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Parameters Facilitating Lexical Processing and Syntactic Retrieval in Neurotypical Adults and Individuals with Aphasia

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

in

Doctor of Philosophy in Language and Communicative Disorders

by

Carolyn Baker

Committee in charge:

University of California San Diego

Professor Seana Coulson
Professor Frank Haist
Professor Robert Kluender

San Diego State University

Professor Tracy Love, Chair
Professor JoAnn Silkes

2023

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Chair

University of California San Diego

San Diego State University

2023

DEDICATION

To my dad, Charles Joseph Baker Jr, it was your dream for me to obtain a Ph.D. Thank you for instilling in me the value of education, a sense of humor, and a down-to-earth approach to life.

To my mom, Christine Elizabeth Baker, who taught me that kindness and patience are the greatest sources of strength.

My parents' unconditional love and unwavering support have made me the person I am today.

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ABSTRACT OF THE DISSERTATION

Parameters Facilitating Lexical Processing and Syntactic Retrieval in Neurotypical Adults and Individuals with Aphasia

by

Carolyn Baker

Doctor of Philosophy in in Language and Communicative Disorders

University of California San Diego, 2023

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Aphasia is a language disorder that affects approximately 1 million US stroke survivors and results in impaired communication across modalities, often with detrimental effects on autonomy and quality of life. While the extent to which these domains are affected varies from person to person, a common symptom found in many individuals with aphasia is sentence

comprehension impairment, which is most notable with complex (noncanonical) sentences that require establishing a long-distance relationship between non-adjacent sentence constituents. Of interest to the work presented here are the ways in which auditory sentence input is processed and interpreted. Evidence in the literature implicates lexical-level processing impairments, such as delayed and/or reduced activation of lexico-semantic information, as contributors to syntactic processing disruptions and sentence comprehension deficits. By limiting timely lexical activation during sentence processing, these impairments can also preclude successful lexical encoding and amplify the processing costs of similarity-based interference during syntactic retrieval (i.e., dependency linking). A series of studies are presented to explore three different approaches (processing time, attentional engagement, and semantic pre-activation) to facilitate lexical access and strengthen concomitant encoding of a target word in a sentence. The effects of these approaches on real-time lexical and syntactic processing during complex (object relative) sentence processing was examined using eye-tracking-while-listening methodology in neurotypical college-age adults (YNC), older adults (age-matched controls, AMC) and individuals with aphasia (IWA). In each of these approaches, I ask whether enhancing the processing of a target lexical item during sentence processing will 1) facilitate its lexical access and encoding, 2) increase its availability for downstream syntactic retrieval operations, and 3) improve sentence comprehension. This novel area of exploration has the potential to improve our understanding of the interaction between lexical and syntactic levels within sentence processing and the cognitive and linguistic factors promoting lexical processing within a sentence context.

CHAPTER 1

1.0 Introduction

The remarkable complexity and variability of spoken language regularly creates challenges for auditory sentence comprehension. Understanding speech in real-time requires a complex interplay of coordinated lexical and syntactic processes to interpret a sentence's meaning. Critically, these processes are temporally constrained as the acoustic signal of speech itself is fleeting. Therefore, as soon as we receive speech input, we identify the sentence constituents while beginning the process of extracting meaning by building rule-based relationships among incoming sentence constituents. Of interest in this dissertation is how word meanings are rapidly accessed and integrated to build an emerging syntactic structure moment-by-moment as a sentence unfolds and what parameters contribute to successful processing. These processes are explored in sentences containing syntactic dependencies in which non-adjacent words have to be linked over long distances to create the proper syntactic representation that allows the listener to understand who is doing what to whom, such as the object relative sentence seen in (1) below.

(1) It was the **child**$_i$ at the park who the mother rushed to **help**$_i$ after the fall.

Under many theoretical accounts, successful processing of this utterance requires the retrieval of the direct object (*the child*) upon processing the verb (*help*) in a process referred to as dependency linking (Kluender & Kutas, 1993; Lewis & Vasishth, 2005; McElree, 2000). Prior research has shown that dependency linking is a fast-acting process that occurs in real time as the sentence components are presented to a listener (Akhavan et al., 2020, 2022; Baker & Love, 2021, 2023; Koring et al., 2012; Love et al., 2008; McElree, 2000; Thompson & Choy, 2009a, and references therein). While neurotypical adults generally arrive at the correct interpretation of these sentences, processing ease has been shown to be constrained by several factors. Based on

observations from neurotypical (unimpaired) processing, cue-based retrieval models have been developed to characterize how the ability of the system to efficiently retrieve target information is constrained by the presence of other sentence constituents that are similar to the to-be-retrieved (target) representation (Lewis et al., 2006; Lewis & Vasishth, 2005; McElree, 2000; Van Dyke, 2007; Van Dyke & Lewis, 2003). According to these models, syntactic and semantic similarities between the target representation and other sentence constituents causes similarity-based interference, which results in slowdowns at the retrieval site and/or misretrieval of a distractor item (Lewis et al., 2006; Van Dyke & Lewis, 2003; Van Dyke & McElree, 2011). While cue-based processing models were originally developed to explain processing difficulties in people without language impairments, studies have demonstrated that retrieval interference can lead to breakdowns in comprehension in individuals with aphasia (IWA, Akhavan et al., 2022; Lissón et al., 2023; Mätzig et al., 2018; Patil et al., 2011, 2016; Sullivan et al., 2017).

Aphasia is an acquired language disorder that occurs subsequent to neural trauma, typically stroke, and can result in deficits in expressive language (e.g., speech production or writing), receptive language (e.g., comprehension), or both. The extent to which these domains are affected varies from person to person depending on factors such as size and location of stroke. Of interest to the work presented here are the ways in which auditory sentence input is processed and interpreted since a common symptom found in many individuals with aphasia is comprehension impairment. Comprehension impairments are most notable with complex (noncanonical) sentences such as (1) above. Various theories have been put forward to explain the comprehension impairments observed in individuals with post-stroke aphasia by focusing on disruptions of the automatic processing routines that underlie sentence comprehension. These processing limitations have been conceptualized in different ways including slowed syntactic

operations (Burkhardt et al., 2008; Haarmann & Kolk, 1991; Piñango, 2000), weakened syntax (Arvutin, 2006), lexical access deficits (Blumstein & Milberg, 2000; Burkhardt et al., 2008; Love et al., 2008; Milberg et al., 1995; Prather et al., 1997; Swinney et al., 2000; Yee et al., 2008), lexical integration deficits (Choy & Thompson, 2010; Hagoort, 1997; Thompson & Choy, 2009b) and reductions in cognitive resources and allocations (Caplan et al., 1997; Caplan & Waters, 2013; Hula & McNeil, 2008; Murray, 2018; Murray et al., 1997; Nozari et al., 2016; Villard & Kiran, 2015).

To gain insight into the underlying factors contributing to sentence processing impairments in aphasia, I explore the integrity of two parameters in lexical access that have been proposed to impede the integration of lexical information into the emerging syntactic structure: timing (Ferrill et al., 2012; Love et al., 2008) and magnitude of activation (Blumstein & Milberg, 2000; Utman et al., 2001; Yee et al., 2008). Specifically, delayed and/or weaker lexical access is argued to disrupt the timely formation of the syntactic and semantic representation of the sentence and result in comprehension impairment (Ferrill et al., 2012; Love et al., 2008; Prather et al., 1997). These deficits can also be explained within the framework of cue-based parsing theories. According to these models, the successful resolution of long-distance dependencies relies on encoding and later retrieving lexical processing for successful structure building (Lewis et al., 2006; Lewis & Vasishth, 2005; McElree, 2000; Van Dyke & Lewis, 2003; Van Dyke & McElree, 2011). Lexical-level impairments in IWA can hinder successful encoding and result in the formation of a degraded memory representation that limits the ability to quickly and accurately activate the information when required for syntactic retrieval. Consistent with this notion, strengthening lexical processing may represent a potential approach to improving retrieval and mitigating comprehension deficits. However, the ways to enhance lexical

processing in service of syntactic structure building during real-time sentence processing are not well understood.

1.1 Overview of Dissertation

The primary goal of this dissertation, then, is to investigate the parameters supporting successful lexical processing and syntactic structure building during real-time auditory sentence processing in both neurologically unimpaired populations and in individuals with aphasia. This goal will have important implications for bridging theories of sentence processing developed from language-unimpaired populations (i.e., cue-based parsing) with theoretical accounts of processing deficits in aphasia. As discussed in more detail below, a series of four studies investigating three approaches to facilitate lexical access during real-time sentence processing in these populations is described; specifically, the manipulation of processing time, attentional engagement, and pre-activation of semantic representations of a word through priming. Before moving to the background literature supporting this work, I provide a brief overview of the method and stimulus types used in the three studies investigating real-time processing in this dissertation (Chapters 4, 5, and 6).

Given the interest in real-time auditory sentence processing, eye-tracking-while listening with a visual world paradigm will be used since this methodology permits a fine-grained analysis of lexical activation and syntactic retrieval (i.e., dependency linking) as it occurs in real-time during the ongoing auditory presentation of a sentence. Additionally, this method is particularly suitable to address questions about language processing in aphasia as it is a passive task that does not require overt engagement during the sentence itself and is therefore better suited to capture processing as it naturally unfolds. In eye-tracking, gazes towards a picture of a recently heard referent are argued to reflect the activation of that lexical item (Tanenhaus et al., 2000). This method has also been used to successfully index dependency linking and similarity-based

interference from competing lexical items (Akhavan et al., 2020, 2022; Baker & Love, 2021, 2023; Koring et al., 2012; Sekerina et al., 2016; Thompson & Choy, 2009b). The gaze patterns of interest in these dissertation studies are 1) **initial lexical activation**, which is reflected as gazes towards a picture of a recently heard referent; 2) **deactivation**, which manifests as looks away from the recently activated referent upon hearing incoming sentence constituent and is interpreted as disengagement from the noun; 3) syntactic **reactivation**, which manifests as looks back to the direct object noun at the syntactically licensed post-verb position; and 4) **interference**, which is shown as extended lexical activation of both subject and direct object noun during dependency linking. Gaze patterns are captured as listeners process object relative sentences, which, as discussed above require dependency linking between the direct object (*clown*) of the verb (*pushed*).

(2) Last year on Halloween, the **clown**$_i$ that the elf **pushed**$_i$ was in the backyard.

Prior to running the eye-tracking investigations to explore real-time auditory sentence processing, the first study (reported in Chapter 3), was conducted to investigate the impact of time on the comprehension of object relative sentences in three groups: college-age neurotypical adults (YNC), older age-matched neurotypical controls (AMC), and individuals with aphasia (IWA) using a sentence-picture matching paradigm. The approach in this study aimed to provide additional processing time for the direct object noun by manipulating time in three ways: stretch condition, disfluent condition, and silence condition. The Delayed Lexical Activation hypothesis (DLA) suggests that delays in lexical access disrupt the availability of lexical-semantic information and result in comprehension breakdowns (Ferrill et al., 2012; Love et al., 2008). The study tested the prediction that increasing processing time for the direct object noun would enhance sentence comprehension by improving accuracy and/or reducing response times.

Whereas Chapter 3 investigated the impact of the temporal manipulations on final (interpretive) comprehension, the studies presented in Chapters 4, 5, and 6 sought to explore the effects of temporal manipulations moment-by-moment on three sentence processes: (a) initial lexical processing of the direct object noun, (b) syntactic dependency linking, and (c) the resolution of similarity-based interference during real time auditory sentence processing. Using eye-tracking technology, Chapters 4 and 5 examine the real time influence of the temporal manipulations on the three processing stages across three populations: YNC (Chapter 4) and AMC and IWA (Chapter 5). Extending these investigations to other factors that have been argued to influence processing in IWA and AMC, Chapter 6 explores if and how the three processing stages are affected by attentional modulation and pre-activation of semantic-level properties of the target word through priming. Lastly, Chapter 7 integrates the findings from Chapters 4, 5 and 6 to provide a discussion on the implications of the research findings and future directions.

Before presenting the four research chapters (3, 4, 5, and 6), Chapter 2, provides the pertinent background, beginning with a general overview of sentence processing models in neurotypical adults. It then provides an overview of sentence processing in aphasia, with a focus on lexical processing accounts. Lastly, the chapter will introduce the goals and contributions of the current studies.

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CHAPTER 2

Sentence processing

1.0 Sentence Processing in Neurotypical Individuals

A large literature focused on sentence processing has investigated the mechanisms that allow comprehenders to construct syntactic structures in real-time and comprehend the meaning of sentences. While this research has elucidated important phenomena, the field has not been without its fair share of theoretical controversies and debates.

From this literature, it is clear that sentence processing occurs incrementally such that readers and listeners begin to build sentence structure immediately as they receive input rather than waiting until the end of the sentence to construct the structure needed for comprehension (Fodor, 1978; Just & Carpenter, 1980; W. Marslen-Wilson, 1973; W. D. Marslen-Wilson, 1975). Part of these models support the notion that part of the process of comprehending speech (or text) requires, at the very least, achieving two important goals: 1) recognizing and accessing individual words and their meanings, and 2) integrating these words together to form phrases (Novick et al., 2003). Additionally, the literature also converges in support of the position that structure-building operations occur to identify constituents so they can be grouped into a hierarchical structure via a rapid analysis and integration of structural and lexical information (J. Fodor et al., 1974; Frazier & Rayner, 1990).

However, when it comes to key issues concerning the interactivity and relative timing of syntactic and lexical constraints during processing, theories diverge rather drastically. In one theoretical camp, syntax serves the primary role of guiding the initial interpretation of a sentence, with semantic information such as lexical argument structure and pragmatic information only influencing a later state of interpretation. This view generally encompasses a modular view of sentence processing (Fodor, 1983). The second camp holds a contrary view; the generation of an initial sentence structure is influenced by lexical, syntactic, semantic, and pragmatic information

in an interactive manner (MacDonald, 1997; McRae et al., 1998; Trueswell et al., 1994). This chapter will briefly review the experimental evidence giving rise to these theoretical perspectives before focusing on another important consideration in sentence processing – the factors that give rise to processing difficulty. A major goal within this literature is to gain a better understanding of the mechanisms that enable readers and listeners to understand syntactically complex sentences. This line of research is particularly relevant to the goals of this dissertation, discussed in more detail at the end of the chapter, as much of this literature pertains to the processing of noncanonical (object relative) sentence structures, which deviate from the expected word order of English (subject-verb-object) and are notoriously more difficult to comprehend than their canonical counterparts (e.g., sentences following a subject-verb-object word order). The difficulty comprehenders face when processing these types of constructions is argued to arise from constraints in memory processes, interpretive processing, and on the basis of the frequency with which different types of sentence constructions are encountered in language, to name a few. A number of these theories will be reviewed below.

1.2 Modular approaches (syntax-based, two-stage model, structural approach)

Modular views of sentence processing are associated with a "two-stage" model of sentence processing, which assumes that an initial syntactic analysis is initially assigned to words solely on the basis of syntactic information without consideration of the overall meaning of the sentence or whether that interpretation makes sense given prior context or knowledge. One of the most influential accounts of sentence processing under this view is the Garden-Path model (Fodor, 1983). According to this model, during the first stage of sentence processing, an initial parse is constructed from the grammatical categories of the words in conjunction with syntactic rules. The phrase structure configuration of the initial parse is based on the operations of

Minimal Attachment and Late Closure. The principle of minimal attachment states that each new lexical or phrase structure node will be constructed using the fewest syntactic nodes possible. In other words, the parser is constrained to construct no potentially unnecessary nodes. The parsing heuristic of late closure stipulates that the parser prefers to attach each new word into the constituent currently being built, as low in the phrase structure as possible, rather than as a new node. Only after the initial sentence structure has been constructed does semantic and pragmatic information become available, where it can be used if necessary to reanalyze the structure built during the first stage.

Many studies supporting the idea of syntax-based or two-stage models have been based on research demonstrating people's structural preferences when they encounter sentences with structural ambiguities (e.g., garden-path sentences), such as (1).

1. The old man the boat.

According to the garden-path model, and assuming minimal attachment and late closure heuristics, the parser initially constructs a syntactic structure as efficiently as possible. In the sequence *the old man the boat*, the parser would be led to initially attach the constituent *man* as the head of the noun phrase *the old man* because that option yields the simplest hierarchical structure with the smallest number of nodes. However, with subsequent input, this analysis turns out to be incorrect and thus requires a reassignment of the role of *man* as the head of the verb phrase *man the boat* to derive the correct meaning of the sentence, which is that the old people operate the boat. In these types of sentences, comprehenders are described as having been "led down the garden path" because the initial syntactic parsing preferences result in a sentence first being parsed erroneously before determining the correct interpretation with further disambiguating information. Importantly, this model posits that semantic and pragmatic

information does not influence the initial parse and only becomes influential during the second stage of processing. Ferreira and Clifton (1986) tested these predictions by measuring readers' eye movements as they read structurally ambiguous sentences that contained thematic information that could potentially bias one interpretation over another. For example, participants were presented with the following sentences:

2a. The defendant examined by the lawyer turned out to be unreliable. (animate, reduced relative clause)

2b. The evidence examined by the lawyer turned out to be unreliable. (inanimate, reduced relative clause)

According to the principle of minimal attachment, the first verb (*examined*) should be parsed as the main verb of the sentence. Upon reaching the point of disambiguation (*by the lawyer*), a reanalysis is cued causing readers processing difficulty as evidenced by longer reading times. Critically, the Garden-Path model predicts that both 2a and 2b will undergo reanalysis, even though 2b begins with an inanimate noun (*evidence*) that is not as plausible as the agent of the verb *examine*. The pattern of eye movements was consistent with the predictions of the Garden-Path model. Processing difficulty during the disambiguating region persisted even when sentences contained an initial inanimate noun phrase (2b) showing that readers did not use the semantic category (animacy) information to guide their initial parse and instead relied on syntactic preferences independently.

1.3 Constraint-based approaches

In contrast to structural approaches which stress compartmentalism and serial processing (Frazier & Fodor, 1978), constraint-based models place emphasis on the integration of multiple levels of information during sentence processing (e.g., Kim et al., 2002; MacDonald et al., 1994;

Trueswell et al., 1994). Under this approach, lexical-semantic, pragmatic, plausibility, and contextual information interact to guide the syntactic interpretation of a sentence (MacDonald et al., 1994; McRae et al., 1998; Spivey & Tanenhaus, 1998). A major focus within this research has been to understand how information is represented at different levels and how it is integrated both within and across levels.

The development of constraint-based models was strongly influenced by connectionist architectures, also referred to as parallel distributed processing (McClelland et al., 1989; Rumelhart et al., 1986; Seidenberg & McClelland, 1989). The major shift in this framework was to represent lexical information not as discrete entries that are accessed, but rather as existing (and therefore activated) in a distributed network. Briefly, this distributed network consists of interconnected processing units corresponding to phonological, semantic, morphological and orthographic features of lexical items (MacDonald, 1997). The network is organized via multiple layers or levels with each level containing units that reflect a higher level of representation than those below. Connections exist between all units within a layer and to all units in adjacent layers, creating a large network through which activation is able to spread (Yelland, 1994). The retrieval of specific lexical items is represented by a specific pattern of activation across multiple levels within the network. Constraint-based models share this view of lexical representation and emphasize that syntactic processing has the same general properties as lexical processing (for review see MacDonald et al., 1994). Although constraint-based models are a family of related models, I will overview the model proposed by MacDonald and colleagues (1994) to demonstrate the main principles and assumptions of this approach. Perhaps the greatest contrast from modular accounts such as the Garden-Path model is the absence of any type of separate syntactic processing module (i.e., parser). Instead, this model proposes that all information

necessary for generating a syntactic structure is contained within the lexical representations. This information includes the grammatical categories, the argument structure, and the X-bar structure associated with each word. Given this design, activating lexical representations not only retrieves the word, but also activates syntactic frames to specify how these representations can be used syntactically and semantically within a sentence. When words are associated with more than one meaning and/or argument structure (i.e., lexically ambiguous), the theory postulates that all possibilities are activated and evaluated in parallel. For example, the word *dance* can be represented in two different grammatical categories –a noun and a verb– and in two different argument structures. When used as a noun, it may be assigned the thematic role of location or goal; when used as an intransitive verb, it requires an agent. As a noun, it is associated with different X-bar structures that specify how nouns can be used (i.e., head of a noun phrase), whereas the verb *dance* is associated with verb phrases. These possible analyses are activated and considered in parallel and are weighted by their frequency of use and the analysis that reaches the highest activation is chosen (Macdonald et al., 1994). Other sources of contextual and pragmatic information can also modulate activation and work to constrain interpretation. Thus, language comprehension is viewed as a constraint satisfaction process that operates over multiple levels of probabilistic information.

To show how local semantic constraints of lexical items can influence the resolution of structurally ambiguous clauses, Trueswell and colleagues (1994) used eye-tracking during a reading task to measure eye gazes as participants read sentences containing a temporary ambiguity between a relative clause and a main clause interpretation:

3a. The thief searched by the police was quite unpleasant.

3b. The room searched by the police was quite unpleasant.

In these sentences, the verb *searched* is structurally ambiguous as it can either be interpreted either as the past tense or the passive participle form. In the past tense, *the thief searched* fragment is the main clause of the sentence, whereas in the participle form, the fragment is part of a reduced relative clause. In this study, thematic fit of the first noun was manipulated to be either a good (plausible) agent of the verb (animate noun, 3a), which supports a main clause interpretation or a poor agent (inanimate noun, room, 3b), which supports a relative clause interpretation.

First and second pass eye gaze measurements revealed that readers evinced longer reading times when the reduced relative clauses were preceded by good agents (3a). These results demonstrated that local semantic constraints can have an immediate effect on processing ambiguous structures. In support of constraint-based approaches, this study provided evidence that thematic fit information is immediately available to be used during parsing, contrary to the predictions made by the garden-path model (i.e., syntactic information is the only source guiding initial structure building).

In a follow-up study, Trueswell (1996) investigated if the frequency with which verbs occur as participles would affect syntactic ambiguity resolution in reduced relative constructions when semantic information supports the relative clause alternative. For verbs with high preferences for being a participle (e.g., *searched*), both main clause and relative clause interpretations were predicted to be readily available, whereas verbs with low preferences for being a participle (e.g., *entertained*) would favor the main clause interpretation and increase processing difficulty.

4. The room $^{\text{inanimate= relative clause}}$ searched by the police contained the missing weapon. (high participle frequency = equal main and relative clause probabilities)

5. The audience $^{\text{animate = main clause}}$ entertained by the comedian left in high spirits. (low participle frequency = main clause preference)

These predictions were borne out, when participants read relative clause sentences with verbs that did not support a relative clause interpretation (i.e., low participle frequency verbs), there were significant increases in reading times during the disambiguating by-phrase (*by the police*). This processing difficulty was eliminated for verbs with high participle frequency, revealing that verb-specific lexical frequencies play a role in syntactic ambiguity resolution. Thus, these results show clear support for a lexically based constraint-based approach.

1.4 Complex sentence processing

A particularly challenging phenomena the human parser is confronted with in language comprehension is the presence of syntactic relationships between two non-adjacent sentence elements, also referred to as long-distance dependencies. Sentence constructions with relative clauses (those beginning with *that* or *which*) are highly studied examples of long-distance dependencies as they present unique challenges to the listener. English has a strict sentence constituent word order of Subject-Verb-Object (S-V-O) which allows for a rapid mapping of thematic roles of the noun phrases (the first noun is the subject or agent, and the second noun post-verb is the object or theme). However, this canonical (basic) form is not the only way individuals can create sentences. Unlike other languages that have grammatical markers to assist the listener in attributing semantic or thematic roles (agent, theme) to arguments of the verb through inflectional or case markings (as found in German or Farsi, for example), English assigns semantic roles based on the way words are related via the syntactic structure. When the surface representation of a sentence deviates from canonical word order, it can result in a discrepancy between the underlying semantic form and its surface representation (the order in

which the sentence constituents are presented to the listener). Thus, in English, non-canonical constructions are grammatical but result in a "surface level" deviation of the underlying canonical S-V-O representation.

To better illustrate this concept, take the example sentences in Figure 2.1 below. All of these sentences have the same underlying meaning /clown pushed elf/. In the canonical examples (6a-6c), the surface form of the sentence matches the S-V-O word order of English. These sentences are relatively easy for most neurotypical adults (and children) to understand. The non-canonical examples (6d-6f) have a different surface word ordering (O-S-V) where the direct object of the verb *pushed* comes before the verb.

6a.	subject *verb* object The clown *pushed* the elf.	Canonical: active
6b.	subject *verb* object The clown that *pushed* the elf was mad.	Canonical: subject-relative
6c.	subject *verb* object It was the clown that *pushed* the elf.	Canonical: subject-cleft
6d.	object *verb* subject The elf was *pushed* by the clown.	Non-canonical: passive
6e.	object subject *verb* The elf that the clown *pushed* was mad.	Non-canonical: object relative
6f.	object subject *verb* It was the elf that the clown pushed.	Non-canonical: object-cleft

Figure 2.1: Example sentence structures demonstrating canonical and non-canonical word order

A number of formal linguistic theories hold that these non-canonical constructions are derived from an underlying S-V-O representation (Chomsky, 1986). In somewhat generic psycholinguistic parlance, in these cases the direct object (*the elf*) 'moves' from its post-verb position (leaving a 'gap') to a position in front of the verb (Chomsky, 1986; Fodor, 1978;

Swinney & Osterhout, 1990). As shown in Figure 2.2 below, this 'gap' remains structurally linked to the moved element (noted in Figure 1 with the subscript i) such that during parsing, the listener links the post verb site with the fronted direct object noun ('filler'), allowing the listener to assign it the role of object or theme. The establishment of a link between the 'filler' and the 'gap' is referred to as dependency linking or dependency completion.

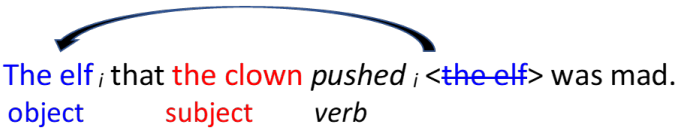


Figure 2.2: Example of movement of the direct object noun phrase (*the elf*), leaving a syntactically linked connection (noted by subscript i) at the post-verb site.

Various theories have been proposed to explain the sources of processing difficulty that are associated with long-distance dependency resolution in object relative sentences. A number of these models appeal to limitations in cognitive resources, such as working memory and attention. In one such model, Gibson (1998) provides the Dependency-Locality Theory (DLT), which proposes that sentence processing difficulty is tied to limitations in working memory capacity. According to the DLT, working memory resources are called upon 1) whenever new linguistic referents are introduced in a sentence (i.e., storage costs) and 2) when those referents need to be integrated into an emerging syntactic structure (i.e., integration costs) (Gibson, 2000). Working memory resources are theorized to have both storage and integration components (Baddeley, 1990; Just & Carpenter, 1980). Under this view, the unattached displaced noun in object relative sentences must be maintained in memory before it can be integrated at the syntactically licensed gap position (post relative clause verb). Thus, processing difficulty

increases as a function of the distance or the number of referents intervening between the displaced noun and the gap site. Critically, referents that are new or peripheral to the discourse are considered less accessible and are therefore predicted to impose higher processing costs than referents that are already familiar and more accessible (e.g., pronouns such as "I", "you", "they"). For example, in the sentences below:

7. The reporter$_i$ who attacked the senator disliked$_i$ the editor.

8. The reporter$_i$ who attacked him disliked$_i$ the editor.

Warren and Gibson (2002), demonstrated that referents that are outside of the discourse and are therefore less accessible (*the senator* in sentence 7 above), resulted in slower reading times than a more discourse relevant referent (*him*, sentence 8). These results were argued to support a discourse-based metric for computing locality and processing costs arising from the limited capacity of working memory (Just & Carpenter, 1992).

In contrast to the DLT's emphasis on the accessibility and number of referents, similarity-based interference accounts have focused on the semantic and syntactic characteristics of the referents to explain processing difficulty (Gordon et al., 2001, 2004; Sekerina et al., 2016; Van Dyke, 2007; Van Dyke & Johns, 2012; Van Dyke & Lewis, 2003). Under these accounts, the semantic and syntactic similarity between the direct object and subject noun phrases has a direct impact on the ease of integration. This view proposes that during sentence processing, both noun phrases are encoded and stored in memory until they can be integrated post-verb at the gap position. Encountering the relative clause verb cues their retrieval, at which point the listener or reader must assign the appropriate agent and patient thematic roles to each noun phrase. Critically, the presence of highly similar noun phrases makes it harder to assign thematic roles due to increased interference between the memory representations. The resulting processing

difficulty is referred to as similarity-based interference. Cue-based retrieval models have been developed to characterize how the ability of the system to efficiently retrieve target information is constrained by the presence of other sentence constituents that are similar to the to-be-retrieved (target) representation (Lewis et al., 2006; Lewis & Vasishth, 2005; McElree, 2000; Van Dyke & Lewis, 2003; Van Dyke & McElree, 2006, 2011).

1.5 Cue-based parsing

The cue-based parsing framework draws from recent theories of working memory to describe the operations involved in encoding and accessing memory representations and building sentence structure (Lewis et al., 2006; Van Dyke & Lewis, 2003; Van Dyke & McElree, 2006). This approach has been shown to account for several key sentence comprehension phenomena including the difficulty associated with long-distance dependency resolution in the presence of similarity-based interference (Van Dyke & McElree, 2006). It differs from capacity-based approaches like the DLT in fundamental ways beginning with the proposition that instead of being actively maintained, previously encoded sentence elements are re-accessed (retrieved) at the point of integration (i.e., the verb). The focus on retrieval begins with the premise that during language processing, the amount of information that can be actively maintained within the focus of attention ("the set of highly activated long-term representations that are currently needed for ongoing processing", Cowan, 2005) is severely limited. While estimates vary, this limit is argued to be as small as one or two items (McElree & Dosher, 1989; Van Dyke & McElree, 2006). Information that is no longer in the current focus of attention, but needed for interpretation to occur, is retrieved via a content-addressable operation that uses syntactic and semantic cues to match current retrieval requirements with previously encoded constituents. Retrieval cues are typically generated by a verb or other reference seeking element, for example agreement features

of a verb include number, gender, animacy, etc. The probability of successful retrieval is thus a function of how closely the retrieval cues match the features of the target item.

Retrieval is described as a direct-access mechanism, which allows the parser to directly match target-items based on its content rather than searching through all elements in memory (McElree et al., 2003). This contrasts with a serial search mechanism in which the constituents are examined individually, typically in a sequence, until a match is found (Parker et al., 2017). The type of retrieval mechanism has important consequences for the timing and constraints of the language processing system. With a direct-access mechanism, retrieval is fast and efficient because items are searched associatively by their content and not by a systematic evaluation of each item (McElree, 2006). Unlike capacity-based approaches, cue-based parsing does not predict a difference in retrieval speed due to the number of items in memory representation (i.e., the amount of material intervening between two dependent elements), contrary to the dependency locality theory (Gibson, 1998, 2000). However, the benefit of retrieval speed comes with a tradeoff. If the features of multiple items in memory also match the retrieval cues, they may cause slowdowns in retrieval or the items with similar features may be erroneously retrieved instead of the target item, an effect known as retrieval interference.

Van Dyke and McElree (2006) investigated retrieval interference using a dual-task memory load paradigm and self-paced reading tasks, where they examined the effects of similar extra-sentential memory items on retrieval. In this experiment, participants were instructed to remember several lexical items prior to reading a sentence (memory set: table, sink, truck). The semantic constraints of the verb were manipulated to either match the items in the memory set ("It was the boat that the guy who lived by the sea fixed in two sunny days.") or uniquely match the target of retrieval ("It was the boat that the guy who lived by the sea sailed in two sunny

days."). When the retrieval cues also matched features of the competitor items in memory (i.e., sentences with the verb fixed matched lexical items that are 'fixable'), interference led to a slow-down in reading times at the verb.

The content-addressable retrieval model in cue-based parsing and the mechanisms underlying retrieval interference have been formalized by Lewis and Vasishth (2005) in a computational model of sentence processing, the Adaptive Character of Thought-Rational model (ACT-R, e.g., Anderson et al., 2004; Anderson & Lebiere, 1998) In ACT-R, retrieval of an element is a function of the activation of a memory trace and similarity-based interference (Lewis & Vasishth, 2005). Activation is based on three components: (1) the baseline activation of the bundle (determined by past activations and reactivations and time-based decay), (2) the strength of the association between the retrieval cues and the bundle of features, and (3) a random noise component (Lewis & Vasishth, 2005; Parker et al., 2017). The representation whose activation passes a certain threshold will be retrieved. The presence of other memory representations that share similar features with the target (i.e., partially match the retrieval cues) reduces activation of the target and interferes with its retrieval.

2.0 Accounts of Sentence Comprehension Deficits in Aphasia

Individuals with aphasia often evince difficulties comprehending sentences with long-distance dependencies. These difficulties arise most readily in non-canonical, semantically reversible sentences where reliance on syntactic structure to derive sentence meaning is highest (Caramazza & Zurif, 1976). Early theoretical accounts based these difficulties on structural impairments or loss of grammatical knowledge of the underlying syntactic representations, which prevent the parser from deriving the correct structure (Grodzinsky, 2000; Grodzinsky et al., 1999; Grodzinsky & Amunts, 2006). Based on data from multiple methodological

approaches, the field has since shifted away from representational accounts towards processing accounts (Caplan, 2006; Choy & Thompson, 2010b; Haarmann & Kolk, 1991; Martin et al., 2011; Prather et al., 1997; Swinney & Zurif, 1995). Processing accounts argue that comprehension deficits in individuals with aphasia are the result of breakdowns in the automatic processing operations, not a loss of the underlying grammatical knowledge. These processing limitations have been conceptualized in different ways and through various theoretical accounts including slowed syntactic operations (Burkhardt et al., 2008; Haarmann & Kolk, 1991; Piñango, 2000), weakened syntax (Avrutin, 2006), lexical access deficits (Blumstein & Milberg, 2000; Love et al., 2008; Milberg et al., 1995; D. Swinney et al., 2000; Yee et al., 2008), lexical integration deficits (Hagoort, 1997; Swab et al., 1996; Thompson & Choy, 2009), and reductions in cognitive resources/allocations (such as attention and working memory) (Caplan, 2006, 2012; Caplan & Waters, 2013; Hula & McNeil, 2008; Murray, 2018; Villard & Kiran, 2015). Of interest in this dissertation are deficits in the formation of lexical-level representations and their retrieval during structure building. In what follows, I review how lexical impairments can preclude successful lexical activation and lead to degraded memory representations that are more vulnerable to similarity-based interference at critical syntactic retrieval points. Investigating the nature of lexical deficits in aphasia under the theoretical context of cue-based parsing provides a way to unify accounts to allow us to determine if existing models of sentence processing can be extended to impaired processing situations, such as those found in certain individuals with aphasia. Doing so also provides a window to explore the interaction between lexico-semantic and syntactic mechanisms involved in sentence composition in IWA.

2.1 Lexical Processing Accounts

Lexical information supplies the foundational building blocks for the construction of syntactic structure and the final interpretation of sentence meaning. Syntactic operations such as dependency linking rely on the rapid, automatic access of lexical-semantic information (i.e., lexical activation) to integrate lexical items into the emerging syntactic frame and arrive at the correct sentence interpretation within the tight temporal constraints of auditory language. As such, lexical level impairments have been shown to have important ramifications for sentence comprehension (Dede, 2012; Ferrill et al., 2012; Love et al., 2008). For example, delays in the timing of access to lexical-semantic information and under-activation of lexical items have both been posited to contribute to sentence comprehension impairments (Love et al., 2008; Milberg et al., 1995). These deficits are most readily observed in individuals with non-fluent aphasia, which has been historically characterized as an expressive impairment (slow, effortful, agrammatic speech). Many studies have investigated individuals with Broca's aphasia, a non-fluent aphasia subtype typically resulting from damage that involves the left inferior frontal cortex, as these individuals generally have spared comprehension abilities for canonically ordered sentences but have difficulties understanding syntactically complex (non-canonical) sentences, such as object relative constructions (Blumstein & Milberg, 2000; Caramazza & Zurif, 1976; D. Swinney & Zurif, 1995). Among a number of theories proposed, these difficulties have been tied to lexical processing impairments such as delayed lexical activation and reduced activation, which will each be discussed below.

2.1.1 Delayed lexical activation

Early evidence for delayed activation theories comes from findings of aberrant patterns in the time course of lexical priming. Lexical (i.e., semantic) priming effects occur when the presentation of a semantically related prime word ("doctor") facilitates processing of the following target word ("nurse") as compared to it being preceded by an unrelated prime word ("chair"). Typically, studies measure the magnitude of priming effects via response times in a binary decision task on the target word (e.g., lexical decision: deciding whether a string of letters represents a real English word). This facilitation effect is presumed to operate on the basis of spreading activation, or the automatic propagation of activation within a network of mental representations (Balota & Lorch, 1986; Collins & Loftus, 1975; Neely, 1991). The time course of priming is typically investigated by altering the delay between the presentation of prime and target words (interstimulus interval or ISI) and observing when facilitation of response times (priming) occurs. Research in support of slowed activation theories has found that individuals with Broca's aphasia only evince semantic priming at longer ISIs compared to neurotypical controls or individuals with other types of post-stroke aphasia (Ferrill et al., 2012; Love et al., 2008; Prather et al., 1997; Silkes et al., 2020). In other words, individuals with Broca's aphasia can evince semantic priming, but they need more time for activation to spread among related associates.

Beyond single-word studies, priming methods have also been used to explore the time-course of lexical activation at various points as a sentence unfolds, to capture what information is active at given points during the processing of a sentence. In a series of studies, Love and colleagues (2008) used cross-modal lexical decision priming (CMLP, Swinney, 1979) to investigate lexical activation in object relative sentences to observe when and at which point the

initial antecedent (direct object noun) was activated in a group of unimpaired controls and individuals with Broca's aphasia. In the CMLP paradigm, participants listen to an uninterrupted sentence while they also complete a secondary visual lexical decision task where letter strings are presented at specific points during the auditory presentation of the sentence. Participants make a binary (YES/NO) decision to the letter string probes, which are sometimes semantically related to the auditorily presented word of interest (i.e., the displaced direct object noun). The underlying assumption is that if the target item from the auditory sentence is currently activated, reaction times in response to related visual probes should be faster than if they were unrelated. In their 2008 study, Love and colleagues presented letter strings at 5 positions, see Figure 2.3.

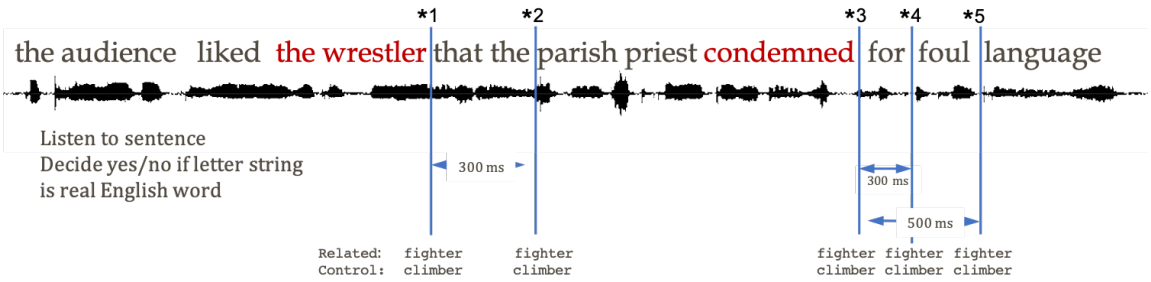


Figure 2.3. Example sentence from Love and colleagues (2008). Each probe position (blue line) is indicated by number and *. Example primes are presented at the bottom for related (fighter) and control (climber) primes.

Participants were asked to decide as quickly and accurately as possible if the letter strings were a real word or a non-word. Probe *1 is positioned at the offset the direct object noun ("wrestler") and probe position *2 occurs 300ms downstream of probe *1. Probe position *3 occurs at the trace (t) or 'gap' site directly after the relative clause verb. Probe position *4 is 300ms after the gap and probe position *5 is 500ms after the gap. The results revealed a typical pattern of activation in unimpaired individuals, which has been replicated in other work (Akhavan et al., 2020; Love et al., 2008; Love & Swinney, 1996, and references therein). The direct object noun ("wrestler") is immediately activated when it is first encountered (probe

position *1) and again at the gap site where its reactivation is syntactically licensed (probe position *3). Importantly, participants did not evince priming at probe position *2, showing that the priming effect found at the gap was the result of reactivation and not due to maintained activation. Individuals with Broca's aphasia showed an aberrant pattern. In this group, there was no significant priming for "wrestler" at probe position *1. Instead, activation was delayed until probe position *2. Similarly, priming post-verb was delayed beyond the gap site and only appeared at probe position *5, 500ms after the gap. Importantly, these studies indicate that individuals with Broca's aphasia can accomplish dependency linking, but they are delayed in doing so.

Delays in lexical activation in sentences with syntactic dependencies are particularly detrimental to both real-time parsing and final comprehension as these sentences involve a coordinated series of fast-acting lexical and syntactically driven processes. The authors concluded that the delay in initial lexical activation did not provide the system with the necessary lexical-semantic information in time and resulted in a concomitant delay in downstream dependency linking (i.e., delayed reactivation). In support of this view, the researchers found that when rate of speech was slowed from a normal rate of 4.47 syllables per second to 3.4 syllables per second (argued to allow for more time for a rise in lexical activation), it facilitated more timely lexical activation and dependency linking. Furthermore, when tested using an offline sentence-picture matching task, individuals with Broca's aphasia showed a significant improvement in their comprehension in the slow rate as compared to the regular rate conditions. Similar findings of delayed lexical activation in individuals with agrammatic aphasia have also been found in canonical sentences (Ferrill et al., 2012). Findings from these investigations have led to the delayed lexical access (DLA) hypothesis, which posits that sentence comprehension

deficits in Broca's aphasia are the result of delays in lexical activation that make lexical information unavailable at a time when that information is required by fast-acting syntactic processes such as dependency linking.

2.1.2 Reduced lexical activation

An alternative to the delayed activation theory is one where activation in individuals with aphasia is reduced to a level that does not allow for priming to be evinced. Data supporting this theory point to deficits in the degree to which lexical information is activated in individuals with Broca's aphasia (Blumstein & Milberg, 2000; Janse, 2006; McNellis & Blumstein, 2001; Utman et al., 2001). This work is borne of investigations of processing under conditions of lexical competition. For example, an auditory semantic priming study conducted by Utman and colleagues (2001) used prime words containing either a good or poor phonetic exemplar of a semantically related word (e.g., "cat" – "dog" vs "c*at" – "dog"). Acoustic manipulations (subphonetic variations) were made by reducing the voice onset time of voiceless initial stop consonants by two-thirds. The effect of the acoustic manipulations on the amount of semantic priming was assessed via lexical decision times. The results showed reduced semantic facilitation in the group of individuals with Broca's aphasia. This effect was magnified when the acoustic alteration of prime words was associated with a potential lexical competitor (e.g., "pill" > "bill") compared to when there was no potential for competition (e.g., "peace" > "bis"). These results were interpreted as evidence of reduced activation for altered prime words, which failed to achieve sufficient activation to overcome the lexical competition. Similar results were found using eye-tracking while listening with a visual world paradigm, which showed that individuals with Broca's aphasia evince impairments in lexical-semantic access in the form of reduced activation under conditions of lexical competition (Yee, Blumstein, & Sedivy, 2008). The effect

of lexical deficits on the memory operations supporting dependency linking have been relatively unexplored; yet, deficits in the speed and level of activation are likely to impact both encoding and retrieval.

Studies investigating the presence of reduced or delayed activation often aim to determine which theory best characterizes lexical processing impairments in aphasia. Unsurprisingly, there has not been a consensus on this point, most likely because both forms of disruption may be present during language comprehension. For this reason, the studies presented herein do not aim to distinguish between these accounts, but rather explore how and when these disruptions influence the availability of lexical representations during sentence processing and their effects on long distance dependency completion and final comprehension.

2.2 The link between lexical-level impairments and sentence processing in aphasia

As previously alluded to, deficits in lexical access can negatively affect real-time structure building and sentence comprehension in aphasia, particularly for noncanonical sentence constructions. These sentences require a coordinated series of fast-acting lexical and syntactic processes to complete real-time dependency linking. Consequentially, disruptions during lexical processing limit the ability to quickly and accurately activate the information required for syntactic integration and can lead to a breakdown in comprehension (Ferrill et al., 2012; Love et al., 2008; Prather et al., 1997). The effects of lexical activation deficits can be conceptualized in two ways, although these are not mutually exclusive. As described above, one type of processing impairment is a delay in the time course of lexical activation. This delay can slow or interrupt the encoding of the lexical features (syntactic or semantic). As the sentence unfolds, these delays can have cascading effects on the access and encoding of subsequent lexical items. Note here that this can occur regardless of sentence construction but may not have as deleterious an effect in

sentences without long-distance dependencies (i.e., canonical constructions). In sentences containing long-distance dependencies, such as (8), a delay in the activation of teacher may result in further interruption of the access and encoding processes as subsequent incoming information is presented (i.e., the second noun boy). This overlap can result in an incomplete representation for that item and/or blur the features associated with each noun. In the context of complex sentences with long-distance dependencies, this will likely increase the difficulty of retrieving the correct target at a critical syntactic point such as that found post verb.

(9) The teacher saw **the boy**$_i$ that the girl **pushed**$_i$ in the classroom.

In cases where lexical activation is reduced, fewer features may be encoded or features may be weakly encoded (i.e., lower activation) leading to a less successful formation of a memory trace. Recall that in the computational framework of ACT-R, the cognitive architecture of cue-based parsing, a memory representation (stored as a bundle of features) is retrieved when it passes a threshold of activation. The representation that reaches the threshold first is retrieved (Lewis & Vasishth, 2005). In our example, any reduction in lexical activation on the direct object (*boy*) could result in a weaker baseline activation and/or fewer features encoded. The resulting representation would thus be a weaker match to the retrieval cues and increase interference from the non-target item making it more difficult to retrieve the direct object at the relative clause verb (*pushed*). Overall, the degradations caused by lexical impairments negatively impact lexical access/encoding and can cause downstream difficulty in establishing the grammatical relationships that require them and amplify interference effects. This is predicted to not only affect real-time processing, but should also give rise to longer-lasting effects resulting in offline comprehension difficulty. Addressing these disruptions by improving the lexical processing is

therefore one route to facilitating syntactic structure building during real-time sentence processing and a central goal of this dissertation.

There is currently a dearth of literature investigating approaches to enhance lexical level processing during an ongoing sentence. The work that has explored levels of lexical processing has largely focused on the production and comprehension of single words. Various lexical properties have been shown to affect access including word length, frequency, neighborhood size, concreteness, context, etc. (Luce & Pisoni, 1998; W. Marslen-Wilson, 1990; McClelland & Elman, 1986; Norris, 1994). This dissertation takes a different approach by asking how we can modulate lexical access by manipulating parameters external to the word itself without changing the core surface form of the target words. To answer this question, I explore ways to facilitate lexical processing of a critical item when it is first encountered in a sentence through the enhanced recruitment of linguistic and cognitive processes. Here, I explore known factors that affect lexical processing: time, attentional modulation, and pre-activating the semantic level properties of the target word through priming. The following sections detail how each of these factors have been shown to affect lexical access in language impaired and unimpaired populations.

3.0 Parameters influencing lexical processing

3.1 Time

The parameter of time, or more specifically, the time associated with processing a lexical item during ongoing sentence processing, is important for sentences in which the presentation of information is fleeting, such as in the auditory modality. This has been shown to influence lexical-level access both at the single-word level and during sentence processing. (Love et al., 2008). Chapters 4 and 5 of this dissertation detail a study investigating the impact of providing

additional time for initial processing of the direct object noun in object relative sentences, presented in a visual world eye-tracking paradigm to a group of college-age neurologically unimpaired college-age adults (Chapter 4) and a group of individuals with aphasia (Chapter 5) while they listened to sentences containing object relative clauses.

3.2 Attention

While aphasia is classically defined as a language-specific disorder, a wide body of literature has centered on attention and its role in auditory comprehension difficulties and individual variability in aphasia (Hula & McNeil, 2008; Murray, 2012). This literature suggests that IWA have greater difficulty allocating attentional resources compared to language-unimpaired individuals. Deficits in engaging, orienting, and focusing attention have been argued to interact with language processes and contribute to difficulties in processing lexical-semantic information (Murray, 2000). Of interest here is how the ability to focus attentional resources (i.e., selective attention) can optimize behavioral performance and mitigate lexical processing deficits in aphasia. In line with this idea, engaging selective attention mechanisms has been shown to enhance processing of items within the focus of attention (Posner, 1980; Oberauer, 2019). In the context of lexical-level processing, directing attention to lexical information is hypothesized to increase the activation of the mental representations for words (Mirman et al., 2008). Chapter 5 of this dissertation applies this idea to sentence processing, and details a study investigating whether directing attention to the critical lexical item (the direct object noun) within an object relative sentence helps to focus attention and increase the activation of that lexical item for age-matched neurotypical adults and individuals with aphasia. In this study, the aim is to direct attention implicitly through the use of disfluencies (e.g., filled pauses, uh), which have been shown to affect comprehension by orienting attention to subsequent words and

facilitating their processing (Brennan & Schober, 2001; Collard et al., 2008; Corley & Hartsuiker, 2011).

3.3 Semantic Priming

The third way I approach mitigating lexical processing deficits is to pre-activate semantic properties associated with the target lexical item to aid in lexical access. Highly influential models of lexical access specify that successful word naming and comprehension requires processing at the semantic and phonological levels (Levelt, Roelofs, & Meyer, 1999; Marslen-Wilson, 1987; McClelland & Elman, 1986). Although there is debate as to the extent of interactivity among these levels, priming research has shown that both form and meaning can be used to influence lexical access. As described above, priming tasks show that the presentation of a prime word can facilitate processing of the subsequent target word by increasing its activation. This facilitation can be achieved through phonological priming, which occurs when prime words are phonologically related or have partly overlapping form, or through semantic priming of conceptually related primes (Baum, 1997). The ability to leverage different sources of lexical information to aid lexical access is critical in a heterogeneous disorder such as aphasia. It is well established that IWA can demonstrate impaired processing in one or both domains (phonemic or semantic) (Howard & Gatehouse, 2006; Meier et al., 2016; Mirman et al., 2013). What is not clear is whether or not the information can still be used in such a way that it can affect real-time processing. The study reported in Chapter 5 also includes an experimental condition that will be used to assess whether semantic cueing as a means to focus attention can boost lexical activation of the target direct object noun upon initial processing and at critical structural junctures, for AMC and IWA.

4.0 Goals of dissertation

This dissertation seeks to investigate the interaction between real-time lexical and syntactic processing during auditory sentence comprehension in both neurologically unimpaired populations and in individuals with aphasia. Within this overarching goal, I explore the parameters underlying successful processing by focusing on ways to facilitate sentence comprehension through manipulations to improve lexical processing. To facilitate lexical access of target items within a sentence, I take a novel approach by manipulating the three elements of time, attention, and semantic pre-activation. In each of these approaches, I ask whether enhancing the processing of a critical lexical item during sentence processing will 1) facilitate its lexical access, 2) increase its availability for downstream syntactic operations, and 3) improve sentence comprehension. Chapters 1 and 2 provided the theoretical background of the proposed work. Chapter 3, to follow, investigates the impact of time on sentence comprehension by extending available processing time of a target noun (direct object) through three temporal manipulations (disfluent, silence, and stretch) in college-aged neurotypical adults (YNC), individuals with post-stroke aphasia (IWA) and their neurotypical age-matched control peers (AMC). Chapter 4 investigates whether these temporal manipulations affect real-time lexical activation and syntactic reactivation using eye-tracking while listening in YNC. Chapter 5 presents the results of a study that extends Chapter 4's work to older populations including IWA and AMC. The study presented in Chapter 6 examines whether implicitly directing attention to the direct object noun during sentence processing will modulate lexical activation and syntactic reactivation (dependency linking) in AMC and IWA. In this study, we use a manipulation from Chapter 3 (disfluencies), but present them in different strategic locations in relation to the target lexical item to tap into different mechanisms. This study also tests whether pre-activation of

semantic properties of the target noun via a pre-sentence priming task influences processing. The central hypothesis is that enhancing lexical access when a critical item is first encountered will facilitate syntactic integration at later points in the sentence and improve comprehension. Chapter 7 concludes with a discussion of how these studies inform our knowledge of the parameters for improved lexical access during sentence processing and lay the groundwork for unique approaches to mitigating sentence comprehension deficits in aphasia. Implications for future work are also discussed.

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CHAPTER 3

Temporal Parameters Affecting Complex Sentence Comprehension

Abstract

Sentence comprehension deficits in aphasia have been linked to disruptions in the automatic processing of lexical items (e.g., delayed lexical activation), which preclude timely structure building and contribute to breakdowns in comprehension. In the present study, we examined if providing additional time for processing a target noun affects listeners' final (offline) interpretation of complex sentences. Using a sentence-picture matching task, we investigated if three forms of focal temporal manipulations (disfluent, silence, stretch) inserted directly after the direct object noun affect listeners' comprehension of object relative sentences in three groups of individuals: college-age neurologically unimpaired adults (YNC, n=41), individuals with aphasia (IWA, n=8), and age-matched neurologically unimpaired control participants (AMC, n=8). Results revealed that, as expected YNC performed near ceiling across all conditions, yet showed faster responses in the silence condition. Interestingly, while also performing near ceiling, the AMC group showed both improved comprehension in the silence condition and faster response times in the disfluent condition. Consistent with the literature, IWA demonstrated at-chance comprehension of control sentences. This group showed improvement to above-chance performance in each of the temporal manipulations. The improved comprehension in IWA provides support that deficits in the timely access of lexical items contribute to complex sentence comprehension deficits.

1.0 Introduction

There is considerable evidence that individuals with aphasia demonstrate impaired sentence comprehension subsequent to left-hemisphere damage in language dominant regions. Comprehension difficulties are most readily observed in semantically reversible sentences with non-canonical word order (e.g., object-subject-verb), which impose additional processing costs

to assign thematic roles compared to sentences with canonical word order (e.g., subject-object-verb) (Burchert et al., 2013; Caramazza & Zurif, 1976; Grodzinsky et al., 1999; Salis & Edwards, 2008; D. Swinney & Zurif, 1995; Thompson et al., 1999; Zurif et al., 1993). For example, in object relative sentences such as (1) below, the direct object of the verb (i.e., *the reporter*) has been displaced from its post-verb canonical position to the front of the sentence, leaving behind a "gap" or trace of the moved noun phrase (Fodor, 1989; Swinney & Fodor, 1989; Swinney & Osterhout, 1990). This movement forms a syntactic relationship between the non-adjacent direct object noun and its canonical post-verb position (noted by the subscript i) and requires rapidly accessing and then *re*-accessing the object noun at the gap for integration into the emerging syntactic structure (Love & Swinney, 1996).

1. The **reporter**$_i$ that the senator **attacked**$_i$ <~~the reporter~~> admitted the error.

Under normal speech conditions (with an average speech rate), this syntactic linking operation has been shown to be vulnerable when timely processing of sentence constituents is obstructed (i.e., impaired lexical access) which ultimately disrupts final interpretative understanding (Love et al., 2008). Delays in activating lexical information during auditory sentence processing have been linked to comprehension deficits in aphasia and are argued to supply information too slowly for syntactic processing, leading to breakdowns in automatic structure building and final comprehension (Ferrill et al., 2012; Love et al., 2008). In support of this argument, research using a temporally sensitive paradigm (cross-modal priming) has shown that when the temporal constraints of accessing and re-accessing critical lexical items are relaxed, by slowing down the overall speech rate, deficits in automatic, real-time gap-filling processes can be mitigated (Love et al., 2008). Additionally, this study investigated the effect of slowed speech rate on final (off-line) comprehension using a sentence-picture matching task (the

SOAP: **S**ubject relative, **O**bject relative, **A**ctive and **P**assive; Love & Oster, 2002). Individuals with agrammatic aphasia showed significant improvement in their comprehension when sentences were spoken at a slowed speech rate compared to normal speed for the non-canonical sentence structures (object relative and passive sentences). In relaxing the normal time constraints at the sentence level, it is yet unclear whether the benefits of slowed speech rate occurred because of the additional time for processing the lexical item itself (mitigating delayed activation) or if it was coupled with additional time at the post-verb dependency site (additional time for reactivation). The current proposal expands on this prior work to test whether more focal temporal manipulations that provide additional time for processing the target direct object noun result in similar comprehension facilitation in aphasia. If so, it bolsters the claim that the source of impairment stems from delayed lexical access. The temporal manipulations consisted of two forms of additional inserted time post-noun via either a **disfluency** (e.g., *uh*) or a **silent** pause or an increased duration of the object noun (**stretch**). In the current study, we investigated if these manipulations affect the final product of the language comprehension process or offline comprehension. To tap into offline comprehension, we use a sentence-picture matching task, which has been widely used to measure syntactic comprehension in language impaired and unimpaired populations (Berndt et al., 1996; Caplan et al., 1997; Caramazza & Zurif, 1976). Findings from these tasks show that IWAs often perform at chance when they process semantically reversible non-canonical sentences such as (1) (Burchert et al., 2013; Caramazza & Zurif, 1976). Based on the deficits in lexical processing identified in the literature, we predicted the three temporal manipulations to increase sentence comprehension accuracy in IWA. In order to capture impaired language processing, we needed to gauge how unimpaired comprehenders (regardless of age) responded to these manipulations. Furthermore, while accuracy is a standard

metric for reflecting comprehension abilities, it is well-known in the literature that other metrics reflect processing effort indicating difficulties. As such, reaction time analyses are included with percent correct to paint a clearer picture of performance.

2.0 Methods

2.1 Participants

57 participants were recruited across three participants groups. Group 1 included 8 individuals (M_{age} = 66.8, SD = 11.5, male = 5) who experienced a left hemisphere cerebral stroke at least 6 months prior to testing and had resulting language impairments (Table 1). These individuals with post-stroke aphasia (IWA) were pre-morbidly right-handed, monolingual native speakers of American English, normal or corrected-to-normal vision and hearing, with no history of neurological disease, head trauma, substance use disorder, or psychiatric disturbances prior to their stroke. Aphasia diagnosis and severity were assessed using standardized aphasia examinations, the Boston Diagnostic Aphasia Examination-III (BDAE-version 3; Goodglass, Kaplan, & Barresi, 2001), the Comprehensive Aphasia Test (CAT, cognitive screening and comprehension subtest; Swinburn, Porter, & Howard, 2004) and were confirmed by clinical consensus. To be included, all IWA had to score within normal limits for a cognitive screening (cutoff score = 26). All AMC performed within normal limits on the Cognitive Linguistic Quick Test (CLQT, Helm-Estabrooks, 2001). IWA results from these tests are presented in Table 3.1.

Groups 2 and 3 were composed of neurologically unimpaired participants: 41 college-age participants (Group two YNC, M_{age} = 23, SD = 2.4, range = 18-30, male = 1) and 8 age-matched controls relative to the IWA group (Group three AMC, M_{age} = 69.1, SD = 7.7, male = 2). Neurotypical participants were right-handed, native English speakers with minimal experience in a second language learned after the age of six. Participants also had normal or corrected vision and hearing, and no self-reported history of substance abuse, active psychiatric illness,

intellectual disability, or other significant brain disorder or dysfunction. All AMC and IWA participants were monetarily compensated for their participation. YNC participants received extra credit for study participation. All methods described below were approved by the University of California San Diego and the San Diego State University Institutional Review Boards.

Table 3.1: Characteristics of IWA (n =8).

IWA	Sex	Age	Years of Education	Years Post-Stroke	Lesion Volume (mL)	BDAE Severity	BDAE Auditory Comprehension	SOAP Canonical (%)	SOAP Noncanonical (%)	CAT Cognitive Screen	CAT Comprehension
9	M	62	17	21	172.52	2	20	65	25	34	25
101	M	74	20	16	146.27	2	68.3	40	55	38	51
130	M	70	16	15	109.08	4	61.7	75	45	34	47
151	F	72	16	14	77.13	4	N/A	100	80	38	64
159	F	71	16	12	N/A	3	80	95	70	35	54
169	M	66	12	10	66.03	1	33	90	20	36	36
181	F	41	16	6	N/A	1	11.7	60	50	33	27
192	M	78	17	8	69.69	4	76.7	100	100	35	55

2.2 Stimuli

2.2.1 Sentences

Stimuli consisted of 20 object relative sentences from Baker and Love (2021). All sentences were constructed following a similar format: an introductory adverbial clause, the object relative clause (containing the direct object and subject nouns and the relative clause verb), and a main verb phrase (see 2 below).

	Intro phrase	**direct object**	**subject**	**relative clause verb**	**main verb phrase**
2.	At the Halloween party,	the elf that the	clown	pushed	was in the backyard

Experimental sentences were constructed to have non-biasing contexts such that both the direct object noun (noun 1, N1) and subject noun (noun 2, N2) were equally plausible as either the agent or theme of the relative clause verb. The two nouns of interest (N1 and N2) were all one to

three syllables and were not phonologically similar or semantically related to one another. Each of the 20 object relative sentences appeared in each of the four temporal conditions, detailed below, for a total of 80 experimental items.

2.2.2 Temporal manipulations

Control sentences (Figure 1) were naturally recorded by a female native English speaker in a sound-treated room at an average speech rate of 4.94 syllables/second (SD = .26s). These sentences served as the base for the three temporal manipulations: stretch, disfluent, and silence. The **stretch condition** was created by digitally elongating the duration of the direct object noun (N1) by 150% while maintaining pitch using Adobe Audition CC. The "stretched" nouns were approximately ~250ms longer than the control nouns. To create the **disfluent condition**, a filled-pause disfluency (*uh*) was spliced into the original (control) recording approximately 100ms after the offset of N1 and 100ms before the upcoming relativizer to allow for a natural buffer before and after the disfluency as is typical in spontaneous speech (Shriberg, 1999). This manipulation resulted in an average of 460.0ms (SD = 3.8ms) of additional time. To create the **silence condition**, the disfluent portion was replaced by an equal length silent pause to maintain the same timing between disfluent and silent conditions (~460ms). This resulted in a total of 40 experimental items (10 sentences per condition). An additional 20 unrelated filler sentences were created to distract participants from developing strategies when listening to the object relative clause construction in the target sentences (i.e., only looking to the first noun, etc.). Filler sentences (e.g., active and subject relative sentences) were recorded by the same female native English speaker at a normal rate of speech and were of similar length, but varied in syntactic structure.

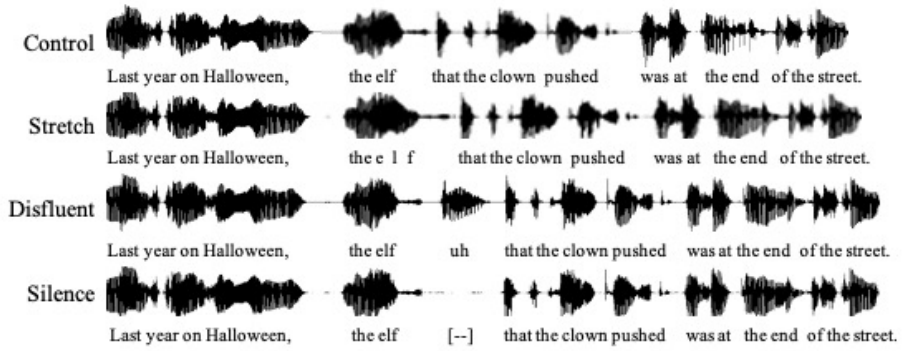


Figure 3.1: Waveforms of example stimuli showing the control condition and temporal manipulations (disfluent, silence, and stretch).

2.2.3 Visual Stimuli

Two sets of images were used for this sentence-picture matching task. The first set of introduction images consisted of two single character images, one for each of the referents mentioned in the sentences (the direct object and subject nouns). The second set of images consisted of the same characters paired to depict semantically reversed action sequences (see Figure 3.2, below).

2.3 Study Design

The 80 experimental items were split into 4 lists such that each list contained 20 experimental items (5 experimental sentences per condition) and 20 filler items for a total of 40 sentences. Due to Covid-19, YNCs participated in the experiment remotely (see details below) and completed one list per session for a total two sessions spaced approximately one week apart. Data from AMC and IWA participants were collected in person across two visits. In each visit, participants completed one list in the beginning of the testing session and one list at the end of the session after completing other neuropsychological assessments (approximately 45 minutes later). List assignment was counterbalanced across sessions and session visits were spaced a minimum of one week apart.

2.4 Procedure

Participants who were seen in-person (AMC, IWA) were seated in front of a computer screen and wore over-the-ear headphones for auditory stimulus presentation. YNC participants were instructed to complete the experiment in a quiet room with headphones. All participants were instructed to listen carefully to each sentence as they would be asked to choose a picture that best matched the sentence they just heard as quickly and accurately as possible, with accuracy being emphasized over speed. Responses (accuracy and reaction time, RT) and timed presentation of auditory and visual stimuli were controlled by Labvanced software (Finger et al., 2017). At the beginning of each visit, participants completed 6 practice trials to familiarize themselves with the task; for the IWA and AMC groups, this allowed for the experimenter to provide feedback as necessary. Each trial began with a screen introducing the two referents (N1 and N2) that would appear in the sentence (see Figure 3.2). The order of picture presentation (i.e., left and right on screen) was counterbalanced across trials. Participants used a mouse to click on a 'next' button to begin each trial. After clicking, participants were simultaneously presented with the auditory sentence and a target picture along with a thematically reversed foil picture (i.e., role reversal of agent and patient) on the computer screen in front of them. Position (left and right) of the target and foil pictures was counterbalanced across trials. Upon completion of the sentence, participants responded by clicking on one of the two pictures. After the response, or after 4,000ms elapsed with no response, the picture array was replaced with a central fixation cross for one second indicating the start of the next trial.

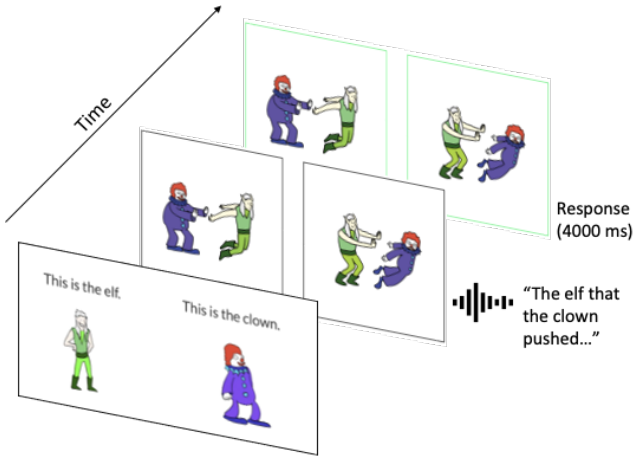


Figure 3.2: Example of sentence-picture matching task. The example display presents the direct object noun (e.g., *elf*), the subject noun (e.g., *clown*) as single characters and pairs of reversed action sequences.

2.5 Data analysis

For accuracy analyses, any trial for which response time was shorter than 200ms was excluded from analyses as those are considered to be too fast to reflect a meaningful cognitive process and likely to be based on automatic processes such as prepotent or reflexive responses (Ratcliff, 1993; Simon, 1990). This resulted in the removal of 2.6% of AMC data, 5.2% for IWA, and 3.5% for YNC. For reaction time (RTs, in milliseconds) analyses, in addition to RTs faster than 200ms, RTs associated with incorrect responses were removed. Responses greater than 2 standard deviations from each participant's mean per condition were also excluded from the analyses to ensure that extraneous factors such as brief distractions or button press mistakes were not being captured. This data trimming procedure was determined *a priori* based on it being a standard and well-studied approach in psycholinguistic research (LaCroix et al., 2020; Silkes et al., 2020). Data trimming resulted in the removal of 2.4% of the data for the IWA group, 3.91% for the AMC group, and .86% for YNC group. Accuracy data were analyzed using mixed effects logistic regression models to predict the relationship between the temporal conditions (control, disfluent, silence, stretch) and the binary dependent variable (e.g., correct and incorrect

responses). RT data were analyzed using mixed effects linear regression models. Group models were first conducted to explore differences in accuracy and RT in the control condition between 1) AMC and YNC to ensure that there were no age effects in this task and 2) AMC and IWA to replicate existing patterns in the literature with IWA. Separate analyses were then conducted to model condition differences (control vs temporal manipulations) in each group, as our predictions were based on specific patterns of condition effects in each group. Analyses were performed using the lme4 package (Bates et al., 2015) in R (R Core Team, 2022), degrees of freedom were calculated using the Satterthwaite's (Kenward-Roger's) approximations for the *t* test and corresponding *p* values in the package lmerTest (Kuznetsova et al., 2015). In each model, condition (control, disfluent, silent, stretch) was included as a fixed effect and participant and item were entered as random effects on intercept terms.

3.0 Results

3.1 Accuracy

In the control sentences, group models between AMC and YNC revealed no significant differences in accuracy ($p > .05$). Overall, the age-matched control participants and younger adults demonstrated good ability to comprehend the object relative sentences with near-ceiling accuracy across conditions (Table 3.2). When comparing the AMC and IWA groups, however, analyses revealed the expected pattern of significantly lower accuracy for these object relative sentences in the IWA group compared to AMCs ($\beta = -2.76$, SE = .54, $p < .001$) in all three conditions. Mean accuracy and standard errors for each condition in the three participant groups are shown in Table 3.2.

Within-group logistic regression models in the YNC group revealed no significant differences in accuracy across conditions. In the AMC group, a significant effect emerged in the

silence condition, which showed higher accuracy for this condition compared to control (β = 2.03, SE = 1.08, $p = .05$). No significant difference emerged in the IWA group. However, given the near chance accuracies in the IWA group, consistent with prior findings (Burchert et al., 2013 and references therein), we conducted further analyses to determine whether sentence comprehension performance was significantly greater than chance (50%) in each of the four conditions. Accuracy scores were submitted to a one-sample *t* test with a comparison value of .50, which is equal to chance performance. In the control condition, results demonstrated that performance was no different from chance in IWA ($t(137) = 1.54$, $p = .13$, 95% CI [.48, .65]). In contrast, comprehension performance was significantly greater than chance in each of the temporal manipulations (disfluent: $t(139) = 2.77$, $p < .05$, 95% CI [.53, .70]; silence: $t(132) = 2.02$, $p < .05$, 95% CI [.51, .67]; stretch: $t(134) = 2.92$, $p < .05$, 95% CI [.54, .71]).

Table 3.2: Accuracy (% correct). Mean (M) and standard deviations (SD) for offline comprehension of object relative sentences for the four conditions.

	YNC n=41		**AMC n=8**		**IWA n=8**	
Condition	**M**	**SD**	**M**	**SD**	**M**	**SD**
Control	96%	21%	95%	22%	57%	50%
Disfluent	98%	15%	98%	15%	61%	49%
Silence	98%	13%	99%	9%	59%	49%
Stretch	97%	17%	96%	19%	62%	49%

3.2 Reaction Time

Group comparisons between AMC and YNC revealed no difference in response speed ($p > .05$). The group model comparing AMC and IWA reaction times revealed that IWAs were significantly slower to respond correctly in the control condition compared to AMCs (β = 793.69, SE = 220.8, $p < .05$). The results for mean RT and standard errors for each condition in the three participant groups are shown in Table 3.3.

Within-group analyses revealed that in the YNC group, reaction times were significantly faster in the silence condition compared to control sentences (β = -178.12, SE = 83.6, $p < .05$). No differences were found when comparing the disfluent or stretch conditions to controls ($p > .05$). In the AMC group, the responses in the disfluent condition were significantly faster than the control condition (β = -129.92, SE = 62.8, $p < .05$). No other significant effects were found in this group. Lastly, in the IWA group, no significant differences between conditions emerged ($p > .05$).

Table 3.3: Reaction time (ms) and standard deviations (SD) for offline comprehension for the four conditions.

	YNC n=41		AMC n=8		IWA n=8	
Condition	**M**	**SD**	**M**	**SD**	**M**	**SD**
Control	985.0	696.8	913.4	637.1	1633.6	832.8
Disfluent	906.7	675.9	783.2	423.8	1438.3	846.0
Silence	818.9	585.4	903.9	689.4	1553.8	944.0
Stretch	928.7	645.5	975.7	641.8	1486.1	828.3

4.0 Discussion and Conclusion

This study used a sentence-picture matching task to investigate the effects of three temporal manipulations (disfluent, silence, stretch) on the comprehension of semantically reversible object relative sentences in college-age individuals (YNC), older age-matched adults (AMC), and individuals with aphasia (IWA). Accuracy and response times of the experimental conditions were compared to naturally recorded control sentences. With regard to accuracy, both YNC and AMC groups demonstrated near-ceiling performance across conditions. In the AMC group, the silence condition resulted in improved comprehension compared to control sentences. No significant differences were found between conditions in the YNC group, suggesting that these participants arrived at the correct interpretation equally across conditions. With regard to

reaction times, YNCs responded correctly faster in the silence condition, while AMCs had faster responses in the disfluent condition. For the IWA group, we replicate at- or below-chance performance for these complex sentence constructions, which is consistent with prior findings (Burchert et al., 2013; Caplan, 2001). Interestingly, while the three temporal manipulations resulted in greater-than-chance performance, they did not alter the response speeds in the IWA group.

Recall that prior work showed that overall slowing of an entire sentence resulted in improved comprehension performance in IWA (Love et al., 2008). Here, the interest was in whether or not focal temporal slowing would have similar outcomes. If so, it would lend support to the Delayed Lexical Activation hypothesis (DLA), which posits that delays in accessing lexical-semantic information feed syntactic processing too slowly and lead to breakdowns in sentence comprehension in aphasia (Ferrill et al., 2012; Love et al., 2008). These results provide initial support to the DLA hypothesis in that when additional time is provided for lexical processing, comprehension improves to above-chance performance in IWA. However, it is important to note that comprehension in IWA remained generally low across conditions with high levels of individual variability. The observed variability in this study and others using temporal manipulations (Love et al., 2008; Martin & Dell, 2019) suggests that IWA may vary in their degree of lexical activation impairment, and therefore the length of additional time that is needed for each person is likely to differ. For example, in a recent picture naming study investigating the effects of time passage on word retrieval in aphasia, Martin and Dell (2017, 2019) found that some IWA performed better after a 5-second delay between picture presentation and response, while others did better after a 1-second response delay. While these findings were in language production, lexical activation is an underlying mechanism in both

word comprehension and production (Dell et al., 1997; Marslen-Wilson & Tyler, 1980). These results highlight that IWA may have differential impairments in lexical access that affect not only their timing of lexical activation but also their response to different mitigations.

While this study lends preliminary support to lexical accounts of sentence comprehension deficits in aphasia, the consideration of behavioral offline data alone is not sufficient to evaluate performance and draw theoretical conclusions (Burchert, Hanne, & Vasishth, 2013). Without consideration of online (real-time) behavioral performance, we cannot evaluate the presence of delayed lexical activation nor whether the temporal manipulations improved lexical processing. To address these questions, Chapters 4 and 5 present studies investigating online processing using eye-tracking-while-listening with a visual world paradigm to capture lexical and syntactic processes as they unfold moment-by-moment during auditorily presented object relative sentences with the same temporal manipulations.

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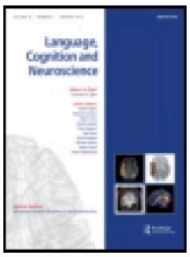
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CHAPTER 4

It’s about time! Time as a parameter for lexical and syntactic processing: an eye-tracking-while-listening investigation



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It's about time! Time as a parameter for lexical and syntactic processing: an eye-tracking-while-listening investigation

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ABSTRACT

We examined the time-course of lexical activation, deactivation, and the syntactic operation of dependency linking during the online processing of object-relative sentence constructions using eye-tracking-while-listening. We explored how manipulating temporal aspects of the language input affects the tight lexical and syntactic temporal constraints found in sentence processing. The three temporal manipulations were (1) increasing the duration of the direct object noun, (2) adding the disfluency *uh* after the noun, and (3) replacing the disfluency with a silent pause. The findings from this experiment revealed that the disfluent and silence temporal manipulations enhanced the processing of subject and object noun phrases by modulating activation and deactivation. The manipulations also changed the time-course of dependency linking (increased reactivation of the direct object). The modulated activation dynamics of these lexical items are thought to play a role in mitigating interference and suggest that deactivation plays a beneficial role in complex sentence processing.

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Sentence processing; lexical activation; lexical deactivation; syntactic reactivation; temporal manipulation

Introduction

Successful auditory comprehension hinges on the listener's ability to access lexical representations and integrate them into an emerging syntactic structure, moment-by-moment, as a sentence unfolds. In building a syntactic structure, there are often times that lexical elements are linked but are not adjacent to one another in a sentence and form long-distance dependencies (such as those created by reference-seeking elements like pronouns, reflexives and other structurally driven constructs). In such cases, success depends on the listener's ability to establish a real-time link between reference-seeking elements and their structurally linked antecedents. This process has been argued to be fast-acting (without conscious reflection) yet requires a complex interplay of successive lexical and syntactic levels of processing (Love & Swinney, 1996). Of interest here is the time-course of these lexical activation dynamics, integration of lexical items into a syntactic frame, and the effect that time has on these processes.

Much of the research exploring the time-course of sentence processing consists of stimuli that have been carefully recorded to remove any interruptions or errors. This swath of research has demonstrated that lexical and syntactic processing during auditory sentence comprehension occurs rapidly and automatically. When surveying natural language samples, however, it is clear that naturally occurring utterances that listeners typically receive have numerous instances of hesitations and interruptions (Gilquin & De Cock, 2013). These interruptions to the temporal flow of speech are characterised as disfluencies, which often take the form of filled and unfilled pauses (*uh* and silent pauses, respectively), though there are of course other forms. Such disfluencies add a temporal delay in the on-going speech signal without adding semantic content. Although listeners are typically unaware of the multitude of interruptions that riddle spoken language, a limited amount of research has looked at the additional time that disfluencies introduce during processing and have revealed that they can enhance word recognition, cue a listener to an upcoming clause boundary, direct listeners' attention to new lexical information, and help disambiguate structural ambiguities (e.g. garden path sentences) (Arnold et al., 2004, 2007; Bailey & Ferreira, 2003; Brennan & Schober, 2001; Collard et al., 2008; Corley et al., 2007; Corley & Hartsuiker, 2011; Ferreira et al., 2004; Ferreira & Bailey, 2004; Fox Tree, 2001). However, the *immediate* effect that disfluencies have on lexical level representations (activation and

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decay) and integration during sentence processing is less clear. In this paper we ask if different forms of temporal manipulations enhance or disrupt lexical activation and if so, do they alter the time-course of lexical integration during sentence processing? Furthermore, we ask what the consequences are on later syntactic operations such as dependency linking.

We first present a brief review of structural dependency linking in sentences followed by an overview of the various ways in which researchers have described how additional time provided by disfluencies affects word recognition and structural parsing in auditory sentences.

Structural parsing: dependency linking in object relative sentence constructions

During auditory processing, the listener receives acoustic input serially and must rapidly access lexical items in a successive fashion. Additionally, sentences may require linking of linguistically dependent information in order to assign thematic roles and arrive at a final understanding. This process is commonly found in a complex sentence structure known as an object-relative construction.

The object-relative sentence below (1) is comprised of two smaller sentences: *The boy was in the park* and *The girl pushed the boy*. Both of these sentences follow the standard word order for English, meaning they observe the canonical word order pattern of subject-verb-object. These two sentences can be combined by fronting the direct object (*the boy*) of the verb (*pushed*) to the beginning of the sentence, resulting in an object-relative sentence construction. While grammatical, this word ordering is considered non-canonical as it deviates from s-v-o word order. It is also considered more complex as the displacement of the direct object creates a long-distance structural dependency (noted by the co-indexation subscript, $_i$).

(1) The boy$_i$ that the girl pushed$_i$ was in the park.

Research has shown that upon processing a verb in an object relative construction, a listener links it to the fronted direct object *the boy* (Love & Swinney, 1996). In the example above, this results in the assignment of the thematic role, "theme", allowing for the final interpretation of who is doing what to whom. The time-course of the processes described require a tight coupling between lexical and syntactic level processing. Studies using cross model priming paradigms (CMP, Swinney, 1979) have shown that there is a predictable time-course of activation of the direct object noun throughout a sentence. In examples with dependency links, such as (2) below, these studies have shown immediate activation of the noun at its offset (*1), fast decay (within 400 ms, *2), and reactivation at a syntactically defined position (*3), in this case, verb offset (Love et al., 2008).

(2) The boy$_i$ ^{*1} from next ^{*2} door that the girl pushed$_i$ ^{*3} was in the park.

Findings of activation followed by reactivation of displaced elements in sentences with syntactic dependencies have also been replicated using eye-tracking methods (Akhavan et al., 2020; Koring et al., 2012; Thompson & Choy, 2009).

Parsing object-relative constructions places tight temporal constraints and increases the demands on the processor. Some theories have focused on the increased processing demands mandated by long distance dependency resolution and successful comprehension. In Cue-Based Retrieval Theory (Lewis et al., 2006; Lewis & Vasishth, 2005; Van Dyke & Lewis, 2003; Van Dyke & McElree, 2006), this sentence processing difficulty is determined by the ease with which a distant dependent (i.e. a displaced direct object noun) can be retrieved (i.e. dependency completion) via an associative search. There are two components to this theory that are particularly relevant to the work presented below.

In object-relative constructions, *interference* could arise during retrieval of the target noun at the post-verb gap site, the direct object, if other items encountered in a sentence match in retrieval cues with the target creating competition in the form of similarity-based interference. Interference makes it harder to retrieve the direct object and has been shown to lead to increased processing times at the verb and overall comprehension difficulty (Gordon et al., 2001; Gordon et al., 2002, 2004, 2006; Van Dyke, 2007; Van Dyke & McElree, 2006). In addition to interference, another factor that can impact retrieval is activation *decay* (Van Dyke & Lewis, 2003). According to decay theory, an element in memory is susceptible to decay over time which lowers the degree of its activation in short-term and working memory (Brown, 1958; Lewis et al., 2006; Lewis & Vasishth, 2005). The combination of *interference and decay* has been argued to dictate the ease with which an item in a sentence is reactivated. Housed within the general framework of Cue-based Retrieval theory (Lewis & Vasishth, 2005), activation-based models assert that the activation level of a constituent determines retrieval latency and the probability of retrieval. Difficulty in reactivating prior constituents is thus a function of how much they have decayed and the degree of interference (Lewis & Vasishth, 2005).

The parameter of time is important when considering interference and decay during sentence processing, as both processes interact with and are affected by time. Investigations on sentence processing have shown that manipulations of time, as defined by speaking rate, can have positive or negative effects depending on how it is manipulated. When time is extended, there are benefits to sentence processing in language impaired individuals (Love et al., 2008; Montgomery, 2005). Research with unimpaired individuals has shown that when time is compressed, or speeded, sentence processing is made more difficult (Chodorow, 1979; Peelle et al., 2004; Wingfield et al., 2003).

Disfluency as a temporal parameter in lexical access

One way to capture time in lexical and sentence processing is by investigating disfluencies. Disfluencies appear in speech quite commonly as they are estimated to occur at a rate of roughly six times per 100 words (Bortfeld et al., 2001; Fox Tree, 1995). Examples of disfluencies include filled and unfilled pauses, repetitions, replacements, and restarts (Clark & Wasow, 1998). Given the ubiquity of disfluencies in spoken language, mechanisms must be in place for the comprehension system to handle such imperfections. At the lexical level, research has focused on the effect of disfluencies on recognising words in upcoming speech. Disfluent utterances have been found to speed up response times to target words in word monitoring tasks (Fox Tree, 2001) and in visual object selection tasks (Brennan & Schober, 2001; Corley & Hartsuiker, 2011), and online identification of unfamiliar referents during comprehension using eye-tracking (Arnold et al., 2004, 2007). The processing benefit provided by disfluencies during word recognition has been explained on the basis of temporal delays and heightened attention.

Using eye-tracking-while-listening in a visual world paradigm, Arnold et al. (2007) examined reference comprehension by presenting participants with graphic displays of familiar easy-to-name objects (e.g. ice cream cones) and unfamiliar difficult-to-name objects (e.g. complex shapes) and heard either fluent auditory instructions (*Click on the* …) or disfluent instructions (*Click on thee uh* …). The results showed that disfluent expressions produced a bias toward unfamiliar objects. The increased attention to unfamiliar objects suggests that listener's show sensitivity to the kind of information that disfluencies signal, such as speaker's uncertainty or production difficulty and use this information during language comprehension to bias attention towards unfamiliar objects (Arnold et al., 2007) or unmentioned objects (Arnold et al., 2004).

Corley and Hartsuiker (2011) investigated the effects of disfluent instructions on word recognition to determine whether the delays caused by disfluencies facilitate comprehension. They proposed a delay hypothesis which posits that delays in word onset facilitate recognition of lexical items. They tested three forms of delay (a disfluency *um*, a silent pause, and an artificial tone) in auditory word recognition tasks. Delays were placed immediately before a target word (delay condition) or earlier in the auditory sentence (control condition). Participants were faster to respond when target words were preceded by a delay, regardless of the type of manipulation. These results suggest that delays, regardless of the form, facilitate auditory word recognition. It has been reasoned that delays serve to heighten attention to upcoming linguistic information (Clark & Fox Tree, 2002; Corley & Hartsuiker, 2011). Consistent with an attentional account, Collard et al. (2008) found modulations in the amplitude of two ERP components associated with attention, mismatch negativity and P300, when participants listened to utterances containing a disfluency. When listeners were given a surprise subsequent recognition memory test, words that had been preceded by a disfluency were more likely to be remembered demonstrating that modulations in attention can have both short and longer-lasting effects. Note that these studies focus on how additional time affects upcoming word recognition but to our knowledge, no one has directly looked at how time affects post lexical selection and integration during sentence processing.

Structural parsing: disfluencies (time) as a parameter for structural parsing

Research has also shown that disfluencies can have effects on both online (automatic) processing and final (reflective) comprehension. Ferreira and colleagues (see review by Ferreira & Bailey, 2004 and Ferreira et al., 2004) have shown that the type and location of disfluencies affect the parsing and reanalysis of temporarily ambiguous (garden-path) sentences. In their 2003 paper, Bailey and Ferreira demonstrated that the parser may use disfluencies as a cue to the upcoming structure. In the example sentences below, they found when the filled-pause *uh* was placed before the onset of a disambiguating word *told* in (3), participants were more likely to mistakenly interpret *the waiter* as part of the object of the verb *bumped* and commit to that incorrect structure longer. In other words, the garden-path effect was enhanced. However, when disfluencies were placed in a position that reinforces the upcoming syntactic structure, in this case at the beginning of a

clause boundary in (4), participants showed shorter garden path effects and judged the sentences as grammatical more often (Ferreira et al., 2004).

(3) Sandra bumped into the busboy and the waiter *uh uh* told her to be careful.

(4) Sandra bumped into the busboy and the *uh uh* waiter told her to be careful.

The authors propose multiple ways that disfluencies disrupt or assist in garden-path sentence processing. One posited role is that disfluencies provide a cue to the correct or incorrect structure owing to their typical distribution in language. Because disfluencies tend to occur before the onset of complex syntactic constituents (Clark & Wasow, 1998; Hawkins, 1971) listeners may use this information during processing of ambiguous sentences to predict a more complex structure (Bailey & Ferreira, 2003). Another mechanism is that disfluencies provide additional time to reinforce the chosen representation at that point in time by delaying the onset of subsequent information. This delay has important ramifications for the current structures or representations under consideration which are given time to increase in activation at the expense of alternative interpretations leading to stronger garden-path effects (Bailey & Ferreira, 2003; Ferreira et al., 2004; Ferreira & Bailey, 2004). One may extend this interpretation to lexical-level processing to say that additional time allows for longer processing of lexical representations. In other words, lexical items may gain activation in a way similar to that of structures under consideration.

Current study

As discussed above, disfluencies afforded more time for unimpaired listeners to process lexical and sentence constructions, however, their effect on both lexical activation and syntactic processing *during* auditory sentence comprehension has not been investigated.

In addition to disfluencies, manipulations to rate of speech input have also been found to influence sentence processing (Love et al., 2008; Montgomery, 2005; Peelle et al., 2004; Wingfield et al., 2003). Of these, slowed rate of speech was accomplished by stretching the entire sentence (while maintaining pitch). This temporal manipulation was found to disrupt the normal time-course of lexical and syntactic processing in unimpaired adults (Love et al., 2008). As such, one condition in this study concentrates the temporal manipulation focally within the direct object noun itself. We believe that this would result in less overall lexical and structural processing hindrances.

In the current study, we seek to investigate if additional time, via disfluencies and a focal rate manipulation, helps or hinders lexical activation and decay as well as if it affects downstream dependency linking (via modulating interference). The present study compares three forms of reduced rate of speech input on the processing of sentences containing object relative clauses. The manipulations resulted in 4 experimental conditions: control, stretch, disfluent, and silence. The *control* condition was the naturally recorded sentences described below in the Stimuli section. The *stretch* condition follows prior research showing an effect of reduced rate of input via temporal elongation on sentence level processing in aphasia (Love et al., 2008). Here though, rather than stretching the entire sentence, we look to enhance lexical processing by only reducing the speech rate of the critical noun, the direct object of the relative clause verb (RC-v). The *disfluent* condition seeks to provide more processing time via a natural temporal delay with the *silence* condition serving as a temporal control.

We use eye-tracking to capture the time-course of lexical and syntactic parsing during auditory sentence processing. This method allows us to explore the nature of interference and the contributions that lexical activation and decay have on subsequent dependency linking during real-time processing. This paradigm has been used to successfully index interference (Akhavan et al., 2020; Sheppard et al., 2015; Sekerina et al., 2016) and allows us to explore how manipulating temporal aspects of the language input affects these processes. We acknowledge, however, that the nature of lexical decay under investigation likely differs from the memory-based decay discussed above due to the method in the current study. In this eye-tracking study, the referents mentioned in the sentences were displayed as characters on screen and thus provided visual support during language processing. The overt presence of the referents' pictures may not directly index memory-based retrieval as it is typically viewed in the memory literature, although no study to our knowledge has explored this effect. To be conservative in our interpretation of our patterns, we will therefore refer to lexical decay as lexical deactivation.

Methods

To examine lexical activation, deactivation, and reactivation as it occurs during real-time sentence processing, this study employs Eye-tracking-While-Listening (ETL) using a visual world paradigm (Allopenna et al., 1998; Tanenhaus et al., 2000). In the current study, participants are presented with an array of four pictures while

listening to sentences. Two of the pictures depict referents mentioned in the sentence and two are distractors. It is hypothesised that while listening to sentence constituents, a listener will demonstrate increased looks towards the picture of the referent recently processed indicating lexical activation, while looks away (disengagement) from a referent are indicative of deactivation. Reactivation of the displaced noun phrase should occur during critical syntactic positions that result in syntactic dependency linking (i.e. gap filling, see Akhavan et al., 2020; Sussman & Sedivy, 2003; Thompson & Choy, 2009).

As previously mentioned, Cue-based Retrieval theory posits that retrieval interference arises during dependency linking as a result of competition between the displaced noun and an intervening noun when they have similar features, in other words when the necessary cues for identifying a dependent are ambiguous (Van Dyke & McElree, 2006). For example in the object-relative sentence below (5), the retrieval cues provided by the verb *pushed* select for an animate noun, however there two noun phrases that fit these cues, the displaced noun (*the elf*) and the intervening noun (*the clown*) which creates interference (Sekerina, et al., 2016).

(5) The elf that the clown *pushed* was at the end of the street.

This interference has been demonstrated in eye-tracking data using a similar paradigm as an extended activation of both nouns during the post-verb time window (Akhavan et al., 2020). Specifically, the process of deactivation of the recently processed intervening noun (here, N2) coupled with the signalling to the parser to reactivate the displaced noun (here, N1) can result in overlapping gaze patterns of both nouns (Akhavan et al., 2020). Thus, this methodology gives us a detailed time-course of lexical activation, deactivation, and interference during reactivation as the auditory sentence unfolds over time. All methods described below were approved by the University of California San Diego and the San Diego State University Institutional Review Boards. Per the Center for Open Science we include this statement to confirm that what follows is a complete reporting of all measures, conditions, data exclusions and participant characteristics.

Participants

33 unimpaired students from San Diego State University were enrolled in this study. Participants were required to be native English speakers with minimal experience in a second language (i.e. any knowledge of a second language was learned after the age of six). They had to be self-reported right hand dominant with normal or corrected vision and hearing and no self-reported history of alcohol and/or drug abuse, active psychiatric illness, intellectual disability, or other significant brain disorder or dysfunction. Non-native knowledge of English was considered an exclusionary criterion and on this this basis, 6 participants were excluded as they were not monolingual English Speakers. In addition, 3 other participants had to be excluded due to computer errors in data collection. The resulting 24 participants ($M_{age} = 21$, $SD = 3.3$, range = 18–29, male = 2) were included in the analyses described below. All participants received extra credit for study participation.

Materials

Stimuli

Experimental stimuli consisted of 40 object-relative sentences which were constructed in a similar format as shown in (5) below:

		Relative Clause	
(6)	Adverbial clause	NP1 NP2 Verb	Main Verb + PP
	[Last year on Halloween],	[the elf that the down pushed]	[was at the end of the street].

All sentences contained non-biasing contexts such that both noun phrases (NPs) were equally plausible as the subject or object of the RC-v (*pushed*). The role of each NP was reversed in a matched sentence design so that each NP served once as the direct-object and once as the subject (see 6 and 7 below).

(7) Last year on Halloween, the elf that the clown *pushed* was at the end of the street.

(8) At the costume party, the clown that the elf *poked* was in the backyard.

Each sentence in the pair contained RC-v's with similar phonetic onsets and were matched in syllable length (e.g. *help*/*hug*, *push*/*poke*). Twenty matched RC-v's were used twice to create a total of 40 experimental items. Importantly, the 2 NPs of interest were not phonologically or semantically related to one another, nor were they related on either dimension with the NPs in the matched set. Regarding the presentation of the images for the visual world portion of the ETL study, the images used to represent each NP were positioned such that across all conditions and items, both NP1 and NP2 appeared equally across all four quadrants of the visual display. The sentences described here formed the basis for the three temporal manipulations detailed in the "Temporal manipulation" section below resulting in 160 experimental items (40 per condition). Finally, an additional 40 unrelated filler sentences were

created to distract participants from the object-relative construction in target sentences and thereby avoid developing strategic processing (i.e. only looking to the first noun, etc.). These were of similar length and speech rate to the experimental sentences but varied in syntactic structure. Thus, there were 200 stimuli in this experiment (experimental plus fillers).

Temporal manipulations

Stimuli were recorded by a female speaker in a sound-treated room. A natural recording of each sentence served as the *control condition* with an average rate of speech of 4.94 syllables/second (SD=.26 s). These sentences served as the base to which the time manipulations were made. Recall that 3 temporal manipulations were used: stretch, disfluent, and silence. The *stretch condition* was created by digitally "stretching" the wave form associated with direct object noun (N1) using Adobe Audition CC by 150% while maintaining pitch (see Figure 1, below). This level was chosen as the maximum duration that words could be stretched without distortion so that it sounded as natural as possible as confirmed by researchers in the laboratory. This time-stretch version resulted in the addition of ~250 ms to the overall time as compared to the control recording. To create the *disfluent condition* (see Figure 1), sentences were recorded by the same female speaker with a disfluency (*uh*) embedded in them. This provided a natural recording of a disfluency in the control sentence context that was then spliced out and inserted into the original recording of the control sentence. Thus, the overall sentence contour remained the same for this condition. The average duration of each disfluency was 250.4 ms (SD=3.56 ms). These disfluencies were inserted approximately 100 ms after the offset of the N1 and 100 ms before the upcoming relativizer to allow for a natural buffer before and after the disfluency as would be heard in typical speech (Shriberg, 1999). This manipulation resulted in an average of 460.9 ms (SD = 3.8 ms) additional time. Since the placement of the disfluencies in the current experiment differs from how they are typically found in sentences (i.e. clause boundaries or word initial, for review see Ferreira et al., 2004; Shriberg, 1999) the naturalness of disfluent sentences was confirmed by five research assistants who were unaware of the aims of the study. This pretest confirmed that other than the speaker "sounding confused", the sentences appeared natural. Finally, to create the *silence condition* (see Figure 1), the disfluent portion was replaced with silence in Adobe Audition CC to maintain the same timing as the disfluent condition.

Visual stimuli

Recall that there were 2 NPs in each of the 20 experimental sentence pairs (see 5 above) and 1 or 2 NPs in the 40 filler sentences. Images for the NPs were coloured cartoon images created by a single artist to maintain general style. In total there were 80 images created for this study.

Pretest of visual images

In order to ensure that each drawing accurately depicted the intended NP, a naming pretest was conducted with a separate group of 19 participants (M age = 28.8, SD=16.4; male = 3). All participants were Native English speakers who were right-handed, had normal to corrected vision, and no self-reported history of head injury, learning disability, or drug abuse.

Using Qualtrics, images were displayed one at a time. Participants were asked to provide a single word to name each of the 80 images. They did so by typing their responses. All data were aggregated across participants to determine the percent accuracy of semantic

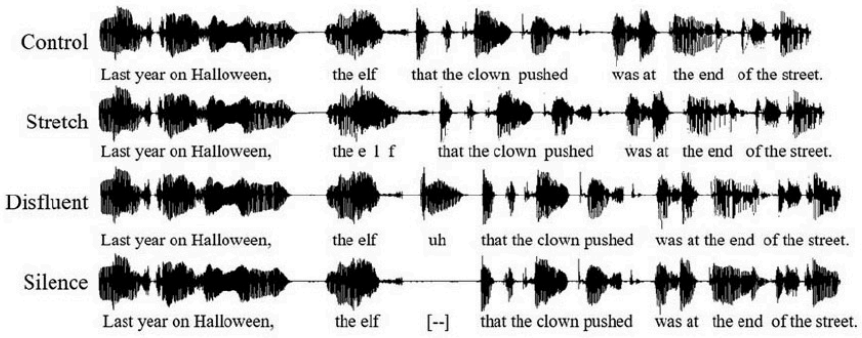


Figure 1. Example waveforms of stimuli showing the control condition and temporal manipulations (disfluent, silence, and stretch).

agreement. Any image for which there was <70% semantic agreement was removed. For example, an acceptable response for the target image *weightlifter* was *bodybuilder* or *powerlifter*, but not *boxer*. Of the 80 images tested, 8 pictures failed to produce at least 70% semantic agreement and were discarded. Of the remaining pool of 72 images, 40 were used for the experimental sentences and the remaining 32 were used in the filler sentences. We converted 8 of the 40 filler sentences from having 2 NPs to 1 NP to accommodate the loss of picture items, thus 25 filler items had 1 noun and 15 had 2 nouns.

Comprehension questions

For each experimental sentence, participants heard a yes/no comprehension question at the end of the trial to ensure that they had listened to the sentence for meaning. All questions for the experimental items were in the form of "Did the NP + verb + someone?" These questions were recorded by another female speaker at a normal rate of speech. Filler sentence comprehension questions took a variety of formats so that the participant could not anticipate what to listen for. Comprehension questions were counterbalanced so half of the total questions had a correct answer of "yes". For the experimental items, the NP used in the comprehension question (NP1 or NP2) was also counterbalanced.

Study design

In this design, participants contributed data to all conditions but never received an item more than one time. In order to ensure that all participants heard an experimental item only once in a given session, the sentences were split into four lists. Each list contained 40 experimental items (10 experimental sentences per condition) and 40 filler items for a total of 80 sentences. Participants were tested on two separate lists in two sessions spaced a minimum of one week apart, contributing data to 20 sentences per condition. List assignment was randomised and counterbalanced.

Procedure

Participants were seated in front of a computer screen equipped with a Tobii X3-120 eye-tracker bar and positioned so that their eyes were approximately 65 cm away from the eye-tracker. At the beginning of each experimental session, the eye-tracker was calibrated to each participant so that both eyes were captured, and the location of the gazes were accurately measured. Reaction time (RT) data (ms, accuracy) and timed presentation of auditory and visual stimuli were controlled by E-Prime 3.0 software (Psychology Software Tools, Pittsburgh, PA).

Participants were instructed to listen carefully to each sentence as they would be asked a comprehension question after each one. These questions were intended both to reinforce the need for the participants to attend to the meaning of the sentences and to maintain task engagement. As shown in Figure 2, each trial began with the presentation of a central fixation cross for 500 ms, followed by a 250 ms blank screen. The four-picture display was then presented for 1500 ms before the experimental (or filler) sentence began. As we were interested in the activation of a lexical item as it is integrated into an ongoing sentence (i.e. post lexical selection), this preview duration provided ample time to form mental representations of each lexical item. The pictures remained on the screen for 500 ms after the sentence ended. For all trials, gaze location was sampled at a rate of 120 Hz resulting in gaze location being recorded every 8 ms across each trial. As described above, each sentence was followed by an aurally presented Y/N comprehension question. Participants were instructed to respond as quickly and as accurately as possible with their right hand using a two-button response box. Comprehension accuracy and response time were also recorded by E-Prime 3.0 software. Ten practice trials were conducted prior to each experimental session to allow the experimenter to provide feedback or redirection prior to the beginning of the experiment.

Data analysis approach: ETL-VWP

Before providing the results of the statistical analyses, we first give an overview of the statistical approaches taken for ETL-VWP.

Pre-processing

Trackloss: The first step in preparing the eye-tracking data for analyses was to evaluate the integrity of the eye-tracking data that was collected every 8 ms by the Tobii eye tracker. Samples in which eye gaze was not registered was considered trackloss. This occurs when the eye-tracker fails to register gaze information from at least one of the participant's eyes, either because the participant is looking off screen, not within an areas of interest (AOI), or the sample contains a blink.

To clean data for trackloss, four AOIs were defined corresponding to the four pictures in each display. Each AOI corresponded to a 450 × 450 pixel quadrant situated in each of the four corners of the computer

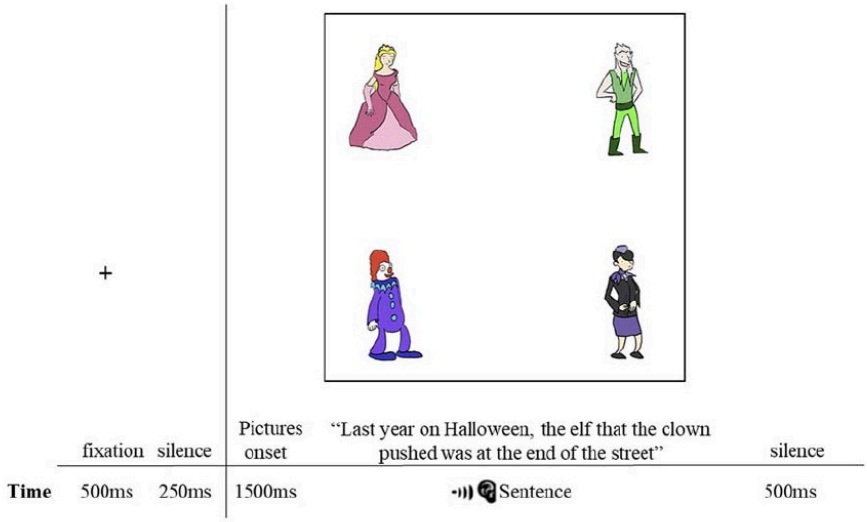


Figure 2. Procedure used in each trial of the experiment. The example display presents the direct object noun (e.g. *clown*), the second noun (e.g. *elf*), and two distractors (e.g. *princess* and *stewardess*). Auditory sentences began after a 1500 ms preview of the display.

screen. Following Huang and Snedeker (2020), any gaze samples that contained trackloss were excluded from further analyses resulting in roughly 13% of the samples being removed. Of the remaining samples, any trial for which less than half of the expected samples remained was excluded from analyses (Huang & Snedeker, 2020). This resulted in the additional removal of .4% of data.

Data preparation: Given the physiological nature of eye movements, there is inherent dependency in time-series eye-tracking data since the location of eye gaze at one time point is likely to be influenced by gaze location at nearby time points. This type of serial dependency can lead to negative consequences such as inflated Type I error rates. One strategy to account for such dependencies is to aggregate observations across trials and group them into temporal bins. Here, for each participant within each session and condition, we grouped observations into 100 ms bins. For each bin, we then estimated the proportion of gaze within each AOI and computed the empirical logit by logit-transforming the proportions. This logistic transformation of a binary response variable (within or outside of an AOI) is argued to be the appropriate choice as it helps reduce eye-movement based dependences (for review, see Barr, 2008). Pre-processing and preparation of eye-tracking data was done using *eyetrackingR* (Dink & Ferguson, 2015) and gazeR (Geller et al., 2020) packages.

Growth curve analyses

To explore the dynamic trajectory of lexical activation as auditory sentences unfold, we employed growth curve analyses, which are a type of multilevel regression modelling technique developed to analyse time-course data (Mirman, 2017; Mirman et al., 2008). In eye-tracking data, gaze trajectory often takes multiple patterns – linear (reflecting constant change over time) and curvilinear (reflecting fluctuations over time). In the models presented below, the time-series variables used to capture linear and curvilinear patterns were orthogonal polynomials (linear, quadratic, and cubic), similar to previous studies (Chen & Mirman, 2015; Magnuson et al., 2007; Nozari et al., 2016). Analyses were conducted in the statistical software R (R Core Team, 2019) using the lme4 package (Bates et al., 2015). Fixed effects of Condition (control, stretch, disfluent, silence) were added as an interaction on all time terms. To evaluate whether adding the fixed effect of Condition on each time term improved model fit, model comparisons were used. Changes in goodness of model fit were assessed using the *likelihood ratio test* with degrees of freedom equal to the number of parameters added. Tests of individual parameter estimates were used to evaluate specific condition differences on each of the time terms (i.e. whether each experimental manipulation was reliably different from the baseline control condition) using the Satterthwaite's (Kenward-Roger's) approximations for the t-test and corresponding *p*-values implemented in

the lmerTest package (Kuznetsova et al., 2017). The control condition was used as the baseline and separate parameters were estimated for each of the temporal manipulations for each time term. Effects on the *intercept* term reflect the average height of the curve (i.e. the overall magnitude of activation) throughout the time window, which is analogous to a repeated measures ANOVA. Effects on the *linear* term reflect differences in the slope of the gaze trajectories, effects on the *quadratic* term reflect the symmetric rise and fall around a central inflection point (i.e. activation and deactivation), and effects on the *cubic* term tend to capture effects in the tails of the curves (Mirman, 2017; Mirman et al., 2008).

Windows of interest: Two time windows were created to explore various aspects of lexical activation at hypothesised points during sentence processing. *Time window 1* encompasses the full-time-course of processing the first noun (N1), which includes lexical activation and deactivation. *Time window 2* captures syntactic reactivation of N1 and resolution of interference post-verb. We are interested in how the temporal manipulations affect the overall magnitude and the pattern of looks to N1 and N2 over time. To create the time windows of interest, the data for every trial was first aligned to particular time points throughout the sentence (e.g. onset of the first noun, onset of the relativizer, and the main verb). Figure 3 shows the averaged time-course of looks to N1 and N2 from the auditory presentation of N1 onset collapsed across conditions. Note that across conditions there were minimal looks to the distractor images throughout the sentences and therefore these are not presented in subsequent analyses or graphs.

Initial N1 Processing (Time window 1): Initial processing of N1 was analysed by modelling eye gaze patterns from the onset of N1 and continued until the offset of the RC-verb. In order to account for planning and execution of an eye movement, a baseline was established by shifting the N1 window to occur 200 ms after N1 onset (Hallett, 1978). Time window 1 is shown in the box on the left in the Figure 3 above and captures the change in activation and deactivation of N1 across all four conditions. Upon visual inspection, it is clear that upon hearing N1 (*elf*), participants direct their eye gaze towards the picture referent of the noun they just heard (red line), representing initial lexical activation. The peak of lexical activation is followed by a disengagement of looks to N1 (downward slope). We argue that this reflects deactivation and allows the participants to shift focus to the upcoming N2 (blue line). Statistical testing of these observations are detailed below. In the analysis presented below, the models include participants and condition (time manipulations) as random intercepts with random slopes on the linear and quadratic terms. Random effects of session for each subject on each time term (intercept and slopes) were also added to capture any variation resulting from two testing sessions.

Syntactic reactivation and interference resolution (Time window 2): Time window 2, encompassing syntactic reactivation, begins at the offset of the verb (time-

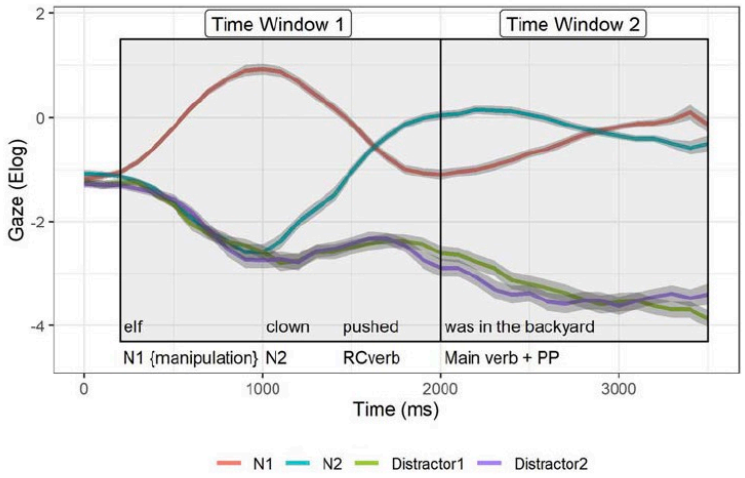


Figure 3. Mean gaze to N1 (the first noun), N2 (second noun), and two distractor images averaged across condition as a function of time beginning at the auditory onset of N1. Windows of interest (1 and 2) are outlined in black. Error bars (shaded areas) are within-subject 95% confidence intervals.

locked to 0 ms) and lasts 500 ms after the end of the sentence. The right box in the Figure 3 captures the pattern of N1 and N2 across all four conditions. As expected, based on prior behavioural findings, we see a decrease in looks to N2 (indicating N2 deactivation) along with an increase in looks back to N1 after the verb constituting reactivation of this constituent (i.e. gap-filling). This is shown visually as a crossover in looks from N2 (blue line) to N1 (red line) after the verb. To statistically establish evidence of reactivation we look to the model's linear term in the results section below. We hypothesise that post-verb, increased rates of reactivation will be demonstrated by a significant incline in the looks to N1 as noted by steeper slopes.

As mentioned earlier, prior research demonstrates that similarity-based interference is evident in unimpaired processing. In order to best capture the retrieval interference process as it unfolds over time, we look at the model's three-way interaction that includes both AOIs (N1and N2), condition (control, stretch, disfluent and silence), and time terms (linear and quadratic) so as to simultaneously capture any effects on the deactivation of N2 (negative linear trend) and the reactivation of N1 (positive linear trend) post-verb (see Mirman, 2017 for a review of growth curve analysis methods and equations). Interference during retrieval is reflected as overlapping gaze trajectories to both nouns, which indicates the listener is processing both items. As has been found in prior eyetracking studies, these overlapping gaze patterns reveal competition between the nouns, resulting in interference. This can be measured via slope coefficients where the two nouns show flatter, but opposing slope patterns (see for example, Akhavan et al., 2020). In cases where interference is reduced, we should expect to see stronger deactivation of N2 coupled with greater reactivation of N1 across time. In other words, there would be a stronger divergence in the gaze trajectories to each noun in the post-verb region (see cluster-based permutation analyses below). The random effects were structured similarly to those for time window 1 with the only difference being the addition of AOI to each random effect term to account for any differences in variation between the two nouns.

Cluster-based permutation analyses

The parameters of growth curve analyses describe how gaze trajectories change over time while taking into account individual differences, however, they do not directly address *when* in time two trajectories differ. To complement the growth curve analyses, we also conducted cluster-based permutation analyses to detect the temporal onset and duration of an effect between two time-series. This method was originally developed to account for the multiple comparison problem and autocorrelation arising in EEG and MEG data (Maris & Oostenveld, 2007), and has been increasingly applied to eyetracking research (Barr et al., 2014; Gerhardstein & Olsen, 2020: Weighall et al., 2017). In cluster-based permutation testing, inferential tests are performed on each time-bin over the analysis window and all adjacent, significant bins (i.e. passing a determined threshold) are grouped together into a single cluster and a cluster-level statistic is computed whose null distribution is derived through data permutation. Finally, a nonparametric statistical test is then performed by calculating a *p*-value under the permutation distribution and comparing with a critical alpha-level. By grouping temporally adjacent bins into a single cluster, individual tests are replaced by a single test for the cluster, thus controlling for family-wise error rate (for more information, see Maris & Oostenveld, 2007).

For each cluster-based permutation analysis, we used the eyetrackingR divergence analysis package (Dink & Ferguson, 2015). As applied here, t-test statistics were computed for each time-bin over the analysis window and all adjacent bins whose t-value exceeded the threshold (97.5th quantile for a two-sided *t*-test) were grouped into a single cluster. A cluster-level statistic was then calculated by taking the sum of the *t*-values to create a cluster mass statistic. Here the data was iteratively sampled 1000 times to build a null distribution. Significant clusters are identified using a critical alpha-level of 0.05. As the questions of interest differ in each time window (1 and 2), we approached the cluster analyses using different comparisons (described in detail below).

Cluster-based analysis: Time window 1

In time window 1, the goal is to compare the effect of each temporal manipulation, against the control condition, on the processing of N1 (i.e. control-stretch, control-disfluent, and control-silence). To complement the results found using GCA, cluster-based analyses were conducted using the same temporal time bin resolution (100 ms), with an extension of the original time window of interest by 300 ms to determine if deactivation continues across the two conditions. Thus, the final time window began at the onset of N1 (baselined 200 ms) and ended past the offset of the RC-verb (2400 ms).

Cluster-based analysis: Time window 2

In time window 2, encompassing syntactic reactivation, the goal in using cluster-based analyses is to quantify the onset and temporal extent of interference resolution

Table 1. Mean (M) and standard deviations (SD) for offline comprehension. Accuracy (% correct) and reaction time (RT in ms).

	Accuracy		RT	
Condition	*M*	SD	*M*	*SD*
Control	82%	38%	560.6	335.7
Stretch	86%	35%	521.1	305.1
Disfluent	84%	37%	512.3	299.3
Silence	84%	37%	527.6	302.7

in each experimental condition. Here, for each condition, we estimate when during the time-course looks to N1 significantly diverge from looks to N2, which we take as evidence interference resolution (Akhavan et al., 2020). Cluster-based analyses in this window were conducted using the same time bin resolution (100 ms) and the same time window of interest (1200 ms total duration; offset of the verb until 500 ms post sentence end) as used in the GCA analyses.

Results

Offline comprehension

Although our primary analyses focused on real-time sentence processing using eye-tracking, we first report performance accuracy and RT for sentence comprehension questions. As a reminder, these served to keep participants on task and were not meant to measure overall comprehension success. As a group, all conditions achieved a minimum of 80% accuracy (see Table 1, below). Accuracy was modelled with mixed effects logistic regression using glmer function with the bobyqa optimiser in R (R Core Team, 2019) in the lme4 package (Bates et al., 2015). Random slopes for condition were added per subject and per item to achieve a maximal random effects structure (Barr et al., 2013). RT was analysed in a mixed effects linear regression model using the lme4 package (Bates, et al., 2015) in R and degrees of freedom were calculated using the Satterthwaite's (Kenward-Roger's) approximations for the t-test and corresponding *p*-values in the package lmerTest (Kuznetsova et al., 2017). To evaluate RT, only correct trials were entered into analyses (84.05% data remained). In addition, any observations for which RT was less than 200 ms and observations greater than twice the standard deviation of that participant's mean (per condition) were removed (83.26% data remained). Table 1 shows the mean accuracy and reaction times (in ms) for each of the four conditions. Logistic mixed effects models revealed no significant effects in accuracy across conditions ($p > .05$). Thus, participants arrived at the correct interpretation equally across conditions. Similarly, linear mixed effects models revealed no significant reaction times effects across conditions ($p > .05$). The temporal manipulations did not alter the response speeds of the participants.

ETL-VWP results

In Figure 4, the effects of the three time manipulations (compared to the control condition) as are shown with time window one outlined in black.

Initial lexical processing of N1 (Time window 1)

In the initial lexical processing window (Time window 1, see Figure 4), we tested the extent to which temporal manipulations modulated the activation and deactivation dynamics of gazes to N1. Recall from above that we begin all analyses with a base model that includes time without any modulation of condition. The addition of Condition improved model fit on all time terms except linear (intercept $\chi^2(26) = 27.79$, $p < .001$; linear $\chi^2(29) = 5.41$, $p > .05$; quadratic $\chi^2(32) = 38.90$, $p < .001$; cubic $\chi^2(35) = 83.86$, $p < .001$). Significance tests on the individual parameter estimates revealed a significant difference in the overall magnitude of N1 activation among the Conditions. Figure 5, below, shows the observed data and model fits in each condition.

As can be seen in Figure 5, there was higher overall activation when N1 was followed by a disfluency or silent pause compared to no manipulation (*disfluent* $\beta = .43$, SE = .08, $p < .001$; *silence* $\beta = .46$, SE = .08, $p < .01$). There were no reliable differences in overall activation between the stretch and control condition (*stretch* $\beta = .07$, SE = .08, $p > .05$). There were also notable effects on gaze trajectory. Significant effects of Condition were found on the quadratic term, indicating steeper curvature (rise and fall) of activation and deactivation in the disfluent, silent, and stretch conditions (*disfluent* $\beta = -2.35$, SE = .38, $p < .001$; *silence* $\beta = -2.18$, SE = .38, $p < .01$; *stretch* $\beta = -.96$, SE = .38, $p = .01$). Table 2, below, contains fixed effect model parameters, deviance statistics, and significance levels (random effects are presented in Appendix A).

Syntactic reactivation and interference resolution window (Time window 2)

In the syntactic reactivation and interference resolution window (Time window 2, starting at verb offset), we tested the extent to which temporal manipulations modulated syntactically driven reactivation and resolution of interference. Overall model comparisons revealed that adding the interaction Condition*AOI significantly improved model fit on the linear, and

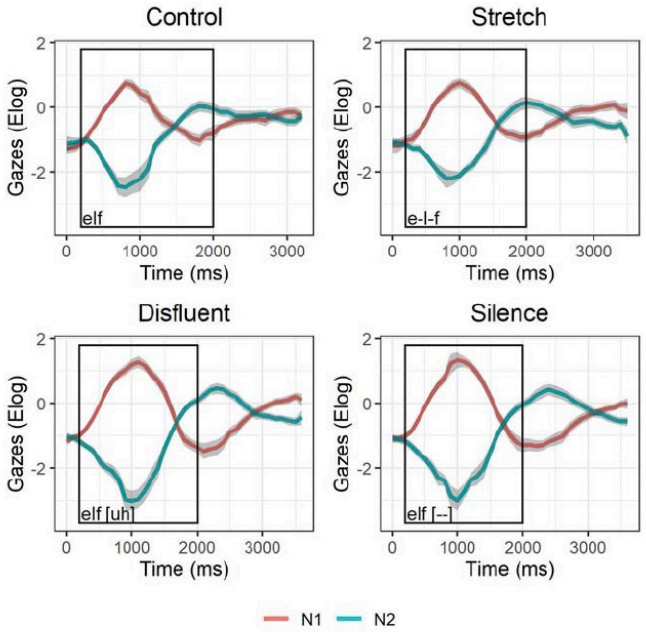


Figure 4. Time window 1 (black box): Mean gaze trajectories and standard error (grey error ribbons) to N1 (red line) and N2 (blue line) in each condition: Control (top-left), Stretch (top-right), Disfluent (bottom-left), and Silence (bottom-right).

quadratic terms (intercept $\chi^2(29) = 5.25$, $p = .63$; linear $\chi^2(36) = 68.19$, $p < .001$; quadratic $\chi^2(43) = 28.05$, $p < .001$). This indicates that there were significant differences in the time-course of gaze trajectories to each noun across the disfluent and silence temporal

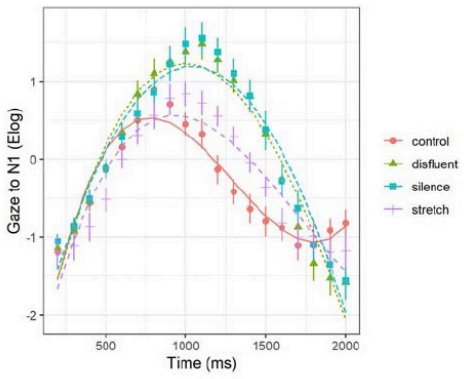


Figure 5. Initial lexical processing of the displaced object (N1). Model fit (lines) of the gaze data (shapes are means for the 4 conditions; error bars are standard errors) from the onset of N1 (Time window 1).

Table 2. GCA model results from initial lexical processing of N1 (Time window 1).

	Model Fit		
Term	−2LL	χ^2	*p*
Intercept	**−5136.2**	**27.79**	**<.001**
Linear	**−5134.5**	**5.41**	**0.14**
Quadratic	**−5114**	**38.90**	**<.001**
Cubic	**−5072.1**	**83.86**	**<.001**

Parameter estimates

Term	Est.	SE	*t*	*p*
Intercept	−0.35	0.10	−3.42	0.001
Linear	−1.01	0.44	−2.30	0.03
Quadratic	−1.96	0.35	−5.56	<.001
Cubic	1.64	0.13	12.80	<.001
Disfluent*Intercept	**0.43**	**0.08**	**5.44**	**<.001**
Silence*Intercept	**0.46**	**0.08**	**5.86**	**<.001**
Stretch*Intercept	**0.07**	**0.08**	**0.91**	**0.37**
Disfluent*Linear	−0.06	0.41	−0.14	0.89
Silence*Linear	0.19	0.41	0.46	0.65
Stretch*Linear	0.43	0.41	1.03	0.31
Disfluent*Quadratic	**−2.35**	**0.38**	**−6.13**	**<.001**
Silence*Quadratic	**−2.18**	**0.38**	**−5.70**	**<.001**
Stretch*Quadratic	**−0.96**	**0.38**	**−2.52**	**0.01**
Disfluent*Cubic	−1.31	0.18	−7.19	<.001
Silence*Cubic	−1.56	0.18	−8.57	<.001
Stretch*Cubic	−0.89	0.18	−4.87	<.001

Note: The table provides the test of the overall interaction (model fit) as well as the test of the specific comparisons between the temporal manipulations for each term of the model (intercept, linear, quadratic, and cubic). Results in **boldface** are presented in the text. LL = log-likelihood.

manipulations. The observed data and model fits are shown in Figure 6, below, separated by condition.

To better understand the nature of the interaction of Condition*AOI*time, we first looked at the linear term and found that the slopes (i.e. rate of change) of deactivation of N2 and reactivation of N1 differed across conditions. Beginning with the deactivation of N2, the disfluent and silence temporal manipulations increased the rate with which N2 was deactivated as compared to the control condition (*disfluent* $\beta = -1.16$, SE = .49, $p = .02$; *silence* $\beta = -1.92$, SE = .49, $p < .001$). There was no difference between stretch and control condition (*stretch* $\beta = -.77$, SE = .49, $p = .12$). With regards to *re*activation of N1, the interaction was due to significantly higher reactivation slopes in the disfluent and silence conditions as compared to the control (*disfluent* $\beta = .68$, SE = .35, $p = .05$; *silence* $\beta = 1.07$, SE = .35, $p < .001$). No differences were found between the stretch and control conditions (*stretch* $\beta = .39$, SE = .35, $p > .05$). Table 3, below, contains fixed effect model parameters, deviance statistics, and significance levels (random effects are presented in Appendix B).

Cluster-based permutation results

Initial lexical processing of N1 (Time window 1)

Recall, cluster-based permutation analyses were conducted to determine when in the time-course the temporal manipulations differed from the control condition. Results below report the summary statistics and the *p*-values of significant clusters. Note that the sign of the cluster (positive or negative) indicates the direction of the effect, such that a positive cluster indicates that gazes in the control are higher than in the manipulation and a negative cluster indicates that gazes for temporal manipulations are higher than for control. Shaded regions in Figure 7 depict the time points in the sentence where significant clusters occur. Analyses revealed that in the *stretch-control* comparison (Figure 7(A)), only one significant cluster was found from 1000 to 1400 ms (cluster sum statistic $= -15.16$, $p < .05$). In the *disfluent-control* comparison (Figure 7(B)), two significant clusters were found: a negative cluster from 800 to 1500 ms (cluster sum statistic = −49.58, $p < .001$) and a positive cluster from 1700 to 2200 ms (cluster sum statistic = 22.29, $p < .05$). Two significant clusters were also found in the *silence-control* comparison (Figure 7(C)): a negative cluster from 700 to 1600 ms (cluster sum statistics = −54.03, $p < .001$) and a positive cluster from 1800 to 2200 ms (cluster sum statistic = 18.02, $p < .05$). Combined with the GCA results, these analyses reveal that the effects of the disfluent and silence conditions occurred in the deactivation portion of the time window (i.e. post peak). The second set of positive clusters indicate that deactivation of N1 was significantly extended in these conditions.

Syntactic reactivation and interference resolution window (Time window 2)

In time window 2, we used cluster-based analysis to determine when during the time-course the temporal manipulations modulated resolution of interference. Here, we are interested in when looks to N1 exceed N2, thus indicating successful interference resolution. For this reason, we only report significant positive clusters.

These analyses revealed that N1 significantly diverged from N2 in each of the temporal manipulations but not in the control condition. Unlike in the GCA analyses, in the *stretch* condition, we found a significant cluster from 800 to 1200 ms (cluster sum statistic = 10.04, $p < .05$). In the *disfluent* condition, a significant cluster was found from 700 to 1100 ms (cluster sum statistic = 11.21, $p < .05$) and in the *silence* condition, the significant cluster was from 900 to 1200 ms (cluster sum statistic = 9.19, $p < .05$). The significant regions of divergence are indicated by shaded areas in Figure 6.

Post hoc analysis of the effect of N1 temporal manipulations on N2

An unexpected observation was the effect of the N1 temporal manipulations on the activation patterns of N2. Upon visual inspection it appeared as though there was an enhancement in the activation dynamics of N2, in the disfluent and silence conditions, similar to those found on N1. To explore this effect, a third time window was created to capture the time-course of activation and deactivation of N2. This window began at the auditory onset of N2 (time-locked to 0 ms) and lasted until the end of the sentence (total duration = 2400 ms). Data analysis followed the same approach as described above for N1, whereby orthogonal polynomial time terms (linear, quadratic, and cubic) were added to GCA models to capture linear and curvilinear patterns in gaze trajectory during this time window. The fixed effects of condition were again added to all time terms to determine model fit and follow-up comparisons of individual parameter estimates were used to evaluate specific condition differences on each of the time terms. The random effects were structured identically to those used in time window 1.

Model comparisons showed significant effects of condition when added to each time term except for the intercept (intercept $\chi^2(26) = 4.23$, $p = .24$; linear $\chi^2(29) = 7.79$, $p = .05$; quadratic $\chi^2(32) = 9.31$, $p < .03$;

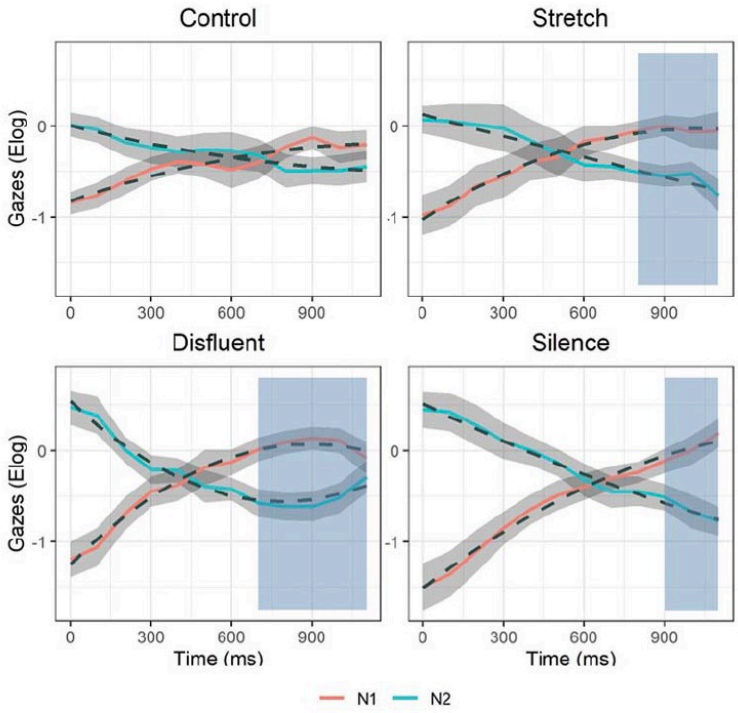


Figure 6. Syntactic reactivation of the displaced object (N1) and deactivation of N2. Model fit (dashed lines) of the observed gaze data (coloured lines are means; shaded ribbons are standard errors) from the onset of the main verb (Time window 2). Blue shaded regions indicate time span of significant clusters (p <.05).

cubic $\chi^2(35) = 37.95$, $p < .001$). As shown in Figure 8, the first effect revealed greater magnitude of looks to NP2 overall in both the disfluent and silence conditions compared to control (*disfluent* $\beta = .25$, SE = .09, $p = .01$; *silence* $\beta = .22$, SE = .09, $p = .01$). The interaction on the quadratic term revealed that the disfluent and silence conditions (as compared to control) increased the steepness of the rise and fall of activation and deactivation (*disfluent* $\beta = -1.08$, SE = .42, $p = .01$; *silence* $\beta = -1.17$, SE = .42, $p = .01$). Table 4 contains fixed effect model parameters, deviance statistics, and significance levels (random effects are presented in Appendix C).

We also conducted cluster-based permutation analyses to determine the timing of the effects established in the GCA. These analyses compared looks to N2 in each temporal manipulation against the control condition and used the same time-bin resolution and time window. All specifications (t-threshold, number of samples, etc.) were identical to the previous analyses in time windows 1 and 2. Consistent with the GCA results, significant clusters were only found in the control-disfluent comparison (Figure 9(B), cluster sum statistic = −37.9, p <.001) and the control-silence comparison (Figure 9(C), cluster sum statistic = −20.7, $p < .05$).

Discussion

The findings from this ETL experiment revealed that temporal manipulations modulated the activation dynamics of subject and object noun phrases during the auditory processing of object-relative sentences. These results provide a number of novel findings relevant to lexical activation, deactivation, and syntactically driven reactivation during sentence processing. In terms of initial lexical activation of the direct object (N1), GCA revealed that the addition of *disfluencies* and *silent* pauses increased the overall magnitude and curvature of activation of N1 (steeper rise and fall). Follow up cluster-based analyses complemented the GCA models by revealing when deactivation was enhanced in the disfluent and silence curvatures. Downstream, similar effects of these manipulations were also found on the subject noun (N2) and the

Table 3. GCA results of the effect of temporal manipulations on N1 reactivation N2 deactivation (Time window 2).

Model Fit			
Term	−2LL	χ^2	*p*
Intercept	**−6033.6**	**5.25**	**0.63**
Linear	**−5999.5**	**68.19**	**<.001**
Quadratic	**−5988.6**	**28.05**	**<.001**

Parameter estimates				
Term	Est.	SE	*t*	*p*
Intercept	−0.43	0.13	−3.28	<.001
Linear	0.68	0.31	2.23	0.03
Quadratic	−0.15	0.20	−0.77	0.44
Disfluent*Intercept	0.11	0.12	0.99	0.33
Silence*Intercept	−0.13	0.12	−1.14	0.26
Stretch*Intercept	0.07	0.12	0.64	0.52
Disfluent*Linear	**0.68**	**0.35**	**1.96**	**0.05**
Silence*Linear	**1.07**	**0.35**	**3.09**	**<.001**
Stretch*Linear	**0.39**	**0.35**	**1.13**	**0.26**
Disfluent*Quadratic	−0.46	0.26	−1.79	0.08
Silence*Quadratic	−0.12	0.26	−0.46	0.65
Stretch*Quadratic	−0.19	0.26	−0.74	0.46
Intercept*N2	0.14	0.19	0.75	0.45
Linear*N2	−1.21	0.43	−2.81	0.01
Quadratic*N2	0.25	0.28	0.89	0.37
Disfluent*N2*Intercept	−0.07	0.16	−0.42	0.67
Silence*N2*Intercept	0.25	0.16	1.55	0.12
Stretch*N2*Intercept	−0.08	0.16	−0.49	0.62
Disfluent*N2*Linear	**−1.16**	**0.49**	**−2.36**	**0.02**
Silence*N2*Linear	**−1.92**	**0.49**	**−3.92**	**<.001**
Stretch*N2*Linear	**−0.77**	**0.49**	**−1.56**	**0.12**
Disfluent*N2*Quadratic	1.01	0.36	2.80	0.01
Silence*N2*Quadratic	0.12	0.36	0.32	0.75
Stretch*N2*Quadratic	0.10	0.36	0.29	0.77

Note: The table provides the test of the overall interaction (model fit) as well as the test of the specific comparisons between the temporal manipulations for each term of the model (intercept, linear, quadratic, and cubic). Results in **boldface** are presented in the text. LL = log-likelihood.

reactivation and interference resolution processes. Critically, after processing the RC-verb, looks back to N1 rose more sharply and exhibited more divergence from the N2 (the competing constituent). In other words, interference was resolved more rapidly.

The effect of additional time on lexical and syntactic processing

The addition of a brief delay in the speech input (via disfluency and silent pause) after the presentation of the N1 enhanced processing of that noun, which resulted in a higher total level of activation followed by enhanced deactivation.

In our investigations of the syntactic reactivation of N1, we found across all cases, significant reactivation which replicates prior reports of real time dependency linking during object-relative sentence processing (Akhavan et al., 2020; Love & Swinney, 1996; Sussman & Sedivy, 2003; Thompson & Choy, 2009). In addition, these ETL data provide insight about the impact that additional time has on the post-verb reactivation process and the extent of the interference patterns of the two nouns.

Comparing the four conditions, there are clear differences in the onset and extent of *lexical reactivation* at the post-verb site. Specifically, the disfluent and silence conditions pattern together and show steeper rises in looks to N1 compared to the control condition. Accompanying these increases is a strengthened rate of deactivation of N2. The coupling of stronger reactivation of N1 and deactivation of N2 are explained in terms of a greater resolution of interference, which can be visualised in the gaze patterns displayed in Figure 6. As can be seen from the figure, the interference region is greatest in the control condition (noted by an extended overlap in looks to the two nouns), whereas it is reduced in the three temporal conditions. This reduction is manifested as greater divergence of gazes between the two nouns such that interference is resolved earlier and maintained longer, as confirmed by cluster-based analyses.

One interpretation of this pattern is that the additional time post N1 (by disfluency or silence) allowed for a deeper processing of the direct object noun (N1), leading to a strengthened representation (see Karimi & Ferreira, 2016 for additional discussion on deeper processing). Prior research supports this notion and is consistent with the view that disfluencies (overt and silent), provide an additional window of time allowing the current representation to strengthen in activation whether that be a structural interpretation as found during the parsing of garden path sentences (Bailey & Ferreira, 2003) or in this case lexical items. This enhanced focus could result in sustained activation making it available at verb offset, however, our results (and those previously reported in the literature) do not support a sustained activation model, as we see clear deactivation.

Another possible interpretation of the effect of the manipulation can be aimed at N2 processing. When considering how disfluencies and silence affect sentence constituents downstream from where they are presented, it is possible that the manipulations caused heightened attention to upcoming information, such as N2. Cluster analyses exploring the time-course of activation of N2 revealed a significant effect for both the disfluent and silence conditions, supporting the enhanced activation found from the GCA analyses. This is in line with auditory recognition research which has found that target words that were preceded by disfluencies were faster to be recognised due to modulations in attention (Collard et al., 2008; Corley et al., 2007; Corley & Hartsuiker, 2011; Fox Tree, 2001). However, this too

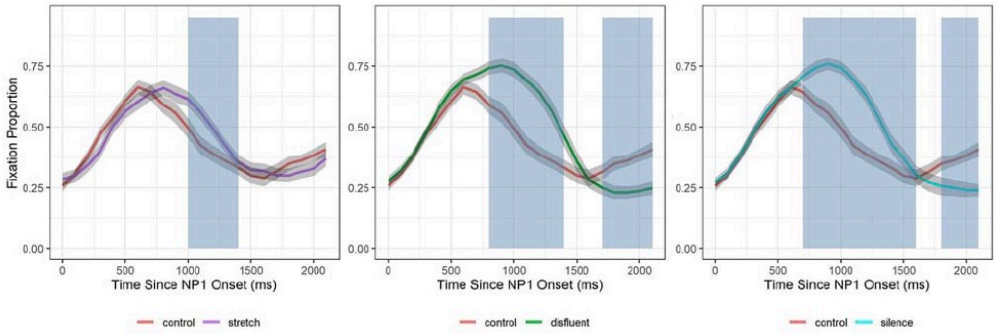


Figure 7. Results of cluster-based permutation analyses on initial N1 processing. This figure shows the mean probability of fixating on N1 and standard error (grey error ribbons) in each comparison: control vs stretch (A), control vs disfluent (B), and control vs silent (C). Blue shaded regions represent the time span for each significant cluster (p <.05).

cannot be the whole story as we find less interference at the post-verb site, yet one would expect that heightened activation of the competing noun would interfere with reactivation. This leaves us to entertain our third option which centres on lexical disengagement.

The enhancement in the activations of N1 and N2 from the manipulations co-occurred with steeper deactivation of N1 pre-verb and N2 post-verb. An example of this can be seen for the disfluent-control comparison as shown in Figure 10. It is believed that these patterns allowed for cleaner linking of the dependency elements at verb offset as there is reduced interference. The finding that disengagement of a noun affected the pattern in which subsequent information is activated is an aspect of lexical processing that is not often investigated. These results indicate that lexical deactivation plays a beneficial role in allowing for the tight lexical and syntactic coupling needed to accomplish real time syntactic linking and interference resolution between sentence constituents in constructions where competition exists (i.e. object relative constructions).

These findings are in conceptual alignment with the functional decay theory, originally put forth by Altmann and Gray (2002), which posits that decay and interference are functionally related; that is, decay plays a functional role in memory by mitigating interference. While this theory was initially proposed for short term memory processing, the current pattern of results fit with this

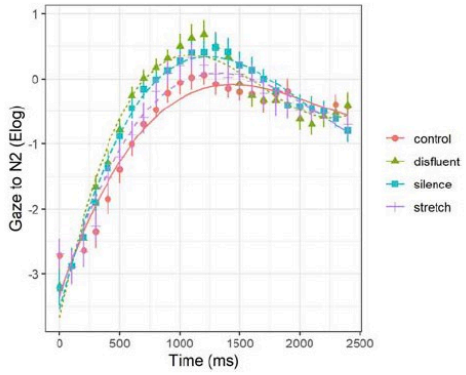


Figure 8. N2 processing. Model fit (lines) of the gaze data (shapes are means for the 4 conditions; error bars are standard errors) from the onset of N2.

Table 4. GCA results of the effect of temporal manipulations on N2 activation.

	Model Fit		
Term	−2LL	χ^2	p
Intercept	**−7100.8**	**4.23**	**0.24**
Linear	**−7096.9**	**7.79**	**0.05**
Quadratic	**−7092.2**	**9.31**	**0.03**
Cubic	**−7073.3**	**37.95**	**<.001**

Parameter estimates

Term	Est.	SE	t	p
Intercept	−0.79	0.11	−7.22	<.001
Linear	3.33	0.50	6.61	<.001
Quadratic	−2.88	0.42	−6.79	<.001
Cubic	0.64	0.14	4.55	<.001
Disfluent*Intercept	**0.25**	**0.09**	**2.85**	**0.01**
Silence*Intercept	**0.22**	**0.09**	**2.54**	**0.01**
Stretch*Intercept	0.09	0.09	0.97	0.33
Disfluent*Linear	−0.86	0.49	−1.74	0.09
Silence*Linear	−0.53	0.49	−1.08	0.28
Stretch*Linear	−0.41	0.49	−0.84	0.41
Disfluent*Quadratic	**−1.08**	**0.42**	**−2.58**	**0.01**
Silence*Quadratic	**−1.17**	**0.42**	**−2.80**	**0.01**
Stretch*Quadratic	−0.59	0.42	−1.42	0.16
Disfluent*Cubic	1.11	0.20	5.55	<.001
Silence*Cubic	0.39	0.20	1.98	0.05
Stretch*Cubic	0.08	0.20	0.42	0.67

Note: The table provides the test of the overall interaction (model fit) as well as the test of the specific comparisons between the temporal manipulations for each term of the model (intercept, linear, quadratic, and cubic). Results in **boldface** are presented in the text. LL = log-likelihood.

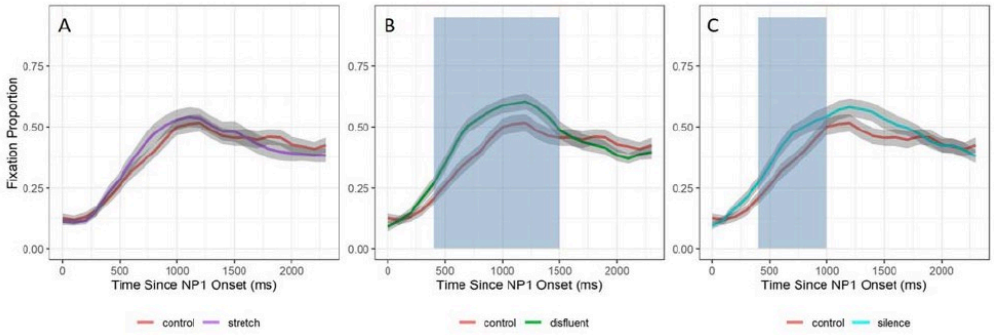


Figure 9. Results of cluster-based permutation analyses on N2 processing. This figure shows the mean probability of fixating on N2 and standard error (grey error ribbons) in each comparison: control vs stretch (A), control vs disfluent (B), and control vs silent (C). Blue shaded regions represent the time span for each significant cluster (p <.05).

schema. This theory rests on the idea that information must decay to some degree to allow the system to more efficiently retrieve the target information. With respect to language processing, this would mean that lexical representations must decay, to some degree, so that the system can process new incoming information without interference. But this does not explain how information is then retrieved and integrated into a syntactic frame when the structure requires linking of the decayed information. In fact, decay theories posit that the more decay that a representation undergoes, the more difficult it is to retrieve that item at a later time (Brown, 1958). Our results show that the greater the deactivation of a noun, the more enhanced the activation and deactivation of a subsequent noun. It is this enhanced process that allows for the reduction of interference and the successful linking of the verb to the prior processed direct object noun.

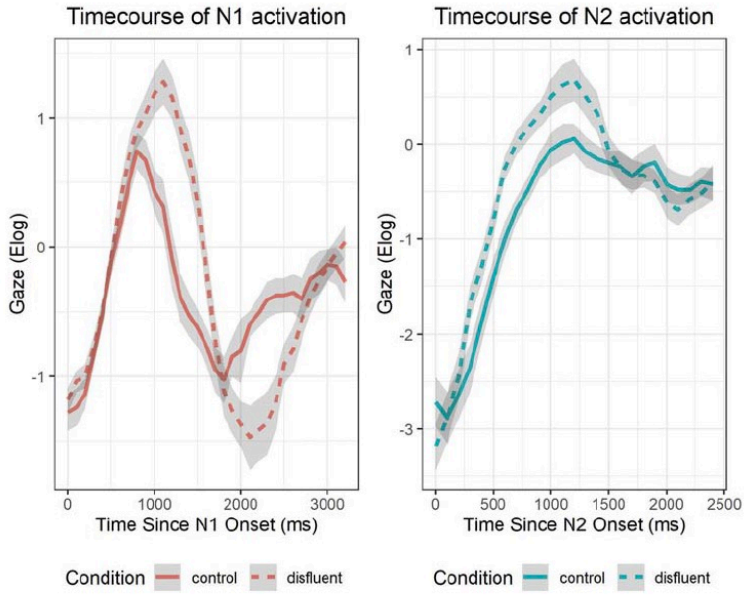


Figure 10. Overlays of the time course of activation of N1 (left) and N2 (right) for the control and disfluent conditions (solid line and dashed line, respectively) showing enhanced activation and deactivation for the disfluent condition as compared to the control condition. Grey ribbons indicate standard error.

Our work hints at avenues for further investigations as the process of decay may take different forms depending on the methods used and the modality of investigation. It is possible that the ETL-VWP task used here is tapping into a different type or level of decay than those tasks typically used in memory research. As our work suggests, some level of decay or deactivation mitigates interference during complex language processing. There are instances, however, in which decay of information has been found to impede processing. Such an example has been demonstrated in garden path sentence processing when an initially chosen structural interpretation turns out to be incorrect and reanalysis must occur in order to reactivate the correct structure and arrive at a correct interpretation (i.e. final comprehension, [Van Dyke & Johns, 2012; Van Dyke & Lewis, 2003]). The logic here is that the more the required representation has decayed[1], the more difficult reanalysis is. In contrast, our findings suggest a different, beneficial, role for decay; that is in minimising interference. In order to tease apart deactivation from memory-based decay, future investigations should explore a variety of methodological approaches.

Temporal parameter for influencing lexical processing and reactivation

The patterning of disfluent and silence conditions suggests that the additional time provided by these manipulations influenced lexical activation regardless of whether the delay was filled (via the disfluency *uh*) or unfilled (silence), indicating that time itself was an essential factor in influencing these processes. The stretch condition, in contrast, only had a reliable effect on the curvature of lexical activation and deactivation in the initial processing window of N1. Compared to the ~460 ms of additional timing the disfluent and silence conditions provided, the stretch condition provided less time, ~250 ms. It is possible that effects of time and the ~250msec addition was not long enough to produce any measurable effects on the initial activation of N2. Another possibility is that in the disfluent and silence conditions, time was manipulated *after* the noun whereas in the stretch condition, time was an internal temporal manipulation, motivating further exploration of these different approaches.

Interestingly, the GCA and cluster analyses provided discrepant findings of post-verb looks to N2. No difference between the control and stretch conditions were revealed from GCA. However, cluster-based analyses revealed a significant positive cluster indicating divergent looks to N1 and N2. This divergent pattern supports reactivation at the post-verb position. As the lack of replication between GCA and cluster analysis weakens the argument that the stretch condition enhanced reactivation, we have taken a measured approach in our interpretation of this condition and focused instead on the clear effects from the disfluent and silence conditions.

Conclusions

The overall emerging picture points to the benefit of time on lexical and syntactic levels of processing. Based on the evidence shown above, the effects from two of the temporal manipulations (disfluent and silence) on N1 cascaded to N2 where we saw enhanced processing similar to that found for N1. Regarding these patterns of effects, we assert that the stronger deactivation of N1 allowed for greater activation of N2. When looking at the point of reactivation at the post-verb site, we found greater deactivation of N2 along with reactivation of the structurally linked object (N1) and argue that N2 deactivation led to reduced interference when N1 was reactivated.

These findings point to a beneficial aspect of decay in mitigating interference (Altmann & Gray, 2002). While these aspects of processing need further investigation, it is clear from the data presented that there is a relationship between lexical activation and deactivated and the effects on subsequent constituent processing. These patterns are clearly affected by the temporal manipulations made with the stimuli. Interestingly, while we see graded activation and disengagement across the conditions, the final gaze level reached in each condition was similar. Thus, the effect of the manipulations reflects the activation dynamics, not the final result. This is critical as we can determine that the disfluent and silence manipulations (and to a lesser extent, the stretch condition), have a direct effect on the nature of the listener's parsing where the additional time provided by those conditions changed the rate with which the direct object was reactivated. These findings lend support to the notion that time can enhance lexical representations and has an effect on later integration within a sentence structure.

Note

1. According to the Cue-based Retrieval framework, successful retrieval of a distant dependent is largely determined by the strength of the association between the retrieval cues and the target item while time-based decay in activation may be more relevant in repair processes associated with the processing of ambiguous sentence structures as described in Van Dyke and Lewis (2003).

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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CHAPTER 5

The effect of time on lexical and syntactic processing in aphasia

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The effect of time on lexical and syntactic processing in aphasia

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ABSTRACT

Processing deficits at the lexical level, such as delayed and reduced lexical activation, have been theorized as the source of breakdowns in syntactic operations and thus contribute to sentence comprehension deficits in individuals with aphasia (IWA). In the current study, we investigate the relationship between lexical and syntactic processing in object-relative sentences using eye-tracking while listening in IWA. We explore whether manipulating the time available to process a critical lexical item (the direct-object noun) when it is initially heard in a sentence has an immediate effect on lexical access as well as a downstream effect on syntactic processing. To achieve this aim, we use novel temporal manipulations to provide additional time for lexical processing to occur. In addition to exploring these temporal effects in IWA, we also seek to understand the effect that additional time has on sentence processing in neurotypical age-matched adults (AMC). We predict that the temporal manipulations designed to provide increased processing time for critical lexical items will 1) enhance lexical processing of the target noun, 2) facilitate syntactic integration, and 3) improve sentence comprehension for both IWA and AMC. We demonstrate that strengthening lexical processing via the addition of time can affect lexical processing and facilitate syntactic retrieval of the target noun and lead to enhanced interference resolution in both unimpaired and impaired systems. In aphasia, additional time can mitigate impairments in spreading activation thereby improving lexical access and reducing interference during downstream dependency linking. However, individuals with aphasia may require longer additions of time to fully realize these benefits.

1. Introduction

The powerful productivity of language regularly creates challenges for the comprehension system. Often, a situation arises in which non-adjacent words in a sentence have to be linked over long distances in real-time to create the proper syntactic representation that results in the comprehender knowing who is doing what to whom. For example, in sentence (1) below, the noun *child* is the object of the verb *help,* but is separated by several words and phrases creating a syntactic relationship referred to as a long-distance dependency (noted by the subscript 'i').

(1) It was the **child**$_i$ at the park who the mother rushed to **help**$_i$ after the fall.

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To successfully understand this utterance, the listener must establish the link between the verb and its direct object to assign the appropriate thematic role of theme (recipient of the action) to the direct-object noun (*child*). The process of establishing the link between non-adjacent constituents—dependency linking—has been argued to be fast-acting and without conscious reflection (i.e., automatic), yet requires a complex interplay of lexical and syntactic processing operations. Auditory processing depends on the listener's ability to rapidly analyze, segment, and integrate the incoming speech stream to build a syntactic structure to allow the listener to correctly interpret a sentence's meaning within the temporal constraints of spoken language. In the absence of language impairments, healthy individuals meet these temporal constraints efficiently and are successful at real-time dependency linking and final comprehension. However, acquired brain lesions post-stroke (which often results in a language impairment known as aphasia) can disrupt automatic operations at numerous processing levels which can lead to sentence comprehension impairments. For individuals with aphasia (IWA), the literature has pointed to a number of theoretical accounts of processing disruptions that lead to comprehension impairments. These processing limitations have been conceptualized in different ways including slowed syntactic operations (Burkhardt, Avrutin, Piñango, & Ruigendijk, 2008; Haarmann & Kolk, 1991; Piñango, 2000), weakened syntax (Avrutin, 2006), lexical access deficits (Blumstein & Milberg, 2000; Burkhardt et al., 2008; Love, Swinney, Walenski, & Zurif, 2008; Milberg, Blumstein, Katz, Gershberg, & Brown, 1995; Prather, Zurif, Love, & Brownell, 1997; Swinney, Prather, & Love, 2000; Yee, Blumstein, & Sedivy, 2008), lexical integration deficits (Choy & Thompson, 2010; Hagoort, 1997; Thompson & Choy, 2009) and reductions in cognitive resource and allocations (Caplan, Waters, & Hildebrandt, 1997, pp. 542–555; Caplan & Waters, 2013; Hula & McNeil, 2008; Murray, 2018; Murray, Holland, & Beeson, 1997; Nozari, Mirman, & Thompson-Schill, 2016; Villard & Kiran, 2015). As a way to delve into the underlying causes of sentence processing impairment in aphasia, we explore the integrity of two parameters in lexical access: timing (Ferrill, Love, Walenski, & Shapiro, 2012; T. Love et al., 2008) and magnitude (Blumstein & Milberg, 2000; Utman, Blumstein, & Sullivan, 2001; Yee et al., 2008) as they have been proposed to impede the integration of lexical information into the emerging syntactic structure and lead to breakdowns in comprehension.

The overarching goal of the current study is to evaluate the role of the parameter of time in lexical activation and syntactic dependency linking. Specifically, we investigate whether manipulating the time available to process a lexical item has an immediate effect on lexical access as well as a downstream effect on dependency linking. It is hypothesized that by mitigating a lexical access impairment (if one exists) during real-time sentence processing, IWA will demonstrate improved syntactic integration and comprehension. To achieve this aim, we use novel temporal manipulations within the sentence to provide more time for initial lexical processing to occur. We also seek to understand the effect that additional time has on sentence processing in neurotypical age-matched adults (AMC).

1.1. Complex sentence processing

The ease of thematic role assignment, and ultimately, sentence comprehension, is influenced by syntactic structure. In sentences that follow the canonical word order of English (subject-verb-object), such as (2), thematic role assignment follows a straightforward mapping of thematic roles to nouns; the first noun (*teacher*) is the subject and is assigned the role of agent and the second noun (*student*) is the object and is assigned the role of theme. On the surface, sentences in English, however, are not bound to canonical word order. For example, object-relative sentences (see (3) below) are noncanonical constructions as they deviate from canonical word order. In object-relative sentences, the direct-object noun *student* has been displaced from its canonical post-verb position (the 'gap' site according to some linguistic theories) to the beginning of the sentence, creating a structural link between the 'gap' and the moved (fronted) element (denoted by the subscript 'i') (Chomsky, 1986; Fodor, 1978). The displacement of the direct-object creates a more challenging process for thematic role assignment. For successful processing, the listener must link the verb to its object to assign it the role of theme, which allows for the final interpretation of *who did what to whom*.

subject	**verb**	**object**
(2) The teacher	helped	the student.
object	**subject**	**verb**
(3) The student$_i$ that	the teacher	helped$_i$ was relieved.

Experimental evidence has shown that in neurotypical adults and children (at least as young as 4 years of age), reactivation of the direct object occurs immediately at the gap position, resulting in the real-time formation of a syntactic dependency (Akhavan, Blumenfeld, & Love, 2020, 2022; Baker & Love, 2021; Koring, Mak, & Reuland, 2012; T. E. Love, 2007; Roberts, Marinis, Felser, & Clahsen, 2007; Thompson & Choy, 2009, 2009, p. 200). Although object-relative sentences are, in general, correctly comprehended by neurologically healthy adults, studies investigating real-time dependency linking have found that this process can be slowed or made more difficult in certain circumstances (Gennari & MacDonald, 2008; Gibson, 1998; Gordon, Hendrick, & Johnson, 2001, 2002; Traxler, Morris, & Seely, 2002). In particular, higher processing costs are associated with semantically reversible sentences such as (4), where either subject (*elf*) or object noun (*clown*) could be plausibly mapped to either agent or theme thematic roles.

(4) The clown$_i$ that the elf pushed$_i$ was in the backyard.

According to the Cue-Based Retrieval Theory of sentence processing, difficulty in dependency linking is a function of the degree of syntactic and semantic similarity between the to-be-retrieved target noun and other sentence constituents (Gordon, Hendrick, &

Levine, 2002; Lewis, Vasishth, & Van Dyke, 2006; McElree, Foraker, & Dyer, 2003; Van Dyke & Johns, 2012; Van Dyke & Lewis, 2003; Van Dyke & McElree, 2006, 2011). In the cue-based framework, retrieval of prior sentence constituents is required whenever a representation that is no longer in the current focus of attention is needed for interpretation to occur (i.e., the direct-object noun at the post-verb gap position). Target information is retrieved via a content-addressable operation that uses syntactic and semantic cues to match current retrieval requirements, typically generated by a verb or other reference seeking element (e.g., pronoun), with previously encoded sentence constituents. The probability of successful retrieval is thus a function of how closely the retrieval cues (e.g., number, gender, animacy) match the features of the target item. The main deterrent of successful retrieval is interference, which arises when retrieval cues match more than one item and are no longer unique to the target. During the processing of semantically reversible object-relative sentences, such as (4) above, the retrieval cues provided by the verb *pushed* select for an animate noun, however the two noun phrases (*clown* and *elf*) both fit these cues. Investigations measuring processing speed during retrieval have found that the competition from *similarity-based interference*, slows processing times at the verb and increases retrieval difficulty (Gordon et al., 2001, 2002, 2004, 2007; Van Dyke, 2007; Van Dyke & McElree, 2006). Retrieval difficulty due to interference is also shown to lead to sentence comprehension deficits in IWA (Akhavan et al., 2022; Lissón et al., 2021; Mätzig, Vasishth, Engelmann, Caplan, & Burchert, 2018; Patil, Hanne, Vasishth, Burchert, & De Bleser, 2011; Sullivan, Walenski, Love, & Shapiro, 2017). Resolving interference and achieving successful dependency linking during real-time spoken language comprehension creates tight temporal constraints for processing. In individuals with aphasia (as detailed below), the presence of lexical impairments is purported to increase vulnerability to interference, which can impede the formation of syntactic dependencies and result in comprehension impairments.

1.2. Evidence from aphasia: the effect of lexical-level deficits and sentence processing

Broadly, lexical access is characterized as the mapping between a word's acoustic input and its representation in the lexicon via the activation of semantic and phonological information. Acquired brain lesions post-stroke have been found to disrupt the timing and the overall level of lexical activation. While these disruptions do not preclude lexical access completely, they limit the ability to activate the necessary information quickly and accurately (i.e., lexical properties, semantic network, etc.). Of interest in the current study are the ways in which lexical deficits such as delayed and/or reduced activation interact with syntactic processing and how they can contribute to breakdowns in sentence comprehension.

Delayed activation is characterized as a slower rise-time of lexical activation. Early evidence for delayed activation has come from semantic priming paradigms, which have alterations in the timing of spreading activation within linguistic networks (T. Love et al., 2008; Prather et al., 1997; D. Swinney et al., 2000). This research has demonstrated delayed priming effects for IWA (Silkes & Rogers, 2012), and particularly for people with lesions in the left inferior frontal gyrus and agrammatism (T. Love et al., 2008; Prather et al., 1997; D. Swinney, 1991; D. Swinney et al., 2000). However, when additional time is presented between the presentation of the target and the prime word, IWA show semantic priming effects suggesting that IWA can access the lexical-semantic network, but they need more time for activation to spread among related associates (Ferrill et al., 2012; T. Love et al., 2008; Prather et al., 1997; Silkes, Baker, & Love, 2020; Stern, Prather, Swinney, & Zurif, 1991). Beyond studies at the word level, priming methods have also been used to explore the time-course of lexical activation during various points during auditory sentence comprehension. In a series of studies, Love et al. (2008) used cross-modal lexical decision priming (CMLP, Swinney, 1979) to investigate the time-course of activation of the direct-object noun in object-relative sentences. In this paradigm, healthy age-matched adults showed immediate activation of the target noun when it was first heard in the sentence and on-time reactivation of that noun downstream in the sentence at the post-verb gap site. In contrast, IWA showed delayed initial activation of the noun and a concomitant slow-down in reactivation (Love et al., 2008). Based on these findings, the authors proposed the Delayed Lexical Activation hypothesis (DLA), which posits that slowed lexical activation precludes the timely formation of syntactic structure building as the system is not provided with the necessary lexical-semantic information when needed. In support of this view, the researchers found that when the rate of speech was slowed, IWA demonstrated more timely lexical activation and dependency linking and improved sentence comprehension compared to the regular speech rate condition.

An alternative to the delayed activation theory, is one in which deficits arise in the *degree* to which lexical information is activated in aphasia (Blumstein & Milberg, 2000; Janse, 2006; McNellis & Blumstein, 2001; Utman et al., 2001; Yee et al., 2008). Findings in support of the *reduced activation hypothesis* are borne out of investigations of processing under conditions of lexical competition. For example, in an eye-tracking while listening using a visual world paradigm study, individuals with Broca's aphasia failed to fixated more on objects that shared a phonetic onset with the target (e.g., hammock → hammer) and objects that were semantically related to the target word (Yee et al., 2008). Similar findings of reduced sensitivity to onset competitors were taken as evidence that IWA are unable to fully access the lexical-semantic network and thus fail to achieve sufficient activation to overcome lexical competition (Blumstein & Milberg, 2000; Janse, 2006; Mirman, Yee, Blumstein, & Magnuson, 2011; Utman et al., 2001; Yee et al., 2008).

The ramifications of lexical access impairments extend beyond the word level and can negatively affect real-time parsing and sentence comprehension in IWA, particularly for noncanonical sentence constructions. These sentences require a coordinated series of fast-acting lexical and syntactic processes to complete real-time dependency linking. Consequentially, disruptions during lexical processing limit the ability to quickly and accurately activate the information required for syntactic integration and can lead to a breakdown in comprehension (Ferrill et al., 2012; T. Love et al., 2008; Prather et al., 1997). When coupling the heavy processing demands of parsing a non-canonical sentence structure with a system that has an impaired level of processing at the lexical level, for example, these lexical activation deficits can amplify processing costs such as interference effects. For example, when activating the

lexical properties upon initially hearing a direct-object noun, delayed or reduced activation can result in an incomplete representation for that item. This degraded representation impedes the listener's ability to integrate the noun into the syntactic frame and makes retrieval of that same item at a syntactically licensed site (e.g., the 'gap') difficult. In line with this idea, improving lexical access in IWA may be one route to mitigating comprehension deficits. Initial support for this aim has shown that when the temporal constraints of auditory comprehension are relaxed, IWA show on-time lexical processing and dependency-linking (Love et al., 2008). These results suggest a key role for the parameter of time in mitigating lexical activation deficits and improving syntactic processing.

1.3. Parameter of time

As shown by Love et al. (2008), one way to relax temporal constraints is through slowing the overall rate of speech. This manipulation was found to result in on-time lexical activation of the direct-object (to-be-retrieved noun) immediately after the auditory presentation of that noun and again at the post-verb gap position in object-relative sentences. However, by slowing the speech rate across the entire sentence, it was unclear whether the benefits occurred because additional time was provided for processing the lexical item itself or if it was coupled with more time throughout the sentence. Additionally, the use of cross-modal priming did not allow for investigations into whether additional time increased the level of lexical activation. Interestingly, while this manipulation benefitted processing in IWA, it was found to disrupt the normal time-course of lexical and syntactic processing in neurologically healthy adults (Love et al., 2008). These performance disruptions were argued to result from a mismatch between the speed of lexical activation and sentence input speed. In other words, the slowed speech input may have disrupted the automatic and rapid quality of lexical access and gap-filling in unimpaired listeners, possibly giving them time to form unhelpful processing strategies.

To explore ways in which additional time could be provided without presenting sentence stimuli outside the typical speech rate, Baker and Love (2021) used discrete temporal additions to investigate how time affects processing in unimpaired young adults. Eye-tracking-while-listening was used to explore whether extra time modulates the time-course and activation levels of lexical access during comprehension. Three temporal manipulations added to naturally recorded sentences in three ways. To see if a local manipulation of speech rate would also impart benefits during processing, the duration of only the direct-object noun was increased (stretch condition). Additional time was created by inserting the disfluency *uh* or an equal length silence pause directly after the target noun in experimental sentences (disfluent and silence conditions, respectively. Compared to control sentences, the temporal manipulations were shown to enhance lexical activation of the target noun via increasing both the rate of lexical processing and the magnitude of lexical activation. Downstream in the sentence, a benefit was also found for dependency linking which showed an increased rate of reactivation and increased resolution of interference. The current study expands on this prior work to test whether the focal temporal manipulations result in similar lexical and syntactic facilitation in aphasia.

1.4. Current study

In the present study, we use the same methodology and temporal manipulations from Baker and Love (2021) to explore if providing additional time for processing the target direct-object noun will 1) enhance lexical processing for both IWA and AMC, 2) facilitate downstream dependency linking (via modulating interference) for both IWA and AMC, and 3) improve sentence comprehension for IWA. Eye-tracking-while-listening in a visual world paradigm allows us to explore how additional time at a specific location in the sentence affects lexical processing, dependency linking, and interference resolution and (Akhavan et al., 2020, 2022; Baker & Love, 2021; Sekerina, Campanelli, & Van Dyke, 2016; Sheppard, Walenski, Love, & Shapiro, 2015). In this paradigm, participants are presented with an array of four pictures while listening to sentences: two of the pictures depict referents mentioned in the sentence and the other two pictures are distractors. To understand the effects of the temporal manipulations on lexical access of the target noun, we explore two components. The first is **initial lexical activation**, which manifests as increased gazes to the picture of a recently heard referent and indicates the processing of phonological and semantic features of the target item. The second is **deactivation,** which is shown as a decrease in looks to the target item upon hearing subsequent sentence constituents and reflects a disengagement of that noun in order to access the new input. Downstream in the post-verb region of the sentence, we are also interested in two processes involved in dependency linking. In this region, we measure **reactivation** of the direct-object, which occurs via looks back to the displaced direct-object noun and indicates that the direct-object has been linked with the verb. During dependency linking, we also measure **interference resolution**. Recall from predictions of Cue-based Retrieval Theory, that interference can arise during retrieval when the target noun and the intervening noun have similar features (i.e., both subject and direct-object nouns match retrieval cues dictated by the verb). The competition arising from similarity-based interference can slow retrieval of the target noun (Van Dyke & McElree, 2006). In eye-tracking data, this interference is shown as an extended activation of both nouns during the post-verb time window and is visualized as overlapping gaze patterns of both nouns (Akhavan et al., 2020, 2022; Baker & Love, 2021). In cases where interference is resolved, eye gazes show a greater divergence between looks to each noun.

We hypothesize that the focal addition of time will facilitate processing in a number of ways for both groups. Based on prior research in healthy young adults, we predict that unimpaired older adults will show on overall enhanced pattern of processing: stronger lexical activation and deactivation and improved dependency linking via greater interference resolution. In IWA, the temporal manipulations are predicted to mitigate lexical activation benefits and facilitate dependency linking via on-time syntactic reactivation. There are no a priori predictions as to whether these mitigations will result from increased activation, improved time-course of activation (on-time activation), or a combination of both. The proposed investigations will help to clarify the interaction between lexical and syntactic processing levels during ongoing sentence processing and the factors that can support processing and comprehension in individuals with aphasia (IWA) and neurotypical age-matched populations (AMC).

2. Materials and methods

2.1. Participants

Sixteen individuals with aphasia (IWA) and 11 age-matched healthy controls (AMC) participated in this study. All participants were monolingual native English speakers (with no exposure to a foreign language before the age of six), right-handed (premorbid for IWA). All participants had normal to corrected vision and hearing, and reported no prior history of psychiatric illness, substance abuse, or neurological disease. Additionally, given that we are using eye-tracking methodology, we assessed visuospatial search abilities via the Cognitive Linguistic Quick Task (CLQT, Helm-Estabrooks, 2001), with all participants performed with zero (to minimal) errors on the visual search subtest. The participants with aphasia all experienced a single left-hemisphere stroke at least 6 months prior to participation (i.e., chronic stage). The diagnosis and severity of aphasia were assessed using a standardized aphasia examination, the Boston Diagnostic Aphasia Examination (BDAE-version 3, Goodglass, Kaplan, & Barresi, 2001) and were confirmed by clinical consensus. All participants completed a battery of standard language assessments. Sentence comprehension ability of sentences with canonical word order (actives and subject-relatives) and noncanonical word order (passives and object-relatives) was assessed using the S.O.A.P Test of Sentence Comprehension (T. Love & Oster, 2002). Results from these tests are presented in Table 1. In addition to these assessments, a baseline eye-tracking task (described in more detail below), was conducted to calculate each individual's saccade latency (the time elapsing between the appearance of a visual target and the initiation of the orienting eye movement), which has been shown to vary post-stroke (Rizzo et al., 2017) and with age (Irving, Steinbach, Lillakas, Babu, & Hutchings, 2006). Mean saccade latencies for each participant are also presented in Table 1. An expanded version of Table 1 is included in Appendix A, which includes lesion size and location (where available) as well as additional results on auditory comprehension performance on the BDAE.

After testing was completed, we determined that one AMC and three IWA had to be excluded from further data analysis due to computer errors in data collection. The resulting 13 IWA (female = 5, M_{age} = 61 years, SD_{age} = 12.9) and 10 AMC (female = 5, M_{age} = 69, years, SD_{age} = 7.9) were included in the analyses described below. All methods described below were approved by the University of California San Diego and the San Diego State University Institutional Review Boards. All participants provided informed consent and were compensated $20 per visit.

2.2. Materials

The experimental stimuli consisted of 40 object-relative sentences, as shown in (5, below). The construction of each sentence followed a similar format: a) an introductory adverbial clause, b) the object relative clause introducing the direct object noun (N1, e.g.,

Table 1
Participant demographics.

IWA	Sex	Age	Years of Education	Years Post-Stroke	BDAE Severity	SOAP Canonical (%)	SOAP Noncanonical (%)	Saccade Latency (ms)
9	M	61	17	21	2	65	25	267
101	M	73	20	15	2	40	55	335
130	M	69	16	14	4	75	45	334
140	F	47	16	21	2	65	40	214
159	F	70	16	12	3	95	70	246
169	M	65	12	10	1	90	20	253
181	F	40	16	5	1	60	50	371
182	F	49	18	8	3	100	85	232
189	M	64	16	3	2	55	45	334
192	M	77	17	8	4	100	100	280
193	M	40	16	8	4	90	75	254
194	M	66	14	6	2	50	45	273
197	F	75	14	10	5	100	100	277
AMC								
2	M	74	18					NA*
3	F	59	16					265
4	F	61	16					251
6	F	54	18					268
172	F	69	16					241
173	M	69	16					260
199	M	78	23					351
201	M	73	16					297
202	F	76	16					288
203	F	72	20					269

M = male, F = female; BDAE = Boston Diagnostic Aphasia Examination (0 = no useable speech or auditory comprehension; 5 = minimal discernible speech impairment). SOAP Canonical = average percent correct on active subject-relative items from the SOAP Test of Auditory Sentence Comprehension. SOAP Noncanonical = average percent correct of passive object relative items from the SOAP Test of Auditory Sentence Comprehension. *Saccade latency not calculated due to equipment error; the AMC group mean was used for this individual's baseline.

elf), the subject noun (N2, e.g., *clown*) and the relative clause verb (e.g., *pushed*), and c) a verb phrase containing the main sentential verb (e.g., *was*) followed by a prepositional phrase.

			Relative Clause		
(5)	Adverbial clause	N1	N2	Verb	Main Verb + PP
	[Last year on Halloween],	[the elf that	the clown	pushed]	[was at the end of the street].

All sentences contained non-biasing contexts such that both object (noun 1, N1) and subject nouns (noun 2, N2) were equally plausible as either the agent or theme of the relative clause verb. To avoid bias due to order of mention, each noun served once as the direct-object and the subject in a matched sentence design in which the role of each noun was reversed (see 6 and 7).

(6) Last year on Halloween, the elf that the clown *pushed* was at the end of the street.
(7) At the costume party, the clown that the elf *poked* was in the backyard.

The relative clause verbs within each sentence in the pair had similar phonetic onsets and were matched in syllable length (e.g., *help/hug, push/poke*). The two nouns of interest (N1 and N2) were all 1–3 syllables and were not phonologically similar or semantically related to one another. These sentences served as the control condition and were modified to create three temporal manipulation conditions (described in the next section). This resulted in a total of 160 experimental items (40 sentences per condition). An additional 40 unrelated filler sentences were created to distract participants from developing strategies when listening to the object-relative clause construction in the target sentences (i.e., only looking to the first noun, etc.). As described below, experimental and filler sentences were recorded by a female Native English speaker at a normal rate of speech. Filler sentences were of similar length but varied in syntactic structure.

For each sentence, participants heard a yes/no comprehension question at the end of the trial to ensure that they attended to the sentences. All questions for the experimental items asked whether one of the nouns mentioned in the sentence had performed the action of the relative clause verb (e.g., *Did the clown push someone?*). The nouns used in the question (N1 or N2) were counterbalanced. Filler sentence comprehension questions took a variety of formats so that the participants could not develop strategies to anticipate what/who to listen for. All comprehension questions were recorded by a different female speaker at a normal rate of speech and were counterbalanced so that half of the questions had a correct answer of "yes".

2.2.1. Temporal manipulations

Sentences in the **control condition** were recorded by a trained female native English speaker in a sound-treated room at an average speech rate of 4.94 syllables/second (SD = 0.26s). Control sentences were used as the base for the three temporal manipulations: stretch, disfluent, and silence (see Fig. 1 below). The **stretch condition** was created by digitally elongating the duration of the wave form associated with the direct object noun (N1) by 150% while maintaining pitch using Adobe Audition CC. The level was chosen as it was the maximum increase in duration that could be obtained without distortion in sound quality. Researchers in the laboratory confirmed that this level of 'stretching' did not result in unnatural sounding speech of the noun. The nouns in this stretch condition were approximately ~250ms longer than the nouns in the control condition. To create the **disfluent condition**, the target sentences were recorded by the same female speaker with a disfluency (*uh*) embedded in them. This provided a natural recording of a disfluency in the control sentence context that was then spliced into the original (control) recording. In doing so, the overall sentence contour remained the same between control and disfluent conditions. Disfluencies had an average duration of 250.5ms (SD = 3.56ms) and were inserted approximately 100ms after the offset of N1 and 100ms before the upcoming relativizer to allow for a natural buffer before and after the disfluency as is typical in spontaneous speech (E. E. Shriberg, 1999). This manipulation resulted in an average of 460.0ms (SD = 3.8ms) of additional time. Since the placement of disfluencies in the current experiment differs from where they typically occur in natural speech (i.e., at clause boundaries or word initial, for review see (Ferreira, Lau, & Bailey, 2004; E. Shriberg, 2001), the naturalness of the disfluent sentences was confirmed by five research assistant naïve to the aims of the study. The pretest

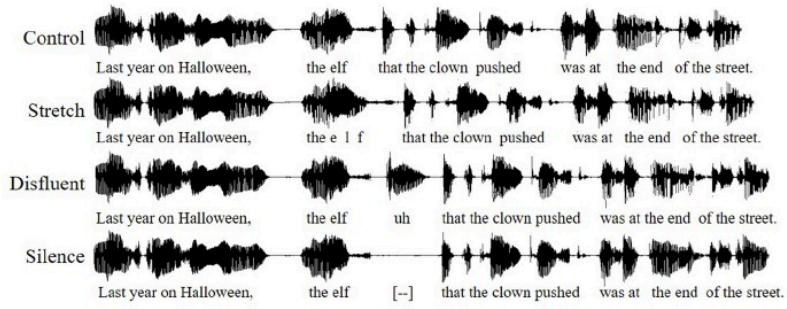


Fig. 1. Waveforms of example stimuli showing the control condition and temporal manipulations (disfluent, silence, and stretch).

confirmed that other than the speaker "sounding slightly confused", the sentences appeared natural. Finally, to create the **silence condition**, the disfluent portion was replaced by an equal length silent pause to maintain the same timing between disfluent and silent conditions (~460ms).

2.2.2. Visual stimuli

For the visual world portion of the ETL study, a 2 × 2 visual array displaying four pictures was created for each sentence. Within this display, four areas of interest (AOIs) were defined corresponding to the four corners of the array (450 × 450 pixels). Two of the pictures in the array depicted referents mentioned in the sentence (N1 and N2), while the other two were unrelated to the sentence. Noun images were colored cartoon images created by a single artist to maintain general style. A total of 80 images were created for this study. The position of N1 and N2 and the two unrelated pictures were counterbalanced such that all picture types appeared equally across all four quadrants of the visual display.

2.2.3. Visual stimuli pretest

To ensure that each drawing accurately depicted the intended noun, a naming preset was conducted with a separate group of 19 neurotypical adults (M age = 28.8 yrs, SD = 16.4; male = 3). All participants were native English speakers who were right-handed, had normal to corrected vision and hearing, and no self-reported history of head injury, learning disability, or drug abuse. A total of 80 images were tested whereby participants were asked to write the name of the picture they saw. As described in Baker and Love (2021), any image for which there was less than 70% semantic agreement was removed. This resulted in a total of 72 images (40 for matched experimental sentences, 32 for the filler sentences) that were used in the present experiment.

3. Study design

This was a within-subjects experiment in which the trials were divided and counterbalanced across 4 scripts. Each participant completed one script in each of the 4 visits which were spaced a minimum of one week apart to ensure that each participant only heard an experimental item once in a given visit. In each script no more than two items of the same condition appeared in a row. Script assignment was randomized and counterbalanced.

4. Procedure

Participants were seated approximately 65 cm in front of a computer screen equipped with a Tobii X3-120 eye-tracking bar and wore over-the-ear headphones for auditory stimulus presentation. At the beginning of each experimental session, the eye-tracker was calibrated to each participant eyes using a nine-point calibration procedure. In each trial, participant's gaze location was sampled and recorded at a rate of 120 Hz (every 8ms) from both eyes. Comprehension accuracy and timed presentation of auditory and visual stimuli were controlled by E-Prime 3.0 software (Psychology software Tools, Pittsburgh, PA, USA).

Prior to the experiment, participants were asked to complete a **baseline gaze task** which served two purposes. First, it allowed them time to familiarize themselves with the experimental environment and second, it provided a measure of saccade latency for each person baseline the eye gaze data to account for the time required to execute goal-directed eye-movements. A standard practice in the eye-tracking field is to shift the onset of the windows of interest by 200ms to control for the delay associated with the programming and execution of eye-movements (Farris-Trimble & McMurray, 2013; Hallett, 1978; Huettig & Altmann, 2005; Matin, Shao, & Boff, 1993). However, 200ms may not be an appropriate value to use for older adults (Irving et al., 2006 and references therein) or for individuals with aphasia as stroke has been found to alter altered oculomotor function persisting into the chronic stages of aphasia (Smith, Schmidt, Wang, Henderson, & Fridriksson, 2018). In order to take into account potential differences in time required to plan an eye-movement, we used the data from this task to individually calculate each participant's time to first gaze on a target. Here, each trial began with a gaze-contingent fixation cross presented in the center of the screen. In order for the trial to commence, participants had to fixate on the cross for 100ms to ensure participants' attention and gaze remain in the center of the screen. After establishing gaze-contingency, directions to look at a shape (circle, triangle, or square) were presented through headphones at a predetermined comfortable listening volume. Immediately after, the shape appeared in one of the four quadrants that represented the four regions of interest for this study. Participants were instructed to direct their gaze to that shape as quickly as possible (no response required). The shape remained on the screen for 1500ms followed by the next gaze-contingent fixation cross to start the following trial.

Upon completion of the baseline task, participants continued with the main study and were instructed to listen carefully to each sentence as they would be asked a comprehension question after each one. These questions were intended both to reinforce the need for participants to attend to the meaning of the sentences and to maintain task engagement. Each trial began with a central fixation cross presented for 500ms, followed by a blank screen for 250ms. The four-picture display was then presented for 1500ms before the auditory sentence began (see Fig. 2). After the auditory sentence ended, the pictures remained on the screen for 500ms. Each sentence was followed by an auditory comprehension question. Participants were instructed to respond "yes" or "no" as quickly and as accurately as possible using a two-button response box. Comprehension accuracy and response time were also recorded by E-Prime 3.0 software. Ten practice trials were conducted prior to each experimental session to allow the experimenter to provide feedback or redirection prior to the beginning of the experiment.

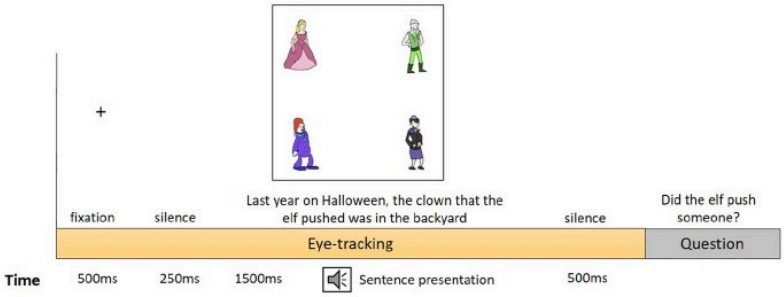


Fig. 2. Example of visual world eye-tracking-while-listening paradigm. The example display presents the direct object noun (e.g., *elf*), the subject noun (e.g., *clown*), and two distractors (e.g., princess and stewardess). Auditory sentences began after a 1500ms preview of the display.

5. Analysis approach

5.1. Preprocessing

Preprocessing of the eye-tracking data was conducted to evaluate and clean for trackloss, aggregate observations across trials, group data into temporal bins, and time-lock data to sentence regions of interest. Here, an observation is characterized as trackloss when the eye-tracker fails to record gaze location data from at least one of the participant's eyes. This likely occurs when the participant is looking off screen or not within the predetermined area of interest (AOI), or if the sample contains a blink. Following Huang and Snedeker (2020), any gaze samples that contained trackloss were excluded from further analyses and of the remaining samples, any trial for which less than half of the expected samples remained was excluded from analyses. Eighty-four percent of the data remained after cleaning for trackloss.

Individual observations (samples) were then aggregated across trials into 100ms time-bins for each participant within each experimental session and condition. This approach is used as a strategy to account for the inherent dependency in time-series eye-tracking data created by constraints on how the eyes move and can lead to inflated Type I error rates (i.e., gaze location at one time point is likely to be influenced by gaze location at nearby time points) (Barr, 2008). For each time bin, we then computed the proportion of gaze to the target nouns, N1 and N2, and the two distractor nouns. Gaze proportions from all sentences per condition, regardless of comprehension response accuracy were included in the statistical analyses. The data were then time-locked to the start of the sentence regions of interest and shifted by each individual's baseline data (see Table 1 for each person's baseline saccade latency). Note that there was no difference in saccade latencies between the IWA and AMC groups ($t_{20} = 0.311$, $p = .759$).

5.2. Eye movement patterns

Binned eye-movement data were modeled using growth curve analysis (GCA) to explore the dynamic gaze patterns in preselected windows of interest within the sentence. GCA is a multi-level modeling technique developed to analyze time-series data and has been applied to the analysis of gaze data in the visual world paradigm (Mirman, 2017; Mirman, Dixon, & Magnuson, 2008). As the temporal trajectory of gaze data may reveal nonlinearities, orthogonal polynomials are used to model linear (reflecting constant change over time) and curvilinear (reflecting fluctuations over time) patterns. Orthogonal polynomials provide a way to quantify and evaluate the effects of the variables of interest on statistically independent (i.e., orthogonal) time terms. The following time variables were selected for the current models based on the overall shape of the data and theoretical motivations: 1) the intercept which reflects the average overall gaze proportion, 2) the linear term which reflects a monotonic change in gaze trajectory, and 3) the quadratic term which reflects the symmetric rise and fall around a central inflection point and captures how much the curve is bent upwards or downwards. Fixed effects of Condition (control, disfluent, silence, and stretch) were added as an interaction on all time terms. These effects were added individually on the model and evaluated using model comparisons to examine whether adding that effect significantly improved model fit. Improvements in model fit were evaluated using changes in goodness of model fit using the *likelihood ratio test* with degrees of freedom equal to the number of parameters added (Mirman, 2017). Analyses were conducted in the statistical software R (R Core Team, 2022) using the lme4 package (Bates, Mächler, Bolker, & Walker, 2015). Tests of individual parameter estimates were used to evaluate specific condition differences on each of the time terms (i.e., whether each experimental manipulation was reliably different from the baseline control condition) using the Satterthwaite's (Kenward-Roger's) approximations for the *t*-test and corresponding p-values implemented in the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2017). Random effects included 1) random slopes for condition per participant on each time term and 2) random slopes by trial. For each time window, two sets of GCA models were created: group comparison models to test for group differences between AMC (served as the reference level) and IWA and within-group models to understand the effect of the experimental manipulations on the gaze patterns for each group (control condition served as the reference level).

5.3. Cluster-based permutation analyses

The parameters of growth curve analyses describe how gaze trajectories change over time while taking into account individual differences, however, they do not directly address when in time two trajectories differ. To complement the growth curve analyses, we also conducted cluster-based permutation analyses to detect the temporal onset and duration of an effect between two time-series. This method was originally developed to account for the multiple comparison problem and autocorrelation arising in EEG and MEG data (Maris & Oostenveld, 2007), and has been increasingly applied to eye-tracking research (Akhavan et al., 2022; Baker & Love, 2021; Barr, Jackson, & Phillips, 2014; Gerhardstein & Olsen, 2020; Weighall, Henderson, Barr, Cairney, & Gaskell, 2017). In cluster-based permutation testing, inferential tests are performed on each time-bin over the analysis window and all adjacent, significant bins (i.e., passing a determined threshold) are grouped together into a single cluster and a cluster-level statistic is computed whose null distribution is derived through data permutation. Finally, a nonparametric statistical test is then performed by calculating a p-value under the permutation distribution and comparing with a critical alpha-level. By grouping temporally adjacent bins into a single cluster, individual tests are replaced by a single test for the cluster, thus controlling for family-wise error rate (for more information, see Maris & Oostenveld, 2007).

For each cluster-based permutation analysis, we used the eyetrackingR divergence analysis package (Dink & Ferguson, 2015). As applied here, *t*-test statistics were computed for each time-bin over the analysis window and all adjacent bins whose t-value exceeded the threshold (97.5th quantile for a two-sided *t*-test) were grouped into a single cluster. A cluster-level statistic was then calculated by taking the sum of the t-values to create a cluster mass statistic. Here the data was iteratively sampled 1000 times to build a null distribution. Significant clusters are identified using a critical alpha-level of 0.05. As the questions of interest differ in each time window (1 and 2), we approached the cluster analyses using different comparisons (described in detail within each time window).

5.3.1. Time windows

We examined processing in two prespecified time windows. **Time window 1** begins at the auditory presentation of the first noun (N1) and continues until the offset of the relative clause verb (average duration = 1600ms). This window encompasses the full time-course of processing and includes initial lexical activation and deactivation. **Time window 2** occurs post-gap (verb) region to the end of the sentence (average duration = 1300ms) and captures syntactic reactivation of N1 and the resolution of interference from noun 2 (N2). Fig. 3 shows the average time-course (collapsed across conditions) of looks to N1 and N2 in the IWA and AMC groups from the onset of N1 until the end of the sentence. Note that across conditions, there were minimal looks to distractor images and therefore these are not included in subsequent analyses or visualizations.

6. Results

6.1. Offline comprehension

Response to yes/no comprehension questions after each trial were analyzed to explore group and condition differences using mixed-effects logistic regression models with a fixed interaction effect of group (AMC, IWA) by condition (control, disfluent, silence, stretch) and crossed random effects of participant and item on the intercept (lme4 R package; Bates et al., 2015). Table 2

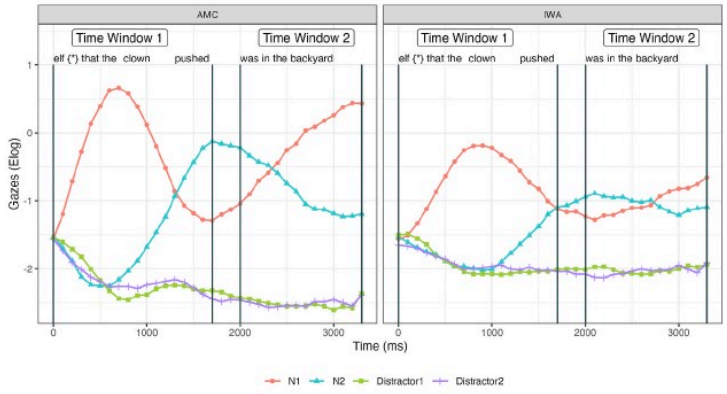


Fig. 3. Mean gaze over time toward N1 (first noun, red line), N2 (second noun, blue line), Distractor 1 (1st distractor noun, green line), and Distractor2 (2nd distractor noun, purple line) averaged across conditions for each group (baselined). Vertical lines correspond to the analyzed time windows. Time window 1 begins at the auditory onset of N1 (0ms) until the relative clause verb offset (1600ms). Time window 2 begins post relative clause verb (2000ms) until the end of the trial (3400ms). {*} = placement of the temporal manipulation directly after N1 in the experimental conditions.

Table 2
Mean accuracy (M, % correct) and standard deviations (SD) for offline comprehension.

	AMC		IWA	
Condition	M	SD	M	SD
Control	79%	41%	44%	50%
Disfluent	84%	37%	45%	50%
Silence	78%	42%	46%	50%
Stretch	82%	39%	46%	50%

shows the mean accuracy for each of the four conditions in both groups. The results revealed an effect of group; specifically, the IWA group performed worse than the AMC group (estimate = −1.83, SE = 0.37, $p < .001$). No effect of condition was found for accuracy in the AMC or IWA group ($p > .05$). Accuracy performance for each participant in the experimental conditions can be found in Appendix B.

6.2. Online processing

6.2.1. Lexical activation deficits in aphasia

Before examining the effects of the temporal manipulations in each time window, we first compared IWA and AMC gaze patterns in the control condition to check for the presence of lexical access deficits as measured by the magnitude and time-course of activation (Fig. 4). Here, we analyzed initial lexical activation from the onset of N1 to the average onset of N2. This sentence region corresponds to the first half of time-window one in the main GCA analyses (~ duration = 700ms) and allowed us to explore the rise of lexical activation before the subject noun (N2) was encountered (i.e., when lexical activation of N1 begins to decay as people shift to looking at the new noun). The GCA model for lexical activation included the interaction of fixed effects of group (AMC, IWA) and time (linear and quadratic orthogonal polynomials) and crossed random effects of participant and item on all time terms. As shown in Fig. 4, the analysis revealed that IWA (red line) looked to N1 significantly less than the AMC group (blue line) indicating a reduced magnitude of N1 activation (intercept estimate $\beta = -0.72$, SE = 0.24, $p < .05$). To measure the time-course of activation, we compared the change in looks to N1 over time (the linear term). The analysis revealed that IWA did not differ from AMC (linear estimate $\beta = -0.13$, SE = 0.34, $p > .05$). These results suggest that, compared to AMC, IWA showed an impairment in the degree of lexical activation, but had a relatively unimpaired time-course (similar time to peak). We note here that in the discussion, we address why the IWA appear to have a normal time course for lexical activation.

6.2.2. Window 1: effect of condition on N1 processing

6.2.2.1. Group results. After establishing the presence of N1 activation deficits (with respect to the degree of activation), we tested the extent to which temporal manipulations modulated the activation and deactivation dynamics of gazes to N1. Gaze patterns for both

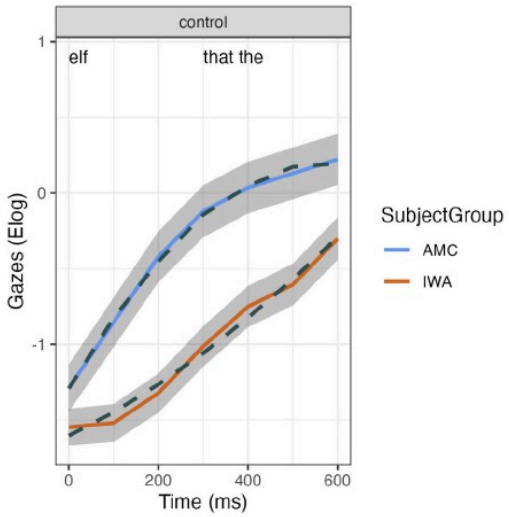


Fig. 4. Initial lexical activation of the direct-object noun (e.g., *elf*) in the control condition by the AMC group (blue line) and IWA group (orange line). Solid lines represent observed data and dashed lines represent the GCA model fit.

groups can be seen in Fig. 5, which shows the change in activation of N1 across all four conditions. Upon visual inspection, it is clear that upon hearing N1 (*elf*), both AMC and IWA groups direct their eye gaze towards the picture referent of the noun they just heard, representing initial lexical activation. The peak of lexical activation is followed by a deactivation or disengagement from N1 (downward slope). The trajectory of this pattern (inverted U-shape) is in line with previous research found in young neurotypical adults (Baker & Love, 2021).

Gaze data and curve fits for the interaction effects of group (AMC, IWA) and condition (control, disfluent, silence, stretch) for processing N1 are plotted above in Fig. 5. Beginning with the group-level models, both groups showed significant (quadratic) patterns of lexical activation and deactivation of N1 (quadratic estimate = −1.69, SE = 0.38, $p < .001$). An interaction effect between group and condition on the quadratic term indicated that in all temporal manipulations, the IWA group showed more a more gradual rate of activation and deactivation of N1. This effect suggests that in response to the temporal manipulations, IWA activation was maintained longer than the AMC group who showed a steeper rise and fall of activation (*disfluent* $\beta = 1.63$, SE = 0.29, $p < .001$; *silence* $\beta = 2.49$, SE = 0.29, $p < .001$; *stretch* $\beta = 1.58$, SE = 0.29, $p < .001$). Table 3, below, contains fixed effect model parameters, deviance statistics, and significance levels.

6.2.2.2. Within-group results: AMC. To explore within-group differences in the effects of the temporal conditions on lexical processing, we first turn to the AMC group. Significant effects of condition were found on the quadratic term (compared to the control condition), indicating a steeper curvature in activation and deactivation in all temporal conditions (*disfluent* $\beta = -1.32$, SE = 0.63, $p < .05$; *silence* $\beta = -1.94$, SE = 0.63, $p < .05$; *stretch* $\beta = -1.33$, SE = 0.63, $p < .05$). To understand *when* in the time course the condition differences on N1 processing occurred, we conducted a permutation cluster analysis to compare the effect of each temporal manipulation against the control condition (i.e., stretch-control, disfluent-control, and silence-control). These analyses revealed a significant cluster in the disfluent-control comparison from 800 to 1300ms (cluster sum statistic = −15.89, $p < .05$) and in the silence-control comparison from 600 to 1200ms (cluster sum statistic = -20.16, $p < .05$). Shaded regions in Fig. 6 depict the time points in the sentence where significant clusters occur. Combined with the GCA results, these analyses reveal that the silent and disfluent manipulations resulted in a larger magnitude peak activation with a more rapid disengagement. Table 4 contains fixed effect model parameters, deviance statistics, and significance levels.

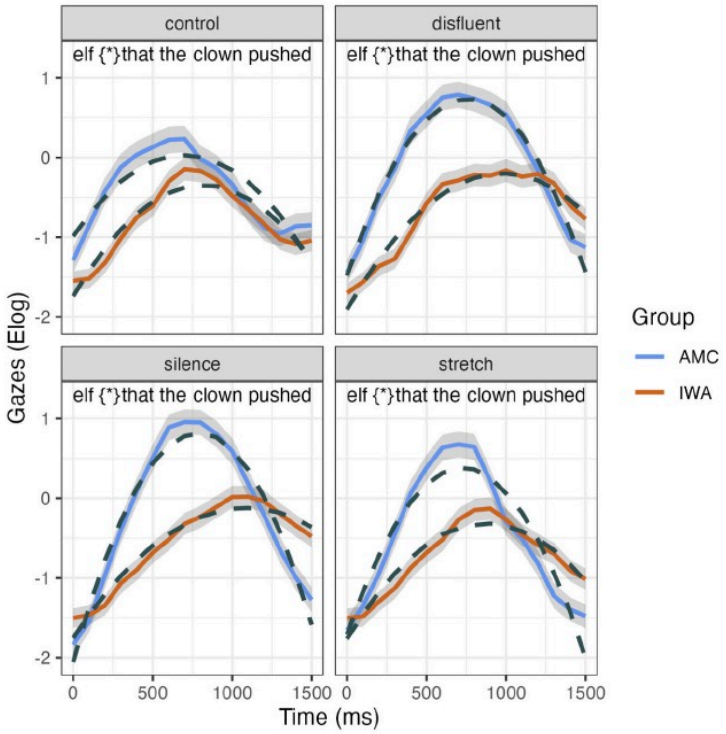


Fig. 5. Full time-course of lexical activation of the direct-object noun (e.g., *elf*) in AMC group (blue line) and IWA group (orange line) in each experimental condition (control, disfluent, silence, stretch). Solid lines represent observed data and dashed lines represent the GCA model fit.

Table 3
Results of GCA group analysis for time window 1 (N1 processing).

Predictor	Est.	SE	p
(Intercept)	−0.38	0.16	0.024
Linear	−0.43	0.47	0.364
Quadratic	**−1.69**	0.38	**<.001**
Group [IWA]	−0.34	0.19	0.086
Condition [Disfluent]	0.32	0.13	0.014
Condition [Silence]	0.22	0.13	0.089
Condition [Stretch]	−0.08	0.13	0.507
Linear X Group [IWA]	1.05	0.56	0.073
Quadratic X Group [IWA]	0.03	0.46	0.954
Linear X Condition [Disfluent]	0.46	0.35	0.194
Linear X Condition [Silence]	0.95	0.35	0.007
Linear X Condition [Stretch]	0.03	0.35	0.921
Quadratic X Condition [Disfluent]	−1.33	0.32	0.000
Quadratic X Condition [Silence]	−1.92	0.32	0.000
Quadratic X Condition [Stretch]	−1.38	0.32	0.000
Group [IWA] X Condition [Disfluent]	−0.23	0.07	0.002
Group [IWA] X Condition [Silence]	−0.04	0.07	0.578
Group [IWA] X Condition [Stretch]	0.07	0.07	0.349
Linear X Group [IWA] X Condition [Disfluent]	0.36	0.29	0.219
Linear X Group [IWA] X Condition [Silence]	0.14	0.29	0.634
Linear X Group [IWA] X Condition [Stretch]	0.28	0.29	0.334
Quadratic X Group [IWA] X Condition [Disfluent]	**1.63**	0.29	**<.001**
Quadratic X Group [IWA] X Condition [Silence]	**2.49**	0.29	**<.001**
Quadratic X Group [IWA] X Condition [Stretch]	**1.58**	0.29	**<.001**

Note: The table provides the test of the full model including the interaction of group and condition on the intercept, linear, and quadratic time terms. The AMC group and the control condition are set as the reference estimates. Results in boldface are presented in the text.

6.2.2.3. Within-group results: IWA. Similar to the AMC group, the disfluent and silence conditions had a significant effect on initial lexical activation and deactivation. However, the IWA group did not have a quadratic effect, but instead showed a linear effect. In other words, while the AMC group showed significant effects in the rise and fall of activation (quadratic curvature) in the disfluent and silence conditions, the IWA group's effect in these two conditions was instead on the linear term (*disfluent* $\beta = .96$, SE = 0.36, $p < .05$; *silence* $\beta = 1.13$, SE = 0.35, $p < .05$). This positive linear effect reveals that N1 activation was higher at the end of the time window than in the beginning and is interpreted as less complete disengagement of N1. In other words, IWA had not fully deactivated N1 by the end of this time window, even though they have been presented with N2 in its entirety. Additionally, the silence condition showed a marginal effect on the quadratic curvature (*silence* $\beta = 0.52$, SE = 0.30, $p = .09$). Although this effect did not reach significance, it indicates a more gradual rise and fall of activation in the silence condition. Follow-up cluster analyses revealed a slightly different pattern than what was found for the AMC; that is, a significant positive cluster in the silence-control comparison indicating a later,

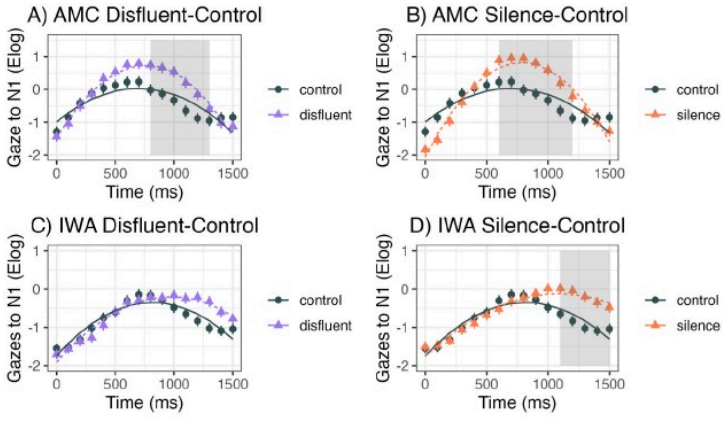


Fig. 6. Full time-course of lexical activation of the direct-object noun (e.g., elf) in the control (gray line) and disfluent condition (purple line) in the AMC group (A) and the IWA group (C) and the control and silence condition (orange line) in the AMC group (B) and the IWA group (D). Shapes represent means of observed data, error bars represent standard error, and dashed lines represent the GCA model fit. Shaded regions indicate time span of significant clusters ($p < .05$).

Table 4
Results of GCA within-group analysis for AMC and IWA in time window 1 (N1 processing).

	AMC			IWA		
Predictor	Est.	SE	p	Est.	SE	p
(Intercept)	−0.40	0.16	0.015	−0.77	0.17	<.001
Linear	−0.46	0.71	0.520	0.56	0.31	0.077
Quadratic	−1.69	0.45	<.001	−1.61	0.37	<.001
Condition [Disfluent]	0.32	0.23	0.162	0.12	0.15	0.424
Condition [Silence]	0.22	0.23	0.336	0.21	0.15	0.145
Condition [Stretch]	−0.08	0.23	0.721	0.03	0.15	0.814
Linear X Condition [Disfluent]	0.58	1.01	0.566	0.96	0.36	0.008
Linear X Condition [Silence]	0.94	1.01	0.354	1.13	0.35	0.002
Linear X Condition [Stretch]	0.08	1.01	0.941	0.35	0.36	0.335
Quadratic X Condition [Disfluent]	−1.32	0.63	0.040	0.21	0.31	0.501
Quadratic X Condition [Silence]	−1.94	0.63	0.003	0.52	0.30	0.088
Quadratic X Condition [Stretch]	−1.33	0.63	0.039	0.16	0.31	0.592

Note: The table provides the test of the full model including the interaction of condition on the intercept, linear, and quadratic time terms. The control condition is set as the reference estimate. Results in boldface are presented in the text.

higher activation in the silence condition that was maintained from 1100 to 1600ms (cluster sum statistic = −17.37, $p < .05$). Shaded regions in Fig. 6 depicts the time points in the sentence where significant clusters occur. These results suggest that the silence manipulation led to increased N1 activation which was maintained for a longer period. Table 4 shows the full results of the GCA analysis.

6.2.3. *Window 2: syntactic reactivation and interference resolution window*

6.2.3.1. Lexical reactivation deficits in aphasia. In the syntactic reactivation and interference resolution window (time window 2, starting post relative-clause verb offset as shown in Fig. 3 above), we tested the extent to which temporal manipulations modulated dependency linking, or looks back to the direct-object noun (N1) in the post-verb sentence region (i.e., reactivation). We also examined interference by analyzing gaze patterns to N2 (the interfering noun). The first analysis conducted intended to confirm the a priori expectations that IWA would show impaired reactivation as compared to the AMC group in the control condition, either via a decreased magnitude of reactivation, increased interference, and/or an altered time-course of dependency linking. As shown in Fig. 7 below, the GCA model of AMC and IWA looks to N1 and N2 included the interaction of fixed effects of group (AMC, IWA), noun (N1, N2) and time (linear and quadratic orthogonal polynomials) and cross random effects of participant and item on all time terms. Clear differences between AMC and IWA emerged.

In the AMC group, there was a significant increase in looks back to N1 over time in the control condition (linear estimate = 1.28, SE = 0.19, $p < .001$). This is evidence of reactivation and replicates prior research in real-time dependency linking during object-relative sentence processing (Akhavan et al., 2020, 2022; Baker & Love, 2021; T. Love & Swinney, 1996; Sussman & Sedivy, 2003; Thompson &

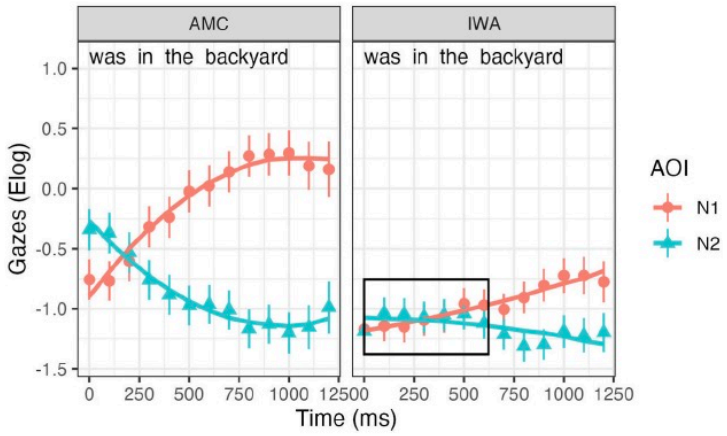


Fig. 7. Syntactic reactivation of the direct-object noun (red line) and deactivation of the subject noun (blue line) in the control condition in the AMC group (left) and the IWA group (right). Shapes represent means of observed data, error bars represent standard error, and dashed lines represent the GCA model fit. Rectangle indicates timespan of increased interference in the IWA group.

Choy, 2009). As expected, this analysis also confirmed a priori predictions of impaired reactivation in the IWA group. Specifically, IWA showed a significantly reduced magnitude of N1 reactivation compared to control participants (estimate = −0.85, SE = 0.12, $p < .001$) and a slower rise in the rate of N1 reactivation (estimate = −0.73, SE = 0.24, $p < .05$). There was also an increased presence of interference in the IWA group (as compared to the AMC group) as shown by an extended overlap, or a reduced divergence, of looks between N1 and N2, noted by the box in Fig. 7 (estimate = 1.39, SE = 0.33, $p < .001$).

6.2.3.2. Group results. Given the possible number of fixed effects in this analysis (group [IWA, AMC], noun [N1, N2], condition [control, disfluent, silence, stretch], and time [linear, quadratic]), we chose to focus solely on looks to N1 between the IWA and AMC groups as we are interested in the effects of temporal manipulations on reactivation during dependency linking and sought to avoid having to interpret a four-way interaction (Fig. 8). Analyses demonstrated that the interaction revealed that in the silence condition, the AMC group showed a steeper slope of looks back to N1 compared to the control condition (*silence* $\beta = -0.83$, SE = 0.32, $p < .05$), whereas IWA showed a steeper slope in the stretch condition (*stretch* $\beta = 1.08$, SE = 0.32, $p < .001$). No differences in reactivation were found in the disfluent condition when compared to control ($p > .05$) (Table 5). Overall, these results show that both groups reactivated the direct-object noun and the temporal manipulations silence and stretch modulated reactivation differently for each group.

What follows are the within-group models that explored the additional question of interference (gazes to both N1 and N2) via the three-way interaction between noun (N1, N2), condition, and time. This interaction term reflects the extent to which differences between gaze trajectories to N1 and N2 differ between the control and temporal manipulations and is used to index interference resolution.

6.2.3.3. Within-group results: AMC. Recall that successful dependency linking and interference resolution occurs when looks to N1 increase (i.e., N1 reactivation) and looks to N2 decrease (i.e., N2 deactivation) over time in the post-verb sentence region. We use the steepness and onset of divergence between N1 and N2 slopes to describe the degree of interference resolution; for example, stronger reactivation coupled with greater deactivation suggests more efficient or enhanced interference resolution (Akhavan et al., 2020, 2022; Baker & Love, 2021). GCA results (Table 6) revealed that the gaze trajectories in the AMC group showed the expected

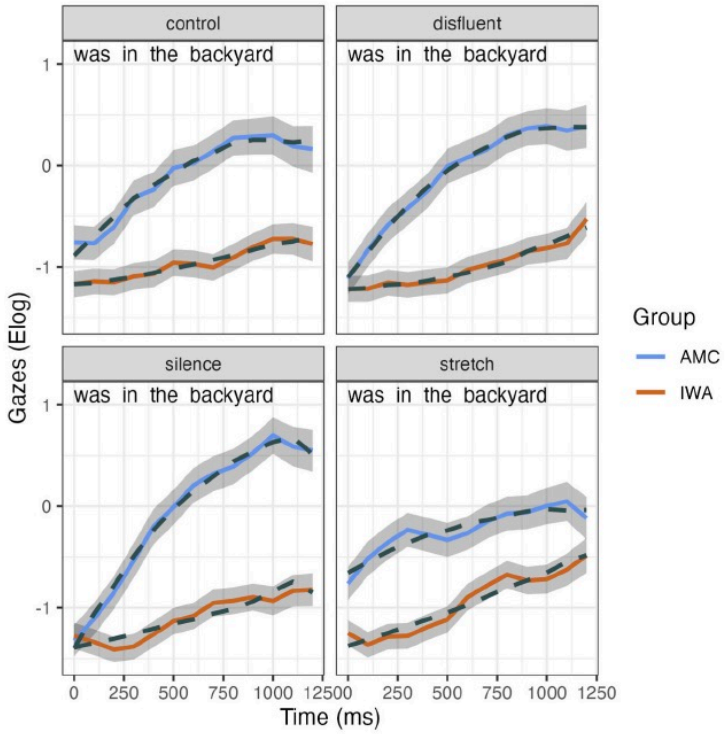


Fig. 8. Syntactic reactivation of the direct object (N1) in AMC (blue line) and IWA (orange line). Model fit (dashed lines) of the observed gaze data (colored lines are means; shaded ribbons are standard errors) from the onset of the main verb (Time window 2).

Table 5
Results of GCA group analysis in time window 2 (syntactic retrieval, N1).

Predictor	Est.	SE	p
(Intercept)	−0.14	0.19	0.480
Linear	1.36	0.45	0.005
Quadratic	−0.44	0.22	0.051
Condition [Disfluent]	−0.01	0.14	0.926
Condition [Silence]	0.02	0.14	0.882
Condition [Stretch]	−0.15	0.14	0.275
Group [IWA]	−0.80	0.23	0.002
Linear X Condition [Disfluent]	0.28	0.35	0.430
Linear X Condition [Silence]	0.90	0.35	0.010
Linear X Condition [Stretch]	−0.67	0.35	0.056
Quadratic X Condition [Disfluent]	−0.12	0.27	0.656
Quadratic X Condition [Silence]	−0.26	0.27	0.333
Quadratic X Condition [Stretch]	0.24	0.27	0.366
Linear X Group [IWA]	−0.79	0.55	0.165
Quadratic X Group [IWA]	0.49	0.27	0.072
Group [IWA] X Condition [Disfluent]	−0.03	0.08	0.688
Group [IWA] X Condition [Silence]	−0.18	0.08	0.028
Group [IWA] X Condition [Stretch]	0.14	0.08	0.084
Linear X Group [IWA] X Condition [Disfluent]	−0.18	0.32	0.580
Linear X Group [IWA] X Condition [Silence]	**−0.83**	**0.32**	**0.009**
Linear X Group [IWA] X Condition [Stretch]	**1.08**	**0.32**	**0.001**
Quadratic X Group [IWA] X Condition [Disfluent]	0.24	0.31	0.452
Quadratic X Group [IWA] X Condition [Silence]	0.21	0.31	0.500
Quadratic X Group [IWA] X Condition [Stretch]	−0.26	0.31	0.403

Note: The table provides the test of the full model including the interaction of group and condition on the intercept, linear, and quadratic time terms. The AMC group and the control condition are set as the reference estimates. Results in boldface are presented in the text.

Table 6
Results of GCA within-group analysis for AMC and IWA groups in time window 2 (syntactic processing, N1 and N2).

	AMC			IWA		
Predictor	Est.	SE	p	Est.	SE	p
(Intercept)	−0.04	0.10	0.704	−0.94	0.10	<.001
Linear	**1.22**	**0.22**	**<.001**	0.55	0.18	0.003
Condition [Disfluent]	0.00	0.14	0.980	−0.02	0.15	0.880
Condition [Silence]	0.03	0.14	0.824	−0.11	0.15	0.449
Condition [Stretch]	−0.21	0.14	0.128	0.03	0.15	0.847
Noun [N2]	−0.89	0.07	<.001	−0.20	0.05	<.001
Linear X Condition [Disfluent]	0.48	0.30	0.112	0.20	0.26	0.449
Linear X Condition [Silence]	1.12	0.30	<.001	0.25	0.26	0.335
Linear X Condition [Stretch]	−0.64	0.30	0.033	0.55	0.26	0.036
Linear X Noun [N2]	**−2.17**	**0.30**	**<.001**	−0.76	0.21	<.001
Condition [Disfluent] X Noun [N2]	0.10	0.10	0.305	0.13	0.08	0.079
Condition [Silence] X Noun [N2]	0.04	0.10	0.666	0.24	0.08	0.002
Condition [Stretch] X Noun [N2]	0.13	0.10	0.202	0.04	0.08	0.592
Linear X [Disfluent] X Noun [N2]	**−0.90**	**0.42**	**0.033**	−0.09	0.30	0.769
Linear X [Silence] X Noun [N2]	**−2.05**	**0.42**	**<.001**	**−0.72**	**0.30**	**0.019**
Linear X [Stretch] X Noun [N2]	**1.11**	**0.42**	**0.008**	**−0.77**	**0.30**	**0.012**
Quadratic	−0.70	0.21	0.001			
Quadratic X Condition [Disfluent]	0.03	0.30	0.924			
Quadratic X Condition [Silence]	−0.09	0.30	0.751			
Quadratic X Condition [Stretch]	0.32	0.29	0.275			
Quadratic X Noun [N2]	1.29	0.29	<.001			
Quadratic X [Disfluent] X Noun [N2]	−0.04	0.41	0.926			
Quadratic X [Silence] X Noun [N2]	0.29	0.41	0.481			
Quadratic X [Stretch] X Noun [N2]	−0.47	0.40	0.240			

Note: The table provides the test of the full model including the interaction of condition on the intercept, linear, and quadratic time terms. The control condition is set as the reference estimate. Results in boldface are presented in the text. In the IWA group, adding the quadratic time term did not significantly improve model fit and therefore this term was not included in the final model.

pattern of interference resolution in the control condition; gazes to N1 significantly increased over time (estimate = 1.22, SE = 0.22, $p < .001$), while gazes to N2 decreased (estimate = −2.17, SE = 0.30, $p < .001$). The degree of interference resolution (magnitude and temporal onset of N1/N2 divergence) was modulated by the temporal manipulations. In the silence and disfluent conditions, the divergence between N1 and N2 slopes was greater indicating increased interference resolution compared to the control condition (*silence* $\beta = -2.05$, SE = 0.42, $p < .001$; *disfluent* $\beta = -0.90$, SE = 0.42, $p < .05$). This pattern was reversed in the stretch condition, which showed a smaller difference between slopes (i.e., more parallel), indicating less successful interference resolution in this condition compared to control (*stretch* $\beta = 1.11$, SE = 0.42, $p < .05$). We note here that the stretch condition shows less divergence; this smaller difference appears to be driven by reduced N1 reactivation. Cluster-based analyses in this time window were conducted to determine whether the temporal manipulations modulated the *time-course* of interference. Specifically, these analyses revealed that N1 significantly diverged from N2 in the disfluent and silence condition, thus indicating interference resolution. In the disfluent condition, a significant cluster was found from 700 to 1300ms (cluster sum statistic = 17.11, $p < .05$) and in the silence condition, the significant cluster was from 600 to 1300ms (cluster sum statistic = 24.05, $p < .05$). The significant regions of divergence are indicated by shaded areas in Fig. 9.

6.2.3.4. Within-group results: IWA. In the IWA group (Fig. 9), interaction effects revealed that the differences between N1 and N2 slopes were significantly greater (i.e., greater interference resolution) in the silence and the stretch conditions compared to control (*silence* $\beta = -0.72$ SE = 0.30, $p < .05$; *stretch* $\beta = -0.77$, SE = 0.30, $p < .05$). However, follow-up cluster-based analyses did not reveal any significant clusters in N1/N2 divergence in any condition. Taken together, these results suggest that while the addition of temporal manipulations influenced gaze dynamics between N1 and N2, the effects may not have been strong enough to produce significant clusters in the cluster analyses. Table 6 shows the full results of the GCA analysis.

7. Discussion

We used a visual world eye-tracking-while-listening paradigm to examine whether focal temporal manipulations modulated real-time processing of sentences containing object-relative clauses (*The elf that the clown pushed was at the end of the street*) in individuals with aphasia and age-matched neurologically unimpaired listeners. The temporal manipulations were designed to provide additional time for processing the direct-object noun (*elf*). Time was added via a brief delay in the speech input via a **disfluency** (*uh*), a **silent** pause, and through an increase in the duration of the noun (**stretch**). The temporal manipulations were inserted into a naturally recorded sentence which also served as the control condition. Eye-gaze patterns during experimental

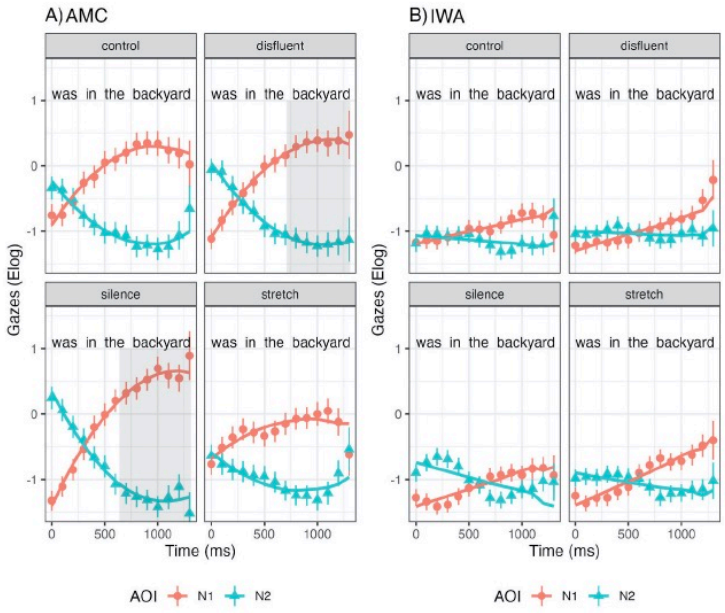


Fig. 9. Syntactic reactivation of the direct object (N1, red line) and deactivation of the subject noun (N2, blue line) in the AMC group (A) and the IWA group (B). Model fit (solid lines) of the observed gaze data (shapes are means; error bars are standard errors) from the onset of the main verb (Time window 2). Shaded regions indicate time span of significant clusters ($p < .05$).

sentences were compared to the control sentences to explore whether the manipulations modulated initial lexical processing (activation and deactivation) of the direct-object noun (N1); if they had an effect downstream during syntactically driven reactivation (dependency linking and interference resolution); and comprehension. We hypothesized that for both groups the temporal manipulations would facilitate 1) initial lexical processing of N1 and 2) dependency linking via enhanced reactivation of N1 and the resolution of interference between N1 and N2 with only the IWA demonstrating improved sentence comprehension.

The results revealed that overall, our hypotheses regarding real-time processing (1) and (2) were borne out. Providing more time for N1 processing led to enhanced lexical activation and improved dependency linking in AMC and IWA; however, the effects of time differed with respect to group and the individual temporal manipulations. With regards to comprehension, we found no significant effects of the temporal manipulations on comprehension accuracy in either group. We suspect this could be due to the complexity of the comprehension questions, which asked whether the subject or object nouns performed the action of the verb (e.g., "*Did the clown push someone*?"). These may have been too difficult to reliably measure comprehension of sentence meaning and led to a high variability in response accuracy (see Table 2).

7.1. The effect of temporal manipulations on sentence processing

7.1.1. Lexical processing

While the magnitude of initial activation differed between groups, both groups displayed a similar rise and fall pattern; that is, upon hearing N1, both groups displayed a similar gaze pattern of initial lexical activation (increased looks to N1) followed by deactivation upon hearing subsequent sentence constituents (decreased looks). The temporal manipulations modulated this pattern in several ways. In the AMC group, all three temporal manipulations amplified lexical activation and deactivation (steeper rise and fall). These results are consistent with prior findings from neurotypical young adults (Baker & Love, 2021), and indicate that when given more time post-noun, both younger and older neurotypical adults evince higher activation of the target noun coupled with stronger disengagement from that noun upon hearing subsequent sentence constituents. In contrast, when IWA were provided with more time (specifically in the silence condition), they demonstrated an increase in looks to and maintenance of N1. Interestingly, this was not coupled with the same degree of deactivation as found with the AMC. Instead, activation was maintained for a longer period of time and did not fully decay by the end of the time window. Notably, this maintained activation only reliably appeared with the time addition via a silent pause (gaze patterns were sustained at a higher activation for 600ms longer than in the control condition Fig. 6), indicating that this extra time may help to strengthen lexical access, a point we return to later in the discussion.

7.1.2. Syntactic processing

The temporal manipulations also resulted in changes to syntactic processing. Recall, that during the post-verb sentence region, dependency linking has been shown to occur in real-time during unimpaired processing but is impaired in aphasia. Based on the theories of lexical activation deficits in IWA such as reduced or delayed lexical activation, it is posited that mitigating these deficits through temporal manipulations would facilitate dependency linking. Under the cue-based parsing framework, we predicted this to occur through enhanced resolution of interference between two competing noun phrases with similar features (Van Dyke & Lewis, 2003). In eye-tracking data, we interpret the coupling of stronger N1 reactivation and N2 deactivation as evidence of a greater resolution of interference. To investigate the effect of the temporal manipulations on dependency linking, we first looked for evidence of reactivation (retrieval) of the direct-object after the verb. While both groups showed evidence of reactivation in the control sentences, there were clear group differences in the strength and time-course of reactivation. In the IWA group, the overall level of N1 reactivation was significantly lower as was the rate of looks over time as compared to the AMC group. These results imply that IWA had impaired lexical reactivation during real-time processing (replicating prior findings in the literature). Of interest was whether or not the temporal manipulations would enhance IWA reactivation to mitigate processing impairments. By relaxing the temporal constraints in the initial presentation of the direct-object noun, we not only found initial enhancements of lexical access in both groups, but downstream facilitation of dependency linking for both groups as well. For the AMC, the silence condition resulted in greater reactivation of N1 (looks back to N1 rose more sharply over time compared to control sentences), whereas in the IWA group, reactivation was enhanced in the stretch condition.

Regarding to the resolution of interference, the AMC group showed greater divergence between N1 and N2 in the disfluent and silence temporal manipulations indicating enhanced interference resolution. Follow-up cluster-based analyses confirmed that this interference was resolved earlier and maintained longer in the disfluent and silence conditions (shaded regions in Fig. 9). The IWA group demonstrated increased interference compared to the AMC group. Interestingly, while interference was found across conditions for the IWA, gaze patterns indicated that the silence and stretch conditions had a positive impact on interference resolution, though this was not confirmed in the cluster-based analyses. These data also lend support to the notion that interference affects real-time processing and integration during sentence comprehension in the aphasia. These findings add to the literature by showing that the parameter of time can impart benefits in lexical processing and downstream dependency linking via enhanced resolution of interference. We cannot overlook the fact that in addition to a small sample size, the IWA group had strong variability in gaze patterns which may have reduced the strength of the effects. Alternatively, it could also be that the manipulations used to provide extra processing time were not long enough to fully capture the benefits. These are issues that should be explored in subsequent studies.

7.2. AMC versus IWA response to temporal manipulations

In summary, in the AMC group, while the non-manipulated condition showed successful dependency linking, the temporal manipulations still resulted in benefits in real-time lexical and syntactic processing. Table 7 presents a summary of these findings. These benefits were found in the disfluent and silence temporal manipulations. In contrast, the IWA group did not show a clear benefit across all manipulations. Surprisingly, for IWA, the temporal manipulations differentially influenced real-time lexical and syntactic processing. For example, the disfluent condition was associated with an increased maintenance of initial lexical activation, but no effects of this condition were found downstream on syntactic reactivation or interference resolution. This pattern is reversed in the stretch condition where there was no apparent effect on initial lexical processing, but an enhanced effect on syntactic processing downstream. So, why the discrepancy in processing patterns across temporal manipulations for the IWA group? It is possible that the presence of a disfluency differentially altered the *quality* of initial processing of N1. While this manipulation resulted longer maintenance of lexical activation, this prolonged activation may not have been driven by deeper (semantic) processing, but rather may be the result of a distraction caused by the surprise or disruption of the disfluency. Anecdotally, several IWA noted their surprise to the presence of disfluencies in this experiment and expressed that the speaker sounded "confused". In contrast to the IWA, AMC showed an increased peak of activation and benefits in dependency linking suggesting that they were able to use this time in the disfluent condition for deeper processing. Consistent with previous research in young neurotypical adults, the AMC effects in disfluent and silence conditions tended to pattern together, suggesting that the additional time provided by these manipulations influenced lexical activation and dependency linking regardless of whether the delay was filled (via the disfluency *'uh'*) or unfilled (silence) (Baker & Love, 2021). This lends support to the conclusion that time itself is an essential factor in influencing processing in unimpaired systems. The finding that disfluencies did not facilitate processing at verb offset (dependency linking) in IWA could suggest that impaired systems may be more vulnerable to these phonetic disruptions in the speech stream, and therefore are not able to benefit from the additional time they provide.

The other unexpected finding within the IWA group was the effect of the stretch condition, which influenced syntactic reactivation without having an initial effect on lexical access in IWA. The different effect of the temporal manipulations in IWA could be caused by varying factors. First, is that the disfluent and silence conditions manipulated time *after* the target noun, whereas the stretch condition manipulated the noun itself. Additionally, compared to the ~460ms of additional time provided by the disfluent and silence conditions, the stretch condition provided only ~250ms. It is possible that differences in the placement and duration of time engaged alternate processing routines. Recall that the Delayed Lexical Activation (DLA) theory posits that more time is needed to successfully process lexical items. In support of the DLA, studies that slowed the speech rate found on-time activation and reactivation, however, it was not clear as to what aspect of language input needed to be slowed. These results indicate that for syntactic reactivation, manipulating the presentation of the direct-object noun itself was more effective for IWA than simply providing more time to process that noun initially. The story is not as clean for initial lexical processing. Here, we saw a clear effect of the disfluent and silence conditions in initial lexical activation but this enhancement was only carried downstream for the silence condition. At this point, it is difficult to speculate which temporal manipulation (stretch or silence) is most effective. Given these discrepancies in initial activation and reactivation in the stretch and disfluent conditions, we take a measured approach in our interpretation and instead focus on the processing benefits from the silence condition on lexical and syntactic processing in aphasia. We would be remiss if we didn't address an additional consideration – the heterogeneity within aphasia typologies. Individual differences in response to the temporal manipulations are addressed below in the context of the theoretical frameworks of processing deficits in aphasia.

7.3. Mechanisms of lexical access deficits in aphasia

Research exploring real-time processing in aphasia has shown reduced or delayed lexical activation, especially in individuals with anterior lesions and the presence of agrammatism. In contrast with previous findings, we did not find evidence of initial delayed activation in our IWA group. However, unlike previous findings that restricted their participants to those with agrammatism, we were interested in initial lexical level deficits and their interaction with interference resolution during syntactic processing in a larger group of neurologically impaired individuals (i.e., aphasia) so as to align with the cue-based parsing literature. Thus, our inclusionary criteria focused solely on a diagnosis of aphasia (i.e., including those who did not show agrammatism). This broad inclusion may help to explain the absence of a delayed access effect. Nevertheless, we felt it was important to look at a

Table 7
Summary of GCA findings from the temporal manipulations at the levels of lexical activation ('Lexical') and downstream dependency linking ('Syntax").

	AMC		IWA	
Condition	Lexical	Syntax	Lexical	Syntax
Disfluent	✔	✔	✔	x
Silence	✔	✔	✔	✔
Stretch	✔	♦	x	✔

Note: ✔ = processing benefit; x = no effect; ♦ = reversed pattern.

subgroup of participants that fit the agrammatic criteria of past studies to see if we could replicate delayed lexical activation patterns (Love et al., 2008; Ferrill et al., 2012, Thompson & Choy, 2009, and references therein). When exploring the time-course of N1 processing within an agrammatic subgroup of IWA (n = 7), we see evidence of a slower-rise time in initial lexical activation of the direct-object (N1) (see Appendix C for figure and model results). Consistent with prior research, we did find evidence of reduced lexical activation in IWA (Blumstein & Milberg, 2000; Janse, 2006; McNellis & Blumstein, 2001; Utman et al., 2001; Yee et al., 2008). Given the benefits of additional time found in previous studies (Baker & Love, 2021; T. Love et al., 2008), we hypothesized that the temporal manipulations would help to mitigate lexical processing impairments. Interestingly, while the addition of a silent pause did not directly increase the *magnitude* of N1 activation, it altered the *time course* of lexical access by sustaining activation for a longer period. In turn, sustained activation may have strengthened processing and allowed for enhanced downstream syntactic processing.

The benefit from sustained lexical activation is in line with a theoretical framework by Martin and Dell (2019), which proposes that deficits in lexical access can involve difficulty in the maintenance and/or transmission of activation within a lexical network. While we acknowledge that this framework is based on language production, our guiding principles presuppose that lexical activation is an underlying mechanism in both comprehension and production. This model is motivated by an interactive activation model of word processing (Dell, Schwartz, Martin, Saffran, & Gagnon, 1997) which posits that word retrieval is achieved through the spreading of activation in a network of units that are connected across semantic, lexical, and phonological levels. Under this view, lexical access deficits in aphasia arise from a failure to activate the correct units due to impaired spreading activation. The mechanisms underlying impairments in spreading activation have been linked to difficulties in (1) transmission, which result from delayed spreading activation between processing levels, and (2) difficulties in maintenance, which result from the failure to maintain activation of a unit. Consequentially, lexical access deficits in IWA may result from a singular or mixed impairment involving activation transmission and/or maintenance. Although the current paradigm is not designed to differentiate between transmission and maintenance deficits, the pattern of findings suggest that silent pauses may have mitigated lexical access deficits arising from impaired activation maintenance. In line with this view, investigations using word retrieval tasks have found similar facilitations from the addition of time. Martin and Dell (2019) demonstrated that lexical access deficits in aphasia can benefit from an added 5s response delay between presentation of a picture and the cue to name the picture. Interestingly, the results from these production studies showed a dissociation in which some individuals showed a benefit from the additional time, while others showed worse performance. The authors proposed that participants who showed naming improvements after the temporal delay have a transmission deficit (i.e., slowed activation), whereas participants with worse performance after a delay have a maintenance deficit (i.e., increased decay rate). In our study, we found that the addition of a silent pause within a sentence context sustained activation for IWA of the direct-object noun and facilitated syntactic processing. These results are consistent with transmission deficits under this framework. Sustained activation may have mitigated this deficit by allowing more time for spreading activation to occur, thus increasing the connection strength parameters (Martin & Dell, 2019). More research is needed to verify and to tease apart transmission from maintenance deficits. Future investigations should explore a variety of methodological approaches and considerations of the neural correlates of these deficits.

8. Conclusions

Altogether, the findings lend support to and extend the results of prior research on the relationship between lexical and syntactic processing in neurotypical adults. While the temporal manipulations did not show a benefit for final sentence comprehension, additional time was found to facilitate the tight linking between lexical and syntactic processes needed to accomplish real time dependency linking and interference resolution between sentence constituents in constructions where competition exists (semantically reversible object relative constructions). In IWA, we see the beginning of such facilitation from the temporal manipulations, however a longer time manipulation may be needed to fully realize enhancements in lexical and syntactic processing. Previous studies investigating the effects of time have found benefits from longer or more widespread temporal manipulations: 5 s delay (Martin & Dell, 2019 described in more detail below) and an overall slowed speech rate (Love et al., 2008). Future investigations are needed to investigate the optimal amount of time that facilitates these lexical and syntactic processing and whether these manipulations will affect final comprehension. In addition, these ETL data provide insight about the impact that additional time has on the post-verb retrieval process and the resolution of interference during dependency linking. Here, we demonstrate that strengthening initial lexical processing via the addition of temporal manipulations can facilitate retrieval of the target noun and lead to enhanced interference resolution in both unimpaired and impaired systems. In aphasia, additional time can mitigate impairments in spreading activation thereby improving lexical access and reduce interference during downstream dependency linking.

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Author statement

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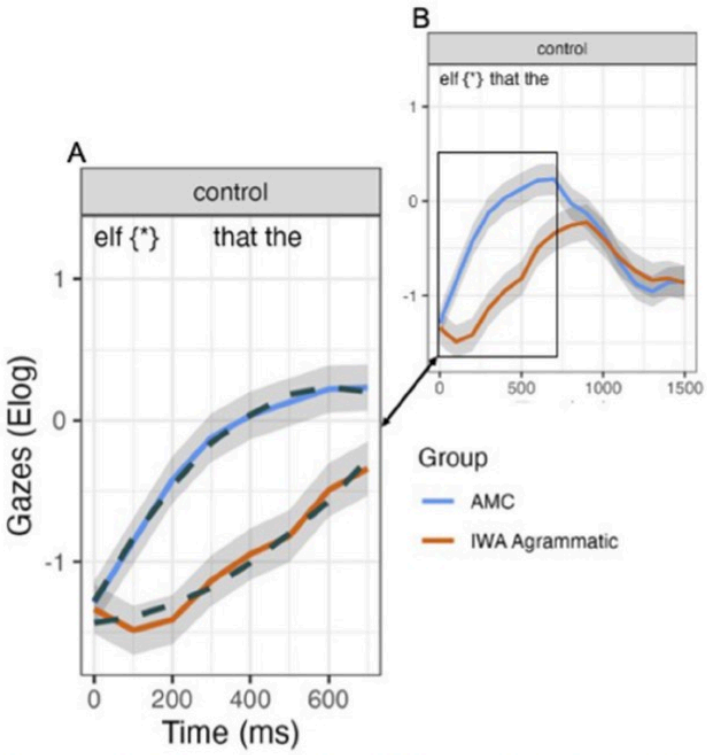


Fig. C.1. (A) Initial lexical activation of the direct-object noun (N1, e.g., *elf*) in the control condition by the AMC group (blue line) and IWA agrammatic subgroup (orange line). Solid lines represent observed data and dashed lines represent the GCA model fit. (B) Full time course of N1 processing (initial lexical activation and deactivation). Black rectangle indicates selected window of initial activation.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

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Appendix A

Table A.1
Participant demographics (expanded version of Table 1)

IWA	Sex	Age	Years Education	Years Post-Stroke	Lesion Location	Lesion Volume (mL)	BDAE Severity	BDAE Auditory Comprehension	SOAP Canonical (%)	SO No
9	M	61	17	21	L inferior (BA44 and BA45) and posterior frontal lobe w/ subcortical extension; anterior, superior and middle temporal lobe; inferior, anterior and posterior parietal lobe	172.52	2	20	65	25
101	M	73	20	15	L inferior (BA44) and posterior frontal lobe w/subcortical extension; superior and middle temporal lobe; inferior and anterior parietal lobe	146.27	2	68.3	40	55
130	M	69	16	14	L IPL w/posterior ext. sparing STG	109.08	4	61.7	75	45
140	F	47	16	21	L inferior frontal w/extension to inferior parietal and superior temporal	124.258	2	30	65	40
159	F	70	16	12	L MCA infarct		3	80	95	70
169	M	65	12	10	L medial and posterior frontal lobe; superior and middle temporal lobe; anterior parietal lobe	66.03	1	33	90	20
181	F	40	16	5	L MCA infarct		1	11.7	60	50
182	F	49	18	8	L MCA infarct		3	100	100	85
189	M	64	16	3	L inferior frontal lobe; parietal lobe; and superior and middle temporal regions	254.49	2	20	55	45
192	M	77	17	8	L inferior frontal lobe	69.69	4	76.7	100	10
193	M	40	16	8	L inferior frontal lobe	44.31	4	70	90	75
194	M	66	14	6	L MCA infarct L medial frontal lobe; posterior parietal lobe; superior temporal lobe	68.43	2	28.3	50	45
197	F	75	14	10	L MCA infarct		5	81.7	100	10
AMC										
2	M	74	18							
3	F	59	16							
4	F	61	16							
6	F	54	18							
172	F	69	16							
173	M	69	16							
199	M	78	23							
201	M	73	16							
202	F	76	16							
203	F	72	20							

Note: M = male, F = female; L = left; BA = Brodmann area; IPL = inferior parietal lobule; STG = superior temporal gyrus; MCA = middle cerebral artery
BDAE = Boston Diagnostic Aphasia Examination (0 = no useable speech or auditory comprehension; 5 = minimal discernible speech handicap). SOAP C
subject-relative items from the SOAP Test of Auditory Sentence Comprehension.
SOAP Noncanonical = average percent correct of passive object relative items from the SOAP Test of Auditory Sentence Comprehension. * Saccade latency
AMC group mean was used for this individual's baseline.

Appendix B

Table B.1
Performance (% correct) on the offline comprehension task per participant and condition.

AMC	Control	Disfluent	Silence	Stretch
2	85%	80%	80%	74%
3	100%	95%	97%	95%
4	62%	89%	64%	86%
6	100%	100%	95%	95%
172	77%	88%	79%	82%
173	65%	83%	75%	72%
199	71%	67%	74%	84%
201	63%	70%	63%	60%
202	65%	68%	41%	79%
203	88%	88%	93%	88%
LHD				
9	42%	34%	40%	34%
101	39%	37%	33%	34%
130	42%	41%	63%	47%
140	24%	32%	35%	29%
159	61%	56%	64%	53%
169	54%	55%	48%	53%
181	32%	51%	40%	50%
182	57%	53%	48%	61%
189	34%	24%	29%	32%
192	50%	59%	54%	73%
193	49%	42%	45%	41%
194	27%	19%	21%	26%
197	59%	71%	74%	71%

Appendix C

The data for this analysis included gazes to the direct-object noun (N1) in the control condition for the full group of 10 AMC and a subgroup of 7 IWA showing patterns of agrammatism. The presence of agrammatism was demonstrated via comprehension deficits on the SOAP, which we defined as at- or below-chance performance on the comprehension of sentences with noncanonical word order (shown in Table 1). As shown in Figure C.1A, this window captures the initial rise in N1 lexical activation and corresponds to first half of time window 1 (Figure C.1B) from the onset of N1 to the average onset of N2. The GCA model for lexical activation included the interaction of fixed effects of group (AMC, IWA) and time (linear and quadratic orthogonal polynomials) and crossed random effects of participant and item on all time terms.

As shown in Table C.1, the analysis revealed that agrammatic IWA (orange line) looked to N1 significantly less than the AMC group (blue line) indicating a reduced magnitude of N1 activation (intercept estimate = −0.76, SE = 0.21, $p < .05$). Additional effects were found in the time-course of activation when comparing the change in looks to N1 over time. The analysis revealed that IWA showed a more gradual rise in lexical than AMC (quadratic estimate = 0.82, SE = 0.31, $p < .05$). These results suggest that, compared to AMC, this agrammatic IWA subgroup showed a reduced degree of lexical activation and a delayed time-course (similar time to peak).

Table C.1
Results of GCA analysis for initial lexical activation in the IWA agrammatic subgroup.

Agrammatic vs AMC N1 initial activation			
Predictor	**Est.**	**SE**	**p**
(Intercept)	−0.21	0.19	0.288
Linear	1.40	0.30	<.001
Quadratic	−0.54	0.21	0.018
Group [IWA]	**−0.76**	**0.25**	**0.008**
Linear X Group [IWA]	−0.25	0.39	0.524
Quadratic X Group [IWA]	**0.82**	**0.31**	**0.016**

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CHAPTER 6

Modulating Complex Sentence Processing in Aphasia through Attention and Semantic Networks

Abstract

Purpose: Lexical processing impairments such as delayed and reduced activation of lexical-semantic information have been linked to syntactic processing disruptions and sentence comprehension deficits in individuals with aphasia (IWA). Lexical-level deficits can also preclude successful lexical encoding during sentence processing and amplify the processing costs of similarity-based interference during syntactic retrieval. We investigate whether two manipulations to engage attention and pre-activate semantic features of a target (to-be-retrieved) noun will 1) boost lexical activation during initial lexical encoding and 2) facilitate syntactic dependency linking through improved resolution of interference in IWA and neurologically unimpaired age-matched adults (AMC).

Method: Eye-tracking-while-listening with a visual world paradigm was used to investigate whether semantic and attentional manipulations modulated initial lexical processing and downstream syntactic retrieval of the direct object noun in object relative sentences.

Results: In the attention and semantic manipulations, the AMC group showed no changes in initial lexical access levels, however, gaze patterns revealed clear facilitations in dependency linking and interference resolution. In the IWA group, the attentional cue increased and maintained activation of N1 with modest facilitations in dependency linking. In the semantic condition, IWA results showed a greater degree of facilitation during dependency linking.

Conclusions: The results suggest that attention and semantic activation are parameters that may be manipulated to strengthen encoding of lexical representations to facilitate retrieval (i.e., dependency linking) and mitigate similarity-based interference. In IWA, these manipulations may help to reduce lexical processing deficits that can preclude successful encoding.

1.0 Introduction

The process of understanding spoken language seems to occur relatively effortlessly and automatically yet, the transient nature of the speech signal requires listeners to rapidly analyze, segment, and integrate the incoming speech stream to correctly interpret sentence meaning. The degree of comprehension difficulty is heavily influenced by two factors: word order and thematic reversibility, both of which affect real-time processing and interpretation of sentence meaning. To illustrate the relationship between word order and ease of comprehension, consider the contrast between sentences (1) and (2) below. Sentence (1) conforms to the typical or *canonical* word order of English (subject – verb – object) and is relatively easy to understand. Here, the assignment of thematic roles (the relationship between a verb and its noun phrase arguments) follows a straightforward mapping: the first noun (*the dog*) is linked to the subject of the sentence (also known linguistically as the 'agent') whereas the second noun (*the ball*) is linked to the object (also known linguistically as the 'theme/patient'). In contrast, sentence structures that deviate from canonical word ordering (such as in Sentence 2 below), create additional challenges for comprehension.

(1) The dog chased the ball.

(2) The ball$_i$ that the dog chased$_i$ <~~the ball~~> was orange.

Sentence (2) is an example of a *noncanonical* sentence (i.e., an object relative construction) where the direct object noun (*ball*) has been displaced from its canonical post-verb position (noted by the strikethrough) to the front of the sentence. This 'movement' creates a long-distance syntactic dependency between the displaced constituent and its syntactically licensed post-verb position (noted by the subscript i). Successfully understanding these sentences requires the listener to retrieve the displaced direct object and integrate it with the verb during sentence

processing in order to complete thematic role assignment and resolve the dependency. Prior research has shown that dependency linking is a fast-acting process that occurs in real time as the sentence components are presented to a listener (Akhavan et al., 2020, 2022; Baker & Love, 2021, 2023; Koring et al., 2012; Love, 2007; Thompson & Choy, 2009).

Challenges in comprehension are not only linked to word order but are also linked to the presence of thematic or semantic reversibility, which plays a crucial role in comprehension difficulty. When both subject and object nouns are thematically reversible (i.e., when both are equally plausible candidates for agent and theme argument roles), the number of constraints acting on theta role assignment are reduced. For example, in sentence (3) below, both subject and object nouns are animate and therefore both could plausibly be mapped to the agent role. In other words, a cat or a dog can do the chasing (this is in contrast to sentence (2) above where only a dog can chase something).

(3) The cat_i that the dog $chased_i$ was orange.

Data from neurotypical adults has shown that semantically reversible sentences such as (3), when coupled with noncanonical sentence order, are prone to misinterpretation and take longer to resolve the long-distance dependencies (Ferreira, 2003; Kemper & Catlin, 1979; Richardson et al., 2010). This difficulty arises in part because people can no longer rely on word order heuristics or theta role constraints to assign thematic roles for the subject and object nouns. Theoretical models of sentence processing centered on cue-based parsing make specific predictions for how and when processing difficulty arises in the resolution of long-distance dependencies (Lewis et al., 2006; Lewis & Vasishth, 2005; McElree, 2000; Van Dyke, 2007; Van Dyke & Lewis, 2003). According to these models, the success of retrieving the displaced constituent during dependency linking is a function of the degree of interference from other

similar words in a sentence (e.g., *dog*), which compete with the retrieval of the target item. The higher the similarity-based interference, the more likely there will be slowdowns at the retrieval site and/or misretrieval of a distractor item (Lewis et al., 2006; Van Dyke & Lewis, 2003; Van Dyke & McElree, 2011)

Although cue-based processing models were developed to characterize processing difficulty in unimpaired populations, research has shown that retrieval interference can lead to comprehension breakdowns in individuals with aphasia (Akhavan et al., 2022; Lissón et al., 2023; Mätzig et al., 2018; Patil et al., 2011, 2016; Sullivan et al., 2017). Recent computational work modeling cue-based retrieval has shown that different theoretical accounts of processing deficits (i.e., slowed processing, intermittent deficiencies, and resource reduction) can be implemented in cue-based models to simulate comprehension impairments individuals with aphasia (Lissón et al., 2023; Mätzig et al., 2018; Patil et al., 2016). While this work has brought to light important ways that theoretical approaches can be instantiated computationally, there has been less work examining how impairments at the lexical level may contribute to or amplify interference effects. Current cue-based retrieval models do not readily account for factors inherent to lexical processing itself (i.e., during initial encoding of to-be-retrieved noun phrases). However, lexical processing impairments such as delays in accessing lexical-semantic information and under-activation of lexical items have been shown to contribute to sentence comprehension deficits in individuals with aphasia (Dede, 2012; Ferrill et al., 2012; Love et al., 2008). By limiting access to lexical-semantic information, lexical processing deficits can also preclude successful lexical level encoding during processing and result in the formation of degraded representations that create a processing environment that is more vulnerable to similarity-based interference at critical syntactic retrieval points. As described below, the current

paper investigates whether attention and priming manipulations aimed to boost lexical activation during initial lexical encoding will 1) enhance lexical processing of the target noun and 2) facilitate syntactic dependency linking through improved resolution of interference in neurologically unimpaired adults and in individuals with aphasia.

1.1 Cue-based processing

As described above, processing object relative sentences involves the automatic linking of lexical representations to complete a syntactic dependency. Cue-based parsing theories posit that upon encountering the verb, the parser triggers a memory retrieval to access the previously encoded direct object noun in order to integrate it with the emerging sentence structure (Lewis & Vasishth, 2005; McElree, 2000; Van Dyke & Lewis, 2003). This linking proceeds via a cue-based retrieval mechanism in which cues consisting of semantic and syntactic features are used to match the requirements of a reference seeking entity (i.e., the verb) with the target of retrieval (i.e., the direct object). A core assumption of this theory is that the ability of the system to efficiently retrieve target information is constrained by the presence of other sentence constituents that are similar to the target representation (Lewis et al., 2006; Lewis & Vasishth, 2005; McElree, 2000; Van Dyke & Lewis, 2003; Van Dyke & McElree, 2011). Because items are searched associatively via their content, the presence of multiple items with similar features can partially match the retrieval cues and interfere with retrieval of the target noun. In neurologically healthy populations, retrieval difficulty is most commonly evidenced as slowdowns when processing the verb. In IWA, retrieval difficulty due to interference has been shown to lead to sentence comprehension deficits (Akhavan et al., 2022; Lissón et al., 2023; Mätzig et al., 2018; Patil et al., 2011, 2016; Sullivan et al., 2017). This population has also been shown to have difficulty in the timely access of lexical information, which as discussed below,

can amplify interference effects by precluding the formation and retrieval of lexical-level representations during structure building.

1.2 Lexical-deficits and syntactic processing in aphasia

Within a sentence, lexical access is the fundamental mechanism that provides the system with timely lexical-semantic information that will be integrated into a syntactic frame. During auditory comprehension, lexical items must be accessed rapidly and accurately from the fleeting speech signal to be available for syntactic processing. In IWA, delayed and/or weaker lexical access is argued to disrupt the timely formation of the syntactic and semantic representation of the sentence and result in comprehension impairment (Ferrill et al., 2012; Love et al., 2008; Prather et al., 1997). Deficits in activating lexical information are particularly detrimental in sentences that require previously encoded noun phrases to be rapidly re-accessed in service of syntactic processing, such as in object relative sentences. According to the delayed lexical activation hypothesis (DLA, Love et al., 2008), when lexical activation is delayed, the system is not provided with the necessary lexical-semantic information in time for fast-acting syntactic operations such as dependency linking, which can lead to breakdowns in comprehension. In sentences with semantically reversible subject and object noun phrases, lexical processing impairments can increase the system's vulnerability to interference. For example, delayed and/or reduced activation during encoding can result in an incomplete or degraded representation for that lexical item. By precluding successful encoding, these disruptions reduce the availability of lexical representations during sentence processing, which can impede their retrieval during dependency resolution and result in comprehension impairments. Strengthening lexical access is therefore one route to facilitating syntactic retrieval through the resolution of interference, thus the focus of the present study.

1.3 Lexical processing and encoding

Recent work in sentence processing has begun to explore the factors that strengthen lexical access when a critical noun is encountered in a sentence (e.g., the direct object noun in an object relative sentence) (Akhavan et al., 2022; Baker & Love, 2021, 2023). As the process of lexical activation provides the basis for memory encoding, increasing or strengthening lexical access may be a route to influence the retrieval difficulty of previously encoded lexical items during sentence processing (Akhavan et al., 2022; Baker & Love, 2021, 2023; Hofmeister, 2011; Hofmeister & Vasishth, 2014; Karimi et al., 2021). One factor that has been shown to facilitate retrieval is the parameter of time (Baker & Love, 2021, 2023; Karimi et al., 2021). In our previous studies (Baker & Love, 2021, 2023), we've shown that providing additional time to process the target direct object noun when it was initially encountered in an object relative sentence increased initial lexical activation and facilitated syntactic retrieval. Improved lexical and syntactic processing also led to enhanced interference resolution in both neurotypical adults and individuals with aphasia.

Previous work has found that increasing the linguistic complexity of a to-be-retrieved noun phrase (e.g., the number and type of adjectives modifying a noun), also modulates encoding and retrieval dynamics (Akhavan et al., 2022; Hofmeister, 2011b; Hofmeister & Vasishth, 2014; Troyer et al., 2016). Using self-paced reading paradigms, research has shown that enriching a noun phrase through the addition of semantically-related adjectives (e.g., *the victorious four-star general*) facilitates the noun's syntactic retrieval, as evidenced by faster reading times, compared to an unmodified version of the noun phrase (e.g., *the general*) (Hofmeister, 2011; Hofmeister & Vasishth, 2014). The authors suggested two (non-mutually exclusive) mechanisms that may underlie the retrieval advantage associated with linguistically more complex expressions. The

first is that increasing the number of semantic features associated with a noun may give rise to a conceptually unique representation that is easier to distinguish from other referents in the sentence. This increased distinctiveness makes it less susceptible to interference and therefore easier to retrieve (Hofmeister, 2011). The second hypothesis is that processing semantically rich noun phrases increases the activation level of the modified element and leads to a more accessible memory representation (Lewis et al., 2006; Lewis & Vasishth, 2005). This idea is motivated by robust findings that semantic similarity drives the process of spreading activation (Budiu & Anderson, 2004). In a sentence context, processing adjectives that are strongly associated with the target noun are predicted to increase spreading activation and create a highly activated memory network in which retrieval is easier. Support for this idea comes from the computationally instantiated cue-based retrieval model of Lewis and Vasishth (2005), which posits that the probability and latency of an item's retrieval is modulated by its activation levels; the higher the activation of a representation during encoding, the higher the probability and speed of retrieval. In cases where retrieval cues cannot discriminate among candidate referents (i.e., in cases where there is similarity-based interference), the processor relies on activation level. Therefore, in sentences with similarity-based interference, boosted activation from semantically-related adjectives makes future retrievals easier (Hofmeister, 2011). It remains an open question whether the modified noun phrases are easier to retrieve due to the increased distinctiveness of memory representation and/or because the process of building a semantically complex representation creates a highly activated memory network that facilitates retrieval (however, see Karimi et al., 2021 for a different view).

Given the lexical activation deficits observed in aphasia, we pursue this latter idea to explore if modulating lexical activation levels during lexical processing benefits retrieval.

Critically, we explore factors that are hypothesized to modulate activation without manipulating representational complexity of the target noun phrase. In doing so, we aim to help elucidate potential mechanisms for influencing encoding-retrieval dynamics during sentence processing. To achieve this aim, we manipulate two factors that have been implicated in influencing lexical activation: attentional cues and semantic priming. We discuss how each of these factors has been shown to affect lexical access below and their implication for lexical processing in aphasia.

1.4 Factors influencing lexical processing

Engaging attentional mechanisms, by heightening or orienting attention to an upcoming word in a sentence, has been argued to facilitate lexical processing and result in more robust encoding and easier subsequent retrieval (Collard et al., 2008; Corley & Hartsuiker, 2011; Karimi et al., 2020, 2021). In auditory sentences, attentional mechanisms have been engaged through the strategic placement of speech disfluencies (e.g., filled pauses such as *um* or *uh*) (Arnold et al., 2007; Brennan & Schober, 2001; Clark & Fox Tree, 2002; Collard et al., 2008; Corley et al., 2007; Corley & Hartsuiker, 2011; Fox Tree, 2001). For example, studies have shown that the presence of a disfluency (e.g., *um*), artificial tone, or simply silence directly before a target word facilitated its processing (Corley & Hartsuiker, 2011). These three forms of delay in an otherwise continuous speech signal were hypothesized to heighten attention to the upcoming linguistic information and result in processing benefits. Consistent with an attentional account, Collard and colleagues (2008) found modulations in the amplitude of two ERP components associated with attention, mismatch negativity and P300, when participants listened to utterances containing a speech disfluency. Later in the experiment, listeners were given a surprise recognition memory test and words that had been preceded by a disfluency were found

to be more likely to be remembered demonstrating that modulations in attention can have both short and longer-lasting memory effects (Collard et al., 2008).

The idea that increased attention during encoding facilitates subsequent retrieval is not new; research in the memory literature has demonstrated that attention plays an important role in encoding information in working memory (Craik et al., 1996, 2018; Fernandas & Moscovitch, 2000; Oberauer, 2019). Increased attention during encoding has been shown to enhance representations of the attended information and assist in resolving competition among multiple candidate responses during retrieval (Aly & Turk-Browne, 2016; Chun & Turk-Browne, 2007; Fernandas & Moscovitch, 2000; Gazzaley & Nobre, 2012; Uncapher & Rugg, 2009). In the context of the encoding-retrieval relationship in sentence processing, Karimi and colleagues (2021) have argued that enhanced attentional resources allocated to encoding, and critically the amount of time spent expecting or maintaining a noun phrase during encoding, are key factors in strengthening a memory trace during encoding and facilitating subsequent retrieval.

With respect to aphasia, there is evidence to suggest that IWA have greater difficulty allocating attentional resources compared to language-unimpaired individuals (Hula et al., 2007; Hula & McNeil, 2008; LaCroix et al., 2020; Murray, 2000, 2012; Villard & Kiran, 2015). Deficits in engaging, orienting, and focusing attention have been argued to interact with language processes and contribute to difficulties in processing lexical-semantic information in aphasia (Murray, 2000, 2012; Villard & Kiran, 2017). We explore this relationship by asking if attention mechanisms (i.e., the ability to focus attentional resources) can be modulated to optimize behavioral performance and improve lexical processing during real time sentence processing. Previous evidence has shown that engaging attention mechanisms enhances the processing of items within the focus of attention (Lewis & Vasishth, 2005; Mirman et al., 2008;

Oberauer, 2019; Posner, 1980). In line with this idea, we hypothesize that directing attention to the critical lexical item (the direct object noun) within an object relative sentence will increase lexical activation of the mental representations for words. We aim to implicitly direct attention to the target noun by inserting a disfluency directly before it (e.g., filled pause, *uh*). Based on prior research, this is hypothesized to orient attention to the target word, facilitate lexical processing and lead to easier retrieval in service of dependency linking.

The second way we aim to enhance lexical processing and concomitant encoding is by pre-activating **semantic properties** associated with the target lexical item via a semantic priming task before presentation of the auditory sentence. Traditional semantic priming paradigms have shown that processing a target item (e.g., *doctor*) is facilitated when it is preceded by a related prime (e.g., *nurse*) compared to when it is preceded by an unrelated prime word (e.g., *niece*) in both IWA and neurotypical controls (Baum, 1997; Dyson et al., 2021; Ostrin & Tyler, 1993; Silkes et al., 2020). The priming effect has been explained via a spreading of activation (Balota & Lorch, 1986; Collins & Loftus, 1975; Neely, 1991), in which the identification of the prime word activates related words (including the target), making the target easier to identify. Here, we are interested in assessing whether semantic priming can be used to boost lexical activation of the target noun upon initial processing and at critical syntactic junctures (dependency linking). As described in the methods section, we integrate the traditional semantic priming approach with an eye-tracking-visual-world paradigm by first presenting two images that are semantically related to a specific noun of interest (direct object noun) in the subsequent experimental sentence. By doing so, we aim to strategically pre-activate the semantic properties of the target noun **before** the auditory presentation of the sentence stimuli.

1.5 Current Study

We use eye-tracking-while-listening with a visual world paradigm to investigate whether semantic and attentional manipulations can facilitate initial processing of the target direct object noun for listeners with and without aphasia during real-time sentence processing. We also investigate whether the manipulations affect syntactic retrieval of the target noun and interference resolution during dependency linking for both groups. In this paradigm, participants listen to sentences while viewing a 2X2 visual-array displaying four pictures (two characters mentioned in the sentence and two unrelated to the sentence). The timing of eye gazes to the characters on the screen while listening to the unfolding sentences is argued to index underlying linguistic processing in real time. Similar to previous studies (Akhavan et al., 2022; Baker & Love, 2021, 2023), we explore the effects of the proposed manipulations on the time course of lexical and syntactic processing as indexed through gaze patterns. Specifically, we examine the process of **initial lexical activation**, which manifests an increasing pattern of looks toward a visual representation of a recently heard noun and indicates the processing of phonological and semantic features associated with the target word. We also measure **lexical deactivation**, or the decrease in looks to the target upon hearing subsequent sentence constituents. This decreasing pattern represents disengagement from the activated noun to access new input. To examine syntactic retrieval/dependency linking in the post-verb sentence region, we measure 1) **reactivation** of the displaced direct object after verb offset, which manifests as looks back to the target item indicating that it has been linked with the verb and 2) **interference**, which is shown as an extended activation of both subject and direct object nouns during the post-verb time window and is visualized as overlapping gaze patterns between the nouns (Akhavan et al., 2020, 2022; Baker & Love, 2021, 2023). We interpret the resolution of interference as when eye gazes

show a greater divergence between looks to each noun (reactivation of the direct object coupled with deactivation of the competing subject noun).

We hypothesize that the attentional cues (in the form of a disfluency, see Table 2) and pre-activation of a target noun's semantic properties will boost initial lexical activation of the target noun. In the post-verb sentence region (where reactivation should occur), we predict that both manipulations will facilitate syntactic dependency linking at some level through increased reactivation of the target noun and enhanced interference resolution in both neurologically unimpaired adults and in individuals with aphasia.

2.0 Methods

2.1 Participants

Eleven individuals with chronic aphasia (IWA) and 10 age-matched neurotypical controls (AMC) were recruited for this study. All participants were monolingual native English speakers (no exposure to a foreign language before the age of six), and were right-handed (premorbidly for IWA). Additionally, all participants had normal to corrected-to-normal self-reported vision and hearing and no prior history of psychiatric illness, substance abuse, or neurological disease. The participants with aphasia all experienced a single left-hemisphere stroke at least 6 months prior to participation (i.e., chronic stage). Diagnosis and severity of aphasia were assessed using standardized aphasia examinations, the Boston Diagnostic Aphasia Examination (BDAE-version 3, Goodglass, Kaplan, & Barresi, 2001) and the Comprehensive Aphasia Test (CAT, cognitive screening and comprehension subtest; Swinburn, Porter, & Howard, 2004) and were confirmed by clinical consensus. To be included, all IWA had to score within normal limits for the cognitive screening (cutoff score = 26). All AMC performed within normal limits on the Cognitive Linguistic Quick Test (CLQT, Helm-Estabrooks, 2001). Auditory sentence

comprehension ability was assessed using the S.O.A.P Test of Sentence Comprehension and the auditory comprehension subtest of the CAT. Results from these tests are presented in Table 1.

Given that we are testing a population that have survived a stroke, it was important to ensure that individual saccade latency (the time elapsing between the appearance of a visual target and the initiation of the goal-directed eye movement) was included in analyses as prior research has shown it to vary with age (Irving et al., 2006) and post-stroke status (Rizzo et al., 2017). As such, we included a baseline eye-tracking task (described in more detail below), to calculate each individual's saccade latency (mean saccade latencies for each participant are also presented in Table 1.)

After testing was completed, data from 6 participants (2 IWA, 3 AMC) had to be excluded from further analysis due to equipment failure. The resulting 9 IWA (female = 3, M_{age} = 66.6 years, SD_{age} = 10.7) and 7 AMC (female = 6, M_{age} = 65.7, years, SD_{age} = 7.9) were included in the analyses described below. All methods described below were approved by the University of California San Diego and the San Diego State University Institutional Review Boards. All participants provided informed consent and were compensated $20 per visit.

Table 6.1: Characteristics of IWA (n =9) and neurotypical age-matched control (AMC) participants (n = 7).

IWA	Sex	Age	Years of Education	Years Post-Stroke	Lesion Location	Lesion Volume (mL)	BDAE Severity	BDAE Auditory Comprehension	SOAP Canonical (%)	SOAP Noncanonical (%)	CAT Cognitive Screen	CAT Comprehension	Saccade Latency (ms)
9	M	62	17	21	L inferior (BA44 and BA45) and posterior frontal lobe w/subcortical extension; anterior, superior and middle temporal lobe; inferior, anterior and posterior parietal lobe	172.52	2	20	65	25	34	25	267
101	M	74	20	16	L inferior (BA44) and posterior frontal lobe w/subcortical extension; superior and middle temporal lobe; inferior and anterior parietal lobe	146.27	2	68.3	40	55	38	51	335
130	M	70	16	15	L IPL w/ posterior ext. sparing STG	109.08	4	61.7	75	45	34	47	334
151	F	72	16	14	L inferior frontal lobe	77.13	4		100	80	38	64	
159	F	71	16	12	L MCA infarct		3	80	95	70	35	54	246
169	M	66	12	10	L medial and posterior frontal lobe; superior and middle temporal lobe; anterior parietal lobe	66.03	1	33	90	20	36	36	253
181	F	41	16	6	L MCA infarct		1	11.7	60	50	33	27	371
189	M	65	16	4	L inferior frontal lobe; parietal lobe; and superior and middle temporal regions	254.49	2	20	55	45	31	NA	334
192	M	78	17	8	L inferior frontal lobe	69.69	4	76.7	100	100	35	55	280
AMC													
3	F	60	16										265
4	F	62	16										251
6	F	55	18										268
172	F	70	16										241
173	M	70	16										260
202	F	77	16										288
203	F	73	20										269

M = male, F = female; BDAE = Boston Diagnostic Aphasia Examination (0 = no usable speech or auditory comprehension; 5 = minimal discernable speech impairment). SOAP Canonical = average percent correct on active subject-relative items from the SOAP Test of Auditory Sentence Comprehension. SOAP Noncanonical= average percent correct of passive object relative items from the. CAT = Comprehensive Aphasia Test.

2.2 Materials

2.2.1 Sentence Stimuli

The same sentence stimuli from Baker and Love (2021) were used for this eye-tracking study. Sentences consisted of 40 object relative sentences containing noncanonical object relative constructions containing a long-distance dependency linking the displaced direct object (e.g., *elf*) and the relative clause verb (e.g., *pushed*) (see examples 4 and 5). All sentences were thematically (semantically) reversible such that both the object noun (noun 1, N1) and the subject noun (noun 2, N2) were equally plausible as either the agent or theme of the relative

clause verb. The role of each noun was reversed in a matched sentence design such that each noun served once as N1 and once as N2 (see 4 and 5).

(4) Last year on Halloween, the elf that the clown *pushed* was at the end of the street.

(5) At the costume party, the clown that the elf *poked* was in the backyard.

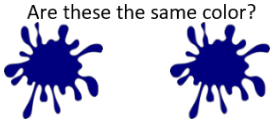
The relative clause verbs in the sentence pairs had similar phonetic onsets and were matched in syllable length (e.g., *push, poke*). The two nouns of interest (N1 and N2) were all 1-3 syllables and were not phonologically similar or semantically related to one another. These sentences served as the control condition. As described in the next section, from these sentences two experimental manipulations (attention and semantic) were created for a total of 120 experimental items (40 sentences per condition). An additional 40 unrelated filler sentences were created to distract participants from developing strategies when listening to the object relative clause construction in the target sentences (i.e., only looking to the first noun, etc.). Filler sentences were of similar length but varied in syntactic structure. Experimental and filler sentences were recorded by a female native English speaker in a sound-treated room at an average speech rate of 4.94 syllables/second (SD = .26s).

2.2.2 Experimental Manipulations

Two experimental conditions were created to investigate attention and semantic priming as potential parameters for facilitating lexical access and structural processing during sentence processing (shown in Table 2). In the **attention** condition, we inserted a disfluency directly before the target direct object noun (N1), which is hypothesized to serve as an attentional cue to implicitly direct attention to processing N1. The disfluency consisted of a prolongation of the determiner (*the*) coupled with the filled pause disfluency (*uh*) inserted directly before N1 in

control sentences. To create the disfluency, the target sentences were recorded by the same female speaker with a disfluency (*uh*) embedded in them. This provided a natural recording of a disfluency in the control sentence context that was then spliced into the original (control) recording to maintain the same overall sentence contour between the control and attention conditions. Disfluencies resulted in an average of 800ms (SD = 53.0ms) of additional time as is typical in spontaneous speech (Shriberg, 1999). To create the **semantic** condition, we added a priming task before each sentence to strategically pre-activate semantic properties of the target noun (i.e., clown). In this task, participants were visually presented with two pictures (*clown shoes – circus tent*) and asked a yes/no question about their semantic relationship (e.g., *are these two pictures related?*). To control for picture presentation and create an environment in which participants are always presented with a task before each auditory sentence begins, in the control and attention conditions, two color splotches were presented with a yes/no question unrelated to the semantic relationship (e.g., *are these two pictures the same color*). Filler sentences were presented with an unrelated pair of images and the semantic question to balance the number of each question type (n= 80 semantic and n=80 color).

Table 6.2: Example of pre-sentence task and experimental sentences for each condition.

Condition	Pre-sentence task	Sample Auditory sentence
Control	Are these the same color? 	"Last year on Halloween, the clown that the elf pushed was in the backyard."
Attention	Are these the same color? 	"Last year on Halloween, ***thee uh*** clown that the elf pushed was in the backyard."
Semantic	Do these pictures go together? 	"Last year on Halloween, the **clown** that the elf pushed was in the backyard."

2.2.3 Eye-tracking Visual Stimuli

Visual stimuli for the pre-sentence priming task consisted of freely available colored drawings of objects obtained from the internet and clip art resources that were resized to 450X450 pixels. For the visual world portion of the eye-tracking study, a 2X2 visual array displaying four pictures was created for each sentence. Within this display, four areas of interest (AOIs) were defined corresponding to the four corners of the array (450x450 pixels). Two of the pictures in the array depicted referents mentioned in the sentence (N1 and N2), while the other two were unrelated to the sentence. Noun images were colored cartoon images created by a single artist to maintain general style and were pretested to ensure that each drawing accurately depicted the intended noun (for more details on this pretest, please see Baker & Love, 2021). The location of the images was counterbalanced across trials such that pictures corresponding to the sentence referents and the two distractors appeared equally across all four quadrants of the visual display.

2.2.4 Semantic Priming Visual Stimuli

Two pretests were conducted to ensure that (a) pairs of images held a strong semantic relatedness to each other (pretest one) and (b) the images were strongly related to the experimental sentence's target noun (pretest two). Both pretests were conducted with separate groups of neurotypical adults. All participants were monolingual native English speakers who were right-handed, had normal or corrected vision and hearing, and no self-reported history of head injury, learning disability, or drug abuse. In pretest one, neurologically unimpaired adults (n = 54, M_{age} = 23.6 years, SD = 7.1) were presented with 84 pairs of images: 40 were intended to be highly related, 22 poorly related and 22 moderately related. Participants were asked to rate the semantic relatedness of each pair using a 5-point Likert scale (1 = not related; 5 = highly

related). Only those pairs that received a rating of 4 and higher (M_{rating} = 4.8, SD = .25) were used in pretest two; which was designed to ensure that each individual picture was deemed to be semantically related to the image of the target noun. In this pretest, participants were presented with the written name of the target noun (i.e., *clown*) and one of the final images from pretest one and asked to rate how related the picture was to the target word (e.g., *Please rate how related the picture is to the word: clown*). To avoid repetition of the target word, each image in a pair was split across two versions of this pretest with separate groups of neurologically unimpaired college-age participants: Version A (n = 14, M_{age} = 23 years, SD = 5.4) and Version B Participants (n = 12, M_{age} = 22 years, SD = 2.9). Using a similar 5-point Likert scale as in pretest one, participants rated the semantic relatedness of each picture-word pair. All pairs received a rating of 4 or higher (no difference between the two versions) and were thus retained for the study (Version A: M_{rating} = 4.73, SD = .30; Version B: M_{rating} = 4.6, SD = .40).

2.3 Procedure

The eye-tracking while listening study was a within-subjects experiment in which the trials containing the semantic priming and attention manipulations were divided and counterbalanced across 2 visits. In order to rule out an effect of a precursor task on gaze patterns when processing an upcoming sentence, a third visit presented the control sentences (no manipulation, from Baker and Love, 2021) with an unrelated color matching task (see Table 2). Each participant contributed data to each condition across the 3 visits, which were spaced a minimum of one week apart.

During each visit, participants were seated approximately 65cm in front of a computer screen equipped with a Tobii Pro Fusion screen-based eye tracker, which records gaze location at a rate of 120 Hz (every 8ms) from both eyes. At the beginning of each experimental session, the

eye-tracker was calibrated using a standard nine-point procedure. Comprehension accuracy and timed presentation of auditory and visual stimuli were controlled by E-Prime 3.0 software (Psychology software Tools, Pittsburgh, PA, USA).

In eye-tracking data analysis, a standard practice is to shift the onset of the analysis windows by 200ms to account for the delay associated with the planning and execution of eye-movements (Lewis & Vasishth, 2005; Oberauer, 2019). However, individuals with aphasia and older adults may have altered oculomotor function and thus 200ms may not be an appropriate value to offset analysis windows (Irving et al., 2006; Smith et al., 2018). Following the protocol from Baker and Love (2023), prior to the experiment, participants completed a baseline gaze task to obtain a measure of saccade latency for each person (see Baker and Love, 2023 for details).

After completing the baseline task, participants continued with the main study. Participants wore over-the-ear headphones for auditory stimulus presentation. As described above (Table 2), each trial began with the presentation of two images and a yes/no question about either the semantic relationship of the two images (semantic condition) or whether the images were the same color (attention and control conditions) that remained onscreen for 5s or until response. All participants responded via a button box using their left hand. Following this response, a central fixation cross was presented for 500ms, followed by a blank screen for 250ms. The four-picture display was then presented for 1500ms before the auditory sentence began to allow for initial gazes that are driven by random factors or visual salience rather than word processing (Ito & Knoeferle, 2022; Zhan, 2018). After the auditory sentence ended, the pictures remained on the screen for 500ms (see Figure 1). In order to ensure that participants paid attention to each sentence, a yes/no auditory comprehension question was asked after each sentence. All questions for the experimental items asked whether one of the nouns mentioned in

the sentence had performed the action of the relative clause verb (e.g., *Did the clown push someone?*). The nouns used in the question (N1 or N2) were counterbalanced. Filler sentence comprehension questions took a variety of formats so that the participants could not develop strategies to anticipate what/who to listen for. All comprehension questions were recorded by a different female speaker at a normal rate of speech and were counterbalanced so that half of the questions had a correct answer of "yes". Participants were instructed to respond as quickly and as accurately as possible with a binary decision via button box (yes/no) using their left, non-dominant hand. Ten practice trials were conducted prior to each experimental session to allow the experimenter to provide feedback prior to the beginning of the experiment.

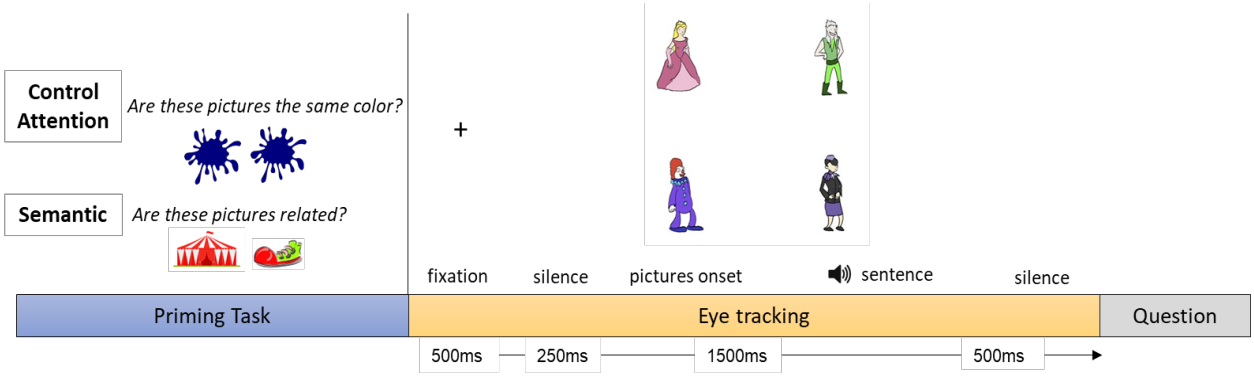


Figure 6.1: Example of visual world eye-tracking-while-listening paradigm. The example display presents pre-sentence priming task for the control, attention, and semantic conditions. The visual display presents the direct object noun (elf), the subject noun (clown), and two distractors (princess and stewardess). After the priming task, auditory sentences began after a 1500ms preview of the display.

2.4 Data Analysis

To analyze the eye-movement data, we first preprocessed the data to clean for trackloss, which is observed when the eye-tracker fails to record gaze data from at least one eye or when the gaze location is outside one of the four predetermined areas of interest (AOI). Trackloss removal occurred in two steps. We first excluded any gaze samples containing trackloss and then

excluded any trial for which half or more samples were eliminated in the first step due to trackloss (Huang & Snedeker, 2020). Eighty-two percent of the data remained after cleaning for trackloss. Following trackloss cleaning, we calculated the proportion of looks to each of the images in the visual display (N1, N2, and the two distractor images) and aggregated the data in 100ms time-bins per participant and condition. We then transformed the gaze proportions to empirical logits to scale the binary response variable (within or outside of an AOI) to a continuous variable (Barr, 2008; Barr et al., 2013; Mirman, Dixon, et al., 2008; Mirman & Britt, 2014). Gaze data were then time-locked to the start of the sentence regions of interest (described below) and shifted by each individual's baseline data (see Table 1 for each person's baseline saccade latency).

Inferential analyses were implemented through growth curve analysis (GCA), which is a multilevel modeling framework that has been developed to analyze change over time (Singer & Willett, 2003), and has been extended to the analysis of gaze data in a visual world paradigm (Magnuson et al., 2007; Mirman, 2017; Mirman, Dixon, et al., 2008). In these models, orthogonal power polynomials are used as predictors to model linear and non-linear gaze changes over time. The following orthogonal polynomials were selected as predictors (time variables) for the current models based on the overall shape of the data and theoretical motivations: 1) the **intercept,** which reflects the overall (average) gaze proportion throughout a time window, 2) the **linear** term, which reflects a monotonic change in gaze trajectory over time (slope), and 3) the **quadratic** term, which reflects the symmetric rise and fall around a central inflection point and captures how much the curve is bent upwards (positive values) or downwards (negative values). In addition to the polynomial terms, fixed effects of Condition (control, attention, and semantic) were added as well as their interaction with the polynomials

(control condition served as the reference level). Tests of individual parameter estimates were used to evaluate specific condition differences on each of the time terms (i.e., whether each experimental manipulation was reliably different from the baseline control condition). The models also included participant random effects on all time terms and participant-by-condition random effects on all time terms that were entered as fixed effects. Analyses were conducted in the statistical software R (R Core Team, 2022) using the lme4 package (Bates et al., 2015). Parameter estimate degrees of freedom and corresponding p-values were estimated using Satterthwaite's method implemented in the lmerTest package (Kuznetsova et al., 2015). For each time window (described below), we created two sets of GCA models to 1) group-level models to test for differences between AMC and IWA and 2) within-group models to explore the effect of the experimental manipulations on the gaze patterns for each group.

2.4.1 Time Windows

Lexical and syntactic processes were analyzed in two predetermined time windows corresponding to sentence regions of interest. The first window, **initial lexical processing**, begins at the auditory onset of the direct -object noun (N1) and ends at the offset of the relative clause verb (duration = 1200ms). This window includes the full time-course of N1 processing and captures initial lexical activation and deactivation. The second window, **dependency linking**, begins at the onset of the main verb and lasts until the end of the sentence (duration = 1800ms). This region includes syntactic reactivation of N1 and the resolution of interference from the subject noun (N2). Figure 2 shows the average time-course (collapsed across conditions) of looks to the four AOIs in the IWA and AMC groups from the onset of N1 until the end of the sentence. Note that across conditions, there were minimal looks to the two distractor images and therefore these are not included in subsequent analyses or visualizations.

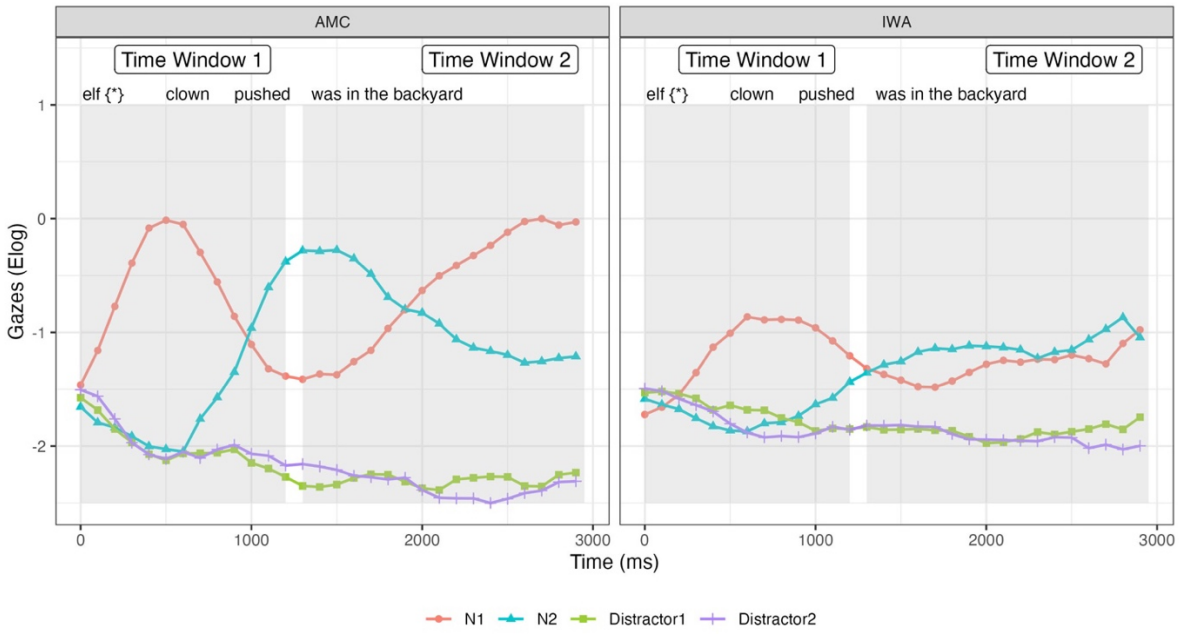


Figure 6.2: Mean gaze over time towards N1 (first noun, red line), N2 (second noun, blue line), Distractor 1 (1st distractor noun, green line), and Distractor2 (2nd distractor noun, purple line) averaged across conditions for each group (baselined). Shaded regions correspond to the analyzed time windows. Time window 1 begins at the auditory onset of N1 until the relative clause verb offset (1200ms). Time window 2 begins post relative clause verb until the end of the trial (1800ms).

3.0 Results

3.1 Offline Comprehension

Responses to the comprehension questions after each trial were analyzed to explore group and condition differences using mixed-effects logistic regression models with a fixed interaction effect of group (AMC, IWA) by condition (control, attention, semantic) and crossed random effects of participant and item on the intercept (lme4 R package; Bates et al., 2015). Table 3 shows the mean accuracy for each of the three conditions in both groups. The results revealed an effect of group; specifically, the IWA group performed worse than the AMC group (estimate = -2.42, SE = .42, $p < .001$). No interaction effect of condition by group was found for accuracy ($p > .05$).

Table 6.3: Accuracy (% correct). Mean (M) and standard deviations (SD) for offline comprehension for the four conditions.

	AMC		**IWA**	
Condition	M	SD	M	SD
Control	89%	32%	44%	50%
Attention	87%	34%	46%	50%
Semantic	80%	40%	45%	50%

3.2 Online Processing

3.2.1 Initial lexical activation in aphasia

To investigate whether IWA show the predicted differences in lexical activation (i.e., reduced activation and/or delayed activation), we first compared IWA and AMC gaze patterns during initial lexical activation in the control condition. Here, we model the initial ascent of gazes to N1 in the control condition before the subject noun (N2) was encountered, which corresponds to the first half of time-window 1 (duration = 600ms). The GCA model for initial lexical activation included the interaction of fixed effects of group (AMC, IWA) and time (linear and quadratic orthogonal polynomials) and random effects of participant and participant-by-condition on all time terms. As shown in Figure 3, the analysis revealed that overall, IWA (red line) looked to N1 significantly less than the AMC group (blue line) indicating a reduced magnitude of N1 activation (intercept estimate $\beta = -.81$, SE = .25, $p < .05$). To measure the time-course of activation, we compared the change in looks to N1 over time (the linear and quadratic terms). IWA showed a slower rise in the rate of N1 activation compared to AMC (linear estimate $\beta = -1.29$, SE = .46, $p < .05$) suggesting that the participants with aphasia showed both reduced lexical activation and a delayed time-course of activation.

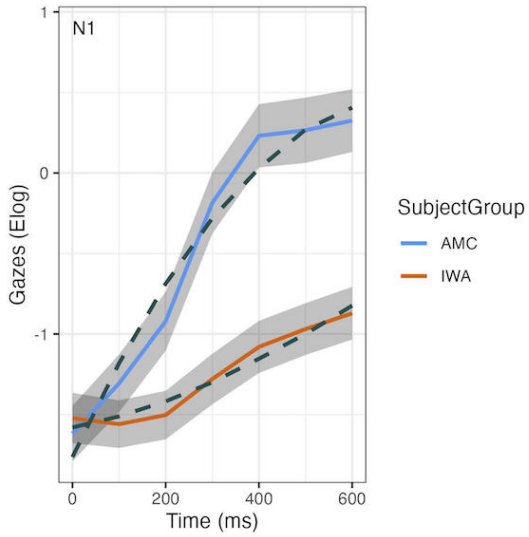


Figure 6.3: Initial lexical activation of the direct object noun (N1) in the control condition by the AMC group (blue line) and IWA group (orange line). Solid lines represent observed data and dashed lines represent the GCA model fit.

3.2.2 Time Window 1: Effect of condition on N1 processing

3.2.2.1 Group results

To investigate whether the experimental conditions modulated the activation and deactivation dynamics of gazes to N1, we first compared group-level differences in gaze patterns in Time Window 1. As shown in Figure 4, upon hearing N1, both AMC (blue lines) and IWA (red lines) groups looked to the picture referent of the noun they just heard indicating initial lexical activation. Then upon hearing N2, both groups begin to look away or disengage from N1 (i.e., lexical deactivation), however this deactivation is attenuated in the IWA group. The trajectory of this inverted U-pattern is modeled with quadratic polynomial time terms, similar to previous studies (Akhavan et al., 2022; Baker & Love, 2021, 2023). GCA models contained effects of condition (control, attention, and semantic), participant group (AMC vs IWA), and the condition by group interaction, which reflects the extent to which the differences in time courses between the experimental conditions (attention and semantic) and the control condition differed

between participant groups. Significant effects of group on the intercept (β = -.55, SE = .24, p < .05) and quadratic time term (β = 1.64, SE = .47, p < .05) indicated that IWAs showed an overall reduced magnitude of activation and a more gradual rise and fall in the control condition when compared to AMCs. An interaction effect between group and condition on the quadratic term revealed that the rise and fall gaze patterns in the IWA group more closely resembled AMC gaze patterns in the semantic condition compared to the control condition (β = -.88, SE = .41, p < .05)

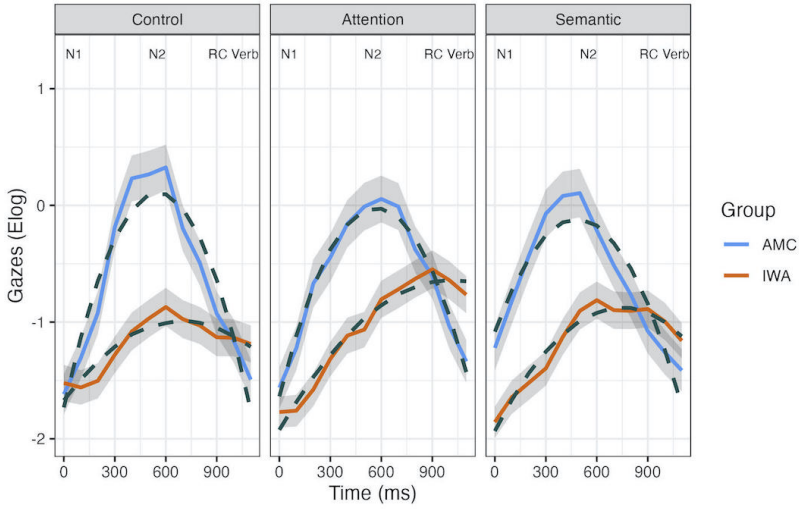


Figure 6.4: Full time-course of lexical activation of the direct object noun (N1) in AMC group (blue line) and IWA group (orange line) in each experimental condition (control, attention, semantic). Solid lines represent observed data and dashed lines represent the GCA model fit. N2 = approximate onset of subject noun, RC Verb = approximate onset of relative clause verb.

3.2.2.2 Within-group results

To explore within-group differences in the effects of the experimental conditions on lexical processing, we conducted GCA models for each group, separately. Gaze data and model curve fits for AMC and IWA groups are plotted in Figure 5. Each model included effects of condition (control, attention, and semantic), time (linear, quadratic), and the critical condition by time interaction, which reflects the extent to which the differences in the attention and semantic time courses differed with respect to the control condition time course. In the AMC group, across

conditions, looks to N1 followed the predicted pattern of lexical activation followed by deactivation. No significant interaction effects were found, suggesting that the attention and semantic conditions did not modulate the temporal dynamics of N1 processing. In the IWA group, a significant effect of the attention condition was found on the linear term (β = .91, SE = .41, $p < .05$). This positive linear effect reveals a steeper increase in N1 activation in the attention condition that did not fully deactivate by the end of the time window (i.e., activation was higher at the end of the Window 1 than in the beginning). These results indicate that overall, the attention manipulations led to increased maintenance of N1 activation in the IWA group.

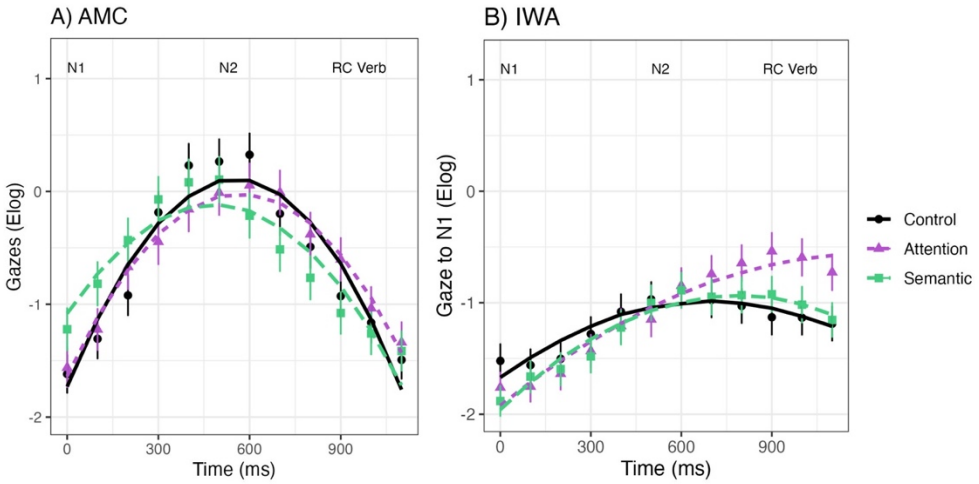


Figure 6.5: Time-course of lexical activation and deactivation of the direct object noun (N1) in the control (black line), attention (purple line), and semantic (green line) conditions in the AMC group (A) and the IWA group (B). Shapes represent means of observed data, error bars represent standard error, and dashed lines represent the GCA model fit. Shaded region indicates the timespan of significant clusters. N2 = approximate onset of subject noun, RC Verb = approximate onset of relative clause verb.

3.2.3 Time Window 2: Effect of condition on dependency linking

3.2.3.1 Group results

In the group-level analysis for Time Window 2, we tested the extent to which the semantic and attention conditions modulated syntactic reactivation of N1. Similar to the group

analysis in Time Window 1, between group GCA models contained fixed effects of participant group (AMC, IWA), condition (control, attention, and semantic), and the interaction of condition X group on all time terms (linear and quadratic polynomials). This analysis revealed between groups differences in both the magnitude and time course of N1 activation in the control condition. As shown in Figure 6, the AMC group (blue line) showed a significant increase in looks back to N1 over time in the control condition (linear estimate $\beta = 1.83$, SE = .67, $p < .05$), indicating evidence of reactivation, which replicates prior research in real-time dependency linking during object relative sentence processing (Akhavan et al., 2022; Baker & Love, 2021, 2023; T. Love & Swinney, 1996; Sussman & Sedivy, 2003; Thompson & Choy, 2009). Compared to the AMCs, the IWA group (red line) exhibited a significantly reduced level of reactivation (intercept estimate $\beta = -.61$, SE = .25, $p < .05$) and a later-rising (delayed) reactivation of N1 as indicated by a significant effect of group on the quadratic time term ($\beta = 1.06$, SE = .40, $p < .05$). An interaction effect of condition X group on the quadric time term revealed smaller differences in the quadratic curvature between AMC and IWA in the attention ($\beta = -.84$, SE = .40, $p < .05$) and semantic ($\beta = -1.43$, SE = .41, $p < .05$) conditions compared to the control condition, reflecting the approximation of a more typical processing pattern in the IWA group.

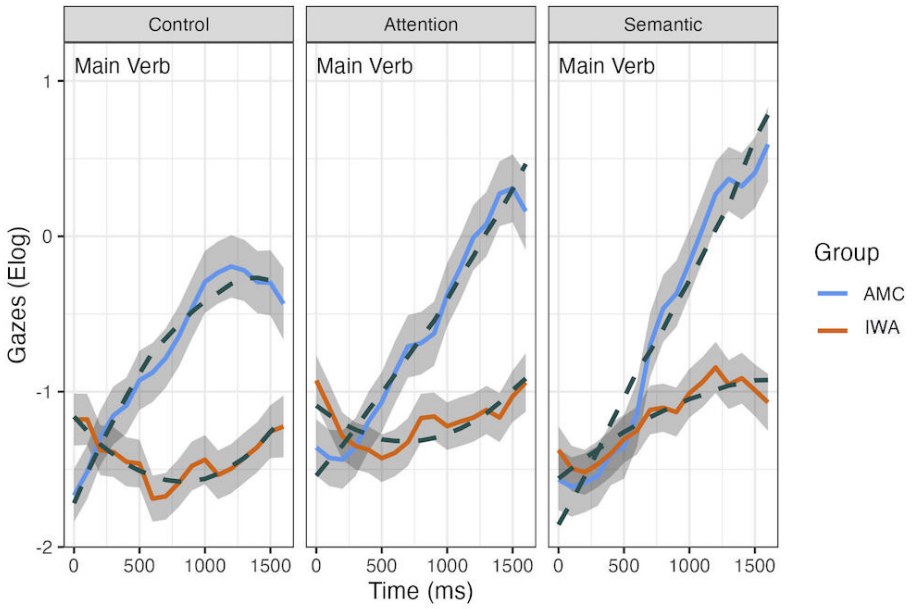


Figure 6.6: Syntactic reactivation of the direct object noun (N1) in AMC (blue line) and IWA (orange line) beginning at the auditory onset of the main verb (Time window 2) in each experimental condition (control, attention, semantic). Solid lines represent means of observed data, error bars represent standard error, and dashed lines represent the GCA model fit.

3.2.3.2 Within-group results

Within-group models explored the additional question of whether the experimental manipulations modulated interference resolution in the post-gap time window. Recall that successful dependency linking and interference resolution occur when looks to the direct object noun increase over time (i.e., N1 reactivation) and looks to the interfering subject noun, N2, decrease (i.e., N2 deactivation). To examine interference and its resolution, within-group GCA models contained fixed effects of condition (control, attention, and semantic), noun (N1, N2), and the condition X noun interaction on all time terms (linear, quadratic). The interaction term reflects the extent to which differences between N1 and N2 gaze trajectories differ between the semantic and attention conditions compared to the control condition. Larger differences (increased N1 reactivation coupled with stronger N2 deactivation) indexes enhanced resolution of interference (Akhavan et al., 2020, 2022; Baker & Love, 2021, 2023).

Beginning with the AMC group, GCA results revealed several significant effects. In the control condition, the trajectories of gazes to N1 and N2 showed the expected pattern of N1 reactivation (β = 1.79, SE = .24, $p < .001$) and N2 deactivation (β = -2.94, SE = .28, $p < .001$) over time. However, the trajectories did not maintain a divergent course. Instead, they begin to converge towards the end of the time window (negative quadratic N1 estimate β = -.61, SE = .20, $p < .05$; positive quadratic N2 estimate β = 1.4, SE = .28, $p < .001$) possibly indicating continued interference. In contrast, both the attention and semantic conditions resulted in significantly enhanced interference resolution (divergent trajectories of N1 and N2) as evidenced by heightened reactivation of N1 (attention linear estimate β = .72, SE = .3, $p < .05$; semantic linear estimate β = 1.59, SE = .30, $p < .001$) and increased deactivation of N2 (attention linear estimate β = -1.21, SE = .40, $p < .05$; semantic linear estimate β = -3.46, SE = .41, $p < .001$), as shown in Figure 7A. Overall, results for the AMC group suggest that the semantic and attention manipulations led to stronger dependency linking with enhanced resolution of interference.

In the IWA group (Figure 7B), the control condition was associated with significant interference arising from delayed reactivation of N1 (quadratic estimate β = .55, SE = .19, $p < .05$) coupled with heightened activation of N2 throughout the time window (intercept estimate β = .25, SE = .06, $p < .001$). Compared to the control condition, the semantic manipulation resulted in significantly more looks to N1 throughout the time window (intercept estimate β = .16, SE = .08, $p < .05$) and increased N1 reactivation (linear estimate β = .75, SE = .25, $p < .05$). The semantic condition also showed decreased looks to N2 (intercept estimate β = -.30, SE = .08, $p < .05$) and stronger N2 deactivation compared to the control condition (linear estimate β = -1.03, SE = .34, $p < .05$). In the attention condition, there were changes to the overall magnitude of looks to both N1 (intercept estimate β = .16, SE = .08, $p < .05$) and N2 (intercept estimate β = -

.18, SE = .08, $p < .05$) in the predicted direction (more looks to N1, less looks to N2). There were no significant changes in the slope of N1 activation nor N2 deactivation in the attention condition compared to control condition.

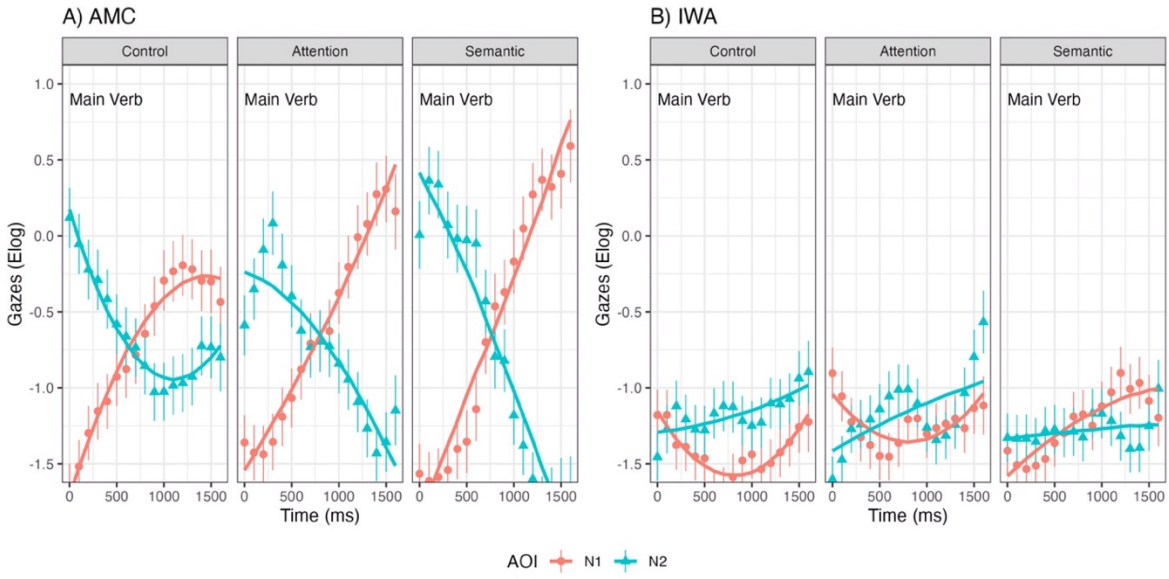


Figure 6.7: Syntactic reactivation of the direct object (N1, red line) and deactivation of the subject noun (N2, blue line) beginning at the auditory onset of the main verb (Time window 2) in the AMC group (A) and the IWA group (B) across conditions (control, attention, semantic). Shapes represent means of observed data, error bars represent standard error, and solid lines represent the GCA model fit.

4.0 Discussion

This study investigated two approaches to facilitate lexical activation, and thus enhance encoding and the subsequent retrieval of the direct object noun during real-time auditory complex sentence processing. The first approach aimed to implicitly direct attention to the target noun by inserting an attentional cue in the form of a disfluency (‘*uh’*) preceding the target noun. In the second approach, a semantic decision task was presented before the presentation of the auditory sentence to pre-activate semantic properties of the target noun. Using eye-tracking-while-listening with a visual world paradigm, eye gaze patterns during the experimental

sentences were compared to control sentences to explore whether the manipulations modulated initial lexical processing of the direct object noun when it was first encountered in the sentence and its syntactic retrieval at a later point in the sentence (post-verb). We also explored the extent to which the attention and semantic conditions modulated the resolution of interference from the thematically similar subject-noun (N2) during retrieval (dependency linking). Both manipulations were predicted to 1) enhance initial lexical processing of the target noun and 2) facilitate its retrieval through stronger reactivation and improved interference resolution in both individuals with aphasia (IWA) and neurologically healthy age-matched controls (AMCs).

In the control condition, processing patterns in both groups were consistent with prior literature such that upon hearing the direct object, AMC gaze patterns exhibited lexical activation followed by deactivation. After processing the relative-clause verb, gazes reflected reactivation of the direct object and initial deactivation of the interfering subject noun indicating dependency linking. We note however, that interference from the subject noun was not completely resolved. In contrast, IWA gazes showed a slower rise time in lexical activation with an overall reduced level of activation. This was followed by a slower time course of reactivation along with substantial interference from N2. The predictions of processing benefits in the attention and semantic conditions were differentially borne out in each group.

With regard to the attention and semantic manipulations, the AMC group showed no observable effects (as indexed by eye-tracking) during initial lexical processing, however, gaze patterns revealed clear benefits during dependency linking. These benefits manifested as stronger reactivation of the direct object noun and enhanced interference resolution (increased deactivation of the subject noun). In the IWA group, an initial lexical processing benefit was found only in the attention condition, which suggested that the attentional cue increased and

maintained activation of N1. This condition also benefited dependency linking by increasing the overall level of activation of the direct object noun and decreasing activation of the competing subject noun (however there was still considerable interference). In the semantic condition, results showed a greater degree of facilitation during dependency linking as evidenced by a stronger rate of target noun reactivation and competing noun deactivation. Interestingly, this condition did not have observable benefits in initial lexical processing.

In looking at the processing costs during dependency linking, we interpret the benefits in syntactic retrieval and interference resolution in the semantic and attention conditions as a result of enhanced encoding, even though the overt gaze patterns did not always show changes during initial lexical processing consistently across groups. We posit that this may be due to the different ways attention and semantic priming affected encoding in language impaired and unimpaired individuals. Recall that implicit attentional cues such as disfluencies, were predicted to direct or orient attention to the target noun during sentence processing and result in improved lexical access and syntactic retrieval (Arnold et al., 2007; Brennan & Schober, 2001; Collard et al., 2008, 2008; Corley & Hartsuiker, 2011; Fox Tree, 2001). Explanations for the mechanism underlying this improvement come from the memory literature, which has shown that modulating attention during encoding enhances representations of the attended information and assists in resolving competition among multiple candidate responses during retrieval (Aly & Turk-Browne, 2016; Chun & Turk-Browne, 2007; Fernandas & Moscovitch, 2000; Gazzaley & Nobre, 2012; Uncapher & Rugg, 2009). In line with these findings, the attentional cue in the current study may have improved the resiliency of the encoded lexical representation to interference at the syntactic point of retrieval. This improvement behaviorally manifested differently between AMCs and IWA. Specifically, we did not find a change in the time course of

initial lexical activation for the AMCs, however, our IWA population, who often have difficulties in both accessing lexical representations and retrieving them in service of dependency linking, did show an initial benefit; the attentional cue resulted in increased and maintained activation during initial lexical processing. For IWA, these behavioral outcomes are similar to those found when additional time (e.g., a silent pause) was provided to extend the temporal window for processing the target noun (Baker & Love, 2023). Both groups demonstrated enhanced dependency linking at the post-verb sentence region in the attention condition. The current findings suggest that leveraging attentional engagement may constitute an additional route in which to facilitate lexical processing in aphasia and mitigate similarity-based interference during retrieval.

For both AMC and IWA, the effects of semantic priming, while showing similar benefits in dependency linking, may have modulated encoding differently than the attentional cues. Recall that the initial hypothesis was that the semantic priming manipulation would have an effect on initial lexical activation. This finding was not borne out in either group. Specifically, the initial semantic priming task (before sentence presentation) was hypothesized to pre-activate semantic concepts associated with the target noun and facilitate processing when that noun was encountered in the sentence. We believe that semantic priming did successfully activate the target noun of interest, just not when we anticipated it would. Given the current paradigm, this pre-activation may have manifested before participants heard the target noun in the sentence. To explore if the semantic task succeeded in pre-activating the semantic network, we looked at the gaze patterns during the initial preview presentation of pictures. Recall that in this study, the visual array of the subject and object nouns and two distractor images were presented for 1500ms to allow participants to form mental representations of each lexical item and control for

any confounding variables that may influence initial eye movements (e.g., basic image features, color, etc.) as is standard in visual world paradigms (Ito & Knoeferle, 2022; Zhan, 2018). If the semantic decision task presented at the beginning of each trial was successful in pre-activating semantic concepts of the target word (N1), this would likely manifest as increased gazes to the target during this preview time. Importantly, this is predicted only in the semantic condition as we would not expect any gaze bias towards N1 in the attention condition as participants completed a neutral color-decision task (i.e., "Are these the same color?") that served as a control task to maintain an environment where participants were always answering a binary question pre-sentence input. Figure 8 shows the time-course of gazes during the first 1200ms of the preview window in the semantic and attention conditions. Upon visual inspection, it is clear that both groups demonstrate a gaze bias towards the direct object noun (N1), although this effect is attenuated in IWA group. This was confirmed via GCA models, which showed an increased magnitude and rise of N1 activation compared to the three unrelated characters in the AMC group (AMC intercept estimate $\beta = .45$, SE = .08, $p < .001$; quadratic estimate $\beta = -69.16$, SE = .29, $p < .05$). In the IWA group, there were significantly greater looks to N1 (IWA intercept estimate $\beta = .18$, SE = .07, $p < .05$).

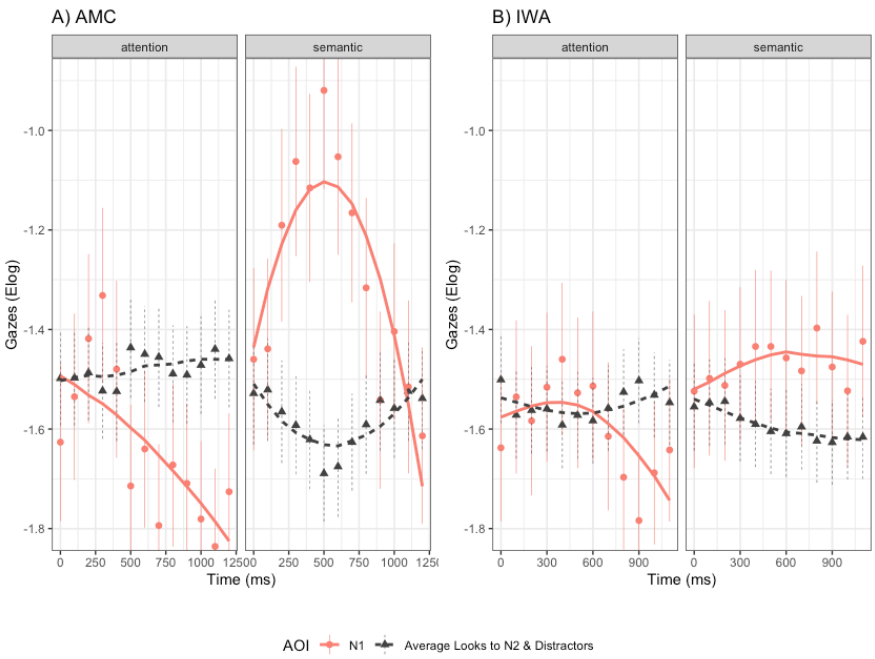


Figure 6.8: Gazes to target direct object noun (N1, red line) and the three unrelated images (subject noun (N2) and two distractor pictures during the preview picture preview (first 1200ms) in the AMC group (A) and the IWA group (B) in the attention and semantic conditions. Shapes represent means of observed data, error bars represent standard error, and solid lines represent the GCA model fit.

Increased looks to the target noun during the preview window suggest that the semantic priming task successfully pre-activated the semantic features of the target, which facilitated processing during auditory sentence presentation. A parallel to this effect can be found in the ERP literature, which shows that sentences with semantically constraining context information (*I like my coffee with cream and* __) serves to pre-activate features of likely upcoming words such that information congruent with the context (i.e., *sugar*) is subsequently easier to process and integrate (i.e., top-down effects on access) (Boudewyn et al., 2015; DeLong et al., 2005; Federmeier, 2007; Federmeier & Kutas, 1999; Kutas & Federmeier, 2011; Kutas & Hillyard, 1980; Van Petten, 1993). The processing facilitations due to pre-activation are argued to result from the ease of accessing recently-activated information in working memory (Federmeier,

2007; Kutas & Federmeier, 2011; Lau et al., 2009) and/or ease of integration into the sentence context (Brown & Hagoort, 1993; Hagoort, 2008; Osterhout & Holcomb, 1992). It is for this reason we believe we did not see an additional increase of activation at the noun itself.

Taken together, the results suggest that attention and semantic activation are parameters that may be manipulated to strengthen lexical encoding and increase the quality of the resulting memory representations to better serve dependency linking. Stronger memory representations are more resilient to similarity-based interference at a later point in the sentence when retrieval is required and can facilitate dependency linking. In individuals with aphasia, these manipulations may help to reduce lexical processing deficits that can disrupt access to lexical-semantic information and preclude successful encoding. However, in IWA retrieval interference was not completely resolved in any condition suggesting that more research is needed to understand the effect of individual variability and the ways in which semantic and attention can be manipulated to reduce processing costs and mitigate comprehension impairment.

Altogether, these findings point to parameters that may affect lexical processing, and ultimately enhance dependency linking. In the present study of auditory sentence processing, we've shown that enhancing initial lexical representations can mitigate later similarity-based interference during dependency linking. By engaging attention and leveraging semantic priming of a target (to-be-retrieved) noun, we were able to facilitate syntactic retrieval and enhance interference resolution in two populations: one which does not show impaired language comprehension (AMCs) and the other which is known to have lexical and syntactic processing impairments (IWA). Not surprisingly, the effects of engaging attention and semantic pre-activation of lexical items resulted in different behavioral patterns across AMC and IWA. Contrary to initial predictions, these factors didn't always manifest as overt changes in looks to

the target noun when first encountered in an auditory sentence, though they did result in enhanced dependency linking. In neurologically healthy adults, the effects of the manipulations were seen in sentence regions where processing costs were highest—during retrieval of the target information in the presence of similarity-based interference. In individuals with aphasia, who experience difficulties in both lexical access and syntactic retrieval, facilitations were observed during initial lexical processing and dependency linking. Overall, we have shown that the quality of encoding can be enhanced to facilitate retrieval and reduce the processing costs of similarity-based interference in both neurotypical adults and in individuals with aphasia.

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Data availability: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Chapter 6 has been submitted for publication of the material in the *Journal of Speech, Language, and Hearing Research*. This chapter is coauthored with Dr. Tracy Love. The dissertation author was the primary investigator and the primary author of this paper.

CHAPTER 7

General Discussion

The primary aim of this dissertation was to explore the parameters supporting successful lexical processing and syntactic structure building during real-time auditory sentence processing in neurotypical college-age adults (YNC), older adults (age-matched controls, AMC) and individuals with aphasia (IWA). The motivation for this work was borne out by findings in the literature showing disruptions to the automatic processing routines involved in lexical access in aphasia (Blumstein et al., 1985; Blumstein & Milberg, 2000; Ferrill et al., 2012; Love et al., 2008; Mirman et al., 2011; Swinney et al., 2000; Utman et al., 2001; Yee et al., 2008) and the effects of such disruptions on structure building during real-time auditory comprehension (Ferrill et al., 2012; Love et al., 2008; Prather et al., 1997). The transient nature of the speech signal places tight temporal constraints on lexical access, which needs to map sensory (acoustic) input to the correct representation in the lexicon and integrate that information into a sentence context. Deficits in activating the semantic (and phonological) information needed to complete this mapping in a timely fashion have been shown to result in reduced or delayed lexical activation (Blumstein et al., 1985; Blumstein & Milberg, 2000; Ferrill et al., 2012; Love et al., 2008; Mirman et al., 2011; Swinney et al., 2000; Utman et al., 2001; Yee et al., 2008) and/or integration (Hagoort et al., 1996; Thompson & Choy, 2009). Of interest in this research are the consequences of lexical impairments in sentences that require the previously activated words to be re-accessed in service of syntactic operations. For example, successful resolution of long-distance syntactic dependencies (noted by the subscript i in Sentence 1) depends on the timely retrieval of words from an earlier part of the sentence to be integrated with later information (i.e., dependency linking). Each of the dissertation studies presented above used object relative sentence structures as a lens through which to investigate the ramifications of lexical access impairments in dependency linking. These sentences included a target noun (i.e., the displaced

direct object noun, *clown*) that was syntactically licensed for retrieval at the verb offset (gap-site) and a subject noun that was syntactically and semantically similar (i.e., *elf*).

1. The clown$_i$ that the elf pushed$_i$ was in the backyard.

As described in **Chapters 1 and 2**, cue-based parsing models predict that the ability of the system to efficiently retrieve target information (i.e., the displaced constituent during dependency linking) is constrained by the presence of other similar sentence constituents, which compete with the retrieval of the target item by creating similarity-based interference (Lewis & Vasishth, 2005; McElree, 2000; McElree et al., 2003; Van Dyke & Lewis, 2003; Van Dyke & McElree, 2006, 2011). During the processing of semantically reversible object relative sentences, such as (1) above, the retrieval cues provided by the verb *pushed* select for an animate noun, however the two noun phrases (*clown* and *elf*) both fit these cues. Evidence from the literature has shown that similarity-based interference increases the processing costs of retrieving previously encoded lexical representations during dependency linking in both neurotypical populations (Van Dyke & Lewis, 2003; Van Dyke & McElree, 2006, 2011) and IWA (Lissón et al., 2023; Mätzig et al., 2018; Patil et al., 2011, 2016). However, in IWA, lexical processing deficits create an additional detriment as the failure to activate lexical information precludes successful lexical level encoding during processing and creates an environment that is more vulnerable to similarity-based interference at critical syntactic retrieval points and results in a breakdown in comprehension.

Given the ways that lexical processing impairments in aphasia and similarity-based interference more broadly can negatively impact syntactic retrieval during processing, I explored three approaches to facilitate lexical access (and concomitant encoding) of a target word in a sentence (direct object noun) by manipulating three elements of time, attention, and semantic

priming. The effect of each of these approaches on real-time lexical and syntactic processing during complex (object relative) sentence processing was examined using eye-tracking-while-listening methodology to obtain a detailed measure of these processes as they change over time throughout the course of an auditory sentence. In each of these approaches, I asked whether enhancing the processing of a target lexical item during sentence processing would 1) facilitate its lexical access and concomitant lexical encoding, 2) increase its availability for downstream syntactic operations, and 3) improve sentence comprehension. This novel area of exploration has the potential to improve our understanding of 1) the interaction between lexical and syntactic levels within sentence processing and 2) the cognitive and linguistic factors promoting lexical processing within a sentence context in individuals with aphasia (IWA) and in neurotypical age-matched adults (AMC).

Chapter 3 presented a study exploring the effect of the parameter of time on final (offline) comprehension of object relative sentences in college-age adults (YNC), AMC, and IWA using a sentence-picture matching paradigm. Similar to the eye-tracking studies presented in Chapters 4 and 5, time was manipulated in three ways to provide additional processing time for the target direct object noun: a **stretch** condition, in which the duration of the target noun was increased by 150%, a **disfluent** condition, in which a speech disfluency (*uh*) was inserted directly after the target noun, and a **silence** condition in which the disfluency was replaced by a silent pause. According to the Delayed Lexical Activation hypothesis (DLA; Ferrill et al., 2012; Love et al., 2008; Prather et al., 1997), delays in lexical access disrupt the availability of lexical-semantic information for fast-acting processes such as syntax and can result in comprehension breakdowns. This study tested the predictions that relaxing the temporal constraints of lexical

access, by providing focal additions of processing time for the direct object noun, would improve sentence comprehension, as reflected by improved accuracy and/or faster response times.

Consistent with these predictions, IWA showed significant improvement in their comprehension of sentences containing the temporal manipulations (i.e., above-chance comprehension compared to at-chance performance in control sentences). Advantages for the temporally manipulated sentences were also found in the two groups of neurologically healthy adults, although across conditions both groups showed near-ceiling comprehension accuracy. The silence condition improved comprehension in both the AMC and YNC groups. The AMC group showed improved comprehension via accuracy whereas the YNC group showed improved comprehension through faster response times. In addition, the AMC group also showed faster response times in the disfluent condition.

Altogether, these results support the DLA by showing that relaxing the temporal constraints can facilitate auditory comprehension in aphasia, while also showing that improvements can be gained even in a population that has little comprehension difficulty. It also brings a new dimension to previous work by showing that even focal manipulations directed at lexical processing, rather than slowing the rate of the entire sentence (Love et al., 2008), can result in comprehension improvements. While comprehension benefited from the temporal manipulations, using an offline method such as sentence-picture matching did not allow for determining where the locus of improvement occurred (i.e., at the point where the lexical item of interest was first encountered in the sentence). To investigate whether the manipulations modulated real-time lexical access and downstream syntactic operations, Chapters 4 and 5 present the results of two eye-tracking-while-listening studies, which yielded detailed measures of the time-course of lexical and syntactic processing as a spoken sentence unfolds.

Having established that focal additions of time impact object relative sentence comprehension in college-age adults, individuals with aphasia, and age-matched controls, Chapters 4 and 5 examined the extent to which the three temporal manipulations (stretch, silence, and disfluent) influence initial lexical processing and syntactic dependency linking in the same populations (college-age adults in Chapter 4 and individuals with aphasia and age-matched controls in Chapter 5). Eye-tracking-while-listening with a visual world paradigm was used to explore how additional time at a specific location in the sentence affects lexical processing, dependency linking, and interference resolution (Akhavan et al., 2020, 2022; Baker & Love, 2021, 2023; Sekerina et al., 2016; Sheppard et al., 2015). In this paradigm, gaze patterns have been shown to reflect what is actively being processed at a given point in time with specific gaze patterns being attributed to different language processes, depending on where in the sentence they occur (Tanenhaus et al., 2000). The patterns of interest of these dissertation studies were: 1) **lexical activation** and **deactivation**, which manifest as gazes towards a picture of a recently heard referent followed by looks away (disengagement) from the activated noun to access new input; 2) **reactivation** or looks back to the direct object noun at the syntactically licensed post-verb position (i.e., dependency linking; Akhavan et al., 2020, 2022; Baker & Love, 2021, 2023; Sekerina et al., 2016; Thompson & Choy, 2009b) and **interference**, which is shown as an extended activation of both subject and direct object nouns during the post-verb time window (Akhavan et al., 2020, 2022; Baker & Love, 2021, 2023). These expected patterns were revealed in both younger and older control populations allowing us to interpret the effects of the manipulations in aphasia. It was hypothesized that the temporal manipulations would facilitate 1) initial lexical processing of N1 and 2) dependency linking via enhanced reactivation of N1 and the resolution of interference between N1 and N2 across the three participant groups.

The results from **Chapter 4** revealed that the YNC group (Baker & Love, 2021) benefited most from the disfluent and silence manipulations, which enhanced initial lexical processing (increased activation and deactivation) and resulted in stronger reactivation of the target noun after processing the verb. During retrieval, there was also evidence for enhanced interference resolution indicated by a stronger deactivation of the competing subject noun. These results suggest that by amplifying activation and deactivation dynamics, the temporal manipulations facilitated the tight linking of lexical and syntactic processes involved in accomplishing real-time dependency linking in younger adults.

Similar results were found in **Chapter 5** for the AMC group (Baker & Love, 2023), which demonstrated amplified lexical activation and deactivation patterns (steeper rise and fall) in the disfluent and silence conditions along with the stretch condition. In contrast, IWA showed lexical processing benefits only in the silence condition, which resulted in increased looks to and maintenance of the direct object noun. The finding of maintained activation during a silent pause indicated that this extra time may have helped to strengthen lexical access. With regard to syntactic processing, IWA evinced both delayed and reduced reactivation of the direct object noun in the control sentences, replicating prior research (Akhavan et al., 2022; Sheppard et al., 2015; Sullivan et al., 2017). Similar to the findings in initial lexical access, differential effects of the manipulations were found on dependency linking in each group. When compared to control sentences, gaze patterns showed stronger reactivation in the silence condition for the AMC group and in the stretch condition for the IWA group. As far as the impact on interference resolution at the post-verb site, different manipulations supported interference resolution for the AMC and IWA groups; both groups responded to the silence manipulation, however the AMC group also responded to the disfluent conditions, whereas IWA responded to the stretch condition.

Overall, by relaxing the temporal constraints during the initial presentation of the direct object noun, we not only found initial enhancements of lexical access in both groups, but downstream facilitation of dependency linking via enhanced resolution of interference for both groups as well. Interestingly, within and across groups we observed a difference in the types of temporal manipulation that individuals were sensitive to. We believe further investigation of individual differences would move this line of enquiry forward.

Although the three temporal manipulations differentially affected lexical and syntactic processing across groups, there are some general takeaways that can be capitalized on. The first is that the silence condition appeared to have the greatest and most consistently positive effect on both lexical activation and dependency linking/interference resolution in all three populations with the disfluent condition not far behind (IWA did not seem to gain as much benefit from disfluencies as the neurotypical participants). The reason for this likely lies in difference in location and duration of additional time provided by the manipulations. Recall that the disfluent and silence conditions manipulated time *after* the target noun, whereas the stretch condition manipulated the noun itself. Additionally, compared to the ~460ms of additional time provided by the disfluent and silence conditions, the stretch condition provided only ~250m, which was spread out across the noun. The finding that the disfluent and silence conditions tended to pattern together in both AMC and YNC groups, suggests that time itself is an essential factor underlying processing facilitations in language-unimpaired systems. This idea is in line with the time-induced attention account proposed by Karimi and colleagues (Karimi et al., 2019, 2020, 2021), which posits that the longer the processing system spends expecting or maintaining the target word during lexical encoding result in a more robust memory representation that is easier to retrieval for dependency linking, an idea I will return to later in the discussion. In contrast IWA

did not seem benefit from disfluencies to the extent that the neurotypical participants did. The finding that disfluencies increased initial maintenance of lexical activation, but did not facilitate processing at verb offset (dependency linking) in IWA could suggest that impaired systems may be more vulnerable to these phonetic disruptions in the speech stream, and therefore are not able to benefit from the additional time they provide. Anecdotally, several IWA noted their surprise to the presence of disfluencies in this experiment and expressed that the speaker sounded "confused", thus increased looks may be the result of a distraction caused by the surprise of the disfluency.

Overall, the IWA results provide support for two current theories in the sentence processing literature that are not mutually exclusive. The first is the DLA, which posits that sentence processing impairments are linked to temporal delays in activating the necessary lexical-semantic information needed for fast-acting syntactic processing. The second is cue-based retrieval models, which, described in detail below, focus on processing costs (i.e., similarity-based interference) associated with dependency linking. In addition to these two theoretical approaches, the findings also add to the literature by pointing to a reduction in the overall level of activation as a component of lexical access impairments in aphasia (Blumstein et al., 1985; Utman et al., 2001; Yee et al., 2008). Chapter 5 has shown that providing more time to process the target noun needed for syntactic retrieval during an auditory sentence improves not only initial lexical access when the noun is encountered but also facilitates downstream dependency linking and interference resolution. As a caveat, the temporal manipulations did not fully mitigate processing impairments in IWA, as gaze patterns showed substantial individual variability in response to the different manipulations. As pointed out by the work conducted by Love and colleagues (2008), it is highly likely that the degree of processing impairment in

aphasia (i.e., speed and level of lexical access during sentence comprehension) is not the same for each individual with aphasia. Thus, depending on the specific impairments, a longer time manipulation may be needed to fully realize enhancements in lexical and syntactic processing. These results point to the temporal parameter of time as a potential mechanism for improving online and offline comprehension of syntactically complex sentences through enhancing lexical processing.

While Chapters 3-5 focused on the parameter of time to facilitate lexical processing in service of syntactic structure building during real time sentence processing, **Chapter 6** (Baker & Love, submitted) explored two additional mechanisms to modulate processing in AMC and IWA: attentional modulation, and pre-activating the semantic level properties of the target word through priming. To engage attentional mechanisms, a disfluency (i.e., prolongation of the determiner *the* coupled with the filled pause *uh*) was inserted directly *before* the target (direct object noun). In this position, disfluencies have been shown to implicitly direct attention to processing the upcoming noun (Collard et al., 2008; Corley et al., 2007; Corley & Hartsuiker, 2011; Corley & Stewart, 2008; Fox Tree, 2001). Critically, because the determiner (*the*) predicts an upcoming head noun, the processor spends more time *expecting* the head noun during the disfluency. This is argued to implicitly heighten attention to the upcoming noun and facilitate its processing (Karimi et al., 2019, 2020, 2021). Therefore, using the same manipulation (disfluency), but in different strategic locations in relation to the target lexical item, was hypothesized to tap into different mechanisms; inserting the disfluency *after* the noun was argued to provide more time for lexical processing, while placing it *before* the noun was predicted to orient attention to the noun. The second approach was to leverage semantic sources of lexical information to aid lexical access. In this condition, a priming task occurred before each

sentence to strategically pre-activate properties of the target noun (*clown*). Before the auditory presentation of a sentence, participants were presented with two images that were semantically related to the target noun (e.g., a circus tent and clown shoes) and asked to decide if they were semantically related to each other (yes/no). This approach was hypothesized to strategically pre-activate the semantic properties of the target noun **before** the auditory presentation of the sentence stimuli. Both manipulations were predicted to boost initial lexical activation of the target noun and facilitate syntactic dependency linking downstream in the post-verb sentence region.

In the attention condition, the results showed that IWA evinced increased maintenance of direct object lexical activation compared to control sentences (similar to the silence manipulation from Chapter 5) and modest facilitations in dependency linking. In contrast, the AMC group showed no changes in initial lexical processing, but substantially greater reactivation of the target noun and enhanced interference resolution (deactivation of the competing subject noun). The semantic conditions resulted in successful pre-activation as shown via increased activation of the target noun during the initial picture preview (before the sentence was heard), but no initial processing differences were found at the onset of the target lexical item across groups. Similar to the attentional manipulation, this condition facilitated dependency linking in both groups with greatly enhanced interference resolution in the AMC group and more modest effects in IWA.

The results of the studies described in this dissertation have several broad implications for bridging sentence processing models developed from language unimpaired populations and theories of comprehension deficits in aphasia. First, when considering how neurologically unimpaired listeners comprehend complex sentences, Chapters 3-5 demonstrated that focal temporal manipulations that extend the processing time of the critical displaced direct object

noun increased lexical activation dynamics and facilitated dependency linking. Chapter 6 demonstrated that attentional manipulations to direct implicit attention to and semantic pre-activation of the critical noun also facilitated dependency linking. All three approaches also led to robust enhancements to the resolution of interference from the syntactically and semantically similar subject noun (i.e., mitigating similarity-based interference).

The findings that, in neurotypical listeners, manipulations aimed at lexical-level processing benefited syntactic retrieval can be explained by cue-based parsing theories. Recall that according to these models, the ease of retrieving previously encoded memory representations of the target lexical item is assumed to determine the difficulty of establishing a linguistic dependency. Critically, retrieval ease is determined by three factors: the representation's baseline activation level, the degree of time-based decay that reduces activation, and the amount of interference that is experienced during retrieval (Lewis et al, 2006; Lewis & Vasishth, 2005). I propose that the outcomes of these studies can be attributed to modulations in encoding strength that result from enhanced lexical processing. By increasing the encoding of the lexical item, activation levels of the target representation increase, which renders its subsequent retrieval easier. Unlike prior studies that have increased the linguistic complexity of the target representation to aid retrieval (Hofmeister, 2011; Hofmeister & Vasishth, 2014), the resulting representation described here has not acquired additional features to increase its distinctiveness, but rather has gained activation. In doing so, it creates a processing environment that is more resilient to the effects of similarity-based interference. Support for this idea is found in the *time-induced attention account*, proposed by Karimi and colleagues (Karimi et al., 2020, 2021), which posits that longer encoding time heightens attention to the target word and creates a more robust memory encoding and facilitates retrieval. This hypothesis is most closely explored in Chapters

3, 4, and 5 by illustrating that extending the duration of time for which a sentence element is accessible during processing leads to heightened lexical activation and subsequent retrieval. Although Chapter 6 did not directly focus on the impact of additional time on the encoding-retrieval relationship, time can still be invoked to explain the results obtained from the attention and semantic manipulations. In the attention condition, using disfluencies as attentional cues added a temporal delay to the speech signal. As previously mentioned, by placing the disfluency after the determiner (*the*)—which cues an upcoming noun—the processor is provided more time to prepare for the upcoming noun. Prolonged expectation of a word is argued to heighten attention to that word when it is eventually encountered, ultimately bolstering its encoding and facilitating its later retrieval (Corley & Hartsuiker, 2011; Karimi et al., 2020, 2021). In the semantic condition, pre-activating the target noun before it was heard in the sentence lowered its threshold for activation when the auditory form was presented. Thus, the semantic condition resulted in a longer duration of activation for the representation in working memory making it subsequently easier to process and integrate during dependency linking. For each of these manipulations, time increases the accessibility of the target noun and makes it easier to retrieve the associated representation in service of dependency linking with reduced interference from similarity-based competition.

There are also numerous implications of the findings for the study of sentence processing in aphasia. First, Chapters 4, 5, and 6 confirmed prior reports that IWA are susceptible to similarity-based interference (Lissón et al., 2023; Mätzig et al., 2018; Patil et al., 2016), as evidenced by eye-tracking patterns during real-time sentence processing. Second, they provide support that lexical-level processing deficits in post-stroke aphasia create a more vulnerable system in which the effects of similarity-based interference are amplified, leading to both

processing and final comprehension impairments. Thirdly, lexical access deficits in aphasia can be framed within a cue-based parsing approach to see how a singular model can parsimoniously account for both processing costs in language unimpaired individuals and comprehension impairments in individuals with aphasia. For IWA, lexical-level impairments such as delayed lexical access and reduced activation can preclude successful encoding and result in the formation of a degraded memory representation. The resulting representation would thus be a weaker match to the retrieval cues and increase susceptibility to interference from the non-target item making it more difficult to retrieve at the syntactically licensed post-verb position. Overall, the degradations caused by lexical impairments negatively impact encoding and can cause downstream difficulty in establishing the grammatical relationships that require them. This not only affects real-time processing, but also gives rise to longer-lasting effects resulting in offline comprehension difficulty.

The studies presented show three different approaches (processing time, attentional engagement, and semantic pre-activation) to strengthen encoding via targeting lexical processing. The results showed that improving initial lexical processing (and concomitant encoding) is one route to reducing interference and facilitating retrieval. It is important to note that the approaches taken here did not fully mitigate processing impairments in aphasia nor did they completely resolve similarity-based interference or comprehension deficits. The likely explanation is that lexical-level impairments coexist with other deficits that collectively contribute to sentence processing difficulties in aphasia (i.e., working memory/resource allocation deficits, etc.). Recent computational instantiations of cue-based parsing models have found that a combination of theoretical explanations (e.g., intermittent deficiencies, slow syntax,

and resource reduction) can explain IWA's deficits in sentence processing (Lissón et al., 2023 and references therein).

The results from the work presented show that incorporating behavioral outcomes from lexical processing impairments into such models will allow for a more complete representation of processing impairments in aphasia to be captured. This work lays the foundation for future translational research that focuses on lexical-level training for auditory sentence level comprehension impairments.

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