e.g., word class), and semantic features (i.e., the word's meaning; Leach & Samuel, 2007), at a minimum. Acquiring this information about a new word is a dynamic, incremental process, typically requiring multiple instances of abstracting these relevant features from the surrounding linguistic (i.e., oral, written) and/or environmental contexts and encoding and integrating the relevant linguistic information to form a lexical representation (Beck et al., 2002; Christ & Wang, 2011; Frishkoff et al., 2008; Fukkink, 2005; Gaskell & Dumay, 2003; Leach & Samuel, 2007; Schwanenflugel et al., 1997; Storkel, 2011). These lexical representations' memory traces vary in strength as a result and are activated during future encounters with and productions of the word (Durso & Shore, 1991; Frishkoff et al., 2008, 2009; Leach & Samuel, 2007; Storkel, 2011). There is substantive literature examining the impact that different features of the lexical information provided (e.g., phonological/orthographic word form, etc.) and the context the word is introduced in (e.g., highly constraining linguistic contexts) have upon abstraction of lexical information and subsequent encoding, retention, and activation of new lexical representations (e.g., Balass et al., 2010; Bolger et al., 2008; Frishkoff et al., 2011; Momsen & Abel, 2021; Shore & Kempe, 1999; Takashima et al., 2014, 2017). What is less well understood is whether differences at encoding influence later recognition of new words and, in particular, whether these effects differ across word classes.

Word recognition tasks, such as reporting whether each word in a list was previously encountered, are a common way of assessing the strength of a new lexical representation's memory trace. Adults can successfully recognize new word forms (i.e., orthographic and/or phonological forms with no semantic information) after one or more exposures in an encoding task (Dumay & Gaskell, 2007; Gaskell & Dumay, 2003; Leach & Samuel, 2007; Takashima et al., 2017). This ability to recognize words is improved when a new word form is explicitly paired with semantic information during encoding via an accompanying picture or definition (Balass et al., 2010; Takashima et al., 2014, 2017). Thus, the *explicit* addition of semantic information during encoding appears to enhance later recognition. However, when semantic information is provided in a less explicit manner, the effects of this semantic information on word recognition remain unclear.

In studies where the process of encoding a new word's meaning occurs through incidental means, such as requiring participants to infer the new word's meaning from the sentence(s) in which it is introduced (i.e., via an incidental encoding paradigm), the addition of semantic information seems to have no impact on immediate behavioral word recognition (Abel et al., 2020; Dumay et al., 2004). Importantly though, despite a lack of behavioral recognition directly following the encoding task, participants in these studies still demonstrate recognition of the new words, either at a later time point or through more sensitive measures. For instance, following a one-day and seven-day delay after encoding, Dumay et al. (2004) found better behavioral recognition of word forms when semantic information was incidentally provided during encoding compared to word forms where no semantic information was provided. Using electroencephalography (EEG), Abel et al. (2020) identified that school-aged children showed neural sensitivity to word forms that had been presented in semantically informative incidental

contexts during encoding compared to word forms presented with inconsistent semantic information during encoding. Critically, this neural sensitivity was present despite children performing at chance on a behavioral recognition task administered directly following the encoding task, suggesting implicit recognition of word forms is possible when presented in incidental encoding contexts, even in the absence of explicit, behavioral recognition.

As Abel et al.'s (2020) study exemplifies, EEG offers a temporally precise way of examining implicit processes of word recognition in real time even without explicit behavioral responses. Two event-related potential (ERP) components, the mismatch negativity (MMN) and the N400, are well-suited for detecting changes in the neural signal thought to underlie the processes that occur during word recognition. The MMN is a negative-going, frontally-distributed ERP component that occurs between 30 and 170 ms after stimulus onset. The MMN is largely automatic and attention-independent in nature and is sensitive to differences in familiarity across a number of stimuli (Aleksandrov et al., 2020; Garrido et al., 2009; Näätänen et al., 1997; Shtyrov et al., 2010). In the traditional oddball paradigm, the MMN is more negative in response to infrequently presented, deviant stimuli versus frequently presented, standard stimuli. Thus, in this paradigm, a lack of familiarity with the stimuli is generally associated with a more negative deflection of the ERP. However, when comparing the MMN elicited by deviants of different features, such as word form familiarity, more familiar deviants elicit a more negative MMN response than less familiar deviants (Aleksandrov et al., 2020; Jacobsen et al., 2005; Pulvermüller et al., 2001; Shtyrov et al., 2010). For example, research has demonstrated that real word deviants result in a more negative MMN than novel word deviants (Pettigrew et al., 2005), and similarly, recently learned words result in a more negative MMN than new words (Shtyrov et al., 2010). In the case of word form familiarity, this enhanced neural response is thought to

reflect automatic activation of an experience-dependent, long-term memory trace for word forms (Hu et al., 2020; Pulvermüller et al., 2001; Shtyrov & Pulvermüller, 2002). Therefore, the MMN might not only reflect the acoustic change in speech stimuli, but also the initial, automatic stages of word recognition, namely lexical processing and word form familiarity (Pettigrew et al., 2005).

A complementary ERP component that is relevant to the study of word recognition is the N400. This component is characterized by a negative deflection of the ERP between 300 and 600 ms after stimulus onset and is largest over centro-parietal sites with a left hemisphere bias (Federmeier & Kutas, 1999; Holcomb & Neville, 1991; Sereno et al., 2003; West & Holcomb, 2000). It has been well-established that the N400 reflects automatic semantic processing, occurring regardless of whether an individual consciously perceives a stimulus (Kiefer, 2002; Kutas & Hillyard, 1980; Misra & Holcomb, 2003). To process semantic information, the encoded semantic information must be automatically activated and accessed in long-term semantic memory, making the N400 an index of implicit recognition of a word's meaning. When limited semantic information is available, the memory trace for that semantic information is less robust, which results in more effortful semantic processing and is reflected by a more negative N400 response relative to words with a stronger semantic memory trace (Kutas & Federmeier, 2011). Thus, if there is not a sufficient amount of semantic information abstracted from context and/or it is not adequately encoded and mapped to the word form, the N400 will reflect the negative effects that failing to abstract, encode, and/or map meaning has on the early, automatic semantic processing stage of word recognition.

Together, these ERP components are useful measures for understanding the roles word form and semantic information play in behavioral word recognition. Further, because these ERP

components reflect automatic processes, separable from behavioral performance, they can also provide insights into the formation of lexical representations that are not yet robust enough to support behavioral demonstrations of recognition. This is particularly important given the evidence that immediate behavioral word recognition is not facilitated by the addition of semantic information in incidental encoding paradigms (Abel et al., 2020; Dumay et al., 2004), but neural signs of recognition still occur (Abel et al., 2020). As such, these ERP components can help us tease apart the impact of word form and semantic information on both implicit and explicit word recognition processes.

Word class differences between nouns and verbs have also been shown to impact word recognition. Behavioral studies have demonstrated that nouns, compared to verbs, are learned at a faster pace, with less effort, and at an earlier age (e.g., Bornstein et al., 2004; Bornstein & Cote, 2005; Childers & Tomasello, 2002; Gentner, 1978, 1982; Gentner & Boroditsky, 2001; Gillette et al., 1999; Goldin-Meadow et al., 1976; Golinkoff et al., 1992, 1996; Maguire et al., 2006; Nelson, 1973; Piccin & Waxman, 2007; Waxman & Lidz, 2006; Woodward & Markman, 1998). Even adults demonstrate this "noun advantage," consistently providing more accurate and faster responses for object nouns than action verbs in picture naming and sentence completion tasks (Colombo & Burani, 2002; Druks, 2002; Federmeier & Bates, 1997; Huttenlocher & Lui, 1979; Kauschke & von Frankenberg, 2008; Mätzig et al., 2009; Szekely et al., 2005). Few studies have investigated word class differences specifically related to word recognition, but those that have reveal that nouns are consistently recognized more frequently than verbs (Earles & Kersten, 2017; Engelkamp & Zimmer, 1995; Kersten & Earles, 2004; Mohr et al., 1989; Reynolds & Flagg, 1976).

The reason for these learning and recognition differences between nouns and verbs is commonly attributed to the fact that verbs are inherently linked to other words and their meanings are more dependent on context (Gentner & Boroditsky, 2001; Gentner & France, 1988; Kersten, 1998, 2003; Kersten & Earles, 2004; Kintsch, 2001). Specifically, verbs require arguments (e.g., *swim* requires some subject, such as *fish*; Huttenlocher & Lui, 1979; Vigliocco et al., 2004) and are more likely to have multiple meanings (i.e., be polysemous; e.g., *ran* means "moved quickly" in *He ran away*, but means "competed" in *She ran for office*; Gentner, 1981; Jenkins & Dixon, 1983; Kintsch, 2001; Levin, 1993), with the relevant meaning determined by the linguistic and/or environmental context. Contrastively, nouns do not require arguments, and their meaning is typically more consistent across contexts (Gentner & Boroditsky, 2001; Gentner & France, 1988). Thus, verbs often entail increased processing demands compared to nouns, especially regarding semantic information.

While the studies mentioned above utilized behavioral methods to compare noun and verb word recognition, there is also evidence of differential neural processing of nouns and verbs. The MMN reflects greater sensitivity to differences between standard and deviant nouns compared to verbs (Hasting et al., 2008; Jacobsen et al., 2021). Additionally, the N400 peak latency is approximately 23 to 32 ms earlier for nouns than verbs (Gomes et al., 1997; Khader et al., 2003; Rösler et al., 2001) and the peak amplitude is generally greater for nouns compared to verbs (e.g., Lee & Federmeier, 2006; Rösler et al., 2001; cf. Khader et al., 2003), indicating faster and more robust processing of the meanings for nouns versus verbs. However, when examining differences between novel nouns and novel verbs (i.e., pseudowords), the difference in peak amplitude is reversed, reflecting the additional effort required to encode the meanings of

novel verbs compared to novel nouns (Federmeier et al., 2000). Thus, neural differences may subserve behavioral differences in how nouns and verbs are processed.

The present study investigates the recognition of novel nouns and verbs after exposure to both word form and semantic information in an incidental encoding task. In the incidental encoding task, novel word forms were introduced in sets of three sentences that supported the identification of the one-word target meaning for the novel word. Directly following the incidental encoding task, participants completed a two-alternative forced-choice (2-AFC) recognition task, the task of interest for this study. In the 2-AFC recognition task, participants were asked to indicate whether the novel word they heard was one they had encountered previously in the incidental encoding task (i.e., old), or if the novel word was one they had not been exposed to previously (i.e., new). We examined both behavioral and neural (i.e., MMN and N400) indicators of word recognition during the recognition task.

We had four predictions for this study:

1. Across word classes, identifying meaning during encoding will facilitate later behavioral recognition of the novel words. This prediction is supported by prior evidence that the combination of semantic information with a word form during the encoding phase facilitates better behavioral recognition than exposure to the word form alone. Even though evidence suggests that recognition is weaker when semantic information is incidentally–rather than explicitly–provided, that evidence comes from studies that considered whether there was merely an opportunity for form-meaning mapping to occur, not whether form-meaning mapping actually occurred. Here, we focus on the latter; specifically, whether successful explicit form-meaning mapping facilitates recognition. Because nouns

consistently result in better recognition and increased processing demands are observed during recognition of verbs, we also predict participants will be more accurate in their behavioral recognition of novel nouns compared to novel verbs.

2. Given the evidence that the MMN is more negative for familiar word forms compared to unfamiliar word forms, even in the absence of semantic information, we predict that, across word classes, there will be a more negative MMN during recognition of novel words that were previously encountered in the encoding task (regardless of whether meaning was explicitly encoded) compared to new novel words. We do not predict any word class differences in the MMN as what distinguishes nouns from verbs relates primarily to semantic and syntactic features and not word form.
3. Across word classes, the N400 amplitude during recognition will be attenuated for novel words in which meaning was successfully encoded (based on behavioral performance on the encoding task), compared to novel words where no meaning was encoded (according to behavioral performance on the encoding task). The N400 reflects the ease of semantically processing a stimulus, and processing the meaning of a word with semantic information encoded should be easier than a word that lacks such information. Given that verbs place higher demands on semantic processing than nouns, we predict that verbs will elicit a larger N400 effect than nouns.

## Experiment 1: Nouns

### Method

#### *Participants*

Fifty-one adults participated in this experiment. Twenty participants were excluded from analyses due to: the demonstration of a handedness bias (details below; $n = 1$), bilingual status ($n = 15$), or technical issues ($n = 4$). The final participant group included 31 right-handed, normal-hearing, monolingual English-speaking adults (2 males), ranging in age from 18.00 to 29.69 years ($M = 21.25$, $SD = 2.64$). Exclusionary criteria included a history of language delays or disorders; a history of significant neurological conditions (i.e., central nervous system diseases, high fevers, seizure disorders, traumatic brain injury, cerebral vascular accident, tumors, or learning disabilities); use of alcohol, controlled substances, and/or medications other than over-the-counter analgesics and contraceptives within 24 hours prior to testing; and lack of right-handed dominance according to the Edinburgh Handedness Inventory (Oldfield, 1971). Participants were recruited from undergraduate courses in Speech, Language, and Hearing Sciences at San Diego State University. All participants gave informed consent in accordance with the Institutional Review Board of San Diego State University and received academic course credit for participation.

#### *General Procedure*

All participants completed two tasks in a fixed order: 1) an experimental incidental encoding task whereby participants were exposed to both word form and semantic information for novel words (Encoding Task) and 2) a word recognition task (Recognition Task). Behavioral and EEG data were collected during both tasks.

### *Encoding Task*

**Stimuli.** Stimuli for this task included 100 sets of three sentences, or sentence triplets, for a total of 300 sentences. Sentences were six to nine words in length with the final word of the sentence being the target word, which was an early-acquired noun (Fenson et al., 2007). Words preceding the target word were a determiner (i.e., *a, the*) or possessive (i.e., *my, your, his, her, its*). Target words were replaced with a novel word drawn from a pool of 200 monosyllabic novel words that followed the phonotactic rules of Standard American English and were initially selected from a corpus of consonant-vowel-consonant (CVC) sequences (Storkel, 2013). None of the novel words began with /s, ʃ/, or the same word-final sound of the word preceding the novel word (e.g., novel words that were preceded by *can* did not begin with /n/) to avoid coarticulation effects. The same novel word was used for each of the three sentences of a sentence triplet but varied across the 100 triplets (see Table 1 for examples), resulting in exposure to a total of 100 different novel words.

Fifty of the 100 sentence triplets were constructed to support the identification of the single target meaning for the novel word (Supportive Context; see Figure 1 for pictorial representation of the breakdown). This was done by all three of the sentences of the triplet ending with the same target word and each sentence increasing in cloze probability across the triplet (Low: $M$ = 4.11, $SD$ = 6.04; Medium: $M$ = 40.60, $SD$ = 10.17; High: $M$ = 87.85, $SD$ = 11.19). Thus, the sentences became increasingly more semantically constraining and supportive of the single target word's meaning with each successive sentence (see Table 1 for examples). The remaining 50 sentence triplets were constructed to *not* support meaning identification for the novel word (Unsupportive Context; see Figure 1 for pictorial representation of the breakdown and Table 1 for examples) and were only included to control for repeated exposure. This was

achieved by each sentence of the triplet having a different target word and all sentences having low cloze probability (*M* = 18.32, *SD* = 17.85). Cloze probability was determined via a separate norming task with 238 adults and was calculated as the proportion of participants who accurately provided the target word in a sentence with the final word removed (see Abel et al., 2015 for details).

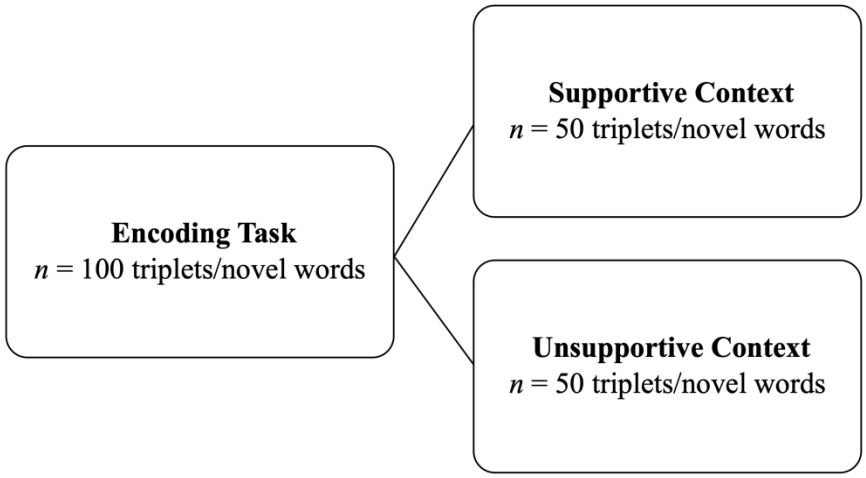


Figure 2.1. Breakdown of the number of stimuli per condition for the Encoding Task. Each participant encountered a total of 100 different novel words in the Encoding Task, 50 of which were presented in the Supportive Context and 50 of which were presented in the Unsupportive Context (control condition).

Novel words appearing in the sentence-final position were counterbalanced across orders such that, over the course of 16 orders, they appeared in both the Supportive Context and Unsupportive Context, consequently serving as their own controls. Within a single order, novel words only ever appeared in one of the two contexts. All sentences were spoken at a natural pace with natural intonation by an adult female native English speaker and audio-recorded in a soundproof room to simulate naturalistic and optimal listening conditions (Length: Supportive Context: *M* = 2,441 ms, *SD* = 363 ms; Unsupportive Context: *M* = 2,582 ms, *SD* = 396 ms).

**Procedure.** The Encoding Task was adapted from Abel et al.'s (2018, 2020) study of

incidental word learning from context in children and Mestres-Missé et al.'s (2007) study investigating incidental word learning from context in adults. Participants were seated in a dimly lit, soundproofed room approximately three feet away from a computer display and two speakers. The participants listened to the sentence triplets and, following each triplet, were asked two test questions: 1) does the novel word have meaning and, if so, what is it? and 2) how sure are you that you provided the correct answer (low, medium, high)? After explaining the task, the experimenter conducted two practice trials (one trial of the Supportive Context and one trial of the Unsupportive Context), making participants aware that some words had a meaning and some did not, and providing feedback and repetition as necessary. No feedback or repetition was provided during the test trials. A researcher sat in the room with the participant to administer the task and record the participants' responses online.

Each stimulus sequence began with a row of crosses appearing on the monitor for 600 ms, followed by a single fixation cross displayed as the spoken sentence was presented at a comfortable volume. After the sentence, participants saw another row of crosses, indicating that they could press a button to move on to the next trial. After the third sentence in each sentence triplet, a row of question marks was displayed that indicated that the researcher was to present the test question about the meaning of the novel word. Once the participants responded to the first test question, the participants were instructed to press a button to proceed to the next screen, which displayed the text, "How sure? / Low / Medium / High." This screen indicated that the researcher was to present the test question about the participant's confidence level (see Figure 2 for a pictorial representation of the stimulus sequence).

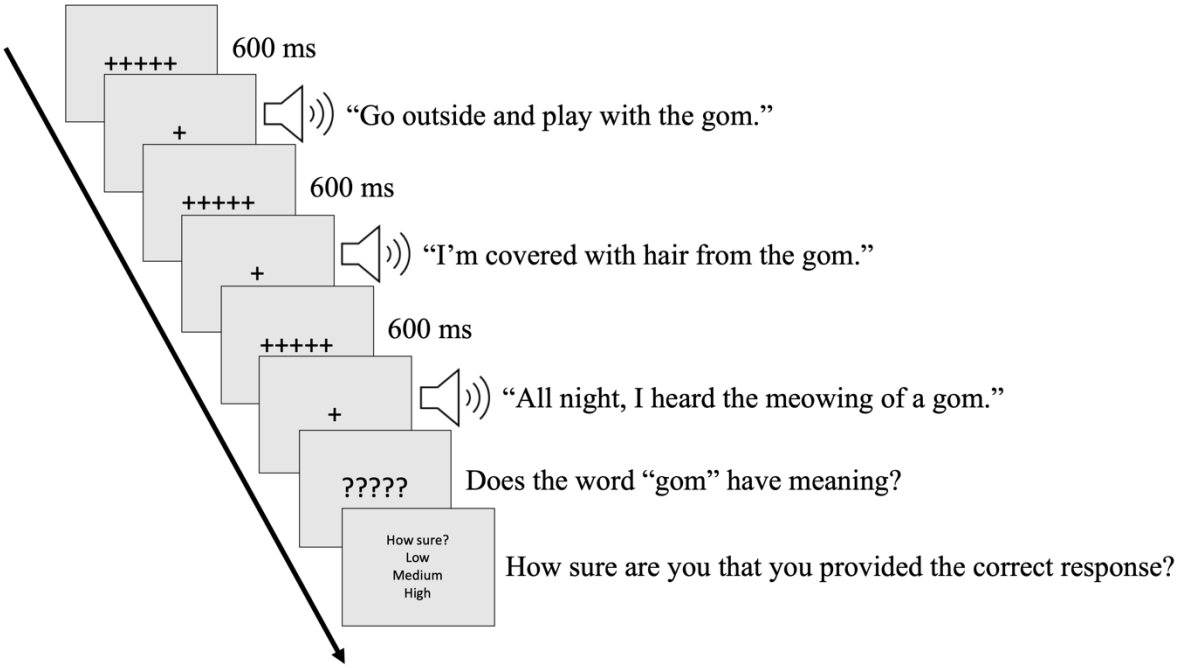


Figure 2.2. Breakdown of the number of stimuli per condition for the Encoding Task. Each participant encountered a total of 100 different novel words in the Encoding Task, 50 of which were presented in the Supportive Context and 50 of which were presented in the Unsupportive Context (control condition).

To examine how encoding word form and semantic information during the encoding task influences later recognition, we focused solely on the responses to novel words from the Supportive Context; responses to novel words from the Unsupportive Context were not included in our analyses. Participants' responses were classified as Meaning Identified or No Meaning Identified following Abel et al.'s (2018) methods for data analysis. A response was classified as Meaning Identified if the participant provided any meaning for the novel word and the response was classified as No Meaning Identified if the participant responded that there was no meaning for the novel word. Response classification disregarded the accuracy of the response (i.e., whether the meaning provided matched the target word or the participant correctly claimed that the novel word had no meaning). Scoring examples are provided in Table 1.

Table 2.1. Example stimuli for the Encoding Task for Experiment 1. Stimuli consisted of sentence triplets in which all three sentences ended with the same CVC novel word. In the Supportive Context, the novel word replaced the same early-acquired noun target word in all three sentences of the triplet and the sentences increased in cloze probability across the triplet. In the Unsupportive Context, which served as a control condition, the novel word replaced a different early acquired noun in each of the triplet's three sentences, resulting in no target word, and the sentences were all low cloze probability. Participants' responses to stimuli from the Supportive Context were classified offline for meaning identification, disregarding response accuracy.

| Sentence Presentation | Supportive Context (target word: *face*) | Unsupportive Context (no target word) |
|---|---|---|
| 1 | He looks just like you in the **deav**. | Before you get food, grab a **pieg**. |
| 2 | Those twins look different in the **deav**. | The cake was decorated with a **pieg**. |
| 3 | She wears a lot of makeup on her **deav**. | When I sit there, I can see the **pieg**. |
| | Scoring Examples | |
| Meaning Identified | Face, Eyes, Picture | N/A |
| No Meaning Identified | No meaning | N/A |

***Recognition Task***

**Stimuli.** Stimuli for the Recognition Task included novel words previously heard in the Encoding Task (old; $n$ = 100, 50 from the Supportive Context and 50 from the Unsupportive Context) and new novel words that had not been presented at all in the previous Encoding Task (new; $n$ = 100; see Figure 3 for pictorial representation of the breakdown). The novel words for the Recognition Task came from the same pool of 200 novel words used in the Encoding Task. All novel words were produced by the same speaker who produced the Encoding Task stimuli and were recorded in the same way (Length: $M$ = 577 ms, $SD$ = 122 ms). The presentation of

novel words as old or new was counterbalanced across orders so that they served as their own controls.

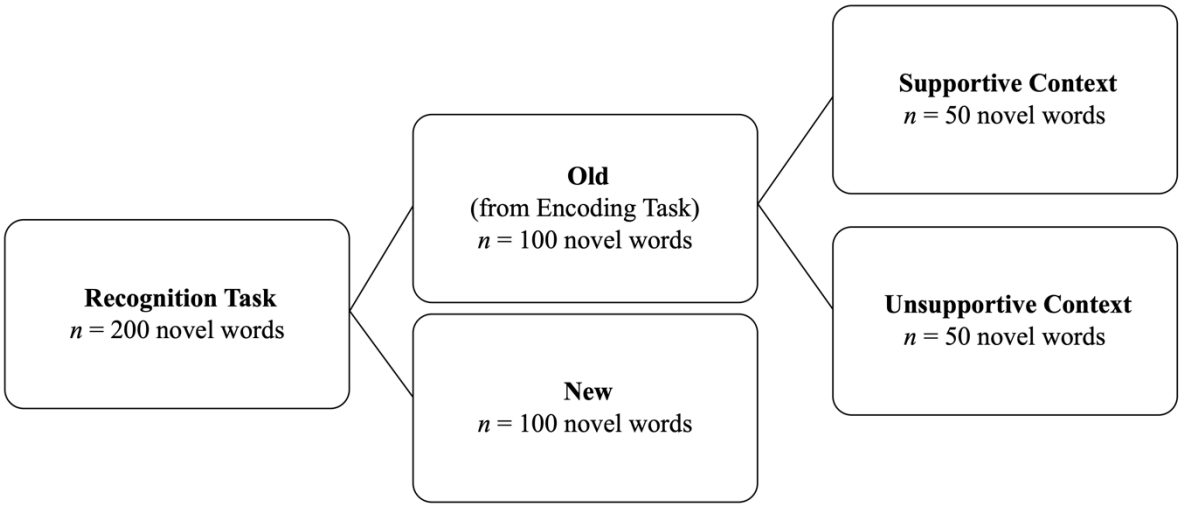


Figure 2.3. Breakdown of the number of stimuli per condition for the Recognition Task. Each participant heard a total of 200 different novel words during the Recognition Task, 100 of which were the 100 novel words that they had encountered previously in the Encoding Task (50 presented in the Supportive Context and 50 presented in the Unsupportive Context), and 100 of which they encountered for the first time in the Recognition Task.

**Procedure.** After completing the Encoding Task, participants were given a short break before beginning the Recognition Task. Prior to beginning the Recognition Task, the experimenter explained the task but there were no training trials. No feedback or repetition was provided during the test trials.

A trial in the Recognition task included a row of crosses that was displayed on the monitor for 600 ms, followed by a single fixation cross displayed with the auditory presentation of the novel word at a comfortable volume. Following the novel word, a row of question marks was displayed in the middle of the monitor which cued the participant to make their response and remained until the response was provided (see Figure 4 for pictorial representation of stimulus sequence). Participants responded by indicating whether they believed the novel words were old

(i.e., previously heard in the Encoding Task) or new (i.e., not previously heard) using a response box with two buttons, one that was marked with a smiling face emoticon and one that was marked with a frowning face emoticon. Participants were instructed to press the smiling face button for old novel words and press the frowning face button for new novel words. The button assignments were counterbalanced across conditions to control for hand bias. Guided by previously used criteria (Abel et al., 2020), participants who demonstrated a bias for one button by providing one type of response (new or old) for more than 90% of their responses and simultaneously providing the other type of response for less than 10% of their responses were excluded from analyses.

Related to the research questions, old novel words were further separated into those with Meaning Identified during the Encoding Task and those with No Meaning Identified during the Encoding Task. Recognition accuracy was calculated to create four conditions of interest: Meaning Identified, Correct Recognition; Meaning Identified, Incorrect Recognition; No Meaning Identified, Correct Recognition; New, Correct Recognition. These conditions provide insight into the recognition of words with recently encoded meanings, failed recognition of words with recently encoded meanings, recognition of recently encountered words without encoded meanings (i.e., likely only encoded forms), and recognition of new words, respectively. Comparing these four conditions allows us to isolate the effect of encoding form and/or meaning on later recognition.

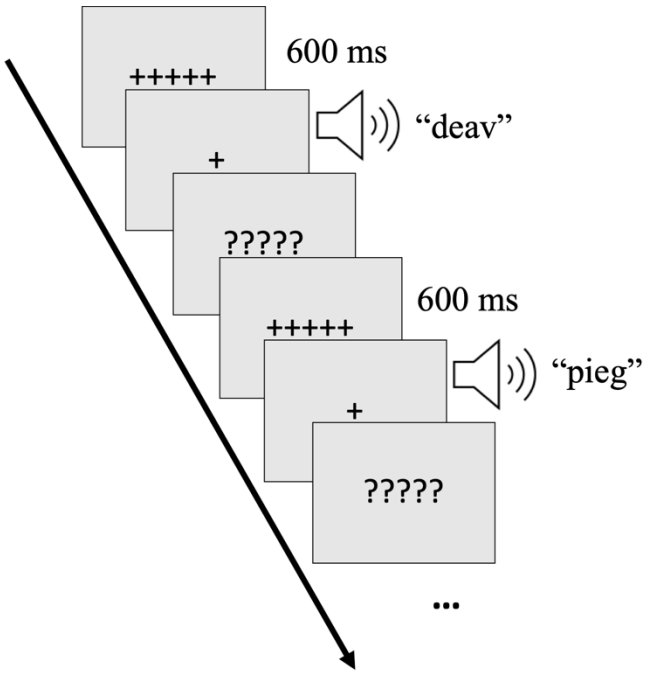


Figure 2.4. Stimulus sequence for the Recognition Task procedure. Each trial consisted of 600 ms of silence followed by an auditorily presented novel word and ended with a response opportunity. The visual stimuli of each trial merely directed attention and indicated trial progression.

***Behavioral Analysis***

The current study investigates the effect of encoding form and meaning on both implicit and explicit recognition of novel words. To explore the impact of encoding form and semantic information on *explicit* word recognition, we examined the behavioral recognition accuracy data from the four conditions of interest from the Recognition Task. Behavioral recognition accuracy data were analyzed using logistic linear mixed-effects regression models that were fit using maximum likelihood estimation via the *lme4* package in R (version 1.1-35.1; Bates et al., 2015). Final models were achieved by first constructing a maximal model that included the fixed effects of interest, all measured covariates (i.e., phonological working memory, age, and gender), and the maximal random effects structure supported by the study design (as determined by the guidelines provided by Brauer and Curtin (2018) and procedure outlined by Barr et al. (2013)). If

this maximal model did not converge or resulted in a (near) singular fit, the model complexity was iteratively reduced by following the steps outlined in Bates et al. (2018) until convergence was achieved and/or singularity was no longer detected. *A priori* contrasts were used with a family-wise type I error rate set at an alpha of 0.05.

***EEG Acquisition***

While completing both tasks, each participant wore a 64 silver/silver-chloride electrode cap (Neuroscan Quickcap). Continuous data were collected throughout the experiment using a Neuroscan SynAmps2 amplifier and Scan 4.3.2 software sampled at 1 kHz with impedances typically below 5 kΩ. Electrodes were placed using the International 10-20 electrode placement standard with one electrode placed above and one below each participant's left eye to monitor ocular motor movement. Impedances were monitored by researchers throughout the study.

***EEG Pre-Processing***

EEG data were analyzed using the EEGlab toolbox of MATLAB (Delorme & Makeig, 2004). Data were resampled offline at 500 Hz, high-pass filtered at 0.1 Hz, and low-pass filtered at 50 Hz. For electrodes with large impedances, data for the electrode was interpolated to yield 62 data channels for each participant (channels interpolated: $M = 1.45$, $SD = 0.87$). EEG data were also re-referenced to temporoparietal electrodes (TP7, TP8) to minimize error found in averaging across electrodes. Blocks of EEG data with visually detectable artifacts were manually identified and removed by trained researchers. Independent components analysis (ICA; Delorme et al., 2001) was run on all EEG data to minimize the effects of ocular motor movement on brain data. Components related to eye and head movement were manually removed from each participant (rejected components: $M = 1.67$, $SD = 0.82$). Data was then epoched from 500 ms before to 1000 ms after the presentation of the novel word. Epochs that were contaminated by

artifacts (i.e., contained abnormal thresholds [upper limit: 75 μV; lower limit: -75 μV], abnormal trends [max slope: 50 μV/epoch], improbable data [single channel limit of 5], and/or abnormal distribution [standard deviation of 5]) were rejected using ERPlab (Lopez-Calderon & Luck, 2014; removed epochs: $M$ = 13.05, $SD$ = 10.21).

***Event-Related Potential Analysis***

To examine the impact of encoding form and semantic information on *implicit* recognition of novel words, we investigated changes in the MMN and N400 across the four conditions of interest from the Recognition Task. We defined the time windows and electrodes of interest by examining significant differences between our four conditions of interest using a Monte Carlo cluster-based permutation test (Oostenveld et al., 2011) within the EEGlab Toolbox of MATLAB. This is done by first comparing every sample (channel, time) within each experimental condition using a *t*-test. All samples with *t*-values significant at an alpha of 0.05 are clustered into connected sets, based on their temporal and spatial adjacency. The cluster-level statistics are then calculated by taking the sum of the *t*-values within every cluster and determining the maximum cluster-level statistic. To then determine statistical significance between groups, we applied the Monte Carlo method. Using the cluster-based test statistic identified by the previous analysis, the Monte Carlo permutation involves: 1) collecting EEG data for each of the experimental conditions, 2) drawing as many trials from each combined data set as there are conditions, and placing these additional trials within separate subsets (referred to as random partitioning), and 3) calculating the test statistic based on this random partition (i.e., the maximum of the cluster-level summed *t*-values). Steps 2 and 3 are repeated 500 times, based on data size and number of variables, and then random test statistics are compared to the observed test statistic. The permutation *p*-value is the proportion of partitions where the observed

test statistic is larger than the value drawn from the permutation test statistic. Permutation accuracy can be quantified by means of the well-known confidence interval of its binomial distribution (Ernst, 2004; Maris & Oostenveld, 2007). Finally, we applied an FDR correction to control for multiple comparisons.

## Results

### *Behavioral Results*

During the Encoding Task, adults identified a meaning for the novel noun presented in the Supportive Context 87.74% of the time (*SD* = 7.22%). Recall that, during the Recognition Task, individuals were required to categorize whether the novel word they heard was new or had been encountered in the Encoding Task (i.e., old). When comparing recognition of all previously encountered novel words to new words, participants were significantly more likely to correctly categorize a word as new versus old (i.e., previously encountered; Old: *M* = 51.03%, *SD* = 13.58%; New: *M* = 61.03%, *SD* = 13.77%; $\beta$ = 0.26, *SE* = 0.10, *z* = 2.55, *p* = .011). For previously-encountered novel nouns, participants were just as likely to recognize a novel noun for which they had identified a meaning during the Encoding Task (*M* = 50.52%, *SD* = 13.44%) compared to those for which they had not identified a meaning during the Encoding Task (*M* = 56.78%, *SD* = 26.79%; $\beta$ = -0.39, *SE* = 0.28, *z* = -1.38, *p* = .17).

### *ERP Results*

Given the evidence that implicit differences in recognition may be present in the absence of explicit behavioral recognition, we also sought to explore whether the presence of neural signals underlying recognition could be attributed to word form familiarity and/or semantic encoding. We focused ERP analyses on two components: the MMN, which shows sensitivity to differences in word form familiarity, and the N400, which reflects automatic semantic access.

Both analyses compared neural activity across the four conditions of interest from the Recognition Task (i.e., Meaning Identified, Correct Recognition; Meaning Identified, Incorrect Recognition; No Meaning Identified, Correct Recognition; New, Correct Recognition).

The MMN analysis included data from 30 to 170 ms after stimulus onset. In this time window, the cluster-based permutation identified significant differences between conditions over left frontocentral electrodes (all significant corrected *p*-values were < .05; see Figures 5 and 6). Post-hoc pairwise comparisons indicate that novel nouns to which individuals were previously exposed (i.e., Meaning Identified, Correct Recognition; No Meaning Identified, Correct Recognition; Meaning Identified, Incorrect Recognition) resulted in a more negative waveform than newly encountered (and correctly categorized) nouns (i.e., New, Correct Recognition; see Supplemental Figure 1). Additionally, novel nouns that were correctly categorized during recognition, but had no identified meaning (i.e., No Meaning Identified, Correct Recognition) had a significantly more negative waveform than novel nouns that were correctly categorized during recognition and had an identified meaning (i.e., Meaning Identified, Correct Recognition).

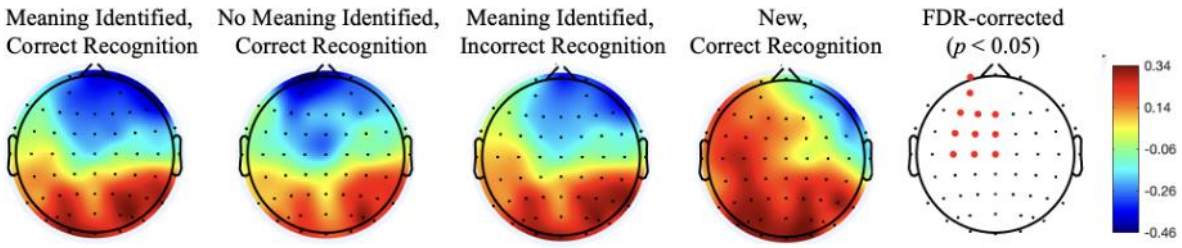


Figure 2.5. Topographic voltage maps for nouns representing the significant differences between all conditions during the time window of 30 to 170 ms after target word onset. Positive voltages are represented in red, and negative voltages are represented in blue. Electrodes identified as significant by the cluster-based permutation test are highlighted in red on the far right scalp map (FDR-corrected *p*-values < .05).

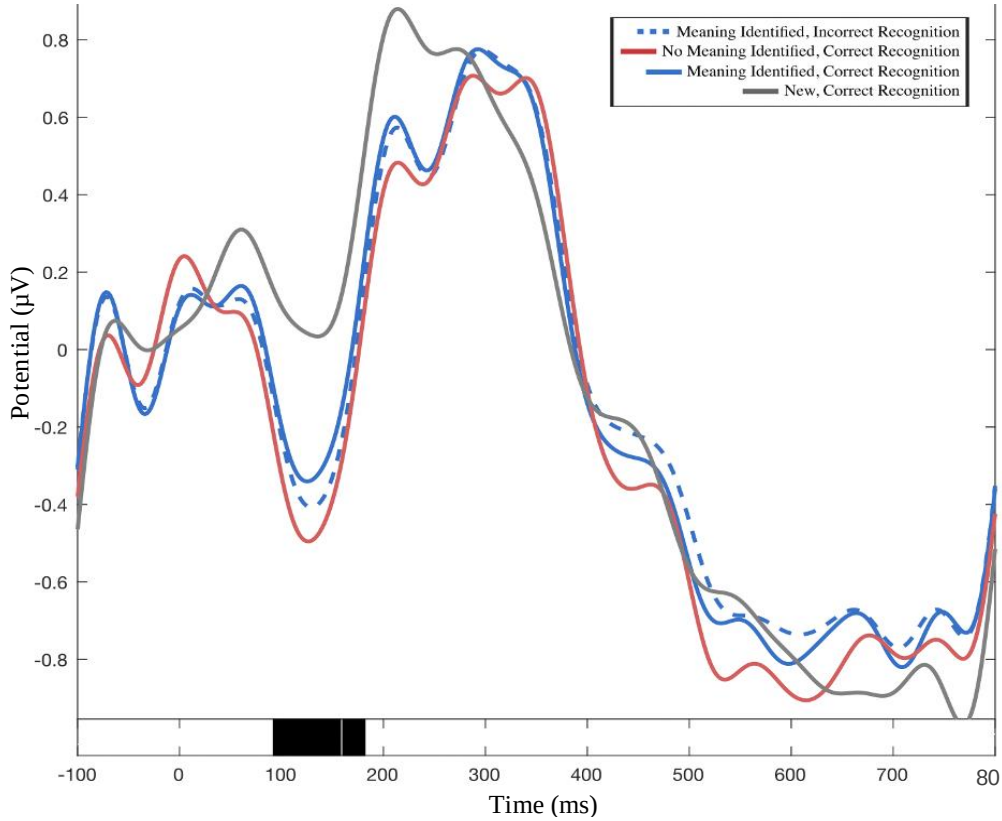


Figure 2.6. ERP waveforms of nouns representing significant differences between all conditions from -100 to 800 ms. Significant differences between 30 and 170 ms are highlighted by the black line along the x-axis. This ERP waveform is from the average of all electrodes identified as significant in the cluster-based permutation test.

The N400 analysis identified a second cluster between 350 and 550 ms after stimulus onset at right frontotemporal and frontocentral electrodes (all significant corrected *p*-values were < .05; see Figure 7 and 8). Post-hoc pairwise comparisons indicate that this effect was driven by a larger negativity for both conditions wherein meaning was identified (i.e., Meaning Identified, Correct Recognition and Meaning Identified, Incorrect Recognition) than novel nouns that had no meaning identified, but were correctly recognized (i.e., No Meaning Identified, Correct Recognition; all significant corrected *p*-values < .048; Supplemental Figure 2). No other pairwise comparisons significantly differed, including all comparisons to new words (i.e., New, Correct Recognition).

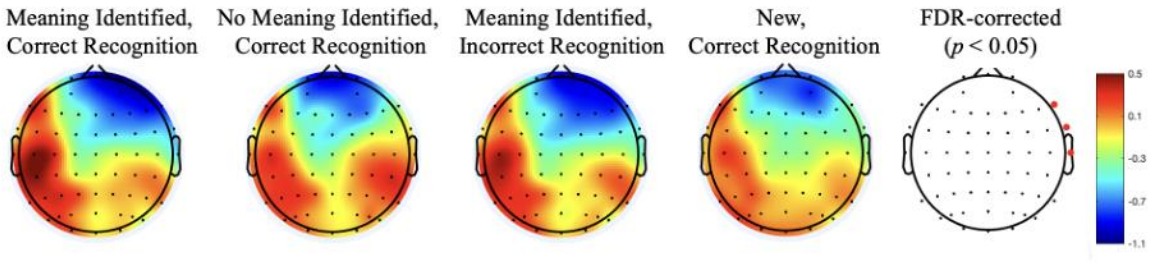


Figure 2.7. Topographic voltage maps for nouns representing the significant differences between all conditions during the time window of 350 to 550 ms after target word onset. Positive voltages are represented in red, and negative voltages are represented in blue. Electrodes identified as significant by the cluster-based permutation test are highlighted in red on the far right scalp map (FDR-corrected *p*-values < 0.05).

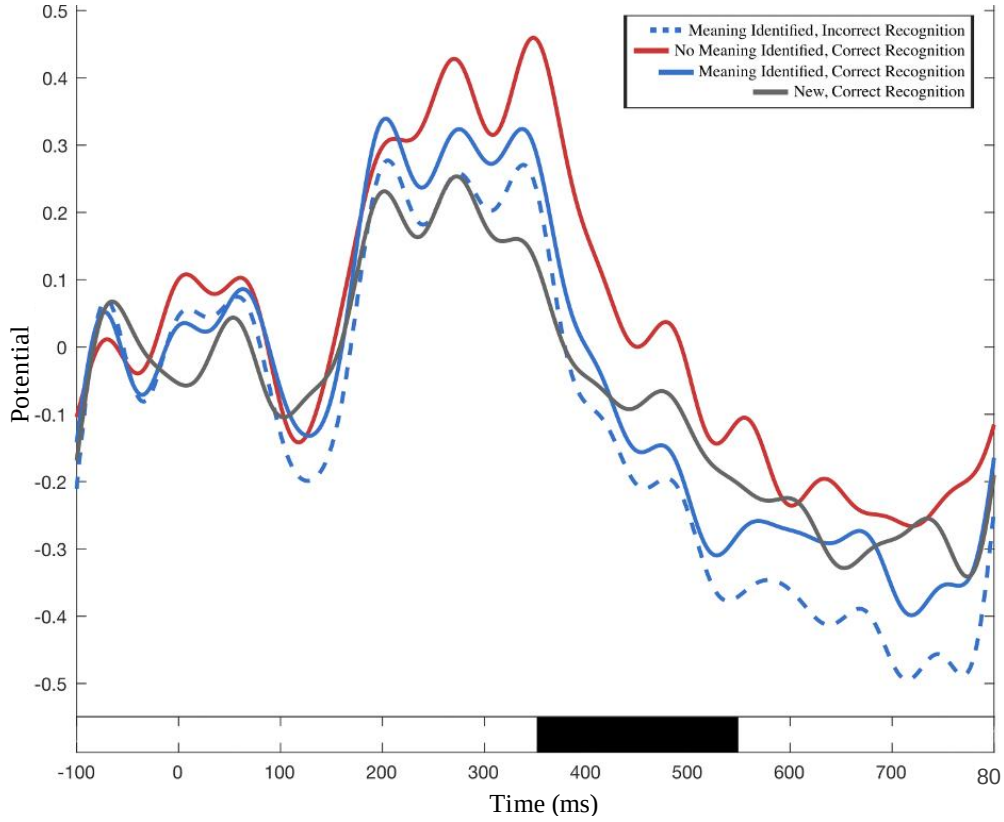


Figure 2.8. ERP waveforms of nouns representing significant differences between all conditions from -100 to 800 ms. Significant differences between 350 and 550 ms are highlighted by the black line along the x-axis. This ERP waveform is from the average of all electrodes identified as significant in the cluster-based permutation test.

## Discussion

In the current study, participants were generally successful in their identification of a novel noun's meaning in the Supportive Context of the Encoding Task. Additionally, participants demonstrated a distinction in behavioral recognition accuracy of novel nouns that they had previously heard and words that they had never encountered. Specifically, participants were significantly better at categorizing new words as new than they were at categorizing old novel nouns as old. However, contrary to our prediction that identifying a meaning for a word during encoding would facilitate later behavioral recognition of it, there was no difference in behavioral recognition of previously encountered novel nouns with an identified meaning and previously encountered novel nouns without an identified meaning. Thus, successfully encoding a meaning for the novel noun did not provide any advantage to later behavioral recognition of the word.

Our finding that encoding meaning did not facilitate immediate behavioral recognition is similar to those of previous research studies utilizing the same paradigm with younger participants (Abel et al., 2020). Some key differences between the current study and the past work are that, here, we focused our analysis on items that were only presented in a context that supported identifying a meaning for the novel nouns in the Encoding Task and separated the Recognition Task responses based on whether participants did or did not explicitly provide a meaning for those novel nouns during the Encoding Task. In contrast, Abel et al.'s (2020) analysis considered items presented in both contexts that were and contexts that were not supportive of identifying a meaning for the novel nouns in the Encoding Task and separating the Recognition Task responses by context in the Encoding Task, not participants' responses during that task. We expected that our focused analysis, which considered evidence of successful form-meaning mapping, would result in greater behavioral accuracy in recognizing the novel word

forms to which participants indicated they had mapped meaning. While we did not find facilitated recognition subsequent to evidence of successful form-meaning mapping, the lack of this effect for novel nouns is consistent with past work that took a broader approach to meaning identification (i.e., whether form-meaning mapping was supported by the encoding environment, not necessarily whether mapping occurred). Possible explanations (relevant to both experiments) for the poor behavioral recognition despite the narrower focus are provided in the General Discussion.

Nevertheless, as Abel et al.'s (2020) study revealed, a lack of behavioral recognition does not mean no recognition occurred whatsoever. Indeed, participants demonstrated neural signals of recognition in the current study. As predicted, participants demonstrated a more negative MMN for all novel nouns that they had previously encountered in the Encoding Task compared to the novel words they encountered for the first time in the Recognition Task. Thus, familiar word forms, regardless of whether their meaning had been encoded, elicited an enhanced MMN response compared to unfamiliar word forms, aligning with previous findings (Aleksandrov et al., 2020; Jacobsen et al., 2005; Pulvermüller et al., 2001; Shtyrov et al., 2010). Notably, finding this predicted pattern and robust effect despite using a less traditional paradigm for eliciting and examining the MMN supplies further evidence that the MMN can serve as an index of word form familiarity, as well as provides a novel avenue for additional investigation of the MMN using paradigms that are more ecologically valid than the oddball paradigm.

Interestingly, in addition to the predicted MMN result, there were also some unexpected distinctions within the neural signals for old words. More specifically, identifying a meaning during encoding had an unanticipated impact on the MMN: participants demonstrated a more negative MMN for old nouns for which they had *failed* to identify a meaning during encoding

compared to old nouns for which they *succeeded* in identifying a meaning during encoding. Importantly, this pattern only emerged for words that participants correctly behaviorally recognized during the Recognition Task; old nouns that participants had incorrectly behaviorally recognized did not show any neural indications of word form familiarity compared to old nouns that participants had correctly behaviorally recognized, regardless of whether they had identified a meaning for them earlier or not. This finding was unexpected given that the MMN is generally thought to be independent of attention and reflects familiarity with word form rather than access to semantic information (Aleksandrov et al., 2020; Garrido et al., 2009; Hu et al., 2020; Näätänen et al., 1997; Pulvermüller et al., 2001; Shtyrov et al., 2010; Shtyrov & Pulvermüller, 2002). Considering this, we expected that the MMN would be unaffected by behavioral performance and previous meaning identification, simply becoming more negative for any previously encountered word form. However, there is some evidence that encoding semantic information can influence the MMN (Aleksandrov et al., 2020), suggesting that the memory trace for a word form might benefit from the integration of semantic information as well.

The interpretation that form-meaning mapping facilitates the MMN does not fully explain our findings, though. Not only did the effect of previous meaning identification vary by behavioral performance but also novel nouns with previous meaning identification were not the words that elicited a more negative MMN. Instead, and unexpectedly, it was the novel nouns *without* previous meaning identification that elicited a more negative MMN. It is possible that using an incidental encoding paradigm revealed nuanced effects of semantic information on the MMN that oddball paradigms are unable to elicit. For example, the Encoding Task's focus on identifying a meaning for the novel noun might have biased participants' attention to abstracting and encoding the word's semantic information as opposed to attending to and storing the word's

form information, hindering their ability to develop a strong word form memory trace (Abel et al., 2020). A weaker memory trace would result in a decreased sense of familiarity. As such, when only considering familiar words, the word form for novel nouns without previous meaning identification might have been comparatively more familiar than the word form for novel nouns with previous meaning identification, leading to a pattern of MMN results like the one we found. Additional studies are required to better understand how incidentally acquired semantic information impacts word form familiarity as indexed by the MMN. Altogether, our MMN results suggest that participants at least implicitly recognized previously encountered novel nouns' forms and that this implicit word form familiarity was, interestingly, affected by the addition of semantic information.

Encoding semantic information also impacted the neural signals of recognition as indexed by the N400. Recall that we had predicted an attenuated N400 effect for words that participants had identified a meaning for compared to words without an identified meaning. While we did find that these conditions differed, interestingly, they did so in the opposite way than predicted. That is, novel nouns with an identified meaning elicited an enhanced N400 compared to previously encountered novel nouns without an identified meaning. This finding suggests increased processing demands for the novel nouns for which participants identified a meaning, which is the condition in which we would expect facilitated, not hindered, semantic processing.

One explanation for our unpredicted N400 finding is that processing novel nouns with an identified meaning (regardless of behavioral recognition accuracy) might have led to increased cognitive efforts to overcome obstacles like lexicosemantic competition, which words without an identified meaning did not entail. As such, sufficiently activating the lexical representations for

the novel nouns with an identified meaning, regardless of the accuracy of behavioral recognition, required more effort than novel nouns without an identified meaning did. When the word forms did not have any meaning associated with them, recognition relied on alternate features (i.e., word form familiarity), allowing participants to recruit fewer cognitive resources for processing the word's meaning or dismiss the need for it altogether. Thus, our findings suggest that encoding meaning increases the amount of cognitive effort involved at later recognition rather than lessening it. Nevertheless, our findings demonstrate that participants' implicit recognition of novel nouns varied depending on whether semantic information was encoded.

Together, the behavioral, MMN, and N400 results indicate that, while encoding semantic information does not facilitate explicit recognition of novel nouns, it does facilitate implicit recognition. A distinction between recognizing old and new words was observed at both the behavioral level and via the MMN, suggesting that word form familiarity, rather than semantic encoding, primarily drove behavioral recognition. Although behavioral recognition was unaffected by semantic encoding (or lack thereof), more nuanced recognition was detected neurally via the N400, in that identifying meaning influenced how cognitive resources were allocated during recognition. The fact that we observed more effortful processing for novel nouns with a previously identified meaning regardless of behavioral recognition performance provides evidence that the N400 revealed a component of the novel nouns' lexical representations that was not yet robust enough to influence recognition at an explicit level. Additionally, at least for novel nouns, the MMN also demonstrated that correctly behaviorally recognized words are processed differently than incorrectly behaviorally recognized words to some extent, showing how the strength of the memory trace for lexical information impacts word recognition processes. Yet, these findings might be word-class specific. Nouns' semantic

simplicity relative to verbs could mean that semantic processing is engaged to a different extent or in a different way during recognition than it is for verbs. Thus, we subsequently turned to verbs to examine the pattern of behavioral performance and neural engagement during recognition of a more semantically complex word class.

## Experiment 2: Verbs

### Method

#### *Participants*

Twenty-six participants completed the second experiment. One participant was excluded from analyses due to the demonstration of a handedness bias, as described above, one due to technical issues, and one due to excessive EEG artifacts. The final participant group included 23 right-handed, normal-hearing, monolingual English-speaking adults ($M$ = 20.89, $SD$ = 1.14, range = 19.05 to 23.05; all female). Exclusionary criteria were identical to those of Experiment 1. Also like Experiment 1, participants were recruited from undergraduate courses in Speech, Language, and Hearing Sciences at San Diego State University. In accordance with the Institutional Review Board of San Diego State University, all participants provided informed consent and received academic course credit for participation.

#### *General Procedure*

The general procedures as well as the design of both the Encoding Task and Recognition Task paralleled those reported for Experiment 1. Specific details regarding the stimuli and procedures for Experiment 2 are provided below.

#### *Encoding Task*

**Stimuli**. For Experiment 2, stimuli were developed to mirror Experiment 1 except that target words were verbs instead of nouns, thus requiring different sentences than in Experiment

1. Like Experiment 1, stimuli included 100 sets of sentence triplets all containing a target word in the sentence-final position. In this study, the target word was an early-acquired verb (Fenson et al., 2007; Hall et al., 1984). Sentences were all six to nine words in length and the words preceding the target word were either the infinitival *to* (e.g., *to run*) or a modal (e.g., *can, will, may*); thus, all verbs appeared in the non-finite form. Target words were replaced with the same novel words from Experiment 1 with minor changes to account for coarticulation effects.

Just as in Experiment 1, for the Supportive Context, sentences within each triplet ended with the same target word and increased in cloze probability (Low: $M$ = 4.64, $SD$ = 5.98; Medium: $M$ = 39.42, $SD$ = 10.34; High: $M$ = 86.95, $SD$ = 11.05) and, for the Unsupportive Context, all sentences ended with a different target word and had low cloze probability ($M$ = 18.97, $SD$ = 19.90). For these stimuli, cloze probability was determined in the same way as for Experiment 1, but participants included 314 adults (238 of which were the same adults as those who normed the nouns; see Abel et al., 2015 for details). An adult female native English speaker audio-recorded herself in a soundproof room speaking all sentences at a natural pace while using natural intonation to simulate optimal listening conditions (Length: Supportive Context: $M$ = 2,297 ms, $SD$ = 355 ms; Unsupportive Context: $M$ = 2,208 ms, $SD$ = 332 ms). Stimuli and scoring examples for Experiment 2 are provided in Table 2.

As in Experiment 1, we limited our focus to responses provided for the novel words from the Supportive Context and did not include responses for the novel words from the control condition (i.e., Unsupportive Context) in our analyses.

Table 2.2. Example stimuli for the Encoding Task in Experiment 2. Following the same construction as Experiment 1, stimuli consisted of sentence triplets in which all three sentences ended with the same CVC novel word. In the Supportive Context, the novel word replaced the same early-acquired verb target word in all three sentences of the triplet and the sentences increased in cloze probability across the triplet. In the Unsupportive Context, which served as a control condition, the novel word replaced a different early acquired verb in each of the triplet's three sentences, resulting in no target word, and the sentences were all low cloze probability. Participants' responses to stimuli from the Supportive Context were classified offline for meaning identification, disregarding response accuracy.

| Sentence Presentation | Supportive Context (target word: *cut*) | Unsupportive Context (no target word) |
|---|---|---|
| 1 | The thick paper was hard to **shap**. | In baseball you do not need to **darl**. |
| 2 | The chef needs a new knife to **shap**. | The movie took two hours to **darl**. |
| 3 | Sharp scissors make it easy to **shap**. | His lunch box was easy to **darl**. |
| | Scoring Examples | |
| Meaning Identified | Cut, Slice, Bang | N/A |
| No Meaning Identified | No meaning | N/A |

***Recognition Task***

The Recognition task stimuli, design, and procedure for Experiment 2 mirrored those used in Experiment 1. All novel words were produced by the same speaker as Experiment 2's Encoding Task and were recorded in the same way (Length: $M$ = 577 ms, $SD$ = 121 ms).

***Behavioral Analysis***

The same data (from four conditions from the Recognition Task: Meaning Identified, Correct Recognition; Meaning Identified, Incorrect Recognition; No Meaning Identified, Correct Recognition; and New, Correct Recognition) and statistical methods as in Experiment 1 were used in Experiment 2.

### *EEG Acquisition and Pre-Processing and ERP Analysis*

The EEG acquisition and pre-processing methods and ERP analysis for Experiment 2 mirrored those used in Experiment 1. Manual removal of components related to eye and head movement resulted in an average of 2.42 rejected components per participant (*SD* = 1.04). Data for electrodes with large impedances was interpolated, yielding 62 data channels for each participant (channels interpolated: *M* = 2.7, *SD* = 1.89). Following epoching -500 ms to 1000 ms after the presentation of the novel word, an average of 9.57 epochs were removed (*SD* = 7.38).

## Results

### *Behavioral Results*

During the Encoding Task, participants identified a meaning for the novel verb 84.70% of the time (*SD* = 9.68%). For the Recognition Task, participants were more likely to correctly categorize new words as new (*M* = 60.22%, *SD* = 16.31%) than previously encountered novel verbs as old (*M* = 48.17%, *SD* = 16.75%; $\beta$ = 0.41, *SE* = 0.09, *z* = 4.84, *p* < .000). Additionally, participants were no more likely to recognize a novel verb with a meaning identified during encoding (*M* = 49.21%, *SD* = 17.58%) than a novel verb without a meaning identified during encoding (*M* = 46.23%, *SD* = 29.00%; $\beta$ = -0.02, *SE* = 0.22, *z* = -0.10, *p* = .92).

### *ERP Results*

The cluster-based permutation analysis resulted in one significant cluster. There were no differences in the earlier MMN time window (30 to 170 ms). However, in the N400 window, new verbs elicited significantly greater negativity than previously encountered novel verbs between 350 and 550 ms at parietal sites (see Figures 9 and 10; all significant corrected *p*-values < .05). Post-hoc pairwise comparisons indicated this was the case not only when collapsing across all conditions wherein novel verbs were previously encountered (i.e., all old novel verbs;

Meaning Identified, Correct Recognition; No Meaning Identified, Correct Recognition; Meaning Identified, Incorrect Recognition), but also when newly encountered words (i.e., New, Correct Recognition words) were compared to each individual condition (see Supplemental Figure 3). No other pairwise comparisons were significantly different.

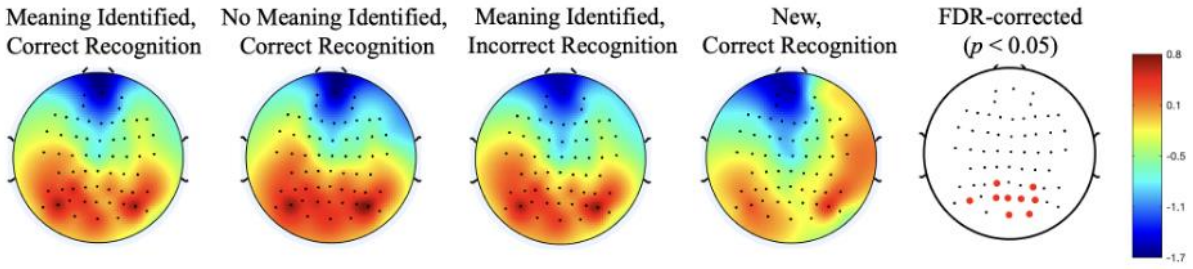


Figure 2.9. Topographic voltage maps for verbs representing the significant differences between all conditions during the time window of 350 to 550 ms after target word onset. Positive voltages are represented in red, and negative voltages are represented in blue. Electrodes identified as significant by the cluster-based permutation test are highlighted in red on the far right scalp map (FDR-corrected *p*-values < .05).

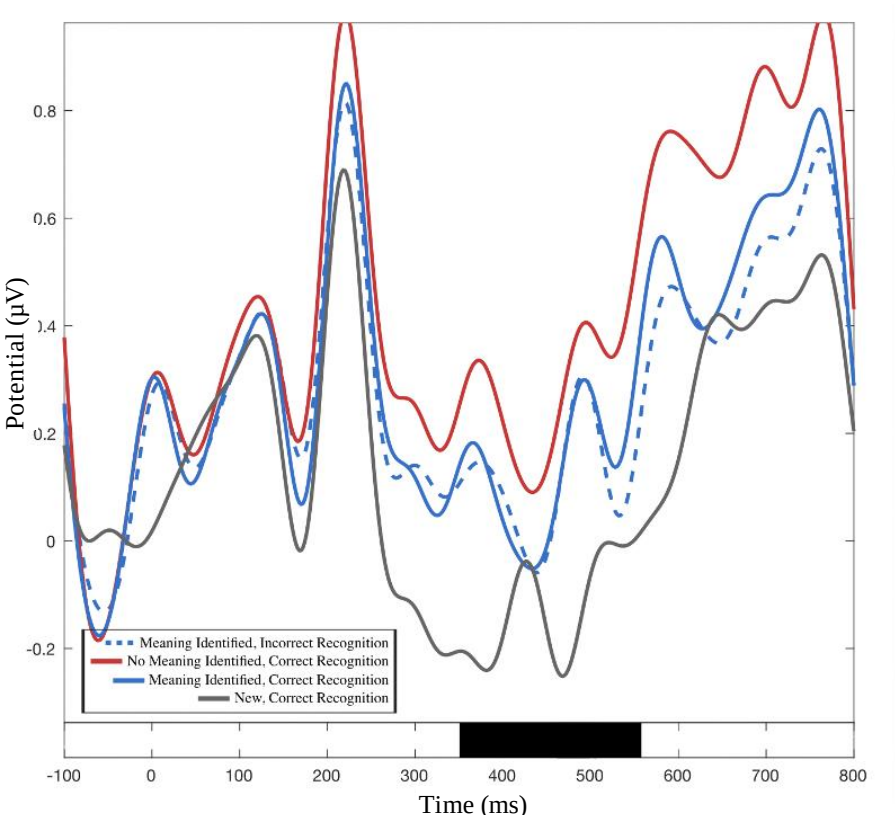


Figure 2.10. ERP waveforms of novel verbs representing significant differences between all conditions from -100 to 800 ms. Significant differences between 350 and 550 ms are highlighted by the black line along the x-axis. This ERP is the average of all electrodes identified as significant in the cluster-based permutation test.

**Discussion**

Similar to Experiment 1, in the Supportive Context condition of the Encoding Task, meanings were identified for a large majority of novel verbs. We also, again, found that behavioral recognition accuracy for old words was significantly different from new words. Although all words were recognized with an accuracy near chance, similar to nouns, new words were recognized with better accuracy than previously encountered novel verbs. Counter to our prediction, though, behavioral recognition of previously encountered novel verbs with an identified meaning did not differ from recognition of either previously encountered novel verbs

with no meaning identified or new words. As such, our findings indicate that identifying a meaning during encoding did not facilitate behavioral recognition of novel verbs.

Verbs' polysemous nature could have also contributed to our findings. The tendency for a single word form to be associated with several, often diverse, meanings only complicates lexical representation development (Foraker & Murphy, 2012; Fukkink et al., 2001; Jenkins & Dixon, 1983). This experiment's design supported encoding only a single meaning for a word form; yet it is possible that participants encoded multiple meanings for a word form and they merely reported the meaning with the most semantic support or the most memorable meaning. If that were the case, when participants encountered the word form at a later point, the competition among the several meanings might have hindered any facilitative effect encoding semantic information might have had on behavioral recognition. Beyond verb-specific features, the lack of facilitatory effect is also consistent with findings from noun stimuli (e.g., Abel et al. (2020) and the findings from Experiment 1). This consistency across word classes holds implications for general lexical representation development, which are discussed in the General Discussion.

Examining the neural signals during the Recognition Task resulted in findings only related to the N400. Interestingly, our pattern of N400 results more closely aligned with a pattern based on implicit familiarity with the words rather than with explicit semantic encoding. More specifically, all novel verbs that had been previously encountered (i.e., old words), regardless of whether participants had or had not identified a meaning for them in the Encoding Task and whether they had correctly or incorrectly recognized them in the Recognition Task elicited a more attenuated N400 amplitude than new words. This suggests greater cognitive effort when attempting to access the nonexistent lexical representations for the new words than when accessing the lexical representations for the previously encountered novel verbs.

The pattern of N400 results in the current study is in line with Rugg, Curran, and others (e.g., Curran, 2000; Rugg et al., 1998; Rugg & Curran, 2007), finding that a specific pattern of parietal neural activity occurring 300 to 500 ms post-stimulus onset to old and new stimuli is a correlate of implicit memory. While several different patterns of neural activity reflecting various aspects of semantic processing and memory have been found to occur during the 300 to 500 ms window (see e.g., Rugg et al., 1998), each can be functionally and topographically disassociated. A defining feature of the implicit memory correlate is that the neural activity occurring 300 to 500 ms post-stimulus onset is elicited from parietal electrodes, just as our ERPs from this latency range were. Moreover, as we found with our N400 results, the pattern of results associated with this index of implicit memory is that all old words, irrespective of other features (e.g., study or processing depth, recognition accuracy), elicit more positive-going waveforms than new words. Thus, our N400 findings strongly suggest that participants implicitly recognized novel verbs to a greater extent than they explicitly recognized them.

Considered together with the lack of any MMN effect, our findings serve as evidence that this implicit recognition was not driven by familiarity with word form alone. It is widely believed that any N400 effect, regardless of its topographical distribution, requires the encoding of semantic information (Kutas & Federmeier, 2011; Voss & Federmeier, 2011). As such, we can interpret our findings as suggesting that participants encoded meaning for all words they encountered in the Encoding Task regardless of whether they explicitly identified a meaning or not. Thus, it seems that semantic information guided the recognition of verbs over and above any word form memory trace although explicitly encoding that semantic information still failed to differentially facilitate behavioral recognition.

Along with the aforementioned implications associated with the Encoding Task's focus on deducing a novel word's meaning (see above), verbs' numerous semantic features (e.g., multiple meanings, argument requirements) also likely contributed to the widespread semantic encoding. The increased semantic complexity of verbs, in addition to the experimental task's design, might have led participants to unconsciously prioritize encoding novel verbs' meanings over their word forms. Consequently, the memory traces for all novel verbs' word forms were weak. This, combined with the phonological similarity of new and old word forms, might have prevented any word form from being more familiar than another at the neural level, leading to no MMN. A weak word form memory trace might have also contributed to the generally poor explicit recognition accuracy as well, including the finding that explicitly encoding semantic information did not facilitate behavioral recognition of novel verbs. Specifically, if the word form memory trace is too weak to be activated when the word form is encountered later, the robustness of any linked semantic information has little impact. This could lead to a lack of differences between neural and behavioral recognition of novel verbs with and without explicitly identified meanings; the semantic information likely differs in robustness between these two types of lexical representations, but a weak word form might obscure that. Further, having any lexical representation stored in memory, regardless of the strength of its memory traces, should allow for less effortful processing than if one attempts to process lexical information that has never been encoded as participants seem to have tried to do with new novel words.

Taken together, it seems that semantic information has an impact on the recognition of novel verbs, albeit not in that explicit meaning identification supports later behavioral recognition as we predicted. According to the N400 findings, meaning encoding was not limited to novel verbs for which participants explicitly identified a meaning. Instead, meaning–but not

form, per the MMN findings–was encoded for all novel verbs encountered in the Encoding Task to some extent. Thus, we found neural indications of recognition of previously encountered novel verbs based on the presence of memory traces for semantic information even when behavioral recognition was lacking. Given that semantic information appears to have been encoded for all old novel verbs, encoding meaning likely drove behavioral recognition. Thus, while there were no distinctions between explicitly and implicitly encoding semantic information at the behavioral level, it seems that encoding meaning in general–even if done unconsciously–did, in fact, facilitate explicit recognition of novel verbs. The difference in the facilitatory impact that explicitly versus implicitly encoding meaning might have had on behavioral recognition of novel verbs might have simply been obscured by weak word form memory traces.

## General Discussion

Previous studies examining the impact of encoding word form and semantic information on recognition have found that, when the semantic information must be deduced from an incidental context, recognition is supported, although the facilitation is only detectable at the neural level or after a delay (Abel et al., 2020; Dumay et al., 2004). Additionally, prior studies exploring word class differences in recognition have found nouns are generally recognized better than verbs (Earles & Kersten, 2017; Engelkamp & Zimmer, 1995; Kersten & Earles, 2004; Mohr et al., 1989; Reynolds & Flagg, 1976). Here, we bring together these two literatures to provide insight into the effect of encoding form and semantic information in incidental contexts on the recognition of novel nouns and verbs, demonstrating both similarities and differences in the recognition process across the two word classes.

Recall that our first prediction revolved around behavioral recognition of novel nouns and verbs and the role of encoding semantic information. We found that identifying meaning during

encoding did not facilitate better behavioral recognition of novel nouns or novel verbs, although previous exposure to the words did influence behavioral recognition. Interestingly, we found this same pattern of performance across word classes. A follow-up analysis that directly compared behavioral performance across the two experiments revealed that novel nouns were not behaviorally recognized with greater accuracy than novel verbs, regardless of whether participants had or had not previously identified meanings for the words (Nouns vs. Verbs x Old vs. New: $\beta = 0.16$, $SE = 0.13$, $z = 1.18$, $p = .24$; Nouns vs. Verbs x Meaning Identified vs. No Meaning Identified: $\beta = 0.37$, $SE = 0.36$, $z = 1.02$, $p = .31$). It appears that even our unique approach of distinguishing between words with and without demonstrable evidence of form-meaning mapping was not sensitive enough to reveal the potentially facilitative effect of explicitly encoding incidentally deduced semantic information on immediate behavioral recognition for either word class. However, findings from previous studies that also used an incidental encoding paradigm and failed to find any effect of encoding semantic information on behavioral recognition immediately following the encoding stage (Abel et al., 2020; Dumay et al., 2004) temper how surprising this finding might be.

Several possibilities could explain why explicitly encoding semantic information did not appear to support behavioral recognition more than general exposure did. First, the similarity of novel word forms across the experiment (i.e., all CVC pseudowords) might have made it difficult to create sufficiently distinct lexical representations for each novel word. Even with the addition of semantic information to the lexical representation, this word form similarity could have introduced significant competition during lexical access and made distinguishing between words difficult. Additionally, as noted above, a weak word form memory trace could have impacted participants' ability to adequately activate and access lexical representations. Word form is an

essential component of lexical development as a sufficiently robust word form memory trace is instrumental to encoding and activating associated semantic information. As such, word form information plays an important role in the recognition process and could hinder activation and access despite adequate encoding of semantic information. Another possibility is that the amount of semantic information provided might not have been sufficient to form a robust lexical representation. Previous studies have demonstrated that only three incidental exposures to a new word in a semantically rich context are necessary for the new word to elicit the same neural responses as a known word (Abel et al., 2018; Batterink & Neville, 2011; Mestres-Missé et al., 2007). However, our results, especially when considered with those of Abel et al. (2020) and Dumay et al. (2004), suggest that more exposures and/or a longer consolidation period might be needed to develop lexical representation memory traces robust enough to support behavioral recognition. A final possibility related to the previous explanations is the sheer number of new words that were encoded into memory in a relatively short period of time. On average, participants successfully identified a meaning for 44 novel nouns or 42 novel verbs (out of 50) over the course of approximately one hour. This is a substantial number of new words to encode and recall with limited opportunity for consolidation. As such, the large number of newly encoded words might have contributed to the competition during the recognition task, regardless of the word form similarity or word from memory trace strength, and the lack of consolidation might have hindered the robustness of the new lexical representations even if the amount of semantic information encoded was sufficient.

Nevertheless, our finding of unfacilitated behavioral recognition following explicit semantic encoding is in line with our greater understanding of the incremental nature of the word learning process (e.g., Storkel, 2011). More specifically, it seems that lexical representations of

newly encountered words are not robust enough until later stages of lexical representation formation have occurred (e.g., forming associations with existing lexical representations) and substantially strengthened the memory trace for incidental encoding of semantic information to support behavioral recognition. Thus, only early stages of lexical representation formation are captured when examining immediate explicit recognition. Given that word learning models are based on the assumption that all word classes undergo the same general process (e.g., Storkel, 2011), finding no difference in behavioral recognition accuracy for novel nouns versus novel verbs can be understood as a result of both word classes' lexical representations being in the same early stage of development. The unexpected lack of word class differences also suggests that extracting semantic information from incidental contexts might essentially level the playing field for developing lexical representations of new nouns and verbs. This is noteworthy given that the majority of words in one's lexicon are acquired via incidental (oral and/or written) contexts and that verbs are typically more difficult to acquire and retrieve (Bornstein & Cote, 2005; Earles & Kersten, 2000; Engelkamp et al., 1990; Gentner, 1981, 1982; Gillette et al., 1999; Mohr et al., 1989; Nagy & Anderson, 1984; Nagy & Herman, 1987; Nelson, 1973; Piccin & Waxman, 2007; Reynolds & Flagg, 1976). If incidental contexts lessen word class differences, at least for learning a new word's meaning, then perhaps part of what underlies the developmental pattern of more easily learning and recognizing nouns over verbs is not challenges with abstracting and encoding semantic information for verbs but rather challenges with refining and integrating semantic information into verbs' lexical representations. More sensitive measures than behavioral ones are necessary to investigate these potential nuances.

Layering on neural measures that are sensitive to implicit processing allows us to examine the earliest stages of lexical representation development that behavioral measures alone

obscure. In addition, these measures can provide insight into the different mechanisms that drive word recognition. Across the two experiments, it became clear that implicit recognition of words as indexed by the MMN and/or N400 occurred for both novel nouns and verbs, but the type of lexical information underlying recognition differed across word classes.

Although the MMN is traditionally examined in oddball paradigms, its links to word form familiarity make it a component of interest in the study of word learning and recognition. We had predicted that there would be no word class differences in the MMN given that word form is not inherently different across nouns and verbs and the word forms were intentionally manipulated to be the same whether they served as nouns or verbs across our experiments. Unexpectedly, our MMN results indicated that novel nouns produced different effects than novel verbs. There were no differences in the MMN across novel verbs whether they were old, new, recognized or not, or with or without an identified meaning. Conversely, the overarching MMN effect for novel nouns followed the predicted pattern distinguishing between previously encountered and newly encountered word forms. Interestingly, while correctly recognized old novel nouns elicited the expected more negative MMN compared to correctly recognized new words, we found an unanticipated pattern among correctly-recognized old novel nouns: novel nouns with no identified meaning elicited a more negative MMN compared to novel nouns with an identified meaning. Thus, encoding word form information from an incidental encoding context seems to be more common for novel nouns than for novel verbs, but encoding semantic information also appears to have played a role in word form familiarity. A semantic encoding effect on the MMN is not unprecedented (e.g., Aleksandrov et al., 2020), although the pattern we found was not consistent with previous studies, possibly due to our pioneering use of examining the MMN in the context of an incidental encoding paradigm rather than oddball paradigm.

Regardless, the greater success with encoding word form information for novel nouns aligns with the evidence that nouns are recognized with greater ease and accuracy compared to verbs (Earles & Kersten, 2017; Engelkamp & Zimmer, 1995; Kersten & Earles, 2004; Mohr et al., 1989; Reynolds & Flagg, 1976), suggesting that word form familiarity underlies behavioral recognition of novel nouns.

As with the MMN, analysis of the N400 led to valuable insights into the implicit processes underlying word recognition. We had predicted a pattern of greater N400 amplitude attenuation for words with an identified meaning compared to words without an identified meaning in both word classes but that the pattern would be more pronounced for novel verbs than novel nouns. We found that the pattern of N400 results did differ for verbs compared to nouns, although not in the way we had predicted. Instead, the N400 effect for verbs suggested that some amount of semantic information was encoded for *all* the novel verbs that participants encountered in the Encoding Task. This contrasts with the noun findings, in which the N400 effect indicated that encoded semantic information influenced the cognitive effort required for processing, with novel nouns with an explicitly encoded meaning requiring more effortful processing than novel nouns without an explicitly encoded meaning. Thus, the N400 results demonstrated that the influence of encoding semantic information varied by word class.

Semantic differences between nouns and verbs might explain why the N400 pattern differed in this unpredicted manner across word classes even when the experimental design of the Encoding Task might have primed participants to focus on meaning over form for both word classes. Verb meanings rely heavily on context and are typically more difficult to process compared to nouns (Gentner & Boroditsky, 2001; Gentner & France, 1988; Huttenlocher & Lui, 1979; Kersten, 1998, 2003; Kersten & Earles, 2004; Kintsch, 2001; Vigliocco et al., 2004). Thus,

to support their processing of verbs, individuals might be more implicitly inclined to seek out and encode any and all available semantic information for verbs. This, at least in part, explains our finding that some degree of semantic information was encoded for all previously encountered novel verbs, sometimes even without the participants' explicit awareness, and suggests that encoded semantic information underlies behavioral recognition of novel verbs. In contrast, less cognitive effort is usually required to deduce and process nouns' meanings. As such, semantic information was likely encoded more selectively, specifically only for words with an explicitly identified meaning. However, contrary to nouns' generally simpler processing demands and semantic features, novel nouns with encoded semantic information did not demonstrate less effortful semantic processing. Instead, novel nouns with identified meanings, whether they were or were not correctly recognized, elicited increased levels of semantic processing, suggesting these lexical representations had semantic information encoded but required more cognitive effort to process. We interpret this finding as indicating that encoding semantic information for novel nouns led to a more complex lexical representation, demanding additional effort to process.

Altogether, the observed ERP and behavioral effects provide evidence that immediate recognition of new words, while only behaviorally distinguishable based on earlier exposure, is driven primarily by word form familiarity for novel nouns and encoded semantic information for novel verbs. Across word classes, encoding semantic information influenced neural signals of recognition, with additional evidence of implicit recognition for novel nouns' forms. Thus, word form and semantic information play distinctive roles in the implicit and explicit recognition of novel nouns and novel verbs.

**Strengths and Limitations**

One of the key strengths of this study includes using a paradigm that is more representative of how individuals typically learn words than most studies exploring word recognition, especially those where a semantic meaning is explicitly provided along with a new word form (e.g., Balass et al., 2010; Takashima et al., 2014, 2017). Given that this is not how individuals learn most words (Nagy & Anderson, 1984; Nagy & Herman, 1987), our use of a more ecologically valid paradigm (albeit much more intense than an individual's typical lexicon-expanding experiences in adulthood unless they are immersively learning a foreign language) uniquely contributes to our understanding of lexical representation formation and lexical access of newly formed lexical representations in real-life situations.

In addition, this study allowed us to isolate the effects of word class by using the same novel word forms paired with different word classes across conditions. We also controlled for the potential confounding variable of prior knowledge of a word form by using novel words as the new word forms for which participants were expected to identify a meaning. Other studies investigating word recognition have used highly infrequent real words (e.g., Balass et al., 2010; Frishkoff et al., 2008, 2009, 2010, 2011). In these designs, it is possible that participants already had lexical representations for the test words, even if the encoded lexical information was limited. By using novel words, we prevented any prior level of familiarity or encoded lexical information from influencing our outcomes. Also, our samples of only monolingual participants allowed us to control for any effects of bilingualism, although that is an area ripe for further investigation.

Despite these strengths, the study also had some limitations. Although the tasks were already relatively time-consuming, there would have been greater control if, instead of the

between-subject design, each participant had participated in both word class conditions. Also, while our participant inclusion criteria allowed strict control of several possible confounding variables, the use of only neurotypical, monolingual, college-educated undergraduate students with typical language development is not a representative sample of the larger population and limits the generalizability of this study's findings. Future research should explore these effects in more diverse populations, including individuals with and without language difficulties. Additionally, this study focused on explicit recognition of a word's phonological form rather than its meaning. Thus, future work should consider using a paradigm that is equipped to examine the nature of the semantic information that can be accessed so as to better understand the impacts of encoding semantic information on word recognition. Lastly, in the Recognition Task there were twice as many new words as there were previously encountered words from the Supportive Context and, further, the words from the Supportive Context were classified based on participants' responses (i.e., whether they identified a meaning for the target word). This led to a different number of trials per condition in both of the experiments (see Supplemental Table 1). Visual inspection of the EEG data does not indicate any impacts of these different numbers of trials, but it is possible that the relatively smaller number of trials in the Meaning Identified and No Meaning Identified conditions affected signal-to-noise ratio and subsequent findings.

**Conclusion**

In conclusion, this study provides insights into the impact of encoding form and semantic information from incidental contexts and word class on explicit and implicit recognition of new words. We found that explicitly encoding incidentally provided semantic information did not observably facilitate the immediate behavioral recognition of novel nouns or verbs, with novel nouns and verbs unexpectedly demonstrating equivalent recognition accuracy. However, neural

measures indexing processes underlying recognition, specifically word form familiarity via the MMN and semantic processing via the N400, revealed distinct patterns of neural engagement across word classes. At the neural level, there was more pronounced word form encoding for novel nouns, and increased cognitive effort to process novel nouns with encoded meanings than those without. For novel verbs, however, there were no neural indications of word form encoding but indications of broad semantic encoding. That is, meanings were encoded for all previously encountered novel verbs, regardless of previous explicit meaning identification. Thus, we did not find any evidence that explicitly encoding incidentally obtained semantic information benefits immediate behavioral recognition of newly learned words. However, we did find evidence that implicit recognition of the novel word still occurs, with the mechanism underlying that recognition process (i.e., form and/or meaning) differing by word class. These results underscore the nuanced and incremental nature of lexical representation formation, especially with regard to encoding form and semantic information, and how that process differs across nouns and verbs.

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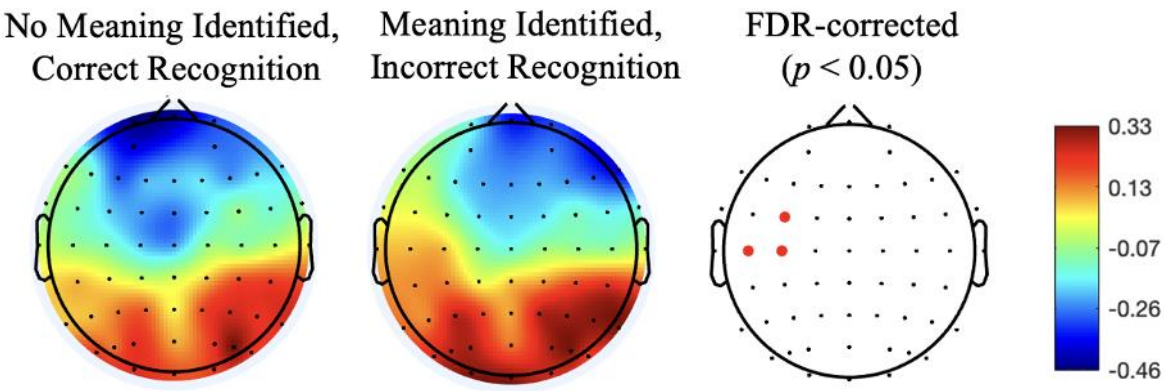
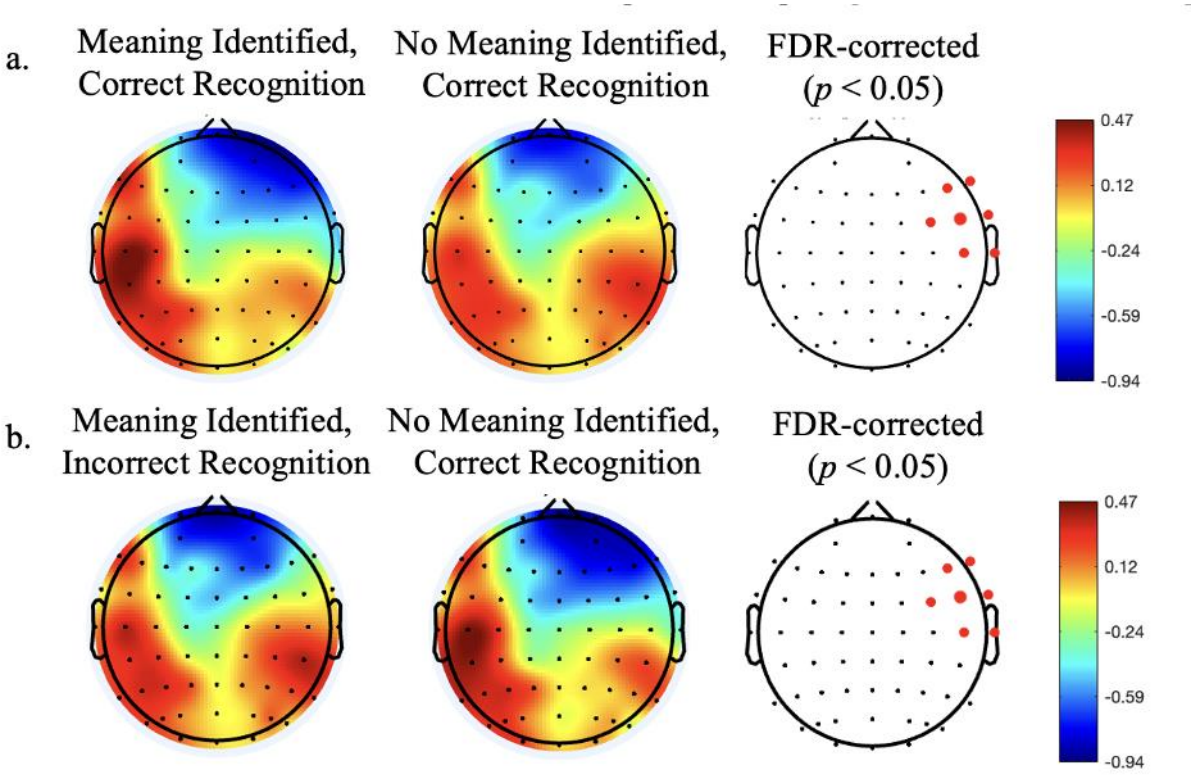
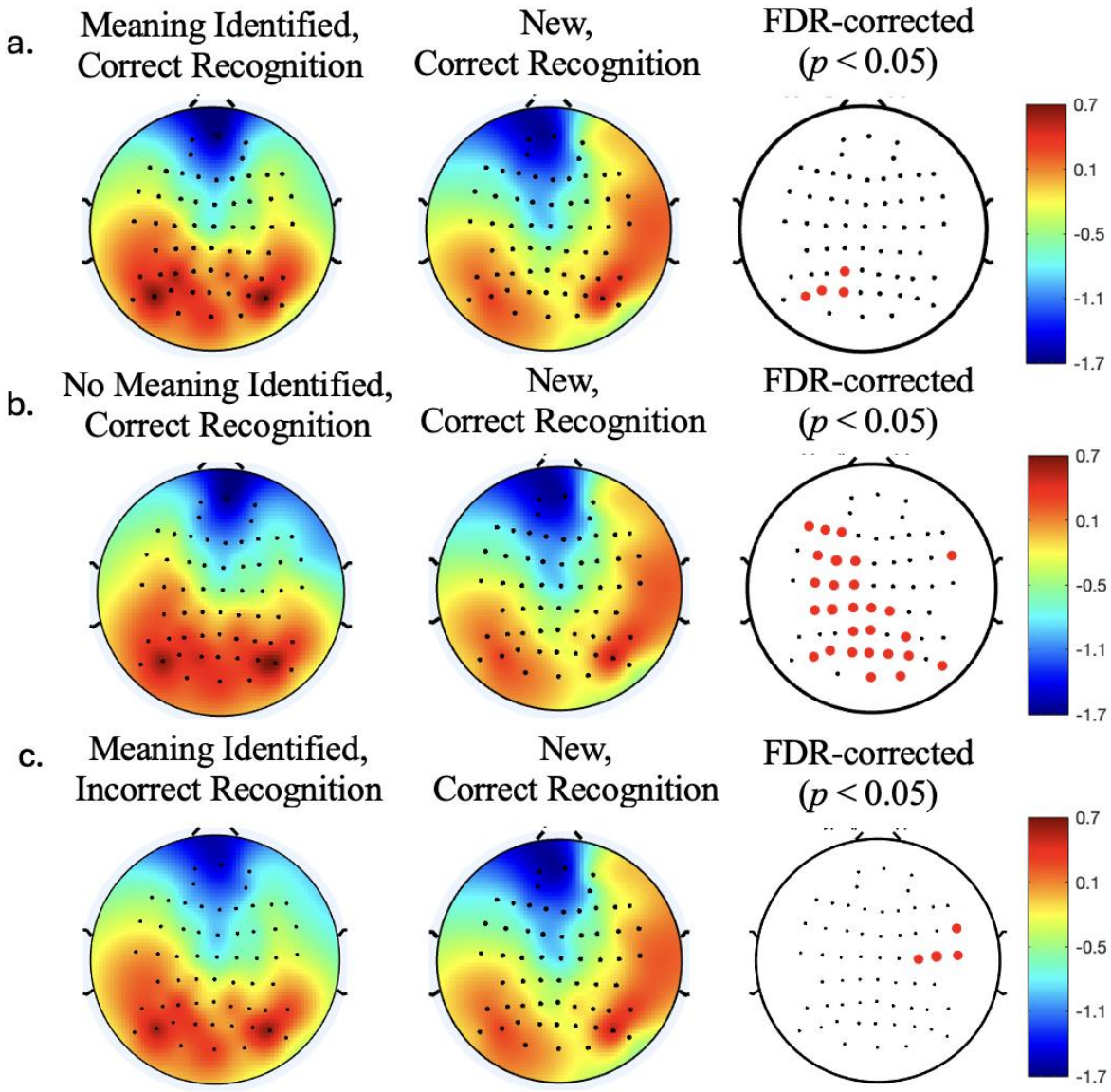
## Supplemental Materials




Supplemental Figure 2.1. Topographic voltage maps for nouns representing significant differences between No Meaning Identified, Correct Recognition and Meaning Identified, Incorrect Recognition during the time window of 30 to 170 ms after target word onset. Positive voltages are represented in red, and negative voltages are represented in blue. Electrodes identified as significant by the cluster-based permutation test are highlighted in red on the far right scalp map (FDR-corrected *p*-values < .05).




Supplemental Figure 2.2. Topographic voltage maps for nouns representing significant differences between a) Meaning Identified, Correct Recognition and No Meaning Identified, Correct Recognition and b) Meaning Identified, Incorrect Recognition and No Meaning Identified, Correct Recognition during the time window of 350 to 550 ms after target word onset. Positive voltages are represented in red, and negative voltages are represented in blue. Electrodes identified as significant by the cluster-based permutation test are highlighted in red on the far right scalp map (FDR-corrected *p*-values < .05).




Supplemental Figure 2.3. Topographic voltage maps for verbs representing significant differences between a) Meaning Identified, Correct Recognition and New, Correct Recognition, b) No Meaning Identified, Correct Recognition and New, Correct Recognition, and c) Meaning Identified, Incorrect Recognition and New, Correct Recognition during the time window of 350 to 550 ms after target word onset. Positive voltages are represented in red, and negative voltages are represented in blue. Electrodes identified as significant by the cluster-based permutation test are highlighted in red on the far right scalp map (FDR-corrected *p*-values < .05).

Supplemental Table 2.1. Average number of trials analyzed per condition in the Recognition Task for each experiment. Due to our research questions, there was an imbalanced number of new and old words of interest in the Recognition Task across Experiment 1 (a) and 2 (b).

a. Nouns

| Condition | Meaning Identified, Correct Recognition | | Meaning Identified, Incorrect Recognition | | No Meaning Identified, Correct Recognition | | New, Correct Recognition | |
|---|---|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| | 16.16 | 9.81 | 16.71 | 9.34 | 29.55 | 7.20 | 57.03 | 13.61 |

b. Verbs

| Condition | Meaning Identified, Correct Recognition | | Meaning Identified, Incorrect Recognition | | No Meaning Identified, Correct Recognition | | New, Correct Recognition | |
|---|---|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| | 14.96 | 8.23 | 14.30 | 6.96 | 26.65 | 7.45 | 52.04 | 15.33 |

## Acknowledgements

Chapter 2, in full, has been submitted for publication of the material as it may appear in *Psychology of Language and Communication*. This chapter is coauthored with Drs. Julie M. Schneider and Alyson D. Abel. The dissertation author was the primary researcher and author of this paper.

# Chapter 3 : TIMING OF IMPLICIT PROCESSES IN APHASIA: AN ERP INVESTIGATION OF MASKED PRIMING EFFECTS


## Abstract

A primary impairment in aphasia is anomia (i.e., difficulty with word retrieval), but the mechanisms responsible for anomia are not well understood. Prior research suggests that anomia could be due to changes in the timing of automatic spreading activation between lexical representations within one's language network. Fourteen people with aphasia (PWA) and 13 typical older adults completed a masked priming paradigm while EEG data were collected. Target words were preceded by masked, visible, or no primes and were either immediate or delayed repetitions of those primes. Prime-target intervals were varied. Analyses primarily focused on N400 effects. The PWA showed N400 priming effects for both immediate and delayed repetitions of masked primes, unlike the typical older adults who only showed priming effects for immediate repetitions of masked primes. Additionally, the size of PWA's priming effects for delayed repetitions of masked and visible primes was the same while the typical older adults showed greater priming effects for delayed repetitions of visible than masked primes. Findings suggest PWA experience delayed decay of activation and might be less able to take advantage of explicit information than typical older adults due to a failure to integrate explicit and implicit processing, limiting reinforcement and/or maintenance of a word's activation. Improved understanding of the underlying mechanisms of language impairment in aphasia will support development of more efficient, effective aphasia treatment methods.

## Introduction

Aphasia is an acquired language disorder, generally resulting from a stroke in the left hemisphere of the brain. People with aphasia (PWA) have problems speaking, listening, reading, and writing, though the severity and balance of impairment across modalities differs between people. The one symptom of aphasia that is ubiquitous, however, is difficulty retrieving words (Benson, 1988; Goodglass & Wingfield, 1997; Laine & Martin, 2013; Raymer, 2018); individuals will often come up with the wrong word or will not be able to say anything at all. As a result, aphasia treatment often focuses on improving word retrieval (Nickels, 2002; Raymer & Roitsch, 2023). To date however, there is still no clear understanding of the mechanism(s) responsible for this particular impairment. Without a clear understanding of the source of the problem, treatment methods cannot be maximally effective. The study described here is designed to improve our understanding of the mechanisms behind word retrieval problems in aphasia through the use of event-related potentials (ERPs), with the ultimate goal of informing improvement of treatment methods.

### Language Processing in Aphasia

Word retrieval problems in aphasia are generally understood to be the result of impaired access to linguistic information, rather than information having been lost or destroyed. This conclusion has been drawn based, in part, on evidence that aphasia can be transient, resolving over hours or days (e.g., Chu et al., 2014; Kimura et al., 2003; Riecker et al., 2004; Wilson et al., 2015) and that language performance can be highly variable from day to day, or even minute to minute (e.g., Cameron et al., 2010; Creet et al., 2019; Duncan et al., 2016; Galletta & Goral, 2018; Tseng et al., 1993). What, then, is the mechanism by which intact language representations cannot be successfully retrieved? Prior research suggests that aphasia may involve an impairment

in the timing of automatic spreading activation between representations within the language networks (Dell et al., 1997; Ferrill et al., 2012; Prather, 1994; Prather et al., 1997; Schwartz et al., 1994; Silkes et al., 2020; Silkes & Rogers, 2012).

Within the context of network models of language processing, such as the Interactive Activation (e.g., Dell, 1986; Dell & O'Seaghdha, 1992) and Parallel Distributed Processing (e.g., Nadeau, 2001) models, language representations are accessed through complex networks that have connections within and across different domains of processing (e.g., semantic, lexical, phonological, orthographic). These representations are accessed through a mechanism of *automatic spreading activation*, in which activation spreads not only between units in a specific domain in the network (e.g., lexical) but also to units in the various domains that comprise the representations; that is, if a single lexical item is activated, its retrieval involves activation spreading between whatever domains in which relevant units for that item exist (e.g., semantic concepts activated by seeing an object will spread activation to the associated units of lexical and phonological information). This spreading activation occurs automatically and implicitly, outside of conscious awareness or control, based on the strength of the connections within the network. This spread of activation is rapid and short-lived; it spreads and decays quickly to allow language processing to proceed without interference.

Because the spread of activation is central to the ability to retrieve words, an alteration in the speed of activation transmission or decay may be an explanatory mechanism for the language processing deficits seen in aphasia, such as anomia. If activation does not spread between elements in the lexical network in a timely fashion and remain activated for the appropriate duration, the system does not have all the information it needs active at the same time to allow for accurate lexical selection. Indeed, anomia has been modeled as the result of two possible

forms of impairment in automatic spreading activation: either a deficit in *activation transmission*, in which activation is not spread successfully between elements within the lexical network, or a deficit in *representation integrity*, in which activation decays too rapidly or remains above its "resting state" for too long for the appropriate element to be retrieved or otherwise influence downstream processing. This theory has been supported by data from network simulations and has been corroborated by comparison with data from PWA (Dell et al., 1997). This understanding of aphasia involving altered operation of the language network continues to motivate how aphasia treatments are designed and implemented (e.g., Boyle et al., 2018; Castro et al., 2022; Kalinyak-Fliszar et al., 2011).

**Masked Priming as a Tool to Understand Implicit Processing in Aphasia**

Additional evidence for impaired automatic spreading activation in aphasia comes from studies of priming effects, in which presentation of particular words (primes) facilitates processing of subsequently presented words (targets). One possible source of priming effects is that the activation of the prime increases the activation of the target via spreading activation, so that the target is more highly activated and easier to access when it is subsequently encountered (de Groot, 1983; Fowler et al., 1981; Neely, 1977). The early studies done to address the question of activation deficits in aphasia used experimental paradigms that often allowed both explicit (i.e., conscious) and implicit (i.e., unconscious) language processing to influence performance. For instance, some of the available evidence arises from list priming paradigms (Prather et al., 1992, 1997), in which the temporal distance between related words in visually-presented lists was manipulated. In these cases, while the participants were not told about the prime-target relationships and distance manipulations, they consciously perceived all the stimuli presented in the list. This type of paradigm complicates interpretation of performance on the

task: with explicit perception of the stimuli, it is unclear whether any resulting priming effects are due to the implicit process of automatic spreading activation or whether some of the effects may result from explicit processing of the visual stimuli (e.g., see Silkes & Rogers, 2010), or even conscious recognition of the prime-target relationships (Posner & Snyder, 1975).

To truly isolate the implicit process of automatic spreading activation between primes and targets, all opportunities for explicit processing of the prime words would, ideally, be eliminated. One way of attempting to do this is to visually mask the primes, which involves two components: 1) presenting primes for very brief durations and 2) presenting additional visual stimuli in close temporal proximity to the primes (before and/or after), which interfere with conscious perception and processing of the rapidly-presented primes (see Forster et al., 2003 and; Van den Bussche et al., 2009 for discussions of the mechanisms of masked priming). If masking is effective, the prime item is not consciously perceived by the participant but still exerts an effect on the language processing system. In this case, any priming effects obtained can safely be attributed to implicit processes, such as automatic spreading activation, without the possibility that explicit processing may also have contributed (Marcel, 1983, p. 198; Van den Bussche et al., 2009).

Masked priming has been used with PWA a few times in the literature, both to try to understand the time course of automatic spreading activation in aphasia (Silkes & Rogers, 2012) and to try to influence word retrieval in the context of treatment for word retrieval impairments in aphasia (Silkes, 2015, 2018; Silkes et al., 2013). Silkes and Rogers (2012) used masked priming along with behavioral responses to investigate the time course of automatic spreading activation in aphasia. By systematically varying the lag between the offset of a masked prime and onset of a target in a lexical decision task (i.e., the interstimulus interval; ISI), they found

that PWA showed a later onset of priming effects and showed priming effects for a smaller range of ISIs than typical adults. This result supported the idea that PWA have slowed, or delayed, automatic spreading activation and that activation decayed (or was suppressed) abnormally quickly. This is consistent with explanations of anomia that implicate alterations in the time course of automatic spreading activation.

Measures of behavioral responses, however, are only an indirect index of automatic spreading activation; they reflect both the implicit processing that results from the presentation of the prime, but also the implicit and explicit processes involved in making judgments about stimuli and an overt motor response. It is possible that the time taken and cognitive effort engaged for the motor response, as well as the top-down cognitive processes involved in completing the task (e.g., making a lexical decision), could obscure the ability to see priming effects to some degree. A more direct measure of cognitive response to the primes would be useful in exploring this phenomenon without these complicating factors. In addition, the response time and accuracy data collected from behavioral responses do not provide any information about the neural instantiation of language processing in aphasia, which is an important part of understanding the impairment.

**Event-Related Potentials as a Methodology for Studying the Time Course of Implicit Language Processes**

One option for moving beyond strictly behavioral data for understanding the time course of language processing in aphasia is found in electroencephalography (EEG); specifically, event-related potentials (ERPs). ERPs can be measured in the absence of a behavioral response, reflecting just the implicit cognitive processing mechanisms involved in a task without the

confound of motor responses. As such, this tool can provide finer-grained insights into the processes and impairments of aphasia.

Numerous studies using ERPs in combination with masked priming with unimpaired individuals have found evidence that a specific ERP component, the N400, reflects semantic processing and, as such, can index automatic spreading activation (e.g., Deacon et al., 2000; Hill et al., 2002; Kiefer, 2002; Kiefer & Brendel, 2006; Li et al., 2019; Liu et al., 2013; Misra & Holcomb, 2003; Schnyer et al., 1997; van Petten et al., 1991). The N400 is a negative-going waveform that typically peaks around 400 ms after stimulus onset that is most commonly associated with semantic processing (Kutas & Federmeier, 2011; Kutas & Hillyard, 1980). It is known to be sensitive to repetition in that its amplitude is attenuated when a stimulus is repeated compared to a non-repeated stimulus (e.g., Brown & Hagoort, 1993; Düzel et al., 1997; Rugg, 1985, 1990; Rugg & Nagy, 1989; van Petten et al., 1991; Wilding et al., 1995). This attenuation is thought to occur because a stimulus is easier to process after a previous encounter, especially when the two encounters occur in close temporal proximity (Forster & Davis, 1984; Misra & Holcomb, 2003; Rugg & Nagy, 1989; van Petten, 1993). Additionally, attenuation of the N400 amplitude will occur even if a stimulus is not consciously perceived during one of its encounters (e.g., Deacon et al., 2000; Hill et al., 2002; Kiefer, 2002; Kiefer & Brendel, 2006; Li et al., 2019; Liu et al., 2013; Misra & Holcomb, 2003; Schnyer et al., 1997), such as in masked priming, although conscious perception of the stimulus does typically lead to more robust attenuation (Brown & Hagoort, 1993; Forster & Davis, 1984; Grainger & Holcomb, 2009; Holcomb et al., 2005; Holcomb & Grainger, 2007; Marcel, 1983; Misra & Holcomb, 2003). Thus, the change in N400 amplitude due to priming, especially when the prime is masked, captures the implicit, automatic, lexical-semantic processing resulting from spreading activation.

One example of a study that has used masked priming to explore implicit language processing was conducted by Misra and Holcomb (2003). In their study, prime and target words were sequentially presented on a computer screen and participants performed a go/no-go semantic categorization task in which they pressed a button whenever the word they saw was an animal name (i.e., probe items). There were both masked and visible primes, and targets were either preceded by unrelated or no words in the prime position (i.e., unprimed) or were identical repetitions of primes (i.e., primed). Critically, primed targets were either immediate repetitions of masked primes or were repetitions of masked or visible primes after a short delay. Behavioral responses to the animal name probes were considered to examine behavioral priming effects and masking effectiveness; however, the neural responses elicited by the critical non-animal words, particularly when they were targets, were the primary interest of this study. Focusing on the ERP components elicited solely by the critical words allowed for unadulterated examination of whether the masked repetition N400 priming effects occurred exclusively due to implicit, automatic processing or were merely a result of residual explicit (and possibly implicit) processing of visible primes. This study exemplifies the implicit nature of the N400 and its utility for examining the time course of spreading activation.

Misra and Holcomb's (2003) results showed a clear differentiation between the ERP repetition effects of masked and visible primes, demonstrating that the N400 priming effects were due to implicit rather than residual explicit processing when the primes were masked. While both the masked and visible primes elicited N400 priming effects for both immediate and delayed repetitions, only the visible primes also elicited late positive component (LPC) priming effects (i.e., an enhanced LPC to primed targets compared to unprimed targets). The LPC is thought to rely on conscious retrieval of episodic memories, and thus can only occur if a repeated

stimulus is consciously perceived at both presentations and recollected at the second presentation (Düzel et al., 1997; Rugg, 1990; Rugg & Nagy, 1989; Schnyer et al., 1997; van Petten et al., 1991). Consequently, considering the LPC can assist in the interpretation of any N400 effects; the presence of an N400 priming effect in the absence of an LPC priming effect indicates that the N400 priming effect is the result of solely implicit processing, rather than conscious processing, of the prime. This pattern of ERP priming effects was precisely what Misra and Holcomb (2003) found with their repeated masked prime words, exemplifying that the N400 reflects unconscious and involuntary lexical-semantic processing characteristic of automatic spreading activation.

While Misra and Holcomb's (2003) study is not the only one, or even the first (e.g., Kiefer, 2002) nor the last (e.g., Liu et al., 2013), to provide evidence that N400 masked priming effects arise from automatic spreading activation, their study design does allow for additional insights into automatic spreading activation, particularly its time course. Misra and Holcomb (2003) varied the ISI of the primes and targets to range from less than 500 ms (i.e., immediate, within-trial repetitions) to greater than 25000 ms (i.e., up to eight trials later), finding that the N400 priming effects elicited by masked primes were reliable regardless of whether the primes were repeated as targets immediately or one to eight trials later. Critically though, and consistent with the view that, in a typical language system, activation spreads rapidly and then decays with time, immediately repeated primes elicited large, robust priming effects while delayed repetitions of primes elicited comparatively smaller, weaker priming effects. This scaling of the effect size with time delineates the typical time course of spreading activation as indexed by N400 priming effects. Thus, examining N400 priming effects obtained using a masked priming paradigm with varied ISIs is an optimal method for exploring automatic spreading activation's temporal dynamics.

## Present Study

Misra and Holcomb's (2003) study combined sensitivity to the neural processes reflecting the time course of automatic spreading activation with a task that involves a relatively low linguistic processing load and no verbal response; this combination lends itself well to being implemented with people with aphasia, who have impaired language. Additionally, by including both masked and visible primes, Misra and Holcomb's (2003) study design prevents the potential issue of failing to find priming effects, which occasionally occurs when all primes are masked (Holcomb et al., 2005; Kahan, 2000). Including both prime types facilitates priming effects to masked primes by encouraging continuous attention to the prime epoch even when the prime is not consciously perceptible (Holcomb et al., 2005; Kahan, 2000). Furthermore, both masked priming and ERPs have proven to be valid methods to use with PWA (see Silkes & Anjum, 2021 for a review of the use of ERPs with PWA) although, to our knowledge, they have never before been combined with this population. Given all of this, Misra and Holcomb's (2003) varied-ISI priming task is ideal for investigating the time course of automatic spreading activation in PWA. Therefore, the study described here implemented this same protocol with adults with aphasia and with a control/comparison group of neurologically unimpaired older adults with typical language abilities.

The aim of this study was to determine how the time course of spreading activation in PWA differs from that of typical older adults, as indexed by ERP responses to words presented as primes or targets after various delays. We compared the ERP responses of people in both groups to immediate and delayed repetitions of masked and visible primes. Informed by typical young adults' performance with this protocol (as reported by Misra & Holcomb, 2003), the robustness of priming effects from masked versus visible primes, and the typical time course of

automatic spreading activation, we predicted that typical controls would show N400 priming effects for immediate repetitions of masked primes and delayed repetitions of visible primes, but no, or substantially reduced, priming effects for the delayed repetitions of masked primes. In contrast, and at the core of the questions investigated in this study, we predicted that PWA would show evidence of a delayed spread of activation, in that they would not show N400 priming effects in response to immediate repetitions of masked primes but would demonstrate N400 priming effects for delayed repetitions of masked and visible primes.

While the focus of our analyses was on the N400 priming effects, we conducted additional analyses on behavioral responses and two other ERP components as validation measures of the experimental design. More specifically, we examined probe identification during the priming task and behavioral priming effects to the non-critical probe items, as well as recognition of critical items during a subsequently completed behavioral recognition task. We also explored the P300, which is often used to measure conscious identification of task-relevant stimuli (e.g., a target stimulus), elicited by probe items, and the LPC elicited by all critical target types. We predicted that both groups would show behavioral priming effects as indexed by faster reaction times to primed probe targets than unprimed probe targets as other many other studies have found (e.g., Ferrill et al., 2012; Prather, 1994; Prather et al., 1992, 1997; Silkes, 2012; Silkes et al., 2020). We also predicted that the rest of these measures would simply confirm that the masked words were not reliably identified nor consciously processed during the priming task while the visible words were. Probe identification during the priming task and behavioral priming effects are reported here. However, given the supplementary nature of these rest of these analyses, detailed report of the methods for obtaining the data, analyses, and results are presented in the Supplemental Materials. See Table 1 for a detailed summary of all the ERP predictions.

Table 3.1. Planned comparisons and the ERP components analyzed, purpose, predictions for each comparison based on prior literature on typical participants, and interpretation. Comparisons 1-2 and the LPC results for comparisons 3-6 are validation measures, not germane to the research questions, so those data are reported in detail in the Supplemental Materials. [a]Because predictions presented here are based on the typical literature, these critical comparisons are the most likely to not have predictions met by PWA due to differences in automatic spreading activation.

| # | Comparison | ERP component(s) analyzed | Purpose of comparison | Prediction(s) based on typical literature | Interpretation(s) |
|---|---|---|---|---|---|
| 1 | Masked animal primes vs. masked non-animal primes | P300 | Measure of masking effectiveness | No difference between stimulus types expected. | Primes were effectively masked. |
| 2 | Unprimed visible animal targets vs. unprimed visible non-animal targets | P300 | Measure of task comprehension and engagement | Enhancement expected for unprimed visible animal targets. | Participant could differentiate animal from non-animal words and were attending to the stimuli. |
| 3 | Delayed repetitions of visible non-animal primes vs. unprimed non-animal targets | N400 | Validation of experimental protocol effectiveness | Attenuation (i.e., priming) expected for delayed repetitions of visible non-animal primes. | The experimental protocol was adequate to elicit the expected effects, in both groups, from the strongest form of priming. |
| | | LPC | Measure of conscious perception of visible non-animal words | Enhancement expected for delayed repetitions of visible non-animal primes. | Participant has perceived the prime and recognized its repetition. |
| 4 | Immediate repetitions of masked non-animal primes vs. unprimed non-animal targets | N400[a] | Examine speed of automatic spreading activation via presence/ absence of automatic semantic processing | Attenuation (i.e., priming) expected for immediate repetitions of masked non-animal primes. | Typical initial spread of activation. If PWA do not meet this prediction (i.e., do not show priming), this would indicate delayed automatic spreading activation. |
| | | LPC | Measure of masking effectiveness | No difference between stimulus types. | Primes were effectively masked. |

Table 3.1 continued

| # | Comparison | ERP component(s) analyzed | Purpose of comparison | Prediction(s) based on typical literature | Interpretation(s) |
|---|---|---|---|---|---|
| 5 | Delayed repetitions of masked non-animal primes vs. unprimed non-animal targets | N400[a] | Examine speed of automatic spreading activation via presence/absence of automatic semantic processing. | Weak (if any) attenuation (i.e., weak, or no, priming) expected for delayed repetitions of masked non-animal primes. | Activation has appropriately decayed over time. If PWA do not meet this prediction (i.e., show priming effects), that would indicate delayed automatic spreading activation or, if priming has occurred for immediate repetitions (Comparison #4), slowed decay of activation. |
| | | LPC | Measure of masking effectiveness | No difference between stimulus types expected. | Primes were effectively masked. |
| 6 | Delayed repetitions of masked non-animal primes vs. delayed repetitions of visible non-animal primes | N400[a] | Examine magnitude of priming effects | Greater attenuation (i.e., priming) expected for delayed repetitions of visible non-animal primes than delayed repetitions of masked non-animal primes. | Effective integration of explicitly and implicitly processed information allowed for stronger priming than solely implicitly processed information. |
| | | LPC | Measure of masking effectiveness | Enhancement expected for delayed repetitions of visible non-animal primes. | Primes were effectively masked and visible targets were consciously perceived. |

## Method

Participants were recruited through the University of Washington Aphasia Registry and Repository and by advertisements on the University of Washington campus. All procedures were approved by the University of Washington Institutional Review Board. Informed consent was obtained from all participants prior to their participation. For PWA, several additional measures were taken to ensure their comprehension and to make sure that all of their questions were answered adequately before obtaining written consent.

Following the informed consent process, screening measures were administered to determine study eligibility. These measures included the Boston Naming Test (BNT; Kaplan et al., 2001), Raven's Coloured Progressive Matrices (RCPM; Raven, 1976)and a vision assessment using a Tumbling E eye chart for all participants. Participants with aphasia were also given the Western Aphasia Battery (WAB; Kertesz et al., 1982) to establish an aphasia diagnosis and profile. Eligible participants then completed a task (described in Sections 2.2 and 2.3) to determine the appropriate duration for the masked primes, which was the longest duration (from three tested) at which they showed chance performance at responding to masked words. If the participant successfully passed all screening measures and showed chance performance for at least one of the tested prime durations, they completed the experimental protocol, which involved a priming task in which EEG data were collected and a behavioral validation measure of masking effectiveness (i.e., a behavioral recognition task described in the Supplemental Materials). All tasks were completed in up to two sessions. Participants received nominal monetary compensation for their participation, prorated for the extent of their involvement.

**Participants**

A total of 51 participants were screened for participation in this study (PWA: $n$ = 22; Controls: $n$ = 29), but the full experimental protocol was not completed by two PWA due to visual field impairments ($n$ = 1) or inability to control their eyeblinks ($n$ = 1) and by 10 controls due to inability to obtain adequate prime duration thresholds (i.e., they showed above-chance conscious perception of primes at even the fastest duration; details below). Of those that completed the full experimental protocol, data collected from 12 participants (PWA: $n$ = 6; Controls: $n$ = 6) were excluded due to excessive EEG artifacts (see below for more details). Thus, data from a total of 27 right-hand-dominant, monolingual, English-speaking adults were included in this study. All participants had no reported history of neurological injury or impairment (other than the event that caused aphasia for the PWA) or untreated psychiatric conditions and had normal or corrected-to-normal vision.

Fourteen of the participants were PWA (see Table 2 for a summary of participant characteristics). All PWA had experienced a left-hemisphere stroke at least six months prior to the study and been diagnosed with aphasia. All had an Aphasia Quotient (AQ) between 22.8/100 and 94.7/100 on the WAB, indicating the presence of impaired language, and scored below 48/60 on the BNT, indicating impaired picture naming abilities (i.e., anomia). They all also showed no evidence of right hemisphere impairment, as evidenced by a score of at least 23/36 on RCPM, or of visual field cut or neglect. Participants in this group ranged from 33 to 74 years old ($M$ = 60.36, $SD$ = 11.34).

Table 3.2. Summary of participant characteristics.

| | Age | | WAB-AQ (Aphasia Severity) #/100 | | BNT (Picture Naming) #/60 | | RCPM (Right Hemisphere Functioning) #/36 | | Years Since Most Recent Stroke | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | *SD* | Mean | *SD* | Mean | *SD* | Mean | *SD* | Mean | *SD* |
| Controls | 58.69 | 9.52 | N/A | | All WNL (> 52) | | All WNL (> 23) | | N/A | |
| PWA | 60.36 | 11.34 | 68.01 | 21.83 | 28.50 | 17.32 | 31.36 | 4.03 | 5.49 | 3.86 |

*Note.* WNL = Within normal limits.

There were 13 control participants. They all scored at least 52/60 on the BNT, indicating no evidence of left hemisphere damage, and at least 23/36 on the RCPM, indicating no evidence of right hemisphere damage. Participants in this group ranged from 45 to 74 years old ($M$ = 58.69, $SD$ = 9.52; not significantly different from the PWA, $t(24.77) = 0.41$, $p = .682$).

**Stimuli**

Each participant engaged in two priming tasks: one to determine an appropriate prime presentation duration for that participant and one that was the main experimental task. All stimuli were the same as those used by Misra and Holcomb (2003). Stimuli were presented using E-Prime on a desktop PC running Windows XP and a 20" ViewSonic P225f CRT monitor. Each stimulus was presented in 30-point Arial font in the center of the computer monitor. Each trial involved presenting both masked and visible words as follows: a briefly presented prime screen (either a word presented in lower-case letters or a blank screen), a backward mask (i.e., XXXXX), and a visible target word (presented in upper-case letters), and a screen indicating the end of the trial (see Figure 1). Button press responses were collected using an E-Prime button box with color-coded keys. All sessions were conducted in a quiet room.

### *Prime Duration Determination Task*

To account for individual variability in sensitivity to masking (Cheesman & Merikle, 1984; Dagenbach et al., 1989; Misra & Holcomb, 2003), each participant completed a task to determine at what duration the masked primes could be presented and still be effectively masked for that individual (i.e., they would be unable to identify the prime's semantic category). The duration of the primes in the main experimental priming task was titrated for each participant based on their performance in this prime duration determination task. Stimuli for this task consisted of 257 four- to five-letter words, 105 of which were food items (probe items), defined as anything one could eat or drink, and 152 of which were non-food, concrete nouns. These stimuli were split across three stimulus lists (one list for each of the three prime durations tested), each consisting of a block of 26 trials and a block of 25 trials.

The stimulus lists for this task were arranged so that for each trial, prior to the presentation of the target, either a blank screen or a word unrelated to the visible target word was presented in the prime position. No words were repeated in a list (nor across lists), resulting in 85 unique words per list. Food items appeared as both primes and targets, but never within the same trial. There were no such constraints on the presentation of non-food words.

### *Experimental Priming Task*

The purpose of the main experimental priming task was to address our research questions. For this task, stimuli consisted of 500 four- to five-letter words, 100 of which were animal names (probe items) and 400 of which were non-animal, concrete nouns (critical items), with a frequency of less than 121.6 per million ($M$ = 8.14 per million, $SD$ = 10.98 per million; Brysbaert & New, 2009). Fifty of the non-animal words were never presented in the experimental protocol so they could serve as foils in the recognition task (see Supplemental

Materials). These 500 words were arranged to create eight counterbalanced stimulus lists. Each stimulus list contained a total of 450 trials that were split into 12 blocks of 36 trials and one block of 18 trials. Across these lists, all words occurred in all possible positions.

The stimulus lists were constructed so that animal names appeared as primes or targets but never appeared as both within a single trial (i.e., no targets were immediate repetitions of masked animal primes). Additionally, and critically, non-animal word presentation was not constrained like the animal names, allowing for five critical target types, as follows (and see Table 3 for details of each type):

1) Unprimed non-animal targets with a blank screen in the prime position (i.e., no prime targets)
2) Unprimed non-animal targets with an unrelated non-animal word in the prime position (i.e., unrelated prime targets)
3) Delayed repetitions of visible primes
4) Immediate repetitions of masked primes
5) Delayed repetitions of masked primes

Unprimed non-animal targets sometimes had a blank screen and sometimes had a masked prime unrelated to the target word in the prime position to allow for comparing targets of identical trial structure. Both trials with unrelated prime targets and immediate repetitions of masked primes always had a word in the prime position, while the other target types always had a blank screen in the prime position within the trial. It also allowed for comparing all primed critical target types to an unprimed target where activation from the prime could not facilitate processing since there was no prime (i.e., no prime targets), thus preventing the potential for both

priming and anti-priming. In addition to these critical non-animal targets, there were four additional types of stimuli:

6) Masked non-animal primes
7) Masked animal primes (probe)
8) Unprimed animal targets (with a blank screen in the prime position; probe)
9) Delayed repetitions of animal words (i.e., primed animal targets; probe)

Table 3.3. A representative sample of a stimulus list and designation of the various stimulus condition.

| prime | TARGET | Prime Condition | Target Condition |
|---|---|---|---|
| | TWIN | blank screen | unprimed non-animal[a] |
| leech | SHANK | masked animal | unprimed non-animal[a] |
| posy | JAIL | masked non-animal | unprimed non-animal[a] |
| | MOOSE | blank screen | unprimed animal |
| | LEECH | blank screen | primed animal[b] |
| | TWIN | blank screen | delayed repetition of visible prime[b] |
| pouch | POUCH | masked non-animal | immediate repetition of masked prime |
| | POSY | blank screen | delayed repetition of masked prime[b] |

*Note.* Each row represents one trial, and the trials are arranged in the order they would be presented to create the stated conditions.
[a]Unprimed non-animal targets were sometimes preceded by a blank screen and sometimes by a masked prime; these two options were used to ensure equivalent comparison with the other conditions, which avoided comparing targets following masked primes to targets following masked blank screens.
[b]Primed animals and both types of delayed repetitions were pseudorandomly varied to occur from one to eight trials following their prime, with an average of four intervening trials

**Procedure**

Participants completed the prime duration determination task before completing the experimental priming task. For both tasks, the participant was seated in a sound-attenuated and dimly lit room in front of a computer monitor and told that they would see items flashed on the

screen, including words, strings of X's, and asterisks. They were instructed to watch carefully and push a button on the E-Prime response box as quickly as they could when they saw stimuli of a particular category (i.e., food items, animal names). By requiring a response to only words of a specific category, participants were required to semantically process each word they saw. In addition, it allowed for obtaining EEG data for the out-of-category words (i.e., non-animal words) that were not contaminated by non-brain-related electrical activity generated by motor responses. No information was provided about the presence of the masked items or the prime-target relationship.

***Prime Duration Determination Task***

To identify the appropriate prime duration to use with each participant, they were first told they would be completing a few sets of practice trials. Each trial of the prime duration determination task was constructed such that a masked word preceded a visible word; some trials presented a masked food item name, some presented a visible food name, and some presented neither (i.e., only presented non-food items). Participants completed three sets of trials, each of which presented the primes for a different duration. The duration of the primes decreased across the three sets, beginning with a prime duration of 66 ms, followed by a prime duration of 50 ms and then of 33 ms. Blocks in each set were separated by a break during which the experimenter provided supportive and/or clarifying feedback to the participant.

Upon completing the three sets of trials, the experimenter calculated the percent of masked items that were correctly identified as a food based on the data collected by E-Prime and experimenter notes of items on which the participant indicated that they had accurately perceived the stimulus but then made an incorrect response. Following Misra and Holcomb's (2003) criteria, the longest duration at which the participant showed between 33 to 66% accuracy (with

as close to 50% accuracy as possible) in responding to a food item in the prime position of a trial was then selected as the masked prime duration to use for the experimental priming task.

***Experimental Priming Task***

Trials in the experimental priming task began with a prime screen presented for the duration determined by the previous task (33 ms: 11 controls, 4 PWA; 50 ms: 2 controls, 4 PWA; 66 ms: 0 Controls, 6 PWA), a backward visual mask for 200 ms, a blank screen of the appropriate duration to create a 500 ms stimulus onset asynchrony (SOA) between the prime and target (e.g., a participant with 33 ms primes had a blank screen of 267 ms while a participant with 66 ms primes had blank screens of 234 ms), and the target word for 300 ms. Following presentation of the target, a blank screen was presented for 900 ms and then an asterisk was presented for 1500 ms as a signal that the trial had ended and blinking was permitted (see Figure 1 for a graphic depiction of the stimulus presentation sequence).

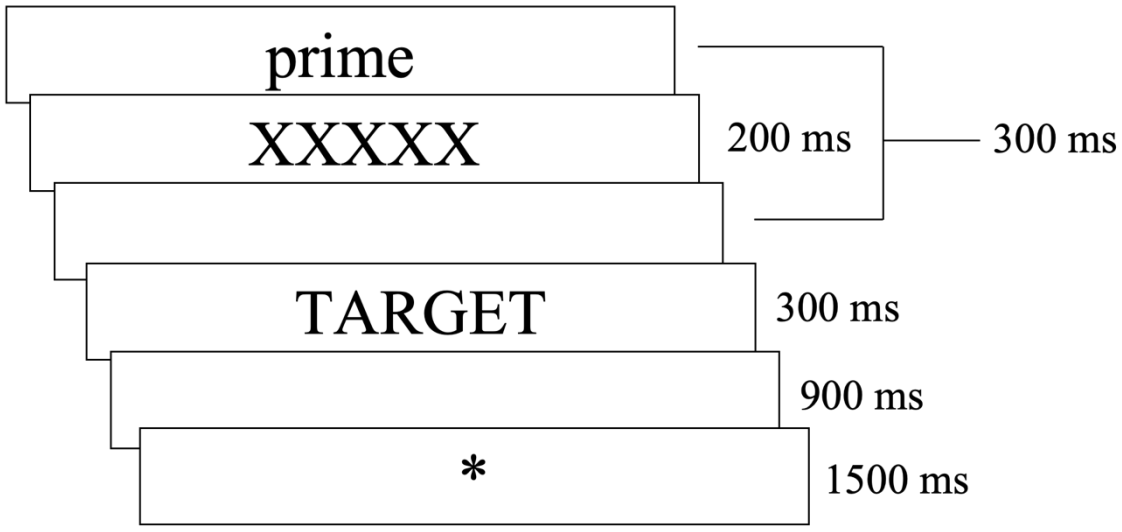



Figure 3.1. Stimulus presentation sequence for a single trial. Primes were presented for 33, 50, or 66 ms (see text for details), with the blank screen following the prime adjusted so that the combined duration of the two screens was 300 ms. This, combined with the backward mask duration, created a 500 ms SOA between the prime and target.

Participants were told that the experimental priming task was identical to the task that they had already completed (i.e., the prime duration determination task). This time, however, they were instructed to watch for animal names and to push a button on the E-Prime response box when they saw one. In addition, movement artifacts were briefly explained, and participants were asked to try to remain relaxed and to limit blinking to the post-trial interval marked by the asterisks. They were also informed that the lists were longer for this task, with each block taking about two minutes, but that there would be opportunities for them to take breaks for as long as they wished between blocks. To familiarize the participants with completing the task while EEG data were collected (e.g., to become comfortable with the pattern of timing for eyeblinks) and to acclimate them to responding to animal names rather than food items, participants completed a set of 51 practice trials with the prime duration individually set for each participant to the pre-determined prime duration. Participants were permitted to repeat the entire set of practice trials as many times as desired. After completing the practice trials, they completed the experimental portion of the task. The entire experimental priming task lasted approximately 25 minutes, not including breaks.

**EEG Procedure**

EEG data were collected using a BioSemi ActiveTwo EEG system (BioSemi B.V., Amsterdam, The Netherlands) with active Ag-AgCl electrodes mounted on a 64-channel elastic cap (Electro-Cap, Inc.) organized according the standard International 10-20 system. Due to the ActiveTwo system's active electrode setup, high electrode impedances are corrected for by the preamplifier stage on the electrode to maintain a good signal-to-noise ratio, so impedance measurements were not recorded but were monitored during electrode placement. EEG data were recorded continuously at a sampling rate of 2048 Hz. Additional monopolar electrodes were

placed below the left eye and lateral to the right eye to monitor eyeblinks and horizontal eye movements, respectively. Another monopolar electrode placed on the left mastoid served as the reference electrode.

**EEG Data Processing**

EEG data were processed in MATLAB using EEGLAB (version 2021.0; Delorme & Makeig, 2004) and ERPLAB (version 8.10; Lopez-Calderon & Luck, 2014) open-source toolboxes. Initial data processing involved the following steps: 1) downsampling the data to 500 Hz; 2) bandpass-filtering the data using a second-order Butterworth filter with half-amplitude bandpass of 0.1–30 Hz; 3) re-referencing the data to the left mastoid, 4) visually identifying and removing data from malfunctioning electrodes; 5) decomposing the data by individual component analysis; and 6) removing components that captured ocular and/or muscular movement artifacts (range = 0-3 components, $M$ = 1.8 components). Then, the EEG data from each participant were segmented into epochs that included a baseline period of 100 ms prior to onset of the target stimulus and ended with the end of the trial (1180 ms). Epochs that were deemed to be free of artifacts (i.e., they did not contain horizontal eye movements, eye blinks, and/or miscellaneous non-brain voltage deflections greater than 75 μV) were then averaged across trials. If greater than 50% of a participant's epochs contained artifacts, the participant's data were excluded from the analyses. On average, 81.42% ($SD$ = 11.92%) of all epochs for each participant were averaged across trials for Controls and 75.19% ($SD$ = 14.54%) of all epochs for each participant were averaged across trials for PWA. There were no significant differences between the proportion of trials rejected for each stimulus type and/or between groups (all $p$s > .05).

**Data Analysis**

Behavioral and EEG data were analyzed with linear mixed effects (LME) regression models fit using restricted maximum likelihood (REML) estimation via the *lme4* package (version 1.1-35.1; Bates et al., 2015) in R (version 4.3.2; R Core Team, 2023). Bonferroni correction was used to control for planned multiple comparisons, using a family-wise type I error rate of 0.05.

Arcsine-transformed proportions of correct button press responses to animal names were analyzed using an LME model with a fixed within-subject factors of Stimulus Type (Prime, Primed Target, Unprimed Target) and Group (PWA, Controls) and random intercept for participant. The model was run with both treatment and Helmert coding applied to compare response accuracy of each type of animal targets to animal primes (treatment coding with animal primes as the reference level) and to compare primed versus unprimed animal targets and of animal primes versus all animal targets (both primed and unprimed; Helmert coding) for both groups. To analyze the behavioral priming effects, we ran an LME model with a fixed within-subject factors of Priming (Primed, Unprimed) and Group (PWA, Controls) and random intercepts for participant and item on the reaction times to correctly responded to animal targets. Treatment coding was applied, so the intercept reflected the Controls' mean reaction time for unprimed trials. Trials in which a participants' reaction time was three standard deviations or more above or below their mean reaction time were excluded from probe detection and behavioral priming effect analyses (Controls: $M$ = 15.40% trials removed, $SD$ = 8.20% trials removed; PWA: $M$ = 10.01% trials removed, $SD$ = 11.68% trials removed).

To analyze the N400 ERP priming effects, the mean amplitude during a time window of 300 ms to 500 ms post-target onset was obtained for each participant from the following

electrodes: F3, Fz, F4, FC3, FCz, FC4, C3, Cz, C4, CP3, CPz, CP4, P3, Pz, P4, PO3, POz, PO4, O1, Oz, and O2. The time window and electrodes were selected based on previous masked N400 priming studies with neurologically unimpaired participants and N400 priming studies with PWA (e.g., Chang et al., 2016; Kiefer, 2002; Kiefer & Brendel, 2006; Misra & Holcomb, 2003; Ortells et al., 2016). The mean amplitudes were subjected to LME model including fixed within-subject factors of Target Type (No Prime Target, Delayed Repetition of Masked Prime, Delayed Repetition of Visible Prime, Immediate Repetition of Masked Prime, Unrelated Prime Target) and Group (PWA, Controls) and random intercepts for participant and electrode. We ran the model using both treatment and repeated contrast coding to test each of the planned comparisons of target types for each group.

After identifying the target types that elicited priming effects, we conducted additional analyses comparing the magnitudes of the priming effects. To do this, we calculated the mean amplitudes of difference waves by subtracting the mean amplitude of the primed condition from the mean amplitude of the unprimed condition for each electrode and participant. The resulting mean amplitudes were analyzed using an LME regression with fixed within-subject factors of Difference Condition (No Prime Targets – Delayed Repetitions of Visible Primes, No Prime Targets – Delayed Repetitions of Masked Primes, No Prime Targets – Immediate Repetitions of Masked Primes, Unrelated Prime Targets – Immediate Repetitions of Masked Primes) and Group (PWA, Controls) and random intercepts for participant and electrode. Treatment coding was used with the No Prime Targets – Delayed Repetitions of Masked Primes Difference Condition as the reference level, making the intercept the grand mean amplitude of that condition for Controls.

## Results

### Behavioral Results

#### *Probe Identification: Verifying Masking Effectiveness and Task Engagement*

Button press responses to animal name probes revealed that both controls and PWA identified a significantly greater proportion of visible animal names (i.e., animal targets), regardless of whether they were primed or unprimed, than masked animal names (Controls: Primes vs. Primed Targets: $\beta = 2.52$, $SE = 0.26$, $t(73) = 9.51$, $p < .001$; Primes vs. Unprimed Targets: $\beta = 2.61$, $SE = 0.26$, $t(73) = 9.87$, $p < .001$; PWA: Primes vs. Primed Targets: $\beta = 2.53$, $SE = 0.26$, $t(73) = 9.92$, $p < .001$; Primes vs. Unprimed Targets: $\beta = 2.26$, $SE = 0.26$, $t(73) = 8.88$, $p < .001$). There was no difference in accuracy of identifying primed animal targets compared to unprimed animal targets (Controls: $\beta = -0.05$ $SE = 0.13$, $t(73) = -0.37$, $p = .716$; PWA: $\beta = 0.13$, $SE = 0.13$, $t(73) = 1.04$, $p = .302$). Response accuracy for each probe stimulus type is provided in Table 4.

Table 3.4. Response accuracy for probe identification.

| | **Controls** | | **PWA** | |
|---|---|---|---|---|
| | **Mean** | ***SD*** | **Mean** | ***SD*** |
| Animal primes | 0.11 | 0.12 | 0.09 | 0.15 |
| Primed animal targets | 0.73 | 0.28 | 0.75 | 0.24 |
| Unprimed animal targets | 0.80 | 0.19 | 0.72 | 0.21 |

#### *Reaction Times: Examining Behavioral Priming Effects*

To examine behavioral priming effects, reaction times for responses to primed and unprimed animal targets were calculated. Neither group showed behavioral priming effects, with

no significant difference between reaction times for primed and unprimed animal targets (Controls: $\beta$ = -21.85, *SE* = 20.61, *t*(1305) = -1.06, *p* = .289; PWA: $\beta$ = -15.34, *SE* = 15.95, *t*(1305) = -0.96, *p* = .336). However, the PWA's reaction times (*M* = 1446 ms, *SD* = 281 ms) were overall slower than the Controls' (*M* = 1312 ms, *SD* = 215 ms; $\beta$ = 165.00, *SE* = 21.31, *t*(1305) = 7.74, *p* < .001).

**ERP Results**

***Delayed Repetitions of Visible Primes versus Unprimed Targets: Verifying Elicitation of Neural Priming Effects Reflecting Implicit and Explicit Processing***

To verify that priming effects could be elicited with at least the strongest form of priming, when both implicit and explicit processing are involved, we analyzed the mean amplitudes for Delayed Repetitions of Visible Primes and No Prime Targets (see Figure 2). When comparing these two conditions, we found that the Controls showed priming effects (i.e., more negative mean amplitudes for unprimed targets than the primed targets) for Delayed Repetitions of Visible Primes when compared to No Prime Targets ($\beta$ = 6.63, *SE* = 1.02, *t*(2822) = 6.51, *p* < .001), as did PWA ($\beta$ = 4.95, *SE* = 0.98, *t*(2822) = 5.04, *p* < .001).

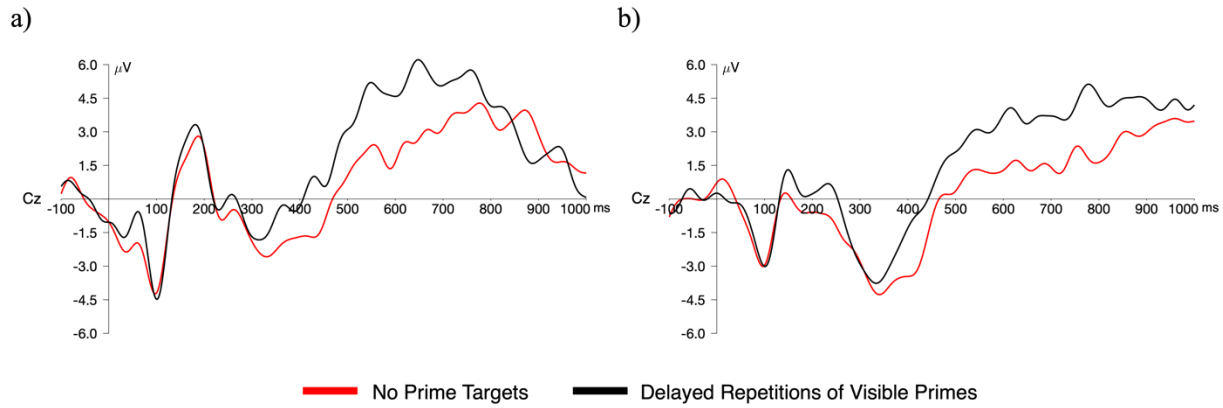



Figure 3.2. a) Typical older adults' (i.e., Controls') and b) PWA's grand average ERP waveforms elicited by delayed repetitions of visible primes and no prime targets.

***Immediate Repetitions of Masked Primes versus Unprimed Targets: Examining Automatic Priming Effects and Speed of Initial Spread of Activation***

To address our main hypothesis and determine whether PWA show a typical or altered ability to rapidly spread activation after a stimulus is presented, we compared the mean amplitudes of the Immediate Repetitions of Masked Primes to both the No Prime Targets and Unrelated Prime Targets (see Figure 3). We compared the Immediate Repetitions of Masked Primes to both unprimed target conditions to ensure that any lack of priming effects in the PWA was not merely due to anti-priming. Both Controls and PWA showed priming effects to Immediate Repetitions of Masked Primes regardless of the unprimed condition (Controls: No Prime Targets: $\beta = 9.51$, $SE = 1.02$, $t(2822) = 9.33$, $p < .001$; Unrelated Prime Targets: $\beta = -3.48$, $SE = 1.02$, $t(2822) = -3.41$, $p = .001$; PWA: No Prime Targets: $\beta = 10.35$, $SE = 0.97$, $t(2822) = 10.54$, $p < .001$; Unrelated Prime Targets: $\beta = -4.25$, $SE = 0.97$, $t(2822) = -4.33$, $p < .001$).

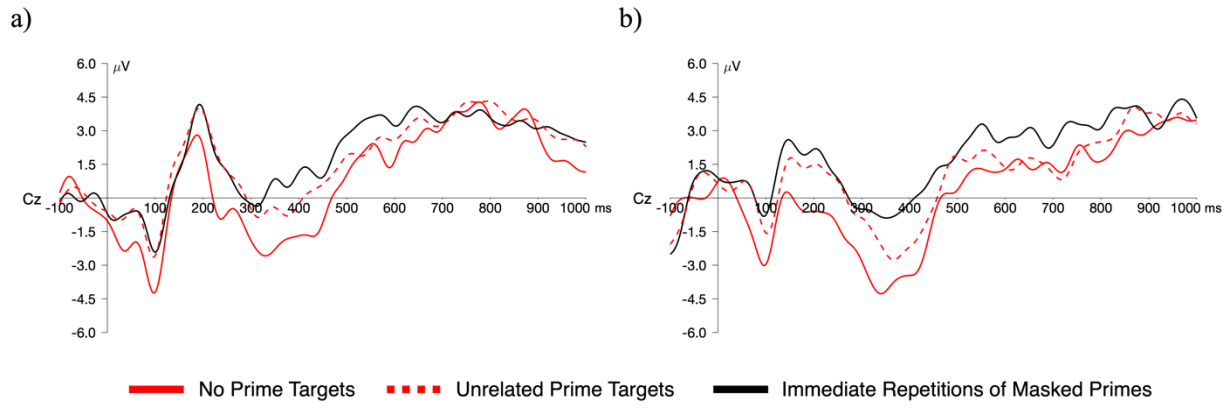



Figure 3.3. a) Typical older adults' (i.e., Controls') and b) PWA's grand average ERP waveforms elicited by immediate repetitions of masked primes, no prime targets, and unrelated prime targets.

***Delayed Repetitions of Masked Primes versus Unprimed Targets: Examining Automatic Priming Effects and Speed of Spread and Decay of Activation***

To further explore how PWA's speed of spreading activation compared to Controls and whether PWA benefitted from a longer period of time to spread activation or maintained activation for longer than typical, we analyzed the mean amplitudes of the Delayed Repetitions of Masked Primes when compared to No Prime Targets (see Figure 4). Here, Controls did not show any priming effects to Delayed Repetitions of Masked Primes ($\beta = 1.75$, $SE = 1.02$, $t(2822) = 1.72$, $p = .086$). The PWA, however, showed priming effects did ($\beta = 3.61$, $SE = 0.98$, $t(2822) = 3.68$, $p < .001$).

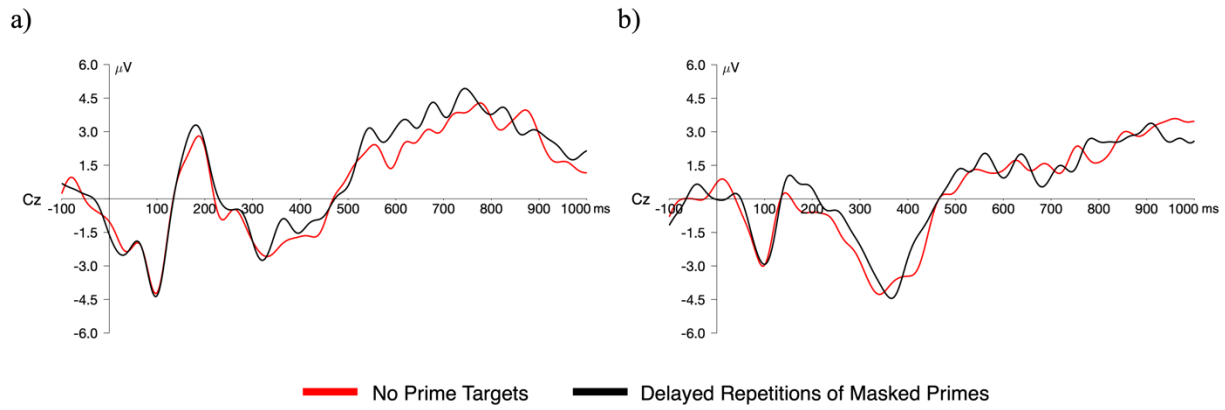



Figure 3.4. a) Typical older adults' (i.e., Controls') and b) PWA's grand average ERP waveforms elicited by delayed repetitions of masked primes and no prime targets.

***Immediate Repetitions of Masked Primes versus Delayed Repetitions of Masked Primes: Further Examining Automatic Priming Effects and Speed of Spread and Decay of Activation***

Because PWA showed priming effects for both Immediate Repetitions of Masked Primes and Delayed Repetitions of Masked Primes, we conducted exploratory analyses comparing the mean amplitudes of these two target types. This analysis was conducted to gain insight into the robustness of the response to each target type, thus revealing whether PWA's activation spread

was, indeed, still delayed as predicted, but that the delay was simply shorter than the 500 ms interval between the prime and target SOA. With a typical spread of activation, more negative-going mean amplitudes would be expected for Delayed Repetitions of Masked Primes, reflecting a less robust priming effect. In contrast, a delayed spread of activation would be expected to elicit more negative amplitudes for Delayed Repetitions of Masked Primes than Immediate Repetitions of Masked Primes, suggesting peak activation was reached after a delay.

Analyses revealed that both Controls and PWA showed significantly more negative mean amplitudes for Delayed Repetitions of Masked Primes than Immediate Repetitions of Masked Primes (Controls: $\beta = 7.76$, $SE = 1.02$, $t(2822) = 7.61$, $p < .001$; PWA: ($\beta = 6.74$, $SE = 0.98$, $t(2822) = 6.86$, $p < .001$; see Figure 5). To more closely examine the differences in mean amplitudes between the primed target types, we conducted follow-up analyses on the magnitude of the priming effects via the mean amplitudes of difference waves (unprimed condition minus primed condition). When the No Prime Targets were used as the unprimed condition, the PWA showed greater priming effects for Immediate Repetitions of Masked Primes than Delayed Repetitions of Masked Primes ($\beta = -6.74$, $SE = 0.86$, $t(2257) = -7.81$, $p < .001$), as did the Controls ($\beta = -7.76$, $SE = 0.90$, $t(2257) = -8.67$, $p < .001$). This difference was lost when Unrelated Prime Targets were used as the baseline unprimed condition for Immediate Repetitions of Masked Primes though (PWA: $\beta = -0.64$, $SE = 0.86$, $t(2257) = -0.74$, $p = .457$; Controls: $\beta = -1.72$, $SE = 0.90$, $t(2257) = -1.93$, $p = .054$). Figure 6 depicts the difference waves for these comparisons.

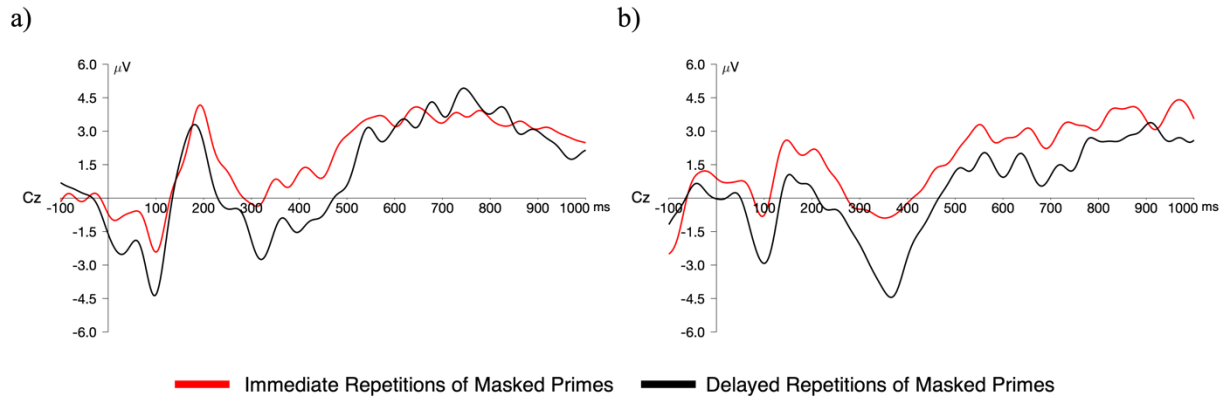



Figure 3.5. a) Typical older adults' (i.e., Controls') and b) PWA's grand average ERP waveforms elicited by immediate repetitions of masked primes and delayed repetitions of masked primes.

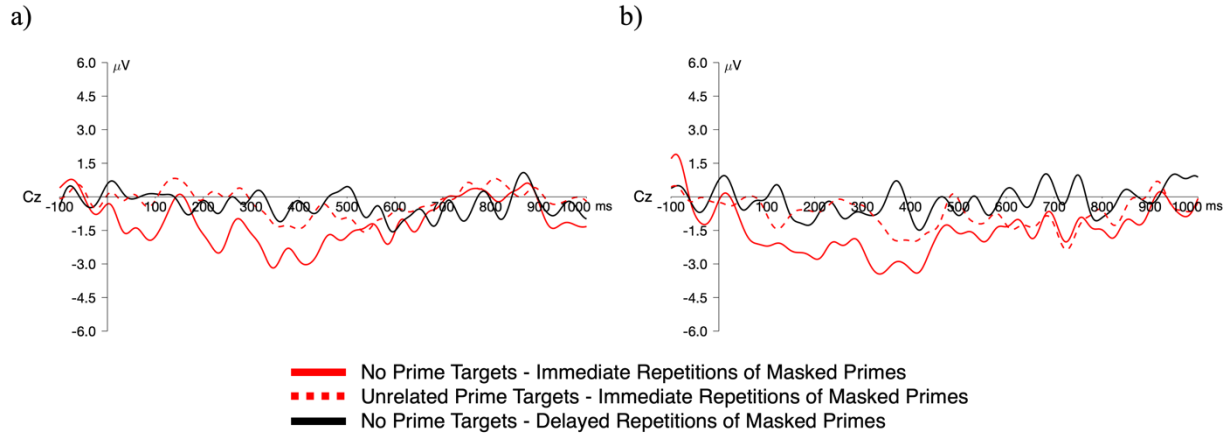



Figure 3.6. a) Typical older adults' (i.e., Controls') and b) PWA's grand average difference waves for immediate repetitions of masked primes (with two different baselines) and delayed repetitions of masked primes. More negative deflections represent larger priming effects.

### *Delayed Repetitions of Masked Primes versus Delayed Repetitions of Visible Primes: Examining Priming Effects Reflecting Only Implicit Processing or Implicit and Explicit Processing*

To directly examine how responses to the primes varied based on whether the priming effects could result from solely implicit processes or both implicit and explicit processes, we

compared the mean amplitudes of the Delayed Repetitions of Masked Primes and Delayed Repetitions of Visible Primes (see Figure 7). There were significant differences between these two target types for Controls ($\beta$ = -4.88, *SE* = 1.02, *t*(2822) = -4.79, *p* < .001), with more negative mean amplitudes for Delayed Repetitions of Masked Primes than for Delayed Repetitions of Visible Primes. The mean amplitudes for Delayed Repetitions of Visible Primes and Delayed Repetitions of Masked Primes were not statistically different for the PWA ($\beta$ = -1.34, *SE* = 0.98, *t*(2822) = -1.36, *p* = .173). This divergent pattern of effects was reflected by a significant interaction of Delayed Repetitions of Visible Primes versus Delayed Repetitions of Masked Primes x Group ($\beta$ = 7.08, *SE* = 2.83, *t*(2822) = 2.50, *p* = .012). No other interactions were significant (*p*s > .05).

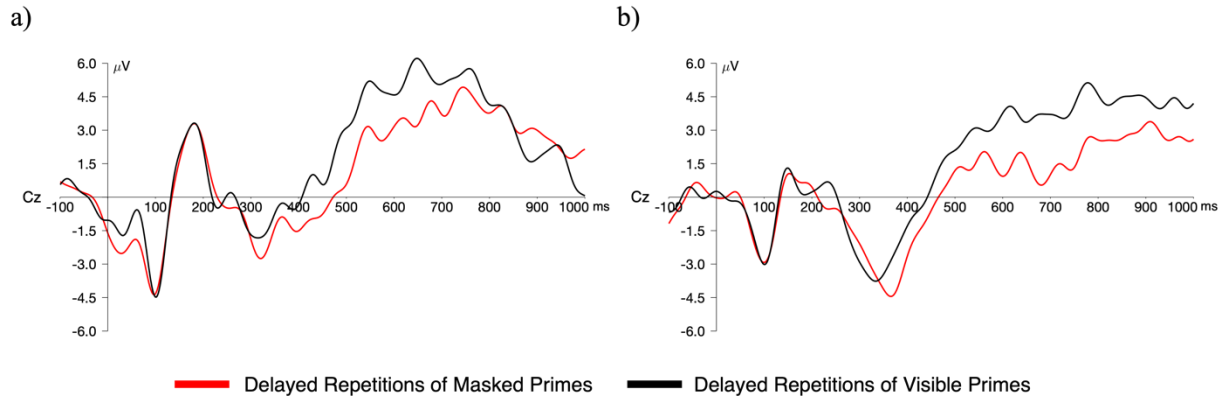



Figure 3.7. a) Typical older adults' (i.e., Controls') and b) PWA's grand average ERP waveforms elicited by delayed repetitions of masked primes and delayed repetitions of visible primes.

To ensure this difference in mean amplitudes was reflecting differences in priming effects, we examined the magnitude of the priming effects via mean amplitudes of difference waves for this comparison as well. Consistent with the initial findings, the Controls demonstrated greater priming effects for Delayed Repetitions of Visible Primes than Delayed Repetitions of

Masked Primes ($\beta$ = -4.88, *SE* = 0.90, *t*(2257) = -5.45, *p* < .001) while there were not differences in priming effects for these two target types for PWA ($\beta$ = -1.34, *SE* = 0.86, *t*(2257) = -1.55, *p* = .121), reflected by the significant Delayed Repetitions of Visible Primes versus Delayed Repetitions of Masked Primes x Group interaction ($\beta$ = 7.08, *SE* = 2.49, *t*(2257) = 2.85, *p* = .004; see Figure 8). There were no other significant interactions (*p*s > .05).

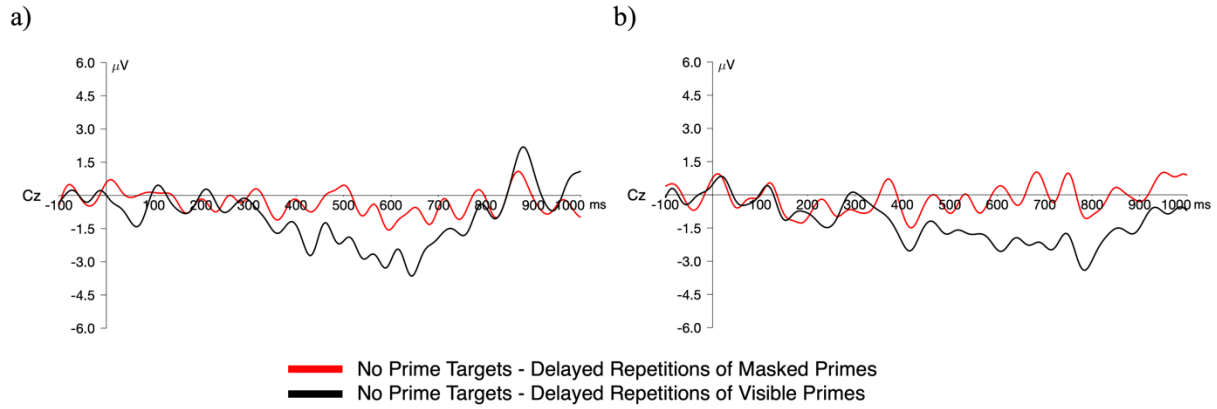



Figure 3.8. a) Typical older adults' (i.e., Controls') and b) PWA's grand average difference waves for delayed repetitions of masked primes and delayed repetitions of visible primes. More negative deflections represent larger priming effects.

## Discussion

In this study, we examined the time course of automatic spreading activation in people with aphasia and older adults with typical language. We used a priming task with both masked and visible primes, combined with EEG, to explore how the time course of spreading activation differed between the groups. We found evidence that PWA experienced extended activation maintenance due to a prolonged decay rate, rather than the predicted delayed spread of activation. In addition, there was unexpected evidence that suggests that PWA also might not be able to take advantage of explicit processes to the same extent as their typical peers. Thus, in PWA, not only might activation of a word be affected by protracted activation decay, but

integration of activation from bottom-up implicit processes and top-down explicit processes might also be affected, leading to a reliance on the implicit process alone.

**Experimental Design Validation**

To ensure that the effects elicited by the masked primes reflected implicit processes and were not contaminated by explicit processes, we included several measures to verify that the masked primes were effectively masked and processed differently than visible stimuli, which was presumably perceived and explicitly processed. Converging evidence from the probe identification data, behavioral recognition task, the P300 analyses, and some of the LPC analyses (see Supplemental Materials) suggests that all the participants, regardless of group, not only understood the task and were engaged with it throughout, but also that they did not consciously perceive, encode, or process the masked primes. The pattern of findings for these measures mirrors those found with the typical young adults of Misra and Holcomb's (2003) experiment, further validating our findings. Greater discussion of the findings from these measures can been found in the Supplemental Materials.

**Automatic Spreading Activation in PWA**

While the primary focus of this study is on neural priming effects as reflected in the N400 ERP component, it is valuable to consider behavioral priming effects in combination with the ERP priming effects. Behavioral priming effects provide an external indicator of the cognitive processes at play and can offer complementary insights into neural mechanisms, thus offering us a more comprehensive understanding of lexical retrieval in PWA. Interestingly, neither the Controls nor the PWA showed any behavioral priming effects via their reaction times. Although less common for typical adults, it is not unprecedented for PWA to fail to show behavioral priming effects from masked primes. In particular, this has been shown when the ISI used are

near 500 ms (Silkes & Rogers, 2012), as they were in this study. Additionally, implicit effects often occur even when the explicit behavioral responses they underly are not observed (e.g., Abel et al., 2020; Pankonin et al., under review). Indeed, despite this lack of behavioral priming effects, we found robust N400 priming effects. While these divergent findings might seem at odds, they exemplify the value of investigating the underlying processes of behavioral responses isolated from conscious processes.

To directly address our research question regarding the time course of spreading activation, we used a series of analyses to examine the N400 priming effects for immediate repetitions of masked primes and delayed repetitions of masked and visible primes. Recall that our primary prediction was that PWA would demonstrate delayed spreading activation via showing priming effects for delayed repetitions of masked primes but not for immediate repetitions of masked primes, which would be the opposite pattern of the older adults with typical language. Contrary to this prediction, both Controls and PWA showed priming effects for immediate repetitions of masked primes, regardless of the comparison unprimed condition. In fact, the magnitude of the priming effect for immediate repetitions of masked primes was greater than for delayed repetitions of masked primes as well (when both primed targets used the no prime targets as their unprimed baseline). This finding suggests that our sample of PWA had no issues with initially activating a word, or at least any delay in initiating the spread of activation was for less than 500 ms (the SOA of the prime and target) and not enough to noticeably affect the activation level reached by the time the target appeared. It also suggests our sample of PWA spread the activation for the masked prime in a typical, rapid manner like the Controls. Instead, the differences arose when considering the delayed repetitions of masked primes. With these targets, PWA continued to show priming effects while the Controls did not. These priming

effects were weaker than those elicited by immediate repetitions of masked primes, indicating that the activation from the primes for these targets had decayed but not back to level of their resting states. Instead, the activation remained high enough to facilitate processing of the target for up to 25 seconds. As such, our results suggest that although our sample of PWA did not show an alteration in the speed of activation transmission, they still showed an alteration in their time course of spreading activation. Specifically, it seems that they showed a deficit in activation inhibition.

This finding contrasts with much of the literature on the time course of spreading activation in PWA, which has typically found evidence suggestive of slowed automatic spreading activation or accelerated activation decay (e.g., Ferrill et al., 2012; Hagoort, 1993; Prather et al., 1997; Silkes et al., 2020; Silkes & Rogers, 2012). However, Prather and colleagues (1994; 1997) also found that some PWA, especially those with fluent aphasia like the majority of our sample of PWA, to initiate activation at typical rate but suppress activation slowly. They proposed that this slow activation decay rate is due to deficits in inhibitory control. Inhibiting activation plays an equally critical role in lexical retrieval as initiating and transmitting it does; without any inhibitory forces to counteract the excitatory ones, there is a risk of too many units being simultaneously active (Berg & Schade, 1992; Dell, 1986; Dell & O'Seaghdha, 1992). Consequently, numerous active lexical items compete to be selected, hindering lexical retrieval (Anderson, 1983; Berg & Schade, 1992; Bjork, 1989; Conway & Engle, 1994; Dell, 1986; Dell et al., 1997; Dell & O'Seaghdha, 1992; Hasher et al., 1991; Postman & Underwood, 1973). This could manifest as word retrieval difficulties as more cognitive resources and/or more time would be needed to sift through the competitors and retrieve the intended lexical item (Anderson, 1983; Hasher et al., 1991; Postman & Underwood, 1973). Additionally, elements of the intended

lexical item could be activated among the many other many activated items, allowing for some but not all aspects of the word an individual is aiming to retrieve to be accessible and leading to strategies and errors seen when one has word finding difficulties (e.g., circumlocutions, semantic and/or phonological substitutions; Dell et al., 1997; Foygel & Dell, 2000; Schwartz et al., 1994).

Our finding that the size of the priming effect for immediate repetitions of masked primes was reduced when a word unrelated to the target immediately preceded the target in the prime position compared to when there was nothing immediately preceding the target in the prime position provides evidence for this proposal of increased lexical competition. It seems the unrelated prime was still active and blocking the target from being processed when the target was encountered (Bjork, 1989; Conway & Engle, 1994). Some level of interference is typical; even the Controls showed a similar reduction in priming effect, but it trended towards being less pronounced and older adults are also susceptible to competition effects (Hasher et al., 1991; Hasher & Zacks, 1988; Kane et al., 1994). Furthermore, there is evidence of inhibitory deficits in PWA for a variety of cognitive and linguistic processes (e.g., Hamilton & Martin, 2005; Lim et al., 2012; Pompon et al., 2015; Wiener et al., 2004). Additionally, given PWA's rapid fluctuations in language performance (e.g., Cameron et al., 2010; Creet et al., 2019; Duncan et al., 2016; Galletta & Goral, 2018; Tseng et al., 1993), the present study's findings and findings of other spreading activation alterations are not mutually exclusive. It is possible that our experimental design obscured very brief delays in spreading activation and/or that the alteration in each PWA—or at least in people with fluent versus nonfluent aphasia—varies as Prather and colleagues have suggested (Prather, 1994; Prather et al., 1997). If the latter is the case, it could be that our sample of PWA merely predominately consisted of PWA with delayed decay rate rather than delayed spread, at least at the time of completing the task. It is an open empirical question

as to whether these alterations vary over short time scales and are reflected in PWAs' variable behavioral performances, or if the alterations are consistent across time and vary by fluency or some other factor and the behavioral performances reflect some other mechanism.

Reduced inhibition of activation leading to extensive activation maintenance was not the only alteration we found in our sample of PWA. We also found that unlike the Controls, PWA unexpectedly showed no stronger priming effects for delayed repetitions of visible primes than for delayed repetitions of masked primes. Typically, masked primes produce weaker effects than visible primes (e.g., Forster & Davis, 1984; Kiefer, 2002; Marcel, 1983; Misra & Holcomb, 2003) as a visible prime allows top-down processing that may reinforce the bottom-up, implicit activation of the target stimulus. This was the pattern shown by the older adults with typical language, who performed as predicted with much larger priming effects when the primes were visible than when they were masked. The finding that the size of the N400 priming effect for PWA was the same regardless of whether the prime was visible or masked suggests that visible primes elicited a relatively weak response from PWA. Put another way, their neural response to a consciously perceived prime was no stronger than their response to a masked prime that never reached conscious awareness. Thus, it appears that the PWA might have also been less able to take advantage of the increased level of activation that should have accompanied an explicit, visible prime.

This lack of a difference in the size of priming effects for PWA merits consideration. Because PWA, like Controls, demonstrated on multiple measures that they had perceived and later recognized the visible primes, it is not that PWA could not explicitly process them. Instead, it might be that PWA's lexical-semantic processing did not benefit from the visible primes in the same way as typical older adults' processing did due to an inability to quickly integrate, or take

advantage of, the explicit information being provided. Without this integration, any priming effects obtained by the PWA would primarily be the result of the automatic, implicit activation elicited by the stimulus, without the benefit of top-down reinforcement. This interpretation is consistent with the aphasia literature that has repeatedly shown that PWA can often access and use information implicitly that they cannot demonstrate explicitly (Coslett & Saffran, 1994; Mimura et al., 1996; Revonsuo, 1995; Roberts et al., 2010).

Lexical retrieval is thought to involve not only the initial activation of elements in the lexical networks but also a need for that activation to be maintained only long enough to allow the system to fully process or act upon whatever has been activated. In the context of network models of language (e.g., Dell, 1986; Foygel & Dell, 2000; Nadeau, 2001), this maintenance is the result of reinforcing spread of activation across reciprocal network connections. Having a strong, visible prime is likely to yield a stronger source of reinforcement than that obtained from a masked prime, but if that incoming information cannot be quickly integrated into the system, then the system cannot take advantage of that information. At the same time, if PWA are also operating with slowed decay of activation as suggested by the data presented here, then the mechanisms for maintaining activation in the lexical-semantic system is impaired in multiple ways, contributing to the ubiquitous problem of anomia in aphasia.

**Implications**

The findings of this study hold implications for both our understanding of the language processing deficits PWA experience, specifically regarding word retrieval, and clinical treatment of such deficits. This study provides indications that a prolonged maintenance of activation and issues integrating activation from implicit and explicit processes are likely mechanisms underlying aphasic language processing impairments, such as anomia. It also suggests that

repeated exposure to a word still allows for increased activation in PWA, albeit for a longer timescale due to a protracted decay rate than in a typical system.

This knowledge can inform aphasia treatments by guiding the way in which stimuli are presented and reinforced in treatment contexts, such as by manipulating the timing or the tasks involved, so that PWA can maximize engagement of their lexical networks. For example, to take advantage of the benefit of repeated exposure to a stimulus, a treatment might involve a relatively extended period of time between trials so as to allow for the activation to adequately dissipate in PWA. In addition, as a result of identifying these impaired mechanisms, treatments may be developed to directly address them, such as treatments that aim to address the timing of automatic spreading activation through manipulating stimulus-response intervals (e.g., Conroy et al., 2018; Kalinyak-Fliszar et al., 2011; Martin et al., 2021). Finally, these results have the potential to guide treatments currently under development that aim to directly engage and improve the function of implicit lexical networks through implicit priming protocols (e.g., Kalinyak-Fliszar et al., 2011; Silkes, 2015, 2018; Silkes et al., 2013; Tabrizi et al., 2022).

**Study Limitations**

Despite these contributions, this study was not without its limitations. To begin with, we were unable to examine the electrophysiological responses to targets that were immediate repetitions of visible primes. This was because the stimulus lists were constructed such that there were no instances in which a visible prime immediately preceded a target (i.e., within a single trial); all prime-target relationships in the visible list involved delays. Due to the complexity of the stimulus lists and study design, it was not feasible to add an additional condition to include immediate repetitions of visible primes. Given the results obtained here, a future study incorporating that condition could be useful for shedding additional light on the question of the

processing of visible primes in both populations. In addition, we were unable to separate the masked and visible delayed prime conditions by the different numbers of intervening trials due to how the EEG data collection was structured. Consequently, we could not analyze the effects of interest at this level of detail. Similarly, we intentionally held the SOA of each trial constant at 500 ms due to the multiple other timing manipulations. However, there is a possibility that delays in spreading activation might have occurred and been overcome in this interval of time. To better understand the both the precise timing of when activation begins spreading and how long it takes to decay in PWA, it would be meaningful to closely examine priming effects at each of various SOAs in future studies.

Another set of limitations relates to the ERP component analyses that were undertaken. Due to the unavoidable individual variability of lesion locations and sizes among the PWA, we did not control for those aspects or the relation of lesion location and size to the placement or selection of electrode sites of interest. At the same time, however, the focus of this study was not to localize the signal, and the effects of interest are not typically isolated to a single electrode site. Thus, looking at larger cortical fields was appropriate and still led to meaningful and interpretable results despite the lack of precision. Nevertheless, more fine-grained analyses that account for lesion size and location could provide an avenue for future research. Additionally, we did not separate our analyses of PWA by their level of fluency because all PWA experience anomia and the aim of this study was to understand the general mechanisms underlying that deficit. In addition, subdividing PWA by fluency would have precluded a detailed analysis due to lack of statistical power. Future studies investigating the extent to which the timing of spreading activation in PWA varies by fluency or other individual characteristics of this population will be

important for moving this line of research forward, especially given the potential that the alteration in the time course of spreading activation might vary based on these characteristics.

**Conclusion**

This study's findings suggest that slowly decaying activation is a mechanism that might explain PWA's deficits in language processing, specifically word retrieval. An inability to adequately integrate the activation from explicit and implicit processes might additionally contribute to this deficit. PWA demonstrates typical priming from masked primes when the prime was immediately repeated but also showed a priming effect when it was repeated after a delay, illustrating how the activation of a word might be extended due to inhibitory deficits in PWA. Also, both masked and visible primes repeated after a delay led to similarly sized priming effects in PWA when that was not the case in older adults with typical language. This finding demonstrated how PWA failed to benefit from the supplementary activation supplied by explicitly processing stimuli that reached conscious awareness, and instead likely relied on their atypical implicit processes. These insights contribute to a more nuanced understanding of aphasia, providing vital information for the development of more effective aphasia treatment methods and paths for future research.

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## Supplemental Materials

### Experimental Design Validation Measures

The purpose of the various experimental design validation measures was to verify that the masked primes were effectively masked–and thus were not consciously perceived, encoded, and/or otherwise processed in any way–so that we could confidently attribute any priming effects from the masked primes to solely automatic, implicit processes. We also wanted to confirm that we had achieved our goal with the stimuli in the experimental priming task that we intended to be consciously perceived, encoded, and/or otherwise processed (i.e., the visible stimuli). As such, in addition to the behavioral priming measures and probe detection task described and reported in the main text, we examined behavioral responses on a recognition task and neural responses indexing conscious processing to the various stimulus types of the experimental priming task. Only information unique to the measures not included in the main text are detailed here.

#### *Stimuli and Procedure*

**Recognition Task**. Immediately after completing the experimental protocol, each participant was given a recognition test to assess their conscious awareness of the content of the masked words that had been presented during the experimental trials. For this task, they were presented with a list of 150 printed words in one of eight random orders. Fifty of those words were the non-animal words that were never presented in the experimental protocol, which served as foils. The remaining 100 were the unrelated masked non-animal prime words ($n$ = 50) and the no prime visible non-animal targets ($n$ = 50) that only appeared once in the entire experimental protocol. Participants were asked to circle any of the words that they had seen on the computer screen during the experiment.

***Data Analysis***

We used the same analytical approach for the behavioral and ERP data described in the main text to analyze the behavioral responses from the recognition task and the mean amplitudes from the P300 and LPC time windows. We analyzed response accuracy in the recognition task just as we analyzed response accuracy in the experimental priming task except that the Stimulus Type factor's levels were Masked, Visible, and Foil for the recognition task data analysis.

Time window and electrode selections for the P300 and LPC were based on previous research studies examining these ERP components (e.g., Geal-Dor et al., 2006; Haebig et al., 2018; Hill et al., 2002; Misra & Holcomb, 2003; van Petten et al., 1991). For the P300 analyses, we obtained mean amplitudes from 400 to 1000 ms post-stimulus onset from the same 21 electrodes specified in the main text for masked animal primes, masked non-animal primes, animal targets, and non-animal targets. We analyzed the data for the primes and targets separately, using the same linear mixed-effects (LME) model as used for analyzing the N400 mean amplitudes but with a two-level factor of Stimulus Type (Animal Prime, Non-Animal Prime; Animal Target, Non-Animal Target) instead of a five-level factor of Target Type.

For the LPC, we obtained mean amplitudes from 500 to 750 ms post-target onset from a more restricted sample of electrodes, specifically C3, Cz, C4, CP3, CPz, CP4, P3, Pz, P4, PO3, POz, PO4, O1, Oz, and O2. Mean amplitudes from the LPC window were analyzed using the same LME model for the N400 mean amplitude analysis. Examining the magnitude of priming effects for the P300 or LPC ERP components were beyond the scope of this study.

## Results and Discussion

### *Recognition Task Results*

Both controls and PWA demonstrated the same pattern of recognition: all participants recognized a significantly greater proportion of visible words than masked words Controls: $\beta$ = 0.37, *SE* = 0.06, *t*(73) = 5.78, *p* < .001; PWA: $\beta$ = 0.18, *SE* = 0.06, *t*(73) = 2.94, *p* = .004) and at least trended towards recognizing a greater proportion of visible words than foils, (Controls: $\beta$ = 0.93, *SE* = 0.13, *t*(73) = 5.78, *p* < .001; PWA: $\beta$ = 0.31, *SE* = 0.12, *t*(73) = 2.53, *p* = .014), while recognition of the masked words and foils did not significantly differ (Controls: $\beta$ = 0.18, *SE* = 0.32, *t*(73) = 1.41, *p* = .164; PWA: $\beta$ = -0.05, *SE* = 0.12, *t*(73) = -0.41, *p* = .681; see Table S1). The Controls also showed a greater difference in accuracy between recognizing visible words and foils than the PWA did, as reflected by the significant interaction of Visible versus Foil x Group ($\beta$ = 1.23, *SE* = 0.36, *t*(73) = 3.42, *p* = .001). Thus, these findings indicate that the masked primes were not encoded while the visible stimuli were, supporting our assumption that the masked primes were, indeed, masked and the visible stimuli were perceived and processed.

Supplemental Table 3.1. Proportion of responses in the recognition task.

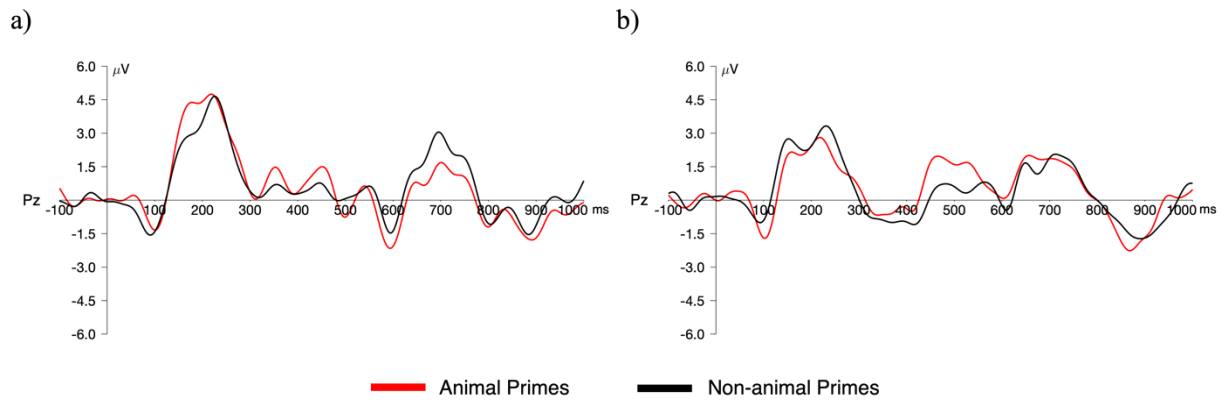
| | PWA | | Controls | |
|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* |
| Visible | 0.25 | 0.27 | 0.28 | 0.2 |
| Masked | 0.16 | 0.16 | 0.12 | 0.14 |
| Foil | 0.16 | 0.18 | 0.08 | 0.11 |

### *P300 Results*

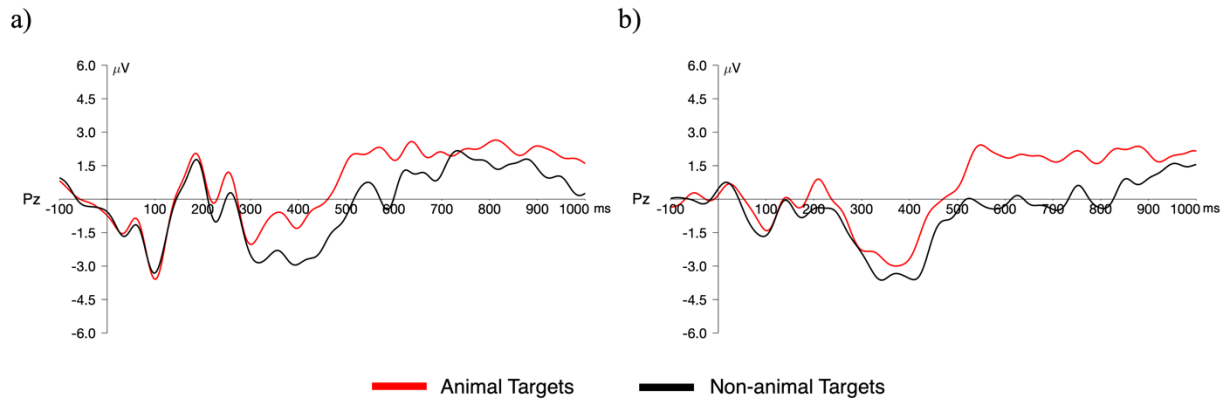
The P300 is larger (i.e., positively enhanced) when a participant *consciously* detects a task-relevant event (Luck, 2012; Polich, 2007), such as the probe stimuli in our experimental priming task. Because non-animal stimuli are not relevant to the task of responding whenever an

animal name is detected, we would not expect any P300 enhancement to non-animal stimuli. Furthermore, because the P300 only occurs when task-relevant stimuli reach conscious awareness, the masked animal primes should not elicit a P300 enhancement even though they are relevant to the semantic categorization task; if the masking prevents them from being consciously received, they cannot be recognized as relevant. Thus, we only expected increased amplitudes in the P300 window for probes that reached conscious awareness, which should only be the visible animal stimuli.

We first compared the mean amplitudes for masked animal primes and masked non-animal primes. We found that there were no significant differences between the mean amplitudes for these two stimulus types for either group when corrected for multiple comparisons (Controls: $\beta$ = 0.38, *SE* = 0.19, *t*(1127) = 2.07, *p* = .038; PWA: $\beta$ = -0.05, *SE* = 0.18, *t*(1127) = -0.30, *p* = .761), providing evidence that masked primes were effectively masked and not consciously perceived or processed. We also compared the mean amplitudes during the P300 window for animal targets and non-animal targets. Both groups demonstrated a significantly more positive mean amplitudes for animal targets compared to non-animal targets (Controls: $\beta$ = -0.87, *SE* = 0.20, *t*(1127) = -4.42, *p* < .001; PWA: $\beta$ = -0.95, *SE* = 0.19, *t*(1127) = -4.98, *p* < .001), indicating the visible animal targets reached participants' conscious awareness and were recognized as relevant. There were no significant interactions of any Stimulus Type with Group (*p*s > .05). Thus, our results verify that targets and primes were perceived or not, respectively, as intended, supporting our interpretations of the priming effects as reflecting implicit, automatic processing. See Supplemental Figure 1 and 2 for the ERP waveforms included in this analysis.




Supplemental Figure 3.1. a) Typical older adults' (i.e., Controls') and b) PWA's grand average ERP waveforms elicited by animal primes and non-animal primes.




Supplemental Figure 3.2. a) Typical older adults' (i.e., Controls') and b) PWA's grand average ERP waveforms elicited by unprimed animal targets and unprimed non-animal targets.

### *LPC Results*

The LPC is sensitive to repetition (e.g., Rugg, 1990), in that it is positively enhanced when a stimulus is repeated compared to the first time the stimulus is presented. Critically, this enhancement is thought to only occur when the stimulus is consciously perceived at both presentations, as it relies on conscious retrieval of episodic memories (van Petten et al., 1991). We expected both controls and PWA to demonstrate the same LPC effects because the LPC reflects explicit processes that are outside the lexical-semantic system. The LPC also assists in the interpretation of any N400 effects that are observed. If an N400 priming effect is observed in

the absence of an enhanced LPC, it is safe to assume that the N400 effect was the result of implicit processing rather than conscious processing of the prime. Based on this on Misra and Holcomb's (2003) findings, we expected both groups to only show increased mean amplitudes during the LPC window for delayed repetitions of visible primes.

Refer to Figures 2 through 7 in the main text for depictions of the LPC waveforms discussed below. Analyses of mean amplitudes during the LPC time window revealed that the Controls showed more positive mean amplitudes for Delayed Repetitions of Visible Primes ($\beta$ = 11.97, *SE* = 1.12, $t(2012) = 10.71$, $p < .001$), Delayed Repetitions of Masked Primes ($\beta$ = 3.38, *SE* = 1.12, $t(2012) = 3.03$, $p = .002$), and Immediate Repetitions of Masked Primes ($\beta$ = 4.40, *SE* = 1.12, $t(2012) = 3.93$, $p < .001$) than No Prime Targets. Delayed Repetitions of Visible Primes also had more positive-going mean amplitudes than Delayed Repetitions of Masked Primes ($\beta$ = -8.59, *SE* = 1.12, $t(2012) = -7.68$, $p < .001$). However, there was no difference between mean amplitudes for Immediate Repetitions of Masked Primes and Unrelated Prime Targets ($\beta$ = -1.43, *SE* = 1.12, $t(2012) = -1.28$, $p = .201$) or Immediate Repetitions of Masked Primes and Delayed Repetitions of Masked Primes ($\beta$ = 1.01, *SE* = 1.12, $t(2012) = 0.90$, $p = .366$).

Compared to No Prime Targets, the PWA also showed more positive mean amplitudes for Delayed Repetitions of Visible Primes ($\beta$ = 7.07, *SE* = 1.08, $t(2012) = 6.56$, $p < .001$) and Immediate Repetitions of Masked Primes ($\beta$ = 5.69, *SE* = 1.08, $t(2012) = 5.28$, $p < .001$), but not for Delayed Repetitions of Masked Primes ($\beta$ = 1.09, *SE* = 1.08, $t(2012) = 1.01$, $p = .310$). Unlike the Controls, the PWA did show more positive deflections during the LPC window for Immediate Repetitions of Masked Primes versus Unrelated Prime Targets ($\beta$ = -4.19, *SE* = 1.08, $t(2012) = -3.89$, $p < .001$), Immediate Repetitions of Masked Primes versus Delayed Repetitions of Masked Primes ($\beta$ = 4.60, *SE* = 1.08, $t(2012) = 4.27$, $p < .001$), and Delayed Repetitions of

Visible Primes versus Delayed Repetitions of Masked Primes ($\beta$ = -5.97, *SE* = 1.08, *t*(2012) = -5.55, $p < .001$). Controls and PWA's different LPC responses to Delayed Repetitions of Masked Primes was also indicated by significant interactions of Delayed Repetitions of Masked Primes versus No Prime Targets x Group ($\beta$ = -9.81, *SE* = 3.10, *t*(2012) = -3.16, $p = .002$) and Delayed Repetitions of Masked Primes versus Immediate Repetitions of Masked Primes x Group ($\beta$ = 7.17, *SE* = 3.10, *t*(2012) = 2.31, $p < .001$). No other interactions were significant (*p*s > .05).

Both groups showed more positive deflections during the LPC time window for delayed repetitions of visible primes, as expected, than no prime targets or delayed repetitions of masked primes. This finding is consistent with Misra and Holcomb's (2003) results and suggests that visible primes were consciously perceived both when they were first presented as a prime and when they were presented again as a target. It also shows that delayed repetitions of visible primed elicited a stronger effect than delayed repetitions of masked primes, as would be expected if the masked primes were never consciously perceived at their first presentation as primes, thus preventing any conscious recollection when they were encountered at their second presentation as targets.

However, the remaining results were largely unexpected. We would only predict increased positivity to all the other types of repetitions of primes if the primes were consciously perceived when they were first (and subsequently) encountered. Yet, all the primes were allegedly masked, which should have stopped any LPC effect from occurring. While this finding implies that participants consciously detected and processed the masked primes, the other data that show a clear distinction between detection of masked versus visible words (i.e., the probe detection task results, the recognition task results, and the P300 results) suggest otherwise. Thus, the effect captured during the LPC time window might reflect a process other than explicit

recognition of a previously consciously perceived stimulus. For example, given that the LPC time window began at the same time point the N400 window ended and is subsumed within the P300 time window, it could be that we are capturing an extension of the N400 effect and/or an inextricable combination of components. Indeed, previous research has found that the N400 effect is often prolonged in both PWA and unimpaired older adults (e.g., Chang et al., 2016; Kutas & Iragui, 1998; Stalpaert et al., 2021), which could have also occurred in our sample. This possibility would require a detailed analysis beyond the scope of this study but is worthy of future research. Therefore, these unexpected findings are tempered by both the behavioral and other ERP data presented as part of this study and the extant literature on the LPC, reducing concerns that these LPC responses indicate the priming effects were due to something more than implicit mechanisms.

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**Acknowledgements**

Chapter 3, in full, is currently being prepared for submission for publication of the material. This chapter is coauthored with Dr. JoAnn P. Silkes. The dissertation author and co-author contributed equally to the research and authorship of this material.

We thank Maya Misra and Phil Holcomb for graciously sharing their experimental protocols. We thank Lee Osterhout, Judy McLaughlin, Mark Pettet, and Alyson Abel for their invaluable contributions to this work.

# Chapter 4 : EXPLORING AN UNDERLYING MECHANISM OF SEMANTIC DEFICITS IN DLD: AN ERP AND MASKED PRIMING INVESTIGATION


## Abstract

Many children with developmental language disorder (DLD) experience semantic deficits, but little is known about the mechanisms underlying those semantic deficits. Alterations in the time course of automatic spreading activation among lexical representations in the language system could contribute to semantic deficits. Using even-related potentials (ERPs) and a masked repetition priming paradigm with two different prime-target interstimulus intervals (ISIs), this study examined the time course of spreading activation for semantic and lexico-semantic processing in school-age children with and without DLD. Children with DLD showed an atypically rapid decay of activation, failing to show N400 priming effects for words (lexico-semantic) and only showing N400 priming effects for objects (semantic) at the shorter ISI, unlike their typically developing peers. Additionally, individual differences in activation timing were related to general language abilities rather than purely semantic skills. These findings provide new insights into the underlying mechanisms of semantic deficits in DLD and how alterations in those mechanisms are related to the language behavior of individuals with DLD.

## Introduction

### Semantic Processing in Developmental Language Disorder

Developmental language disorder (DLD) is language impairment that occurs in the absence of concomitant disorders (e.g., intellectual disability, autism spectrum disorder) and has no known biomedical causes (Bishop et al., 2017; Leonard, 2014; Watkins & Rice, 1994). It is the most prevalent neurodevelopmental language disorder in children, affecting 7.4% of children—over 5.4 million children in the US alone (Maenner et al., 2020; Norbury et al., 2016; Tomblin et al., 1997; U.S. Census Bureau, 2020; Zablotsky et al., 2019). Deficits in morphosyntax are considered a hallmark characteristic of children with DLD (Rice et al., 2004; Rice & Wexler, 1996) but are not the only impairment. One of the most impactful linguistic deficits in individuals with DLD—although overlooked, especially in school-age children with DLD—is in the domain of semantics (Alt et al., 2004; Alt & Plante, 2006; Botting & Adams, 2005; Dockrell et al., 2003; Drljan & Vuković, 2019; Gray, 2005; McGregor et al., 2002; McGregor, 2009; McGregor et al., 2013; McGregor & Appel, 2002; Nash & Donaldson, 2005; Rice et al., 1992, 1994; Sheng & McGregor, 2010a; Steele et al., 2013). This deficit greatly hinders individuals with DLD's ability to develop and use vocabulary and, consequently, negatively impacts not only academic success, literacy, and social relationships beginning in childhood, but also socioeconomic, independent living, and vocational outcomes (Adlof & Hogan, 2019; Conti-Ramsden et al., 2012; Conti-Ramsden & Botting, 2004; Dubois et al., 2020; Johnson et al., 2010; Norbury et al., 2016)

There is substantial evidence to suggest that individuals with DLD struggle to process semantic information and that their semantic representations are underdeveloped and/or harder to access compared to individuals with typical language development (e.g., Alt et al., 2004; Botting

& Adams, 2005; Drljan & Vuković, 2019; Gray, 2004; Hung & Sun, 2022; Mainela-Arnold et al., 2010; McGregor et al., 2013; Sheng & McGregor, 2010a; Velez & Schwartz, 2010). Much of this evidence comes from studies of children with DLD's word learning abilities, which have consistently found children with DLD demonstrate difficulties with learning new words (see Kan & Windsor, 2010 for an overview). Importantly, though, individuals with DLD's semantic deficits are not limited to issues with vocabulary expansion. Studies using methods that tap into how semantic information is processed, described more below, have found that individuals with DLD demonstrate impairments in the very mechanisms of semantic processing (e.g., Helenius et al., 2009, 2014; Pizzioli & Schelstraete, 2011; Velez & Schwartz, 2010).

**Semantic Processing and Automatic Spreading Activation**

Semantic processing is often viewed within the context of connectionist network models of lexical-semantic processing, like the Interactive Activation (e.g., Dell, 1986; Dell & O'Seaghdha, 1992) and Parallel Distributed Processing (e.g., Nadeau, 2001) models. In these models, mental representations (e.g., lexical items) are composed of individual units that each consist of a different and specific piece of information (e.g., the letter *c* or the concept *meows*) and form an interconnected and interactive network. Processing of these representations occurs by activation automatically spreading from one unit to other, related units and back. Activation spreads among units both within and across multiple domains (e.g., phonology, semantics) based on connection strength, heightening the activation of some units to the point of selection and allowing the activation of others to decay over time. Put another way, input to the system (e.g., reading the word *cat*) activates the units of a lexical item in one domain (e.g., orthography), which then automatically spread activation to the corresponding units in the other domains (e.g., lexical, semantic), as well as to units that are less closely related to the lexical item within the

same domain (e.g., the semantic units for *mouse* will also be activated, but to a lesser degree than for *cat*). The activation continues spreading back-and-forth between units, interacting to consistently reactivate some units and letting other units lose their activation so that specific units emerge as the most highly activated, ultimately leading to lexical selection. Thus, the mechanism of automatic spreading activation is a driving force behind lexical and semantic processing in these models.

Importantly, automatic spreading activation operates very quickly and is entirely implicit (i.e., occurring without any conscious awareness or control). In a typical language system, activation both spreads and decays rapidly, only maintaining activation long enough for the system to act upon the active units, so as to prevent interference in downstream language processing. If the timing of the automatic spread or decay of activation is impaired (e.g., delayed or accelerated), the correct units might not be activated at all or at the right time, hindering integration and selection of lexical and semantic information and impacting subsequent higher-level language (e.g., sentence, discourse) processing. There is evidence that an alteration in the time course of spreading activation explains linguistic deficits in individuals with aphasia (e.g., Ferrill et al., 2012; Pankonin & Silkes, in prep; Silkes & Rogers, 2012), and some researchers have suggested an impairment in spreading activation might also be implicated in individuals with DLD (e.g., Borovsky et al., 2013; Helenius et al., 2009, 2014; McMurray et al., 2014; Pizzioli & Schelstraete, 2011; Velez & Schwartz, 2010).

**Priming**

A common method used to examine the time course of spreading activation and how it might be altered in individuals with linguistic deficits is priming (e.g., Ferrill et al., 2012; Helenius et al., 2009, 2014; Kiefer, 2002; McNamara, 1992; Neely, 1977; Pankonin & Silkes, in

prep; Pizzioli & Schelstraete, 2011; Prather, 1994; Prather et al., 1992, 1997; Silkes & Rogers, 2012; Velez & Schwartz, 2010). In the priming paradigm, a prime stimulus (e.g., a word, a picture), which might or might not be consciously perceptible or responded to, precedes a consciously perceptible target stimulus that the individual usually overtly responds to in some way (e.g., naming, semantically categorizing). Typically, the target is related to or the same as the prime, thus allowing the prime to influence the response to the target via spreading activation. That is, the prime activates the same units that the target will eventually activate, thereby reducing the additional spread of activation needed to process the target when it is subsequently encountered (Forster et al., 2003; Meyer & Schvaneveldt, 1971; Schacter, 1992; Tulving & Schacter, 1990). This facilitated processing leads to a faster, more robust, and/or more accurate response to the target relative to some "baseline" performance (e.g., when a target is encountered after an unrelated prime), which is referred to as a priming effect.

Priming is thought to operate primarily through automatic spreading activation, making it an ideal window into the timing of this mechanism (Forster et al., 2003; Posner & Snyder, 1975). Atypical priming effects (e.g., slowed or unchanged reaction times, delayed onsets of priming effects or long-lasting priming effects), then, can be interpreted as reflecting alterations in the time course of spreading activation and reveal how one's processing—including (lexico-) semantic processing—is impaired. Several researchers have capitalized on this with individuals with aphasia, using priming tasks to characterize the underlying nature of these individuals' linguistic impairments (e.g., Avila et al., 2001; Ferrill et al., 2012; Pankonin & Silkes, in prep; Prather et al., 1992; Prather, 1994; Prather et al., 1997; Silkes et al., 2020; Silkes & Rogers, 2012). Priming studies with children, particularly those with DLD, are far less common, with

few using the priming paradigm to specifically investigate the time course of spreading activation in children with DLD.

**Priming in Children With DLD**

The small number of priming studies with children with DLD have used various types of priming (e.g., semantic, phonological, repetition), all of which have provided insight into semantic processing abilities in these children (e.g., Brooks et al., 2015; Kornilov et al., 2015; Lahey & Edwards, 1996; Velez & Schwartz, 2010). Many of the findings across these studies are inconsistent and sometimes even contradictory. Children with DLD have shown the most consistent behavioral priming effects when provided a prime that is both phonologically and semantically identical to the target, as is the case in repetition priming (e.g., Helenius et al., 2014; Lahey & Edwards, 1996; Velez & Schwartz, 2010). With repetition priming, children with DLD have been found to be faster to name or make a lexical decision about a repeated (i.e., primed) target than an unrepeated (i.e., unprimed) target (Lahey & Edwards, 1996; Velez & Schwartz, 2010). However, even in this case, children with DLD continued to show overall slower reaction times than their peers, suggesting the mechanism underlying lexical and semantic processing is altered and affects language processing even in the simplest and most supportive priming situation. The slower reaction times imply this alteration could involve delayed spreading activation, which would align with a generalized slowing hypothesis (Kail, 1994) and evidence from other studies with children with DLD that they are slower at recognizing words and naming (Montgomery, 2002, 2006; Sheng & McGregor, 2010b) and benefit from a slower input rate (Ellis Weismer & Hesketh, 1996; Montgomery, 2004, 2005).

Studies that have examined priming effects in individuals with DLD using more sensitive methods, such as electroencephalography (EEG) and magnetoencephalography (MEG), provide

additional evidence of an alteration in individuals with DLD's semantic processing abilities. Using an auditory primed-pair paradigm, where an auditory prime word and auditory target word are presented one after the other (i.e., in pairs), children with DLD showed the same general patterns of neural priming effects as their typically developing (TD) peers (i.e., the effect peaked at the same time and was of the same strength for both groups) for repeated targets compared to their first presentation (Helenius et al., 2014) or compared to when they were unrelated to their prime (Shafer et al., 2004). However, when Helenius and colleagues (2014) examined their priming effect in more detail by exploring the effect by hemisphere, they found virtually no neural priming effect in the language-dominant left hemisphere and that all responses were isolated to the right hemisphere. In contrast, TD children showed the responses in both hemispheres but stronger responses in the left. Interestingly, this atypical distribution of responses was not found in young adults with DLD, but the young adults with DLD did show an overall weaker neural priming effect compared to their typical peers, illustrating the persistent nature of the language processing deficits of DLD (Helenius et al., 2009).

Thus, the few studies considering the underlying mechanism of semantic processing in DLD that used priming have found evidence indicating an altered time course of spreading activation in children with DLD. Importantly, though, the nature of the alteration is variable across these studies. In some cases, children with DLD showed nearly nonexistent priming effects (Helenius et al., 2014) while, in other cases, they showed equivalent (Velez & Schwartz, 2010) priming effects but still slower reaction times than their TD peers. Some of this variability might be due to the heterogeneity of the DLD profile (Bishop, 2006), but it is also likely due to the use of priming tasks in which both primes and targets were consciously perceptible (i.e., visible/audible).

**Masked ERP Priming**

When primes are consciously perceptible, individuals are likely to make use of conscious, strategic processes (Forster, 1998; Forster et al., 2003; Posner & Snyder, 1975; Prather et al., 1997; Silkes et al., 2020). This is noteworthy because semantic processing typically involves not only automatic spreading activation but also conscious, top-down processing. If participants can see and identify primes in priming tasks, then priming effects will be the result of both conscious and unconscious processing (Forster et al., 2003; Posner & Snyder, 1975). When both implicit and explicit processing is involved, it is impossible to disentangle the extent to which priming effects are due to strategic adaptations to the experiment versus implicit mechanisms, like spreading activation facilitating processing (Forster, 1998; Forster et al., 2003; Posner & Snyder, 1975; Prather et al., 1997; Silkes et al., 2020). Consequently, studies that attempt to understand or identify spreading activation without carefully controlling the stimulus presentation face challenges in interpreting their findings as implicit processes are not isolated.

To directly examine how the time course of automatic spreading activation is altered in children with DLD, priming must be restricted to solely the implicit, automatic mechanisms and measured in real time. "Masking" the prime, or preventing it from reaching conscious awareness, is one way of isolating priming to spreading activation, as it removes the opportunity to identify a relationship between the target and prime. A prime is typically masked by presenting it for a very brief amount of time and immediately preceding and/or immediately following its presentation with additional stimuli (e.g., a series of hashmarks if the prime is a word), which interfere with the conscious perception of the prime but not its unconscious effect on language processing (Forster, 1998; Forster et al., 2003; Holcomb & Grainger, 2007). After the masked

prime, a target is presented for a duration long enough to be consciously perceived, and the participant responds to it.

Once the mechanism of spreading activation is isolated via masked priming, neurophysiological measures with precise temporal resolution, such as event-related potentials (ERPs), can be used to directly index it. The N400 ERP component is often the component of choice for examining the time course of automatic spreading activation, especially once the priming effects can be constrained to only automatic, unconscious mechanisms. The N400 component is a negative-going waveform that typically occurs between 300 and 500 ms post-stimulus onset, peaking around 400 ms, and is thought to reflect semantic processing (Kutas & Federmeier, 2011; Kutas & Hillyard, 1984). In both children and adults, easier and more efficient semantic processing, as typically results from priming, is associated with an attenuated (i.e., less negative) amplitude, while more difficult and/or more effortful semantic processing is associated with an enhanced (i.e., more negative) amplitude of the N400 component (e.g., Abel et al., 2018; Eddy et al., 2014; Holcomb et al., 1992, 2002; Holcomb & Grainger, 2006; Kiefer, 2002; Kiyonaga et al., 2007; Misra & Holcomb, 2003). Additionally, this change in amplitude will occur even if stimuli are not consciously perceived (e.g., in the case of masked priming), suggesting that the semantic processing that the N400 component indexes is automatic (Kiefer, 2002; Misra & Holcomb, 2003). As such, the N400 component can serve as a measure of the impact of priming on semantic processing, revealing the (dys)functioning of the mechanisms underlying semantic processing, such as automatic spreading activation, as it happens. Indeed, the use of the N400 component in combination with the masked priming paradigm for such investigations is supported by evidence from studies with several different populations, including

TD children as young as 7 (Eddy et al., 2014), but never, to our knowledge, with children with DLD until the present study.

**Lexico-semantic and Semantic Processing**

An important step in systematically examining the semantic deficits in children with DLD is isolating semantic processing from processing other lexical features with which this population might also have difficulties (e.g., orthography/reading words; Buil-Legaz et al., 2015; Catts et al., 2002; Dockrell et al., 2009; Hall & Tomblin, 1978; Johnson et al., 2010; Ricketts, 2011; Stoeckel et al., 2013). Using a masked ERP priming approach helps to isolate semantic processing, but complete isolation is virtually impossible when the stimulus is a word as a word's semantic information is inextricably tied to other lexical (e.g., phonological) information as well. Semantic information is, in fact, amodal in nature, though (Holcomb & McPherson, 1994; McPherson & Holcomb, 1999), and is processed for more than solely words; objects, or images (e.g., line drawings, color photographs, 3D computer-rendered models) of objects, also carry semantic information. Indeed, the same robust N400 priming effects found in visual word priming studies have also been obtained in several object perception priming studies (with typical adults and children; e.g., Collette et al., 2016; Eddy et al., 2006; Eddy & Holcomb, 2009, 2010, 2011; Holcomb & McPherson, 1994; B. Li et al., 2019). These priming effects are considered to be indicative of facilitated semantic processing. Thus, using objects as the prime and target stimuli, one can investigate exclusively semantic processing abilities with reduced lexical influences. Both semantic processing and lexico-semantic processing provide valuable insight into our understanding of the nature of the semantic deficits seen in children with DLD, motivating the exploration of both.

**Present Study**

The present study investigates the time-course of spreading activation for semantic and lexico-semantic processing in school-aged children with and without DLD. It also explores the possible link between differences in the time course of spreading activation and semantic abilities across individuals given the wide variability of language impairment in DLD and evidence that the extent of the semantic deficits in children with DLD overlaps with the spectrum of semantic abilities in TD children (Gray, 2003, 2004; Kiernan & Gray, 1998). To achieve this, we used a combined EEG and behavioral approach and a masked repetition priming paradigm with two different prime-target interstimulus intervals (ISIs). Children with DLD and typical language completed a behavioral assessment battery, including a measure of their semantic abilities. In addition, they did a priming task during which EEG data was collected while they saw sequentially presented prime and target stimuli and completed a go/no-go semantic categorization button-press task. Critically, in the priming task, the prime-target ISI for each trial was either comparatively long (317 ms) or comparatively short (67 ms) while both still being short enough to elicit masked priming effects via purely automatic mechanisms (Cheesman & Merikle, 1984; Eddy & Holcomb, 2010; Emmorey et al., 2021; Kiefer, 2002) but different enough that an alteration in the time course of spreading activation should lead to a different pattern of priming effects (Silkes & Rogers, 2012). Additionally, the priming task included two experimental conditions that all children completed: a visual word priming condition and an object (i.e., picture) priming condition. We examined the N400 ERP component responses in the two groups of children to primed and unprimed targets following each prime-target ISI across the Word and Object Priming conditions. We also explored how the individual differences in the neural priming patterns across the ISIs relate to the children's behavioral measures.

We predicted the following:

1. In both the word priming and object priming conditions, children with DLD would show priming effects at only the longer ISI, unlike their TD peers who would show priming effects at both shorter and longer ISIs. This was hypothesized to occur based on other studies using a similar masked priming paradigm with TD children and other clinical populations (Eddy et al., 2014; Silkes & Rogers, 2012) that have found that using different lengths of ISIs is a valid way to identify variations in the time course of spreading activation. Additionally, evidence of generalized slowing in children with DLD led us to predict that spreading activation would be delayed in children with DLD compared to their TD peers, and that both lexico-semantic and semantic processing would be similarly affected. This pattern of findings would suggest the alteration in children with DLD's time course is atypically slow spreading activation, partially explaining their semantic deficits.
2. The difference in N400 priming effects across the two ISIs would predict individual differences in semantic abilities, with N400 priming differences from the visual word priming condition better predicting semantic ability than the N400 priming differences from the object priming condition. This prediction was based on the fact that several individual factors, such as existing vocabulary knowledge (Kiernan & Gray, 1998) or processing speed (Leonard et al., 2007), have been suggested to play a role in the variability in semantic abilities across children with and without DLD, but none have been conclusively identified as the variability's source. Furthermore, because spreading activation underlies semantic processing, individual variations in the time course of spreading activation could play a role in differences in semantic

abilities across individuals. Finally, due to the lexico-semantic nature of most behavioral measures of semantic abilities, priming differences from the lexico-semantic priming condition (i.e., word priming) should be the most closely aligned with individual differences in such measures. Finding these results would provide additional evidence that the time course of spreading activation underlies semantic abilities and that alterations like delayed spreading activation contribute to semantic deficits, especially lexico-semantic deficits, in DLD.

## Method

### Participants

Participants were recruited from the Southern California community through flyers posted on social media and at local businesses and speech-language pathology clinics. To be eligible to participate, participants were required to primarily or only speak English; have no hearing or uncorrected visual impairments; be able to read early-acquired single words; have no history of significant neurological and/or genetic conditions (e.g., autism spectrum disorder, Down syndrome, intellectual disability, epilepsy, central nervous system diseases, high fevers, seizure disorders, traumatic brain injury, cerebral vascular accident, or tumors); and not to use medications other than over-the-counter analgesics within 24 hours prior to testing, per parent report. If they were deemed eligible, prior to participating, all participants gave informed assent and a legal guardian of each participant gave informed consent, in accordance with the Institutional Review Board of San Diego State University. Each participant received monetary compensation for their participation.

A total of 42 children participated in this study. One child withdrew before completing the study, leading to the exclusion of all their data. Another child's EEG data from only the

object priming condition of the priming task were excluded due to excessive movement artifacts; however, all other data from this child were retained, allowing them to remain part of the final participant group. Thus, the final participant group consisted of 41 children aged 7;11 to 14;6. Of these children, nine (two female, seven male) were classified as presenting with DLD and 32 (13 female, 19 male) were classified as TD, making up the control group. Children were classified into these groups based on the composite scaled scores they earned on subtests of a standardized global language measure, the Clinical Evaluation of Language Fundamentals – Fifth Edition (CELF-5; Wiig et al., 2013). Children who earned a scaled score that was 1.5 or more standard deviations below the mean on two or more subtests composing the CELF-5 Core Language Score were classified into the DLD group.

In addition to the CELF-5, children completed a behavioral assessment battery that included the Test of Integrated Language and Literacy Skills (TILLS) Vocabulary Awareness test (Nelson et al., 2016); the Woodcock-Johnson III Normative Update Tests of Achievement (WJ III NU ACH) Letter-Word Identification test (Woodcock et al., 2001); Dollaghan and Campbell's (1998) nonword repetition task; the Test of Nonverbal Intelligence, Third Edition (Form A; TONI-3; L. Brown et al., 1997); the NIH Toolbox Flanker Inhibitory Control and Attention Test (Gershon et al., 2013); and the Edinburgh Handedness Inventory (Oldfield, 1971). The TILLS test served as our behavioral measure of semantic ability, while the primary purpose of including the other measures was to control for other individual differences, specifically differences in single word reading ability, phonological memory, nonverbal cognition, inhibition and attention, and hand dominance (a proxy for language lateralization in the brain; M. Li et al., 2014), respectively. All the tasks, including both the behavioral assessments and priming task, were counterbalanced across participants and completed across at least two sessions.

Table 1 summarizes the assessment results of the two groups. The groups did not significantly differ on any measures except for the CELF-5 Core Language Score, in which the children with DLD earned significantly lower scores than the TD children (see Table 4). Similarities across groups on all other measures demonstrate that the groups were matched in many ways and further motivates our exploration of individual difference in addition to group differences.

Table 4.1. Summary of behavioral assessment results (mean standard scores and standard deviations) for the DLD and TD groups.

| Group | Age | CELF-5 CLS | TILLS VA | WJ III LWI | NWR PPC | TONI-3 | Flanker | Right-Handed |
|---|---|---|---|---|---|---|---|---|
| DLD | | | | | | | | |
| *M* | 10.90 | 83.78 | 4.11 | 89.78 | 89.47 | 100.33 | 99.33 | *n* = 9 |
| *SD* | 2.32 | 4.68 | 2.32 | 9.22 | 7.04 | 8.59 | 18.75 | |
| TD | | | | | | | | |
| *M* | 11.53 | 106.06 | 7.84 | 107.13 | 94.21 | 106.59 | 114.72 | *n* = 26 |
| *SD* | 1.81 | 10.97 | 2.85 | 14.69 | 6.00 | 16.45 | 19.85 | |
| *t* test | 0.005 | 3.45** | -0.76 | 1.55 | -1.26 | -0.49 | -0.43 | — |
| *p* | .996 | .001 | .46 | .14 | .23 | .64 | .67 | — |

*Note.* DLD = developmental language disorder; TD = typically developing; CELF-5 CLS = Clinical Evaluation of Language Fundamentals – Fifth Edition Core Language Score; TLLS VA = Test of Integrated Language and Literacy Skills Vocabulary Awareness; WJ III LWI = Woodcock-Johnson III Normative Update Tests of Achievement Letter-Word Identification; NWR PCC = nonword repetition percent consonants correct; TONI-3 = Test of Nonverbal Intelligence, Third Edition; *$p < .05$; **$p < .01$.

## Priming Task

The Word and Object Priming conditions were constructed to be identical in every way except for the appearance of the stimuli, so all descriptions of the stimuli and procedure apply to both of these experimental conditions unless specified otherwise.

### *Stimuli*

Seventy-two non-animal and 30 animal stimuli were repeated as visible and masked primes and visible targets across a total of 338 trials per experimental condition. All trials

included a prime stimulus, which was preceded and followed by a mask stimulus, and a subsequent target stimulus. Critical trials consisted of prime-target pairs of non-animal stimuli whereas non-critical trials included pairs composed of non-animal and animal stimuli, described further below.

Stimuli used in the Word Priming condition were three- to five-letter-long labels of common objects and animals (i.e., concrete nouns) and easily recognized by beginning readers (i.e., "sight" words with a mean age of acquisition rating of 5;0; Brysbaert & Biemiller, 2017). Prime words were presented in lowercase letters and target words were presented in uppercase letters. A series of hashmarks (######) were used for the mask for the word priming condition.

Stimuli used in the Object Priming condition were colored pictures of the same common objects and animals that comprised the word stimuli. Pictures were drawn from Martindale's (2024) object database. To approximate the visual differences between the lowercase and uppercase presentations of the prime and target word stimuli, prime pictures were presented at 300 x 300 pixels and target pictures were presented at 480 x 480 pixels. A kaleidoscopic picture taken from Voss et al. (2008) presented at 500 x 500 pixels was used for the mask for the object priming condition.

Within each condition, there were both masked and visible primes. The primary purpose of this prime visibility manipulation was to facilitate participants' attention to the prime epoch across the experiment and potentially enhance the priming effects in masked trials, as the inclusion of visible primes does (Holcomb et al., 2005; Kahan, 2000). Data from the masked trials were our main interest and the source for our key analyses.

To elicit priming effects, within each experimental condition, there were 168 critical trials in which the target was either primed (84 trials: 42 visible trials, 42 masked trials) or

unprimed (84 trials: 42 visible trials, 42 masked trials). In the primed trials, the prime and target were the same non-animal stimulus (i.e., the prime stimulus was repeated as the target stimulus). In the unprimed trials, the prime and target were two different, unrelated non-animal stimuli. Each non-animal stimulus appeared in each position of each type of critical trial, thus appearing in six trials, but only in one position in one trial per block of a stimulus list. There was a total of seven blocks per stimulus list, and the blocks were counterbalanced using a Latin Square, resulting in seven lists. The lists were also counterbalanced across experimental conditions and participants.

There were an additional 120 unprimed trials (60 masked trials, 60 visible trials) that served as the non-critical, semantic categorization probe trials. In these trials, an animal stimulus appeared in one of the prime-target positions and an unrelated non-animal stimulus unique to the probe trials (i.e., never presented in the critical trials) appeared in the other. While an animal stimulus appeared as both a prime (in 60 trials: 30 masked trials, 30 visible trials) and a target (in 60 trials: 30 masked trials, 30 visible trials) across a list, it never appeared as both the prime and target within a single trial (i.e., there were no primed probe trials). Probe trials were included in the aforementioned counterbalancing procedure. Table 2 provides examples of the each of the different trial types.

A final set of 50 unprimed trials (all masked), 20 of which included animal stimuli in the prime position, were used to determine participants' thresholds for consciously perceiving masked primes. Non-animal stimuli appeared in the target position for all trials, as well as in the prime position for the remaining 30 trials. The order of these 50 trials was constant across stimulus lists but varied across experimental conditions. Thresholds obtained from this task were not used as exclusionary criteria but instead as another measure to control for individual

differences outside of semantic abilities. By accounting for individual differences in how long a masked prime can be presented for before becoming "visible" (e.g., the prime's semantic category is identifiable) to each participant, we could ensure priming effects were attributable to unconscious processing (Cheesman & Merikle, 1984; Dagenbach et al., 1989; Misra & Holcomb, 2003). Efforts, such as these, to prevent explicit processing from contaminating the priming effects were especially critical given the aims of this study.

Table 4.2. Examples of each of the trial types used in the priming task. The visibility of the prime determined whether the trial was a masked or visible trial. The trial was considered primed if the target was a repetition of the prime and unprimed if the target was unrelated to the prime. All trials containing animal stimuli were non-critical probe trials and trials consisting of only non-animal stimuli were critical trials. Although trials from the Word Priming condition are provided as examples here, the same trial types were present in the Object Priming condition.

| prime | TARGET | Prime Type | Target Type |
|---|---|---|---|
| rope | ROPE | visible non-animal | primed non-animal |
| pizza | HUSKY | masked non-animal | animal probe |
| jeep | HARP | visible non-animal | unprimed non-animal |
| pool | POOL | masked non-animal | primed non-animal |
| orange | TROPHY | masked non-animal | unprimed non-animal |
| finger | FINGER | visible non-animal | primed non-animal |
| crab | MASK | visible animal probe | unprimed non-animal |
| belt | SWAN | visible non-animal | animal probe |
| shark | CARROT | masked animal probe | unprimed non-animal |
| tie | CAKE | visible non-animal | unprimed non-animal |

***Procedure***

Participants were seated in a dimly lit, acoustically attenuated room approximately three feet away from a computer monitor on which stimuli were presented against a white background

in the center of a screen time-locked to the vertical refresh rate of the monitor (60 Hz). Each trial consisted of the following stimuli in this order: a 500-ms forward mask or mask placeholder, a 500-ms or 83-ms prime stimulus, either a 67- or 317-ms backward mask or mask placeholder, a 500-ms visible target stimulus, and a 2500-ms "+" marking the end of the trial and when to blink (see Figure 1 for a structure of a single trial). The duration of the prime stimulus presentation and whether the trial contained masks or mask placeholders depended on whether the trial was a masked trial (83-ms prime stimulus, masks) or a visible trial (500-ms prime stimulus, mask placeholders). The two durations of the backward mask were pseudorandomly interspersed (neither duration occurred for more than three consecutive trials). Stimuli durations were selected based on previous masked ERP priming studies with children and clinical populations (e.g., Eddy et al., 2014; Emmorey et al., 2021; Silkes & Rogers, 2012) and technical constraints of the computer monitor used to display the stimuli.

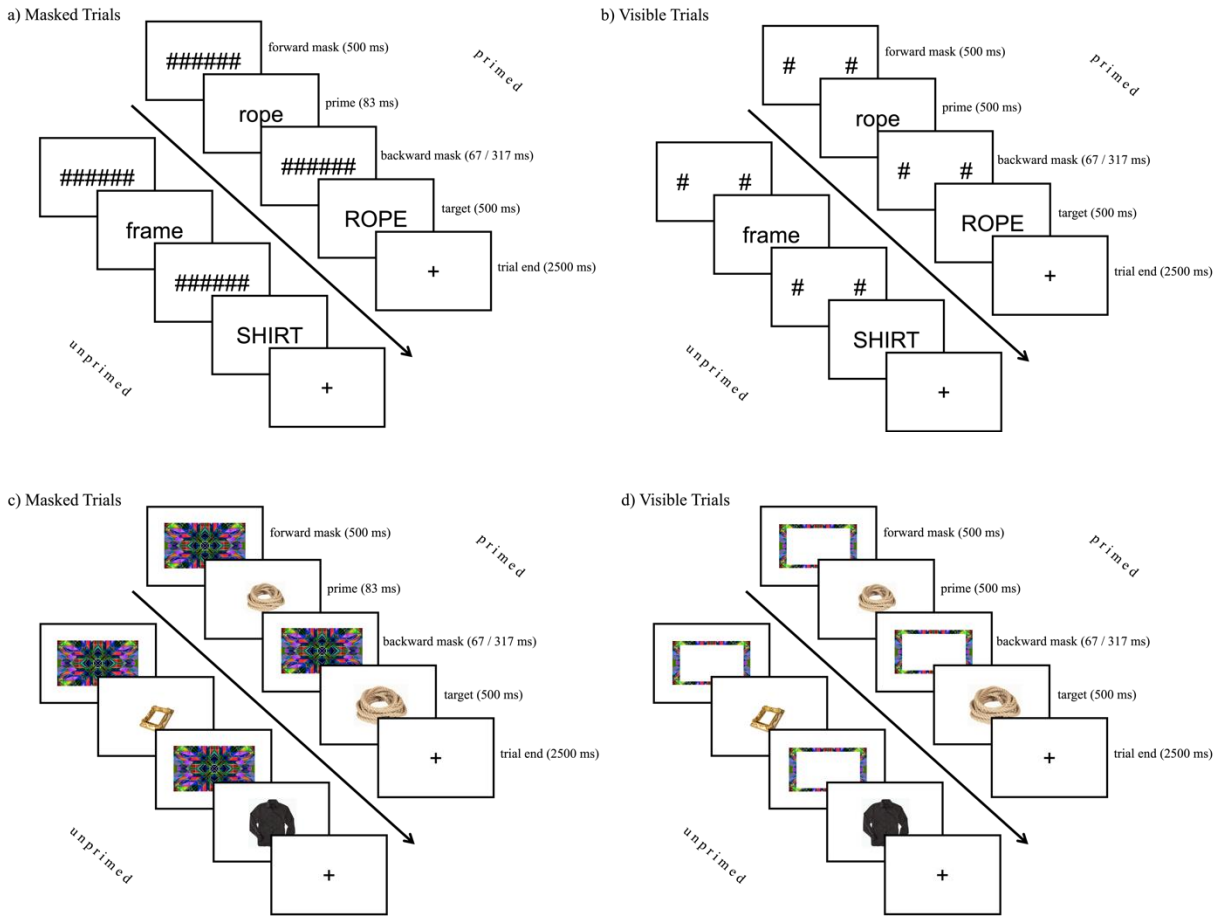


Figure 4.1. Typical critical trials and timing for a) a masked trial and b) a visible trial in the Word Priming condition and c) a masked trial and d) a visible trial in the Object Priming condition.

Children were asked to press a button on a Contour ShuttleXpress controller every time the stimulus they saw was an animal (i.e., a go/no-go semantic categorization task). No response to the non-animal stimuli was required, and the researcher highlighted response accuracy, not speed, during the task instructions. To familiarize participants with completing the task, they first completed a set of 10 practice trials that included at least one of each trial type, with feedback provided as needed. No feedback was provided during the experimental portion of the task. Requiring a response to animal stimuli facilitated ongoing engagement with the task and required

semantic processing of each stimulus. In addition, it allowed for ensuring effective masking by reviewing the proportion of responses to animal stimuli in the masked prime position (see behavioral results below). Moreover, not requiring a response to the non-animal stimuli prevented the neural responses during the critical trials from being contaminated by the electrical activity generated by motor movements.

As the final block of the task, participants completed the set of prime duration visibility threshold trials so we could obtain a measure for controlling individual variations in priming thresholds. In the probe trials of this set, the duration of the animal prime stimulus was systematically varied across the trials to test participants' ability to detect a masked prime of five different prime durations: 50 ms, 67 ms, 83 ms, 100 ms, and 117 ms. Each of these prime durations occurred with each of the two ISIs across the trial set, and the timing of all other stimuli composing a trial was the same as for the standard trials preceding this block. The remaining non-animal trials had the same structure and timing parameters as standard trials. A participant's threshold was determined as the shortest duration of the five tested at which the participant identified the masked animal primes with greater than 50% accuracy. See Table 3 for the prime duration thresholds obtained for each group in each experimental condition.

Table 4.3. Number of participants with each prime duration threshold. The dotted line separates the durations by whether they are less than or equal to (above the line) or greater than (below the line) the duration at which masked primes were presented during the experimental priming task.

| Prime Duration | Word Priming | | Object Priming | |
|---|---|---|---|---|
| | DLD | TD | DLD | TD |
| 50 ms | 3 | 7 | 5 | 9 |
| 67 ms | 2 | 7 | 1 | 5 |
| 83 ms | 2 | 0 | 1 | 0 |
| 100 ms | 0 | 1 | 0 | 2 |
| 117 ms | 0 | 0 | 0 | 0 |
| > 117 ms | 2 | 17 | 2 | 16 |

### *EEG Procedure*

EEG data were continuously recorded via a 64 silver/silver-chloride electrode cap (Neuroscan Quickcap), Neuroscan Neuvo amplifier, and CURRY 7 software at a 1 kHz sampling rate. Electrodes were placed using the standard International 10-20 system positioning with two additional electrodes placed on the face (one above and one below each participant's left eye) to measure the electrooculogram (EOG) and monitor ocular motor movement. Impedances were reduced to 5 kΩ or less when possible and monitored by researchers throughout the study.

EEG data were processed using the EEGLAB (version 2024.0; Delorme & Makeig, 2004) and ERPLAB (version 11.02; Lopez-Calderon & Luck, 2014) open-source toolboxes of MATLAB. Offline, data were resampled at 500 Hz, filtered between 0.2 and 10 Hz, and re-referenced to temporoparietal electrodes (TP7, TP8). To correct for the effects of ocular motor movement on brain data, independent components analysis (ICA) decomposition (Delorme et al., 2001) was performed. Trained researchers manually inspected and removed components related to ocular motor movement artifacts from each participant (rejected components: DLD: $M = 4.40$, $SD = 1.33$; TD: $M = 3.74$, $SD = 1.24$; $t(10.73) = 1.41$, $p = .188$) and visually identified and interpolated data for electrodes with large impedances to yield 62 data channels for each participant (channels interpolated: DLD: $M = 1.50$, $SD = 1.90$; TD: $M = 1.18$, $SD = 1.40$; $t(18.06) = -0.53$, $p = .602$). Using the same baseline of 50 ms pre- and post-target onset as previous pediatric masked priming research (Eddy et al., 2014) to line up the early portions of the ERP waveforms across conditions, average ERPs time-locked to target onsets were formed for primed and unprimed trials from trials that were not contaminated by ocular or non-brain artifacts. For each experimental condition, participants with an average of 50% or more trials rejected due to artifact contamination were excluded from further analyses for that experimental condition. For

the Word Priming condition, an average of 9.57 trials were rejected for TD children (*SD* = 10.46) and 14.54 trials were rejected for children with DLD (*SD* = 13.57), and an average of 10.91 trials were rejected for TD children (*SD* = 13.38) and 13.41 trials were rejected for children with DLD (*SD* = 13.67) for the Object Priming condition (there were no significant differences between groups or conditions, all *p*s > .05).

## Analyses and Results

All data were analyzed using simple linear or linear mixed-effects (LME) regression models fit using restricted maximum likelihood (REML) estimation in R (version 4.3.2; R Core Team, 2023) with the *lme4* package (version 1.1-35.1; Bates et al., 2015). A priori comparisons were conducted using the *emmeans* package (version 1.10.0; Lenth, 2022). Data from each of the experimental conditions were analyzed separately unless specified otherwise.

### Behavioral Analysis

As a measure of masking effectiveness, analyzed behavioral responses to probes during the experimental trials of the priming task. We analyzed the data from both experimental conditions together via an LME regression with fixed within-subject factors of Stimulus Type (prime vs. target), ISI (67 ms vs. 317 ms), Group (TD vs. DLD), and Experimental Condition (Word Priming vs. Object Priming) and random intercepts for participant. We used planned follow-up pairwise comparisons to compare responses to each stimulus type and performances across groups, controlling for multiple comparisons with a Bonferroni correction. Because these behavioral responses were merely a measure of masking effectiveness, we were only interested in the probe detection rate comparisons, so the overall model results are not reported.

**Behavioral Results**

Both groups of participants successfully detected most of the animal probe stimuli in the target position, with an average accuracy of 84.86% (*SD* = 21.91%) for words and 94.26% (*SD* = 15.39%) for objects. Additionally, both groups responded to fewer animal probe stimuli in the masked prime position, particularly in the word priming condition, than in the target position (all *p*s < .001). There were no significant differences between the two groups on any probe measures (all *p*s > .05). See Table 4 for a more in-depth breakdown of detection rates.

Table 4.4. Percent accuracy of detecting probes in the prime and target position for each experimental condition.

| | Word Priming | | Object Priming | |
|---|---|---|---|---|
| DLD | Prime | Target | Prime | Target |
| *M* | 0.66 | 0.79 | 0.85 | 0.96 |
| *SD* | 0.26 | 0.23 | 0.22 | 0.07 |
| TD | | | | |
| *M* | 0.75 | 0.86 | 0.81 | 0.94 |
| *SD* | 0.28 | 0.22 | 0.28 | 0.17 |

**Omnibus ERP Analyses and Results**

***Analysis***

Given this study's pioneering approach of using masked priming with children with DLD, we initially conducted omnibus analyses of the ERP data to determine whether it was appropriate to analyze the data from solely the masked trials or whether separate analyses of the masked and visible data were unwarranted. For these omnibus analyses, we pooled the data from both participant groups. As previous pediatric masked ERP priming studies have done (e.g., Eddy et al., 2014), we measured mean amplitudes during a time window of 300-500 ms from 12 electrode sites: F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, Oz, and O2. We selected our time window based on

both prior pediatric masked N400 priming studies (e.g., Eddy et al., 2014) and visual inspection of the grand average waveforms. We subjected those mean amplitude measures to LME regressions that included fixed within-subject factors of Priming (primed vs. unprimed), ISI (67 ms vs. 317 ms), and Prime Visibility (masked vs. visible) and random intercepts for participant and electrode. All fixed factors were sum coded (-0.5, 0.5), meaning the model intercept reflects the average N400 mean amplitude across the three factors.

***Word Priming Condition Results***

The omnibus analysis of the Word Priming condition data revealed significant main effects of Priming (ß = -0.26, *SE* = 0.06, $p < .001$), reflecting a more negative amplitude for unprimed targets than primed targets (i.e., a typical priming effect), and ISI (ß = -0.59, *SE* = 0.06, $p < .001$), with targets following the shorter ISI showing a more negative amplitude than targets following the longer ISI. This analysis also revealed a significant interaction of Prime Visibility x ISI (ß = -1.69, *SE* = 0.12, $p < .001$), reflecting a reversed ISI pattern (i.e., more negative amplitudes for targets following the longer ISI) in the visible trials. Given these contrasting patterns and our interest in implicit processes, we further analyzed the data from solely the masked trials.

***Object Priming Condition Results***

Significant effects of Priming (ß = -0.34, *SE* = 0.07, $p < .001$), ISI (ß = -0.40, *SE* = 0.07, $p < .001$), and Prime Visibility x ISI (ß = -2.15, *SE* = 0.15, $p < .001$) emerged from the omnibus analysis of the Object Priming condition data. These effects reflected the more negative going amplitudes for unprimed targets versus primed targets (i.e., typical priming effect) and more negative amplitudes for targets following the shorter ISI versus the longer ISI, showing the same patterns as we found in the Word Priming condition data. The Prime Visibility x ISI interaction,

again, captured the ISI pattern reversal occurring with targets following visible primes. In the visible trial data, targets following the longer ISI elicited a more negative deflection compared to targets following the shorter ISI. Based on the differing ISI patterns and our interests, only the masked trial data were analyzed further.

## Masked Trial ERP Analyses and Results

### *Analysis*

To test our specific hypotheses regarding the masked priming differences across ISIs in each group, we performed analyses on the mean amplitude measurements during the same time window from a cluster of 18 central through parietal (C3, C1, Cz, C2, C4, C6, CP3, CP1, CPz, CP2, CP4, CP6, CP3, P1, Pz, P2, P4, P6; for Word Priming data) or frontocentral through centroparietal (FC3, FC1, FCz, FC2, FC4, FC6, C3, C1, Cz, C2, C4, C6, CP1, CPz, CP2, CP4, CP6, CP3; for Object Priming data) electrode sites. Electrode site selection was guided by prior masked priming research using larger EEG montages (e.g., B. Li & Jiang, 2022; Ortells et al., 2016) and topographical distributions for word and object priming N400 effects supported by the literature (e.g., Doyle et al., 1996; Eddy et al., 2006; Eddy & Holcomb, 2009; Pickering & Schweinberger, 2003), and verified by visual inspection of the grand average waveforms. We ran an LME regression with fixed within-subject factors of Priming (primed vs. unprimed), ISI (67 ms vs. 317 ms), and Group (TD vs. DLD) and random intercepts for participant and electrode on these mean amplitude measurements from the masked trials. As part of testing our hypotheses, we then conducted planned pairwise comparisons to directly examine the priming effects at each ISI in each group, protected with a family-wise alpha of 0.05, regardless of the Priming x ISI x Group interaction's significance. Again, sum coding (-0.5, 0.5) was applied to all the fixed

factors, leading the model intercept to reflect the average N400 mean amplitude across those factors.

***Word Priming Condition Results***

Analysis of the masked trial data from the 18 electrode sites with the additional factor of Group revealed a significant main effect of Priming (*ß* = -0.32, *SE* = 0.07, $p < .001$) and ISI (*ß* = -1.64, *SE* = 0.07, $p < .001$), showing the same patterns as found in the omnibus analysis. There were also differences between groups regarding both the priming effects (*ß* = -0.29, *SE* = 0.15, $p = .050$) and ISI (*ß* = -0.63, *SE* = 0.15, $p < .001$). Planned follow-up comparisons to examine the Priming x ISI x Group interaction (*ß* = -0.39, *SE* = 0.29, $p = 0.180$) revealed that these differences in priming (and lack of differences in priming by ISI) were driven by TD children showing priming effects at both ISIs (shorter ISI: $z = -6.04$, $p < .001$; longer ISI: $z = -3.58$, $p < .001$) and the children with DLD failing to show any priming effects at either ISI (shorter ISI: $z = -0.57$, $p = .569$; longer ISI: $z = -1.40$, $p = .162$). The differences in ISI across groups reflected a more positive amplitude for targets following the longer ISI for TD children than for children with DLD, thus resulting in a greater difference in amplitudes across the two ISIs for TD children than children with DLD. See Figure 2 for the ERP waveforms elicited in the masked trials for the Word Priming condition.

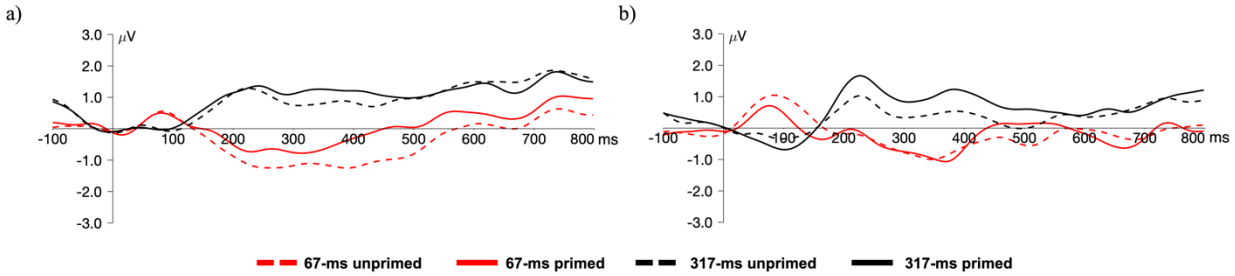


Figure 4.2. Grand average ERPs elicited by primed and unprimed targets with each ISI for a) TD children and b) children with DLD in the Word Priming condition. Waveforms are generated from the cluster of 18 electrodes.

### *Object Priming Condition Results*

When analyzing the masked trial data from the 18 electrodes, there were significant effects of Priming (*ß* = -0.56, *SE* = 0.08, $p < .001$), ISI (*ß* = -1.39, *SE* = 0.08, $p < .001$), and ISI x Group (*ß* = -1.42, *SE* = 0.16, $p < .001$). The main effects of priming and ISI found in this data set mirrored those found in the omnibus analysis. Group differences across ISIs were characterized by both groups showing the same general pattern across the two ISIs, but with the DLD children demonstrating a less pronounced difference between mean amplitudes at each ISI (i.e., children with DLD's amplitudes at the shorter ISI were less negative than their TD peers' and, at the longer ISI, were less positive than the TD children's amplitudes). Our planned comparisons that broke down the Priming x ISI x Group interaction (*ß* = 0.57, *SE* = 0.31, $p = .066$) revealed group differences in priming effects as well, with TD children demonstrating priming effects at both ISIs (shorter ISI: $z = -5.56$, $p < .001$; longer ISI: $z = -7.97$, $p < .001$) and children with DLD demonstrating priming effects only at the shorter ISI (shorter ISI: $z = -3.01$, $p = .003$; longer ISI: $z = -1.35$, $p = .178$). See Figure 3 for the ERP waveforms elicited in the masked trials for the Object Priming condition.

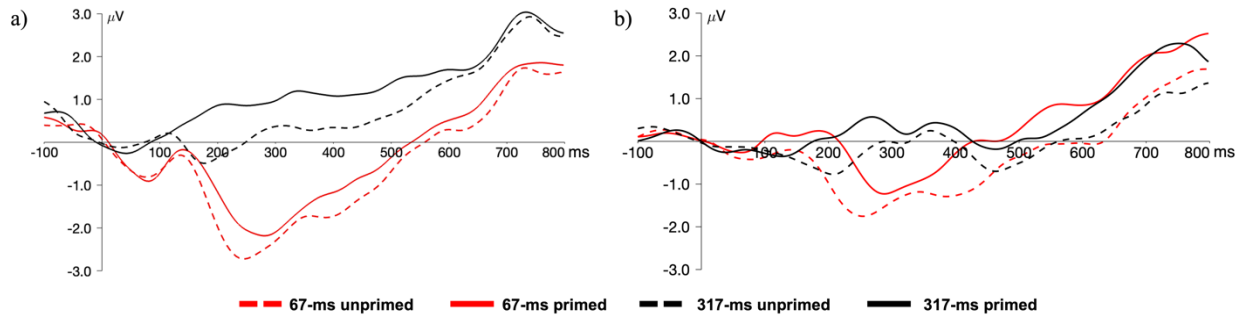


Figure 4.3. Grand average ERPs elicited by primed and unprimed targets with each ISI for a) TD children and b) children with DLD in the Object Priming condition. Waveforms are generated from the cluster of 18 electrodes.

**Planned Individual Differences Analyses**

Given our additional interest in individual differences, specifically in semantic ability, we ran simple linear regressions on the z-scored TILLS Vocabulary Awareness test scores and a difference score computed from the masked priming ERP measures. To compute the difference score, we first determined the mean amplitudes of the priming difference waves (unprimed minus primed) from the same time window and 18 electrodes. We then calculated the average mean amplitude of that cluster of electrodes for each ISI, resulting in one mean amplitude measure of the difference in priming effects for the shorter ISI and one for the longer ISI for each participant. We subtracted the value from the longer ISI from the shorter ISI to obtain a Priming x ISI difference score. The z-scored TILLS Vocabulary Awareness test scores were then regressed on this difference score to examine the link between individual differences in automatic spreading activation (via N400 priming effects) and semantic ability. Pearson's correlation was also conducted on these two variables to examine their relationship in more detail.

**Individual Differences Results**

We found no significant effects in our analyses examining the link between these differential priming effect patterns and semantic ability. Specifically, neither the priming by ISI difference score from the Word Priming condition nor the Object Priming condition significantly predicted participants' TILLS Vocabulary Awareness test scores (Word Priming: $ß = 0.05$, $SE = 0.08$, $p = .568$; Object Priming: $ß = -0.04$, $SE = 0.06$, $p = .562$). The TILLS Vocabulary Awareness test scores also did not correlate with either ISI difference score (Word Priming: $r = 0.09$, $p = .876$; Object Priming: $r = -0.09$, $p = .348$).

**Exploratory Individual Differences Analyses**

To further explore individual differences, we ran an additional set of exploratory LME regressions on the mean amplitudes of the priming difference waves (unprimed minus primed) from the 300-500 ms post-target onset time window and 18 electrodes. We analyzed the data from masked trials with each ISI separately, leading to a set of two LME regressions for each experimental condition. We included fixed within-subject factors of each behavioral assessment measure (all z-scored; see Table 1), including our critical measure of semantic ability, and the prime duration visibility threshold measure, and random intercepts for participant and electrode.[1] Lastly, we explored the relationships between the battery of standardized assessment test scores and our computed difference score with Pearson's correlation.

**Exploratory Individual Differences Results**

Further exploratory analyses examining the relationship between the priming difference waves and other behavioral measures revealed no significant correlations between priming differences at either ISI in the Word or Object Priming condition and all behavioral measures (all *p*s > .05). However, the CELF-5 Core Language Scores shared a weak negative correlation with our computed difference score for the Object Priming condition ($r$ = -0.26, $p$ = .0328; *p*s for all other correlations > .05), such that children with more pronounced priming effects at the shorter ISI than at the longer ISI had higher global language scores. However, this correlation was not robust enough to remain significant when data from a single outlier (a participant with a CELF-5 Core Language Score greater than two standard deviations above the group mean) was removed.

[1] Random intercepts for electrode were dropped if their inclusion resulted in singularity issues. This only occurred when analyzing the word priming data from the masked trials with the longer ISI.

## Discussion

The present study aimed to characterize how the time course of automatic spreading activation for both lexico-semantic and semantic processing in school-age children with DLD is altered compared to their TD peers, as well as aimed to investigate the relation between individual differences in this mechanism's timing and semantic abilities in children with and without DLD. Toward these aims, we used standardized behavioral measures and a masked ERP priming paradigm with two prime-target ISIs to isolate and examine the time course of this temporally sensitive cognitive-linguistic mechanism underlying (lexico-) semantic processing and its potential link to semantic deficits in DLD. Based on patterns of N400 priming effects, we found evidence that the time course of spreading activation for both lexico-semantic and semantic processing was altered in children with DLD compared to TD children. In addition, we found individual differences in the time course of spreading activation to be related to individual variations in language abilities, but not semantic skill, and only for semantic processing, not lexico-semantic processing.

Several studies have found evidence suggestive of an altered time course of spreading activation in children with DLD (e.g., Helenius et al., 2009, 2014; Hennessey et al., 2010; Lahey & Edwards, 1996; Pizzioli & Schelstraete, 2011; Seiger-Gardner & Schwartz, 2008; Velez & Schwartz, 2010). However, interpretation of prior works' results is complicated by the fact that children's performances in typical experimental paradigms can be influenced by explicit as well as implicit processing mechanisms, resulting in an unclear understanding of how the timing of spreading activation is altered in DLD. The present study is unique in that it attempted to remove the influence of explicit processing mechanisms, allowing for direct examination of the time course of spreading activation in children with DLD. Our findings suggest the nature of the

alteration is one of abnormally accelerated activation decay. Children with DLD failed to prime in the Word Priming condition at either ISI and only primed at the shorter ISI in the Object Priming condition, unlike their TD peers who showed N400 priming effects at both ISIs for both experimental conditions. Although activation does typically decay rapidly, only showing priming with a 67 ms delay between repetitions of a stimulus indicates activation was atypically short-lived for children with DLD. Given that children with DLD only showed priming effects with this short of a delay with objects, it is possible that an even shorter ISI is necessary to elicit masked priming effects with word stimuli in children with DLD. Further exploration of masked priming effects in children with DLD with other ISI manipulations is needed to better understand the temporal dynamics of activation decay in DLD.

Although this finding of atypically rapid activation decay is contrary to our prediction that the alteration would be a slowed spread of activation, it nevertheless aligns with explanations that children with DLD have weak semantic representations and/or weak connections between semantic representations and representations of different domains (e.g., phonological; Bragard & Schelstraete, 2007; Gray, 2005; Hennessey et al., 2010; Lahey & Edwards, 1999; McGregor & Appel, 2002; McGregor & Waxman, 1998; Seiger-Gardner & Schwartz, 2008; Sheng & McGregor, 2010a; Velez & Schwartz, 2010). Underdeveloped lexical representations (i.e., representations composed of few units and lacking defining features and/or characterized by sparse connections between units) could restrict the ability for the activation to sufficiently spread or be maintained and limit overall activation levels. If activation cannot adequately build and be sustained through the interactive connections, it will be much more difficult for all the correct units to emerge as the most highly activated and stay activated long enough to be acted upon by the system, hindering processing of the word. In such a case, encountering a prime

would not activate units strongly enough to have the "long"-lasting effect needed to facilitate processing of the subsequent target unless the target was presented almost immediately after the prime. An atypically fast decay rate is also consistent with the repeated finding that children with DLD need at least two to three times more exposures to new word forms and their meanings in order to learn new words (Gray, 2003; Kan & Windsor, 2010; Nash & Donaldson, 2005; Rice et al., 1994; Riches et al., 2005; Storkel, 2019). If a word's semantic information is only actively processed for a very brief amount of time, it will be challenging to map it to other lexical information before the semantic information has lost its activation. Thus, frequent, repeated exposures to the information would be necessary to maintain the activation long enough to form connections and strengthen the lexical representation as a whole. Furthermore, the robust priming effects from the TD children across the ISIs and experimental conditions and the finding that children with DLD did show some priming effects not only validates the use of masked priming with children with DLD but also provides credence to our interpretations of the data.

Considering children with DLD's pattern of priming across experimental conditions provides notable insights into the nature of their semantic processing beyond the nature of how the time course of spreading activation is altered. The lack of priming altogether for words but presence of priming at the shorter ISI for objects implies that both lexico-semantic and semantic processing is impaired in children with DLD, but lexico-semantic processing is affected more. Reading skill might have played a role in this finding, as children with DLD typically have weaker reading abilities than the TD children (Buil-Legaz et al., 2015; Catts et al., 2002; Dockrell et al., 2009; Hall & Tomblin, 1978; Johnson et al., 2010; Ricketts, 2011; Stoeckel et al., 2013). However, word-level reading skill did not significantly differ between groups in our sample ($t(14.24) = -1.55$, $p = .142$) and reading skill was not predictive of or correlated with

priming differences at either ISI, suggesting this finding resulted from impairments at a more fundamental level.

Another factor to consider is attention and inhibition. Research has consistently found children with DLD to have deficits in attention and inhibition, which could significantly impact language learning and processing (e.g., Blom & Boerma, 2020; Finneran et al., 2009; Smolak et al., 2020). Sustained attention and inhibitory control play an especially critical role in the priming task used in this study, as a lack of attention to the stimuli could prevent semantic processing and poor inhibition could allow processing of primes (both unrelated and repeated) to interfere with processing of targets, as well as lead to motor responses to non-animal stimuli that could contaminate the neural signals of interest. At least in our sample, children with DLD's inhibition and attention skills were no different from TD children's ($t(10.84) = 0.43$, $p = .673$), and our measure of these skills were not predictive of or related to priming differences either, indicating differences in priming were not likely due to variations in this skill.

These results also contribute to the ongoing debate as to whether the linguistic deficits in DLD are due to impairments of purely linguistic skills and knowledge (e.g., limited phonological working memory capacity, delayed mastery of tense and agreement rules; Gathercole & Baddeley, 1990; Rice et al., 1995) or due to impairments of broader, non-linguistic cognitive skills that are also involved in language, such as processing speed or procedural learning (e.g, the generalized slowing hypothesis; Kail, 1994; Leonard et al., 2007; or the procedural deficit hypothesis; Schwartz, 2017; Ullman & Pierpont, 2005). The present findings support the perspective that, with respect to semantic processing in particular, children with DLD experience impairments in both general non-linguistic cognitive *and* specific linguistic skills. However, based on our lack of group differences in our other behavioral measures besides our measure of

general language abilities, our results suggest that children with DLD's other impairments result primarily from language-specific skills and knowledge. These diverging findings are only preliminary, but intriguing nonetheless and worthy of further exploration.

The Object Priming condition uniquely resulted in interesting findings even when we moved away from group differences in favor of examining individual differences. Specifically, the only statistically significant relationships between individual variations in the differences in priming effects across the ISIs and behavioral measures occurred with data from the Object Priming condition. Unexpectedly, we did not find that differences in priming effects across ISIs for word or object stimuli predicted or were even related to the TILLS Vocabulary Awareness test scores. Instead, we found that differences in priming effects across ISIs (for object stimuli only) were more strongly related to global language abilities than the solely semantic abilities, although the relationship between priming effect differences and global language abilities was still notably weak. Nevertheless, the relationship between these two measures suggested that stronger priming effects at the shorter ISI than the longer ISI correlated with stronger general language abilities. This relationship is counter to expectations given that the children with DLD (i.e., the children with the lowest global language scores) were the ones who showed more robust priming effects at the shorter ISI than at the longer one in the group-level analyses. Moreover, our findings that the children with DLD elicited more negative amplitudes at the longer ISI for words and less of a difference in priming effects between ISIs for objects suggest children with DLD were working harder than their TD peers to process words after a longer delay and for all objects. However, when inspecting the distribution of the data, most difference scores indicative of priming at both ISIs aligned with CELF-5 Core Language Scores around the standard mean, suggesting children with average language abilities generally showed priming effects at both

ISIs. The direction of this correlation was substantially influenced by a child with advanced language abilities (i.e., they earned a standard score of 135, falling in the 99$^{th}$ percentile). Perhaps this child's time course of spreading activation was also atypically accelerated, but with regard to both spread *and* decay and as a result of highly efficient processing, well-developed lexical representations, and/or numerous strong connections between representations rather than due to deficits. Of course, replication of this finding is necessary before drawing any substantive conclusions.

The implications of finding no relationship between the difference in neural priming effects between ISIs for word or object stimuli and our standardized behavioral measure of semantic abilities are that other and/or additional variables might predict semantic abilities. One possibility is that a cognitive-linguistic mechanism other than, or in addition to, automatic spreading activation might underlie individual differences in observable language behaviors of individuals with DLD. However, it is more likely that our measure of semantic abilities was simply too broadly focused, capturing more than only semantically related knowledge and skills. One of the components of the CELF-5 Core Language Score is a measure of semantic abilities. Given that the CELF-5 Core Language was the only measure with any relationship with individual differences in timing of spreading activation, it seems semantic skill might have contributed to this result. However, some aspect of language outside of semantic abilities that we did not directly measure could also be driving this relationship. Thus, this study provides preliminary evidence that differences in the time course of spreading activation might be implicated in differences in general language abilities, but further research is needed.

**Study Limitations**

The present study provides valuable insights into how children with DLD's time course of spreading activation differs from that of their TD peers and how individual differences in the timing of spreading activation is related to individual differences in language behavior. However, there were some limitations to this study. First, detection rates for the masked prime probe stimuli and the results from the prime duration visibility threshold measure suggest that at least some participants might have been able to consciously perceive the masked primes at times. This is likely a result of using a relatively long prime duration, which was selected based on previous pediatric masked priming studies (Collette et al., 2016; Eddy et al., 2014) and to amplify any priming effects. Longer prime durations lead to more robust N400 effects (Eddy & Holcomb, 2010; Holcomb et al., 2005; Holcomb & Grainger, 2007), and efforts to facilitate priming effects were critical given that masked priming effects are generally weaker than supraliminal priming effects (e.g., de Groot, 1983; Forster & Davis, 1984; Kiefer, 2002; Marcel, 1983; Misra & Holcomb, 2003), and priming effects in individuals with DLD are often weaker than in individuals with typical language development (e.g., Helenius et al., 2009; Kornilov et al., 2015).

However, because the aim of this study was to examine an implicit cognitive-linguistic mechanism in an isolated manner uncontaminated by conscious processing, it is important to note that detecting a substantial number of probe items does not equivocally signify that the observed priming effects were a result of (residual) conscious processing of the masked primes that reached participants' awareness (Eddy & Holcomb, 2010; Grainger & Holcomb, 2009; Holcomb et al., 2005; Holcomb & Grainger, 2007). This is especially the case when the prime-target ISI is brief, as unconscious processing mechanisms like automatic spreading activation operate on shorter timescales than conscious processes, beginning (and sometimes even ending) before any

higher-level processing occurs. By rapidly presenting the targets after the primes, we prevented conscious processing of the prime from significantly influencing early processing of the target, as any conscious processing of the prime was likely not even begun until after the target appeared. Thus, priming effects from the masked prime stimuli, even if behaviorally detected, can still be safely attributed predominantly to unconscious processing. Additionally, the results of the prime duration visibility threshold task must be interpreted with caution. There was reduced participant engagement towards the end of the priming task when this set of trials was completed, with many children exhibiting frequent, non-discriminatory button presses throughout these final trials. The behavior during these trials and our finding that the prime visibility threshold measure was not predictive or correlated with priming differences, along with the difference in the priming effect magnitudes for targets that followed masked versus visible primes (not reported here) support our interpretation that the effects obtained in this study were primarily due to implicit, automatic mechanisms.

In addition, while this study's sample size is similar (or even larger in some cases) to what is typically reported in DLD research with children of this age range (e.g., Abel et al., 2020; Brooks et al., 2014, 2015; Hennessey et al., 2010; Pizzioli & Schelstraete, 2011; Seiger-Gardner & Schwartz, 2008; Velez & Schwartz, 2010), the two groups were unbalanced. It is possible that we would be better equipped to detect effects or find different effects with a larger sample size of children with DLD. Relatedly, our sample size of children with DLD was too small to allow for subdivided analysis of the group. Yet, some researchers have argued for subtypes of the disorder (e.g., Bishop, 1979; Conti-Ramsden et al., 2001; Conti-Ramsden et al., 1997; Conti-Ramsden & Botting, 1999; 2006; Dockrell & Messer, 2007; Friedmann & Novogrodsky, 2007; Korkman & Häkkinen-Rihu, 1994; Rapin & Allen, 1983; van Daal et al., 2004; van der Lely, 2005). Based on

the distribution of standardized scores of our participants with DLD, our sample was relatively homogeneous and had no obvious subgroupings. Furthermore, this study aimed to provide a broad characterization of the alteration underlying semantic deficits in DLD, making separate analyses by DLD subtypes outside the scope of this study. Conducting this detailed analysis would be a valuable option for future work.

**Conclusion**

This study substantiates previous studies' claims that children with DLD exhibit an altered time course of spreading activation, revealing that the alteration is one of accelerated decay of activation. This was evidenced by children with DLD only showing priming effects from a masked identity prime with a 67-ms prime-target ISI and failing to show priming effects with a longer (317-ms) ISI that elicited priming effects in their typical peers. This atypically rapid decay likely impaired children with DLD's ability to effectively spread and maintain activation in their language system, resulting in impaired (lexico-)semantic processing. The alteration was most evident in the experimental condition that elicited lexico-semantic processing, as priming effects were absent at both ISIs for word stimuli, only appearing at the shorter ISI for object stimuli. In contrast, TD children showed priming effects at both ISIs with both word and object stimuli. Additionally, the study found that individual differences in the time course of spreading activation were related to general language abilities rather than purely semantic abilities, unlike our initial expectations, although only in the context of semantic processing of objects. This link suggests alterations in the time course of spreading activation might have implications for broader language abilities, including language impairments in DLD. Altogether, these findings offer invaluable insight into the nature of the (lexico-)semantic processing in children with DLD and underscore the importance of considering individual

differences in research on semantic abilities in children with and without DLD. Furthermore, it contributes to the theoretical foundation for clinical research in DLD and adds to our understanding of how implicit mechanisms of semantic processing underlie language behavior. This knowledge is critical to developing targeted and more efficacious clinical interventions that treat underlying factors rather than only the language behavior, which will better mitigate the immediate and future risks associated with a DLD diagnosis.

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**Acknowledgements**

Chapter 4, in full, is currently being prepared for submission for publication of the material. This chapter is coauthored with Dr. Alyson D. Abel. The dissertation author was the primary researcher and author of this material.

We thank Phillip Holcomb and Seana Coulson for their invaluable contributions to the experimental design and statistical analysis of this work.

# Chapter 5 : GENERAL DISCUSSION

This dissertation's overarching goal was to demonstrate how different factors affect the encoding and accessing—or overall processing—of lexical and semantic information at the behavioral and neural level in individuals with typical language and individuals with communication disorders. In doing so, I also sought to illustrate how investigating underlying, implicit processes, which often are not discernable in behavioral outcomes, provides valuable insights that cannot be gained through behavioral measures alone. In **Chapter 1**, I identified some of the factors that impact lexical representation development and lexical-semantic processing, including lexical features, like word class, and neurological differences resulting from acquired and developmental communication disorders. I briefly outlined the gaps in the literature on encoding and accessing lexical information abstracted from incidental contexts, as well as on potential mechanisms underlying lexical retrieval and lexical-semantic processing deficits in PWA and children with DLD. Throughout, I described innovative methods and paradigms by which my co-authors and I have addressed these gaps and advanced the understanding of lexical representation development and lexical-semantic processing in individuals with and without communication disorders.

The results of the study detailed in **Chapter 2** exemplify the value of taking a brain-behavior approach to investigating how lexical representation development and lexical-semantic processing is impacted, demonstrating its benefit even when examining these processes in a typical language system. Specifically, we found that even in the absence of behavioral differences, the lexical information that was encoded and accessed was different for novel nouns and verbs. Based on behavioral measures of recognition, explicitly deducing a novel word form's meaning from an incidental context did not facilitate later recognition of the word form, contrary

to our predictions. This finding was consistent across word classes; only exposure to the word form (or lack thereof), not the additional identification of its meaning, was reflected in behavioral recognition for both novel nouns and novel verbs. In addition, there were, unexpectedly, no word class differences in recognition accuracy. Neural measures of the lexical-semantic processes involved in word recognition revealed different results, though. By using the MMN ERP component as an index of word form familiarity (i.e., encoding and access of form information) and the N400 ERP component as an index of semantic processing (i.e., encoding and access of semantic information), we found that novel nouns showed encoding of word form information. Interestingly, novel nouns also required increased rather than decreased cognitive effort to process the semantic information of words with explicitly identified meanings. In contrast, novel verbs failed to show neural signs of word form encoding and displayed encoding of semantic information for all verbs that had been encountered in the incidental context, regardless of explicit meaning identification. These results suggest two things: First, explicitly abstracting semantic information from incidental contexts might not improve immediate behavioral recognition, but lexical information is still encoded, allowing implicit processes of recognition to occur. Second, implicit recognition is supported by different mechanisms for nouns and verbs, specifically in that the types of lexical information that is encoded and the ease with which it is accessed varies. Thus, while perhaps not behaviorally apparent, lexical features like word class have unconscious influences on how lexical representations are first developed in real-world contexts.

**Chapter 3** turned from exploring lexical representation development and lexical-semantic processing in individuals with typical language to lexical-semantic processing in individuals with communication disorders. The study described in Chapter 3 focused on PWA

and their lexical retrieval deficits, investigating the proposal that an alteration in the time course of automatic spreading activation affects their lexical-semantic processing. This study's results provide evidence to support the altered time course proposal, although they suggest the alteration is different than we had predicted. That is, we did not find that activation begins to spread among the elements in the lexical-semantic network after a delay as some researchers have suggested (e.g., Ferrill et al., 2012; Hagoort, 1993; Prather et al., 1992; Silkes & Rogers, 2012). Instead, we found that the activation might initially spread as in a typical system but that the elements then remain active for an extended period as the activation fails to decay at the typically rapid pace, likely due to inhibitory deficits. This was evidenced by the presence of N400 ERP priming effects for masked primes that were repeated as targets immediately within a trial *and* after a substantial delay. In contrast, the older adults with typical language only showed priming effects for the immediate repetitions. We also found that PWAs' lexical retrieval deficits might be compounded by difficulties with integrating explicitly and implicitly processed information as their N400 ERP priming effects from visible primes were, unexpectedly, no stronger than from masked primes. Notably, these robust neural differences were present despite finding no behavioral priming effects, which underscores the benefits of examining neural measures even when behavioral measures are indiscriminating. Overall, the results of this study indicate that PWA's lexical-semantic processing is impacted by their communication disorder, specifically via an alteration to the timing of an underlying, implicit mechanism and deficits in integrating information.

The study in **Chapter 4** revealed that lexical-semantic processing is also affected by developmental communication disorders. In this study, I shifted from PWA to children with DLD but explored whether a similar explanation of an altered time course of automatic spreading

activation could account for children with DLD's lexical-semantic deficits. Here, I found that children with DLD only showed N400 ERP priming effects with a very brief prime-target interval, and only when the stimuli consisted of images of objects, not words. This was unlike their typical peers who showed priming effects for both the short and a longer prime-target interval regardless of the stimulus type. As such, the results of this study are evidence that children with DLD experience an atypically fast rate of activation decay, which impairs both lexical-semantic and more general semantic processing. Further exploration of individual differences in the timing of spreading activation revealed a modest connection with overall language abilities, not semantic abilities, contrary to predictions. Interestingly, this relationship only emerged when examining general semantic processing abilities rather than abilities to process specifically lexical-semantic information. This unexpected finding shows that combining behavioral and neural measures has a synergistic effect, providing credence to examining implicit processes along with explicit ones. Together, the findings of this study show that differences in the timing of spreading activation influences (lexical-)semantic processing via general language behavior for all children, not only those with communication disorders. However, lexical-semantic processing in children with DLD is particularly affected, as the impairment is not only present in behavioral outcomes but also at the implicit, mechanistic level.

In conclusion, this dissertation demonstrates the critical role that multiple factors play in lexical representation development and lexical-semantic processing in typical and clinical populations. By focusing on the implicit processes that underlie encoding and accessing lexical-semantic information, which behavior does not always reflect, I have provided new insights into how these mechanisms operate in both typical and disordered language systems. The studies presented serve as prime examples of why the brain signals behind behavior are worthy of

investigation, showing that valuable insights can be gained when measures from both the brain and behavior are jointly considered. Even without differences in behavior, significant variations in neural processing can occur, such as seen in the distinct encoding and accessing patterns for novel nouns and verbs but lack of behavioral differences. Additionally, the research highlights how seemingly disparate communication disorders, such as aphasia and DLD, might have similar deficits due to impairments of the same implicit mechanism. Importantly, although an alteration to the same mechanism might be involved in both populations' deficits, the nature of the alteration is different and reflects PWA's impaired access to existing representations (thus being able to maintain activation of a representation for too long) and children with DLD's underdeveloped representations (thus being unable to maintain activation for a representation long enough). Only by examining the underlying mechanisms of lexical and semantic processing can such an insight be reached.

Altogether, these findings not only enhance our understanding of lexical representation development and lexical-semantic processing in individuals with and without communication disorders. They also demonstrate how valuable evaluation of neural data, along with—and, sometimes, even in spite of—behavioral data, can be. Integrating findings from both perspectives, as I have done in this dissertation, is essential for advancing the field and improving clinical interventions for individuals with communication disorders.

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