Neural and Behavioral Dissociations in Aphasic Verb Retrieval

by

Haley C. Dresang

Bachelor of Science, University of Wisconsin-Madison, 2015

Doctor of Philosophy, University of Pittsburgh, 2020

Submitted to the Graduate Faculty of

the School of Health and Rehabilitation Sciences in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2020

UNIVERSITY OF PITTSBURGH

SCHOOL OF HEALTH AND REHABILITATION SCIENCES

This dissertation was presented

by

Haley C. Dresang

It was defended on

April 20, 2020

and approved by

Julie Fiez, Professor, Departments of Neuroscience and Psychology

William D. Hula, Speech Pathologist & Adjunct Professor, VA Pittsburgh Healthcare System

Tessa Warren, Associate Professor, Department of Psychology

Fang-Cheng Yeh, Assistant Professor, Department of Neurological Surgery

Dissertation Director: Michael Walsh Dickey, Associate Professor, Department of Communication Science and Disorders

Neural and Behavioral Dissociations in Aphasic Verb Retrieval

Haley C. Dresang, PhD

University of Pittsburgh, 2020

Verb-retrieval deficits are pervasive impairments that negatively impact communicative function for individuals living with aphasia, a language disorder caused by brain damage. Behavioral treatments can ameliorate these deficits, but the nature of the deficits remains controversial, and the neurocognitive mechanisms supporting treatment are poorly understood. Aphasia accounts traditionally follow cognitive-linguistic theories, which maintain language as a separate system from other cognitive processes and that aphasia results from distinct damage to language. However, recent cognitive neuroscience theories make contrasting predictions. Grounded cognition claims that language is accomplished by a general-purpose cognitive system that operates over distributed representations encoding both linguistic and non-linguistic knowledge. Rational adaptation predicts that people with aphasia adapt to their language impairments by relying more heavily on non-linguistic knowledge in order to communicate. This dissertation examines these predictions in patients with chronic aphasia due to left-hemisphere stroke and age-matched neurotypical controls. The first experiment examined the degree to which conceptual versus lexical action-processing abilities are impaired and may contribute to verb-retrieval deficits in adults with aphasia. The second experiment employed diffusion spectrum imaging and connectometry analyses to identify white-matter tracts associated with verb retrieval and to assess the involvement of conceptual-motor pathways not considered part of standard dual-stream neurocognitive models of language. The third experiment investigated the extent to which adults with aphasia rationally adapt to their language impairments by relying more on conceptual rather than lexical information during verb retrieval, as compared to controls. The results from these experiments indicate that conceptual processing can be impaired and contributes to verb-retrieval deficits in aphasia. However, relatively unimpaired conceptual processing can ameliorate the influence of lexical impairments on verb-retrieval deficits. Furthermore, the structural integrity of classical motor pathways strongly predicts verb retrieval ability. These findings are consistent with rational adaptation and grounded cognition accounts. This research is the first to systematically evaluate grounded cognition accounts of aphasic language impairments, white-matter connectivity contributions to verb retrieval in aphasia, and rational adaptation to rely on conceptual information. This work provides treatment-relevant evidence by assessing the underlying neurocognitive nature of aphasic impairments and cues that are facilitative of verb retrieval.

Table of Contents

List of Tables

List of Figures

Preface

This has been my most challenging and rewarding experience to date. I am grateful for every minute of the past five years and every individual who has supported me through this adventure. At a moment when the world is plagued with uncertainty and isolation, I cherish this opportunity to express my gratitude for the people who have supported me. You have instilled in me the strength to navigate arduous times and the desire to help others do the same. I look forward to thanking you in person.

This dissertation research was supported through funding received from the National Institutes of Health (NIH) National Institute on Deafness and Other Communication Disorders (NIDCD) F31DC017896; the William Orr Dingwall Foundation's Dissertation Fellowship in the Cognitive, Clinical, and Neural Foundations of Language; the Council of Academic Programs in Communication Sciences and Disorders (CAPCSD) Ph.D. Scholarship; the Audrey Holland Endowed Student Resource Fund; and the University of Pittsburgh's School of Health and Rehabilitation Sciences (SHRS) Ph.D. Student Award for dissertation research.

Over the last five years, many people have fueled and focused my curiosity, passion, and ambition that has culminated in this dissertation work. No one compares to Dr. Michael Walsh Dickey. Mike, you have inspired me and pushed me to explore depths of thought and science I never thought I was capable of. Your enthusiasm is unparalleled, and I aspire to light up a lab as well as you do. Thank you to the rest of my dissertation committee – Drs. Tessa Warren, Will Hula, Frank Yeh, and Julie Fiez – as well as my pre-dissertation committee members – Drs. Connie Tompkins, Malcolm McNeil, Will Evans, and Dawna Duff. It has been a privilege to work with each of you as my mentors and collaborators. Thank you all for your guidance throughout my doctoral adventures. To Tessa and Will, thank you for welcoming me into each of your labs. It was a pleasure to be part of your teams. You have both inspired my thinking and guided my development indescribably.

Thank you to the Pittsburgh community, including my friends and colleagues at the University of Pittsburgh, Carnegie Mellon University, the VA Pittsburgh Healthcare System, the University of Pittsburgh Medical Center, and the Language and Brain Lab. I have had the tremendous fortune of working with many individuals who have inspired me to grow as a thoughtful and creative scientific researcher. First and foremost, thank you to the sympathetic ears and supportive words of Yina Quique, Christina Dastolfo-Hromack, Caryn Herring, Michelle Colvin, Becca Hayes, Alex Swiderski, Rob Cavanaugh, and Abel Lei. I am so glad to have your friendship during our Ph.D. journeys and to have shared endless conversations and coffees to discuss science and life. I would also like to thank Michelle Gravier, Angela Grzybowski, Jessica Barrios, Yutong Zhang, Alyssa Autenreith, Brooke Lang, and Emily Boss for their considerate support. And to our magnificent family in the Language and Brain Lab, it was a joy to lead you for a semester, to share baked goods and popcorn snacks, and to watch you grow into the next wave of young scientists. Finally, thank you to the wonderful individuals who chose to participate in this research. This dissertation would not have been possible without each and every one of you.

Most of all, thank you to my family and friends who have supported me endlessly. To my grandparents, godparents, aunts, uncles, cousins, and friends, your love and encouragement motivate me every day. I am eternally grateful. To my selfless and nurturing parents, Mary and Joel, for their wise words and weekly calls; to my brilliant sisters, Hannah and Grace, for their light-hearted but limitless love; and to Dylan for being by my side every day, keeping me grounded, and always putting a smile on my face – I love you all.

1.0 Specific Aims

Impairments in accessing words and their meanings are common symptoms of *aphasia*, a persistent communication disorder that is among the most debilitating sequelae of stroke. Research into these impairments has primarily focused on nouns. But verb-retrieval deficits are a pervasive and enduring problem for people with aphasia (Mätzig et al., 2009; Rofes et al., 2015). Despite this, evidence is limited as to how people with aphasia access different types of knowledge to support verb retrieval. Identifying the cognitive and neural bases of verb retrieval in people with aphasia is essential to understanding these aphasic retrieval deficits and to formulating efficacious verb treatments. This dissertation research tests competing models of impairments in aphasia with the goal of characterizing conceptual and lexical components of aphasic verb-retrieval (naming) deficits.

Successful verb retrieval can rely on both *conceptual event knowledge* (expectations about events in the world, represented in long-term semantic memory; McRae et al., 2001) and *lexical co-occurrence knowledge* (knowledge of word frequency patterns that occur in language; Dowty, 1982; Jackendoff, 1978), but the roles that these types of knowledge play in aphasic verb-retrieval deficits are not yet clear. Traditional models of aphasia follow *classic cognitive-linguistic accounts*, which assume a separation between conceptual and lexical knowledge (Goodglass, 1993; McNeil & Pratt, 2001). Such accounts predict that people with aphasia have primary impairments in linguistic processes – predominantly associated with damage to the perisylvian language network (e.g., Broca's and Wernicke's areas, and white-matter tracts connecting them, such as the arcuate fasciculus; see Study 2 introduction for more detail). However, individuals with aphasia might use conceptual knowledge to support compensatory strategies (Caramazza & Zurif, 1976; Grodzinsky, 2000).

In contrast, *grounded cognition accounts* contend that knowledge of meaning is encoded in distributed modality-specific sub-systems (Simmons & Barsalou, 2003), such that action knowledge is encoded in primary motor cortex. Language research from this perspective has primarily focused on demonstrating embodied influences and has not considered how language impairment might be explained in this framework. The current project does so. According to grounded cognition accounts, experience with language, action, and events creates distributed, multi-faceted meaning representations that encode information and support performance across both language and conceptual (non-language) systems (Burgess, 1998; Elman, 1990, 1991; Lund & Burgess, 1996; Tabor & Tanenhaus, 1999). Neural damage affecting these distributed representations should therefore impair performance on both language and conceptual tasks. The predictions that individuals with aphasia will experience both lexical *and* conceptual impairments, and that both will impact verb retrieval, are not made by the cognitive-linguistic account (Dresang et al., 2019; Jefferies, 2006; Lei et al., 2016). The experiments in Aim 1 (Chapters 3-4) test the diverging brain-behavior predictions of cognitive-linguistic and grounded cognition accounts with respect to verb retrieval (more specifically, verb production) in aphasia. See section 1.1 for additional information.

In addition to examining how cognitive-linguistic and grounded-cognition models may explain aphasic verb-retrieval deficits, the current project also considers how *rational adaptation* may underlie aphasic language-processing performance. Evidence indicates that people can independently access whichever kind of knowledge best satisfies task demands (Willits et al., 2015); the fact that they do suggests the cognitive system may have been shaped by rational adaptation. Rational adaptation frameworks assume that the cognitive system is optimized to adapt to computational limitations, environmental cues, and specific task goals (Anderson, 1991; Chater & Oaksford, 1999). It is essential to investigate whether and how rational adaptation might be maintained or spared in aphasia, because knowing which information types individuals with aphasia rely on may have critical consequences for treatment success. Aim 2 (Chapter 5) does this by examining how individuals with aphasia respond to lexical versus conceptual cues that facilitate verb naming. See section 1.2 for additional information.

1.1 Aim 1

The purpose of Aim 1 was to examine behavioral (Study 1 in Chapter 3) and neuroanatomical (Study 2 in Chapter 4) predictors of verb retrieval in individuals with aphasia. A validated behavioral battery with both linguistic and non-linguistic stimuli was used to characterize deficits in lexical and conceptual knowledge for actions in adults with and without chronic stroke aphasia (Fiez & Tranel, 1997). Study 1, which is reported in Chapter 3, examined patterns of behavioral impairments to test whether conceptual and lexical knowledge are distinct, with lexical knowledge driving verb retrieval (*cognitive-linguistic account*), or instead both support verb retrieval (*grounded cognition account*). Study 2, which is reported in Chapter 4, relates these patterns of verb-retrieval deficits to structural brain integrity via white matter connectomtery (Yeh et al., 2016), testing whether verb-retrieval deficits are associated with damage to the perisylvian language network (*cognitive-linguistic account*) or a distributed network involving both the perisylvian network *and* motor pathways (*grounded cognition account*). The complementary studies in Aim 1 assess how conceptual, lexical, and neuroanatomical variation influence verb-retrieval deficits in adults with aphasia. These findings will advance neurocognitive accounts of language impairments and will aid the development of neurorehabilitation and speech-language therapies.

1.2 Aim 2

The purpose of Aim 2 was to investigate the principle of *rational adaptation* and to characterize how conceptual versus lexical knowledge support verb retrieval in individuals with aphasia. Study 3, which is presented in Chapter 5, investigated rational adaptation in adults with and without aphasia by comparing how conceptual relatedness versus lexical co-occurrence affects verb retrieval in a naming task, a task in which unimpaired participants preferentially rely on lexical co-occurrence knowledge (Willits et al., 2015). If people with aphasia rationally adapt to the damage in their language system, they should rely primarily on conceptual cues. But if people with aphasia maintain the task biases developed before their impairment, they should show similar or possibly larger effects of lexical co-occurrence knowledge (DeDe, 2012; Gahl, 2002). Results from this study will identify the cues that most strongly facilitate verb retrieval in a cohort of individuals with aphasia. Characterizing the types of knowledge that facilitate verb retrieval will have direct applications to aphasia treatment.

2.0 Background and Significance

Aphasia is a neurological language disorder resulting from brain damage, most commonly due to left-hemisphere cerebrovascular accidents. Chronic aphasia occurs in more than 30 percent of stroke survivors (Flowers et al., 2016; Pedersen et al., 2004), making the estimated prevalence of aphasia in the United States between 2.5 and 4 million (Simmons-Mackie & Cherney, 2018). The consequences of living with aphasia are profound and may reduce health-related quality of life more than cancer or Alzheimer's disease (Lam & Wodchis, 2010). According to the *World Health Organization (WHO) International Classification of Functioning, Disability and Health* framework (ICF; WHO | World Health Organization, n.d.), aphasia extends beyond specific language impairments to limit communication activities and participation in daily life (e.g., talking with significant others, maintaining employment; Simmons-Mackie & Kagan, 2007). Individuals with aphasia report greater levels of general depression and poorer quality of life (Hilari, 2011; Kauhanen et al., 2000; Thomas & Lincoln, 2008). Due to the reduced functional independence of individuals with aphasia, the impact of aphasia is furthermore associated with increased caregiver burden and costs to the health care system (Boehme et al., 2016; Gialanella et al., 2011; Graham et al., 2011; Grawburg et al., 2013a, 2013b; Tsouli et al., 2009). Because the population is aging and the risk of stroke more than doubles for each successive decade after the age of 55 years, more individuals will be affected by aphasia than ever before (Ovbiagele et al., 2013). For these reasons, this dissertation project seeks to further investigate a hallmark of aphasia: anomia.

Anomia, or word-retrieval impairment, is a cardinal feature of aphasia (Goodglass & Wingfield, 1997; Nickels, 2002). Around 70 percent of people with aphasia have pronounced *verb-retrieval deficits* (Mätzig et al., 2009), which are more predictive of everyday communicative function than noun-retrieval impairments are (Rofes et al., 2015). Behavioral treatments targeting verb retrieval can result in improved sentence production (Edmonds, 2016) and communicative effectiveness (Loverso et al., 1988). Despite this, the preponderance of aphasia research and treatment has focused on noun-retrieval impairments. This dissertation provides a careful examination of verb retrieval (specifically, verb naming), investigating behavioral and neuroanatomical variables that characterize verb-retrieval impairments and promote successful verb retrieval in individuals with aphasia. The long-term goal of this research is to inform verb-treatment strategies by identifying factors that determine both the degree and nature of verb-naming impairments as well as the types of cues that are most facilitative of verb naming in individuals with aphasia.

2.1 Models of cognition in aphasic verb-retrieval

Retrieving a verb and its meaning requires activating knowledge gleaned from prior experience with both language and events/actions in the world. Patients with brain damage can show dissociations between linguistic (lexical) and conceptual knowledge regarding verbs and actions, respectively (Kemmerer et al., 2001, 2012). However, psycholinguistic studies of aphasia offer evidence supporting significant overlap between linguistic and conceptual deficits (Dresang et al., 2019; Lei et al., 2016). In Aim 1 of this dissertation, Study 1 assessed the concomitance and relative contribution of verb (lexical) and action (conceptual) knowledge impairments to verb-retrieval deficits in aphasia. In complement to this, Study 2 identified the white matter tracts associated with these deficits in an action naming task, examining whether canonical language tracts or motor tracts (or both) accounted for variation in action-naming performance. In Aim 2, Study 3 further characterized how these two information types facilitate verb retrieval by comparing the influence of lexical co-occurrence patterns and conceptual knowledge regarding actions on verb naming. In doing so, this dissertation work is the first project to characterize the roles of conceptual and linguistic knowledge in aphasic verb-retrieval impairments, and to consider their implications for competing models of cognition and approaches to aphasia treatment.

2.1.1 Cognitive-linguistic accounts

Most theoretical and clinical approaches to aphasia follow traditional *cognitive-linguistic accounts*, which claim that cognition is a modular system that maintains linguistic representations separate from conceptual information (Goodglass, 1993; McNeil & Pratt, 2001). Cognitive-linguistic accounts assume modules are specialized for domain-specific representations and/or processing (Flombaum et al., 2002; Fodor, 1983). The notion of a language module was popularized by Noam Chomsky's theory of Universal Grammar (Coltheart, 1999 for review), and aphasia has historically served as evidence for such modular cognitive-linguistic accounts because people with aphasia generally experience selective language deficits while non-linguistic cognitive computations (including conceptual knowledge) remain relatively unimpaired (Pulvermüller, 2003 for review).

According to cognitive-linguistic accounts, verb retrieval depends on linguistic processes that are supported by perisylvian primary language cortex (Goodglass, 1993). These accounts assume that linguistic and conceptual representations depend on distinct and dissociable neural substrates: linguistic representations (Goodglass, 1993) and aphasic language-performance deficits) are associated with primary language cortex (e.g., left posterior middle temporal gyrus, posterior superior temporal gyrus, inferior frontal gyrus; Hickok & Poeppel, 2004, 2007), whereas conceptual representations are associated with modality-specific regions (e.g., motor cortex/left precentral gyrus).

Cognitive-linguistic accounts are consonant with neurocognitive *dual-stream models of language function*, which propose that language is subserved by two bidirectional functionally and anatomically differentiated pathways (Hickok & Poeppel, 2004, 2007; Roelofs, 2014; Saur et al., 2008; Ueno et al., 2011). First, a ventral semantic stream maps sound to meaning by projecting ventrolaterally to connect speech input to speech recognition areas in bilateral middle and inferior temporal cortices (Hickok & Poeppel, 2004, 2007). White matter tracts that are commonly implicated in the ventral stream include the inferior fronto-occipital fasciculus (IFOF), middle longitudinal fasciculus (MdLF), extreme capsule (EmC), and potentially the uncinate fasciculus (UF; Almairac et al., 2015; Duffau et al., 2013; Han et al., 2013; Ueno et al., 2011). Second, a more strongly left hemisphere lateralized dorsal phonological stream maps sound to articulation. The dorsal stream projects dorsoparietally to regions in the posterior frontal lobe, posterior-dorsal temporal lobe, and parietal operculum, thus reaching regions associated with articulatory representations (Hickok & Poeppel, 2004, 2007). The primary component of the dorsal stream is the arcuate fasciculus (AF), which is associated with phonological and motor processing for speech production (Fernández-Miranda et al., 2015; Glasser & Rilling, 2008; Isenberg et al., 2012; Roelofs, 2014; Saur et al., 2008; Ueno et al., 2011). Additional white matter tracts implicated in the dorsal stream include the middle longitudinal fasciculus (MdLF) and superior longitudinal fasciculus (SLF; Hula et al., in revision; Saur et al., 2008).

The specific white matter tracts involved in the ventral and dorsal processing streams, as well as their particular functional properties, are still a subject of debate (Dick & Tremblay, 2012; Hula et al., in revision; see also discussion in Study 2 below). Critically however, current dual stream language models are primarily or exclusively motivated by evidence regarding the neural correlates of noun processing. Study 2 tests whether the dual-stream tracts identified are also associated with verb naming. This is among the first studies to characterize the white matter tracts involved with verb-retrieval deficits in individuals with aphasia.

Applied to verb retrieval in aphasia, cognitive-linguistic accounts make the following predictions, which are examined in Study 1 and Study 2. First, cognitive-linguistic accounts make the following prediction for Study 1 (Chapter 3): People with aphasia will exhibit dissociable (greater) deficits in verb (linguistic) versus action (conceptual) domains, and linguistic deficits alone will predict success in verb retrieval, because these domains have distinct neural bases and people with aphasia experience greater damage to language brain networks. Second, cognitive-linguistic accounts make a related prediction for Study 2 (Chapter 4): Damage to tracts implicated in dual stream models of language function will be predictive of verb-retrieval deficits among people with aphasia. The former prediction is consistent with findings of double dissociations between verb and action knowledge in some individuals with brain damage (Kemmerer et al., 2012). The latter prediction extends findings regarding the neural substrates of noun-retrieval impairments to verbs, which are particularly associated with language abilities in daily living (Rofes et al., 2015).

2.1.2 Grounded cognition accounts

In contrast to the cognitive-linguistic framework, *grounded cognition accounts* assert that the brain integrates information from sensory, motor, and affective modalities as we experience the world around us (e.g., *eating a cookie*: how the cookie looks and smells, the actions of biting and chewing, introspections of comfort; Barsalou, 2008; see also Study 1 and General Discussion chapters for additional detail). These multimodal experiences are stored as distributed memory representations that can later be activated and retrieved for use (e.g., ordering a *cookie* with your tea). Under this perspective, language processing is accomplished by a general-purpose cognitive system that operates over distributed representations encoding both linguistic and non-linguistic (e.g., affective, sensorimotor) knowledge (Altmann, 2017; Martin, 2016; Zwaan & Madden, 2005). This entails that damage to part of the cognitive system (e.g., motor networks) can result in specific deficits to *both* verb and action processing. Evidence for this prediction comes from neurodegenerative diseases affecting the motor system (e.g., Bak, 2013). For instance, patients with amyotrophic lateral sclerosis are more impaired in action-knowledge tasks than object-knowledge tasks, and their degree of action knowledge impairment is correlated with their degree of motor-cortex atrophy (Grossman et al., 2008). In addition, patients with Parkinson's Disease who have upper limb impairments experience greater deficits retrieving upper-limb (*grab*) than lower-limb verbs (*kick*; Roberts et al., 2017). Such findings suggest that motor systems play a key role in both conceptual and lexical (linguistic) action/verb representations (Gentsch et al., 2016).

Grounded cognition accounts have not yet been applied to aphasia, but this framework predicts that people with aphasia will have deficits in both lexical and conceptual performance. This is because of two key features of grounded cognition models. First, such models assume that language and sensorimotor systems encode similar experience-driven information regarding objects, actions, and events, leading to the emergence of distributed, multimodal meaning representations (Altmann & Mirković, 2009; Elman, 1990). Grounded cognition accounts thus claim that conceptual and lexical representations are inherently intertwined, emerging from the same input and being encoded in the same distributed representations, coded across both sensorimotor and perisylvian language systems (Chen et al., 2017; Simmons & Barsalou, 2003). Second, these accounts claim that these distributed meaning representations support performance in both language and (non-language) conceptual domains. As a result, damage to any part of the neural network critical to activating these representations would yield impairments in *both* lexical and conceptual (e.g., picture-based) tasks (Lambon Ralph, 2014; Patterson, 2007).

Applying grounded cognition accounts to verb retrieval in aphasia predicts that integrity of both primary language and motor neural pathways will be associated with action naming performance. This differs from cognitive-linguistic accounts, which only predict that tracts implicated in the dual-stream model of language function should predict action naming (section 2.1.1). In addition to dual-stream language tracts, grounded cognition accounts predict the involvement of white matter underneath primary motor regions like the dorsal premotor cortex and supplementary motor area (e.g., Rech et al., 2016). These hypothesized fiber tracts include projection fibers that couple motor cortices with subcortical regions and the spinal cord, such as the corticospinal tract (CST), and fibers anterior to the CST including the frontopontine and frontostriatal tracts (a.k.a., subcallosal fascicle). These tracts connect cortical motor representations to subcortical regions that are critically engaged in voluntary movement initiation, execution, and inhibition (Alexander & Crutcher, 1990; Duffau, 2015; Morris et al., 2016; Rea, 2015). There have been very few studies characterizing white matter tracts involved in action naming (c.f., Akinina et al., 2019; Bello et al., 2006, 2007, 2008; see Study 2 for discussion), so it remains unclear the extent to which motor pathways may play a role in verb-retrieval deficits.

Study 1 and Study 2 thus examine two distinct predictions of grounded cognition accounts. First, Study 1 (Chapter 3) investigates the hypothesis that people with aphasia will exhibit deficits in lexical (verb) and conceptual (action) domains, both of which will contribute to verb retrieval impairments. Second, Study 2 (Chapter 4) tests the prediction that damage to white matter tracts subserving both primary language and motor pathways will predict verb-retrieval deficits in people with aphasia. These predictions stand in stark contrast to the predictions of cognitive-linguistic accounts described above. Grounded cognition accounts make these predictions because, by hypothesis, lesion to either motor or language systems can impair access to distributed meaning representations that support performance in both language and (non-language) conceptual domains. These predictions are consistent with evidence that lesion to left primary motor and pre-motor regions are predictive of impaired retrieval of both lexical and conceptual verb/action knowledge in a large sample of adults with brain injury (Kemmerer et al., 2012). This finding provides evidence in favor of grounded cognition accounts of verb meaning (Simmons & Barsalou, 2003). However, no studies to date have examined the behavioral and white-matter neurological predictions of grounded cognition accounts in adults with aphasia.

2.1.3 Rational adaptation

Rational adaptation may be vital to understanding both cognitive models and approaches to language treatment. The principle of *rational adaptation* states that the human cognitive system optimizes its behavior to its environment at all times (Anderson, 1991). If a system exhibits normative rationality, then optimal behavior is defined as a function of the task environment. In addition, systems exhibit architectural rationality when cognition itself is optimally suited for the task environment. And in particular, cognitively bounded rationality exists when behavior is maximized given the constraints of the task environment and the cognitive architecture available (Howes et al., 2009). Cognitively bounded rational adaptation has provided explanations for phenomena that cannot be accounted for by cognitive mechanisms or normative rationality alone (Howes et al., 2009), including probabilistic decision-making (Oaksford & Chater, 1994) and memory decay (Anderson, 1991; Anderson & Milson, 1989; Anderson & Schooler, 1991). Furthermore, evidence also suggests that both neurotypical individuals and people with aphasia rationally adapt to use the most reliable information they have to accomplish a task (Gibson et al., 2015; Warren et al., 2017; see further discussion in Study 3 introduction, section 4.1).

However, rational adaptation has not yet been examined in aphasic verb retrieval, or in aphasic language production more broadly. Aim 2 (Chapter 5) examined whether individuals with aphasia adapt to rely on conceptual cues in a verb naming task in which unimpaired participants preferentially rely on linguistic information (Willits et al., 2015). If people with aphasia rationally adapt to their linguistic deficits, they should rely on conceptual cues to a greater extent than lexical cues (Gibson et al., 2015; Warren et al., 2017). However, if people with aphasia maintain the task approaches or biases they developed before their impairments, they should show similar or possibly larger effects of lexical knowledge on each task compared to neurotypical adults. The potential for larger effects is supported by findings by Gahl and DeDe indicating that individuals with aphasia show outsize effects of lexical co-occurrence (a key component of linguistic knowledge) in acceptability judgments (Gahl, 2002) and self-paced reading (DeDe, 2013a, 2013b), both canonical language-processing tasks.

Study 3 (Chapter 5) tested how conceptual versus lexical information types influence verb retrieval (specifically, verb naming) in people with aphasia. Analyses characterized how individuals with aphasia use rational adaptation to perform speeded verb naming. Regardless of the effects of rational adaptation in this experiment, these findings will contribute directly to verb-retrieval treatment by identifying what cues are most facilitative of verb retrieval in chronic stroke aphasia. This study addresses a critical evidence gap in verb-naming treatments for aphasia – such treatments vary not only in their efficacy but also in the type of cues they use: conceptual (Faroqi-Shah & Graham, 2011; Rose & Sussmilch, 2008), linguistic (de Aguiar et al., 2015; Links et al., 2010), or both (Edmonds, 2016; Loverso et al., 1988). Knowing which cues are most beneficial for which people with aphasia will improve both the design and the selection of maximally efficacious verb-naming treatments.

2.2 Overall significance & innovation

Verb-retrieval impairments are widespread and negatively impact communicative function for individuals living with aphasia. Behavioral treatments can ameliorate these deficits, but the nature of the deficits remains controversial and the action mechanisms of the treatments are poorly understood. Motivated by the contrasting models and hypotheses above, this dissertation examines two primary research questions, which correspond to the two specific aims:

(1) What linguistic and conceptual-motor behavioral and neuroanatomical variables characterize individual variation in verb retrieval in individuals with aphasia?

(2) (How) do people with aphasia rationally adapt their verb-retrieval behavior (reliance on linguistic versus conceptual knowledge) in response to their impairments?

To preview, Study 1 (Chapter 3) investigates the first question by examining the degree to which lexical versus conceptual knowledge of actions predicts variation in verb-retrieval performance on an action naming task. Next, Study 2 (Chapter 4) characterizes how the integrity of language and conceptual-motor fiber tracts predicts verb retrieval. Finally, Study 3 (Chapter 5) examines whether and how individuals with aphasia rationally adapt to their language impairments by relying more on conceptual knowledge than lexical information, as compared to healthy language users. All three studies were conducted in the same sample of adults with chronic stroke aphasia and age-matched controls. The findings of these studies are synthesized, and their implications are discussed in relation to cognitive-linguistic accounts, grounded cognition, and rational adaptation theory in the General Discussion and Conclusion chapters (Chapters 6-7).

This dissertation research is unique in its integration of neuroimaging and behavioral methods to systematically evaluate the behavioral signatures and neurocognitive mechanisms of verb retrieval (naming) impairments in aphasia. Furthermore, this work makes valuable theoretical, methodological, and empirical contributions. It is the first project to use and test a grounded cognition account of aphasic language impairments; it is the first project to directly examine the contributions of white-matter connectivity to verb processing in aphasia; and it provides critical, treatment-relevant evidence regarding the cues that are most facilitative of verb retrieval.

3.0 Study 1: How grounded cognition theory can help characterize behavioral variability in aphasic verb retrieval

3.1 Introduction

Classic cognitive-linguistic accounts assume that aphasia occurs due to breakdowns in the linguistic processing system (Geschwind, 1972; Goodglass, 1993; Lichteim, 1885; McNeil & Pratt, 2001). However, people with aphasia can exhibit both language-specific and conceptual semantic processing deficits (Antonucci & Reilly, 2008; Jefferies, 2006). Theoretical frameworks of cognition make contrasting claims regarding whether language and conceptual semantics are separate systems that can be differentially impaired or whether they form a single intertwined system—damage to which yields impairments in both linguistic and conceptual processing (see section 3.1.1). This theoretical distinction has critical repercussions for aphasia therapies, which treat patient impairments by strengthening residual, unimpaired neural systems for optimal language recovery and performance. Detailed characterization of the neurocognitive systems that are damaged or intact in people with aphasia may therefore inform treatments by identifying which cognitive systems should be targeted in order to improve language performance.

Psycholinguistic and neuropsychological evidence challenges the assumption that breakdowns in linguistic processing are the exclusive source of aphasic impairments (see section 3.1.2). Although conceptual semantic deficits have been documented in some people with aphasia, it remains unclear to what extent and in what ways linguistic versus conceptual impairments might contribute to aphasic deficits. The purpose of this study was to examine individual differences in conceptual versus linguistic processing that characterize variation in a canonical and pervasive symptom of aphasia: verb-retrieval deficits.

The remainder of this introduction will describe how classic accounts of aphasia may not explain the full breadth of verb- and action-retrieval results in the literature and will discuss an alternative framework that may better account for findings of conceptual-semantic impairments in aphasia. Like classic theories, traditional aphasia therapies assume that patients have preserved conceptual knowledge (Antonucci & Reilly, 2008; Jefferies, 2006; Mirman & Britt, 2014). However, this may not always be true, and characterizing conceptual-semantic processing in patients with aphasia will provide better understanding of their locus of impairment and the optimal cognitive systems to target in treatment. Models of aphasia should continuously be revised to acknowledge the complex interactions between language and other cognitive systems. Revising previous models or considering new ones is vital to advancing aphasia treatment and improving patient outcomes.

This study examines how individual differences in the degree of conceptual versus linguistic impairments impact verb-retrieval performance in a sample of individuals with aphasia. Specifically, it examines how performance on a battery of conceptual (picture-based) versus lexical (word-based) action-processing tasks predict variation in action naming, a deficit experienced by 70 percent of people with aphasia (Mätzig et al., 2009). To accomplish this, a standardized battery was used to assess lexical and conceptual knowledge of verbs and actions in people with aphasia and age-matched controls (Fiez & Tranel, 1997; section 3.2). This set of tasks is ideally suited to examine the independent contributions of, and interactions between, lexical and conceptual processing critical to verb/action naming. The battery is designed to measure retrieval of lexical versus conceptual action information, to assess a wide range of action categories (e.g., force, manner), and to discriminate between mild, moderate, and severe impairments (see

Kemmerer et al., 2012). Fiez and Tranel (1997) did extensive norming of this battery, including analyses of name agreement for target verbs, and visual complexity, familiarity, and image agreement for picture stimuli. Previous studies have reported patterns of behavioral associations and dissociations on this set of tasks in a large group of patients with a variety of acquired brain injuries (Kemmerer et al., 2001, 2012). The current study extends this work by focusing more specifically on patients diagnosed with chronic stroke aphasia and examining how retrieval of lexical versus conceptual action information is related to verb-retrieval deficits on the action-naming task.

3.1.1 Theoretical frameworks and hypotheses

Most theoretical and clinical approaches to aphasia follow traditional *cognitive-linguistic accounts*, which assume that cognition is a modular system that maintains linguistic representations separate from conceptual information (Goodglass, 1993; McNeil & Pratt, 2001). According to cognitive-linguistic accounts, linguistic and conceptual representations are distinct and aphasia results from damage to only linguistic processes. Applied to aphasic verb retrieval, cognitive-linguistic accounts predict that people with aphasia will exhibit dissociable (greater) deficits in verb (linguistic) versus action (conceptual) domains. Furthermore, according to such accounts, linguistic deficits but not conceptual deficits will predict success in verb retrieval, because these domains have distinct neural bases and people with aphasia experience (greater) damage to language-related brain networks. This prediction is consistent with findings of double dissociations between verb and action knowledge in some individuals with brain damage (Kemmerer et al., 2012).

In contrast to traditional cognitive-linguistic accounts, *grounded cognition accounts* assert that the brain integrates information from sensory, motor, and affective modalities as we experience the world around us (e.g., *eating a cookie*: how the cookie looks and smells, the actions of biting and chewing, introspections of comfort; Barsalou, 2008). These multimodal experiences are stored as distributed memory representations that can later be activated and retrieved for use (e.g., ordering a *cookie* with your tea). Under this perspective, language processing is accomplished by a general-purpose cognitive system that operates over representations encoding both linguistic and non-linguistic (e.g., affective, sensorimotor) knowledge (Altmann, 2017; Martin, 2016; Zwaan & Madden, 2005). This entails that damage to part of the cognitive system (e.g., motor networks) can result in specific deficits to *both* verb and action processing.

Grounded cognition accounts have not yet been systematically applied to stroke aphasia, but this framework predicts that people with aphasia will have deficits in both linguistic and conceptual performance. This is because of two key features of grounded cognition models. First, such models assume that language and sensorimotor systems encode similar experience-driven information regarding objects, actions, and events, leading to the emergence of distributed, multimodal meaning representations (Altmann & Mirković, 2009; Elman, 1990). Grounded cognition accounts thus claim that linguistic and conceptual representations are inherently intertwined, emerging from the same input and being encoded in the same distributed representations, coded across both sensorimotor and perisylvian language systems (Chen et al., 2017; Simmons & Barsalou, 2003). Second, these accounts claim that these distributed meaning representations support performance in both language and (non-language) conceptual domains. As a result, damage to any part of the neural network critical to activating these representations would yield impairments in *both* linguistic and conceptual (e.g., picture-based) tasks (Altmann & Mirković, 2009; Barsalou, 2008). Applying grounded cognition accounts to aphasic verb retrieval predicts that people with aphasia will exhibit deficits in linguistic (verb) and conceptual (action) domains, both of which will contribute to impaired action naming performance. However, no studies to date have characterized the intricate differences between how conceptual and linguistic components of action knowledge influence verb retrieval in individuals with aphasia.

3.1.2 Conceptual semantics in aphasic language impairments

This section reviews a set of psycholinguistic and neuropsychological findings that challenge the assumption that breakdowns in linguistic processing are necessarily or exclusively the source of verb-retrieval deficits in aphasia.

Although aphasia is primarily characterized by language impairments following brain injury, people with aphasia can exhibit both language-specific and conceptual semantic processing deficits (Antonucci & Reilly, 2008; Jefferies & Lambon Ralph, 2006). Psycholinguistic studies suggest that linguistic and conceptual verb/action deficits are co-present in people with aphasia (Dresang et al., 2019; Kemmerer et al., 2012). Dresang, Dickey, and Warren (2019) found that individuals with chronic stroke aphasia often experience both semantic memory and language impairments, which may be attributed to breakdowns in the complex dynamics between the conceptual semantic system and functional-level language processing, which includes lexical selection (selecting lexical concepts to convey an intended meaning) and function assignment (assigning grammatical roles: who did what to whom; Bock & Levelt, 1994; Garrett, 1975). For example, measures of event- and action-related semantic memory were shown to predict the severity of lexical-selection deficits as measured by the Verb Naming Test and Verb Comprehension Test respectively, from the Northwestern Assessment of Verbs and Sentences (NAVS; Cho-Reyes & Thompson, 2012). In addition, event-related semantic memory performance reliably predicted functional-level verb retrieval and function (thematic role) assignment during sentence production. Taken together, these findings are consistent with models that assume that semantic memory and conceptual knowledge play a critical role in supporting language comprehension (e.g., McRae & Matsuki, 2009; Zwaan, 2016) and production (e.g., Foygel & Dell, 2000; Levelt, 1989). However, classic cognitive-linguistic accounts of aphasia would not predict correlations between semantic memory and language impairments.

On the other hand, there is also evidence suggesting that language and conceptual semantics are distinct systems that can be differentially damaged by brain injury. Neuropsychological studies have found dissociations between linguistic and conceptual processing of actions in a comprehension/object-selection task given to patients with aphasia (Saygin et al., 2004), and on a comprehensive action-knowledge battery (Fiez & Tranel, 1997) given to a large sample of patients with brain damage (Kemmerer et al., 2001, 2012). Saygin and colleagues (2004) employed an object-selection task to examine linguistic and conceptual deficits of action comprehension in 29 participants with aphasia and 18 age-matched controls. Participants were given either a linguistic (text) stimulus (e.g., "he is licking the...") or a conceptual (line drawing) stimulus (e.g., a boy holding and licking an invisible ice cream cone). Participants were instructed to select one of two object pictures that matched or completed the sentence or picture. Participants with aphasia showed deficits on both the linguistic and conceptual tasks, but these deficits were not reliably correlated. In particular, patients who had more severe and non-fluent aphasia profiles showed greater impairment in the linguistic domain compared to the conceptual domain.

However, despite a lack of reliable sample-wide correlation between performance in the language and conceptual domains, Saygin and colleagues (2004) did find other evidence supporting an interrelation between linguistic and conceptual verb/action performance.

Specifically, they found that participants with relatively mild and fluent aphasia profiles showed more robust correlations between impairments on the linguistic and conceptual tasks. Furthermore, no double dissociations between performance on language and conceptual tasks were observed in any of the participants they tested. These data suggest that conceptual-linguistic correlations may be observed only in a subset of individuals with aphasia, perhaps individuals with certain aphasia profiles or with milder aphasia severity.

In a separate series of experiments, Kemmerer and colleagues (2001, 2012) investigated patterns of associations and dissociations from a standardized battery of six verb and action processing tests (Fiez & Tranel, 1997; see section 3.2). In a group of 89 patients with a variety of acquired brain injuries, they found 22 distinct performance profiles (Kemmerer et al., 2001). Similarly, in a subsequent larger-sample study, 226 patients displayed 27 out of 30 possible one-way dissociations among the six tasks (Kemmerer et al., 2012).

Although there was a high amount of variance across individuals, a principal components analysis of 30 participants who were impaired on at least one task indicated that three factors could account for 93% of the observed variance among impaired performances: *voluntary verb retrieval* (verb naming task), *linguistic stimuli* (word-picture matching, word attribute, and word comparison tasks), and *pictorial stimuli* (word-picture matching, picture attribute, and picture comparison tasks; Kemmerer et al., 2001). Each factor accounted for significant covariance in impairment across tasks in the comprehensive battery. The *verb retrieval factor* likely reflects disruptions in the ability to recall and retrieve specific, precise lexical representations that correspond 'best' to the depicted action concept and/or impaired ability to produce phonological forms of specific verbs. Processing shared among verb naming and other tasks are less likely to be reflected by this factor, including visual processing of images, activation of action concepts, and referential processing to map the picture-derived action concepts to a lexical verb structure.

Naming was the most difficult task so it might be expected that a single factor would reflect this difficulty. But importantly, the fact that the verb-naming task loaded very highly (0.99 correlation) on a single independent factor underscores its special status and the need to examine the underlying components of word retrieval in greater detail.

The other factors likely reflect linguistic versus pictorial stimulus types, as well as the distinct processing demands each stimulus type involves. The *linguistic stimuli factor* requires language-specific processing and could capture participant deficits in processing an orthographic or phonological word form or activating its verb-specific semantic structure. As discussed by Kemmerer and colleagues (2001), this factor might also reflect disruptions in the ability to generate mental images of an action and its associated attributes. In contrast, the *pictorial stimuli factor* relies more on conceptual-semantic processing and could reflect impaired activation or identification of appropriate action concepts from picture input. Tasks associated with the linguistic and pictorial stimuli factors share task demands (attribute judgment or comparison) but differ in their input modalities and whether they require or bypass the language system. Comparing linguistic versus pictorial tasks therefore provides critical insight into whether individuals with aphasia have solely impaired retrieval/mapping of linguistic information or additionally have disrupted conceptual-semantic processing.

In addition, Kemmerer and colleagues found that patients with brain damage consistently showed more severe impairments on verb production than verb comprehension tasks (Kemmerer et al., 2001, 2012). This is a common finding in the literature (Bastiaanse & Jonkers, 1998; Berndt, Mitchum, et al., 1997; Breedin et al., 1998; Cho-Reyes & Thompson, 2012; Gabriele Miceli et al., 1988) and highlights the significance of verb-naming deficits and the need for detailed investigation of these impairments. The current study expands on previous work by focusing on verb naming in people with aphasia, who are expected to display different performance patterns than a non-selected group of individuals with brain damage.

3.1.3 Summary

Taken together, these findings suggest that in addition to language-specific impairments, people with aphasia can also have conceptual semantic impairments. Verb naming is associated with unique variance, but it remains unclear how linguistic and conceptual processing support successful verb retrieval. This study examines whether language and conceptual-semantics are distinct or integrally intertwined systems, the extent to which they are each impaired in people with aphasia, and what the (possibly dissociable) contributions of linguistic and conceptual impairments are to aphasic verb-retrieval deficits. Traditional *cognitive-linguistic accounts* hypothesize that language and conceptual processing are separate systems, that individuals with aphasia are distinctly impaired on linguistic (word-based) tasks, and that only linguistic ability robustly predicts retrieval performance during verb naming. This is because the cognitive-linguistic account assumes that linguistic representations are distinct and differentially damaged in individuals with aphasia. In contrast, the *grounded cognition account* predicts that language and conceptual processing are intertwined systems, and that people with aphasia have parallel degrees of impairment on conceptual (picture-based) and linguistic (word-based) tasks, such that performance on both task types are similarly predictive of verb-naming retrieval. This is because grounded cognition accounts assume commingled conceptual-linguistic representations, which would be jointly damaged by stroke.

The current study is designed to probe how well classic cognitive-linguistic accounts of aphasia explain the state of evidence and evaluate whether these frameworks should be revised or abandoned in favor of a more grounded, embodied account of cognition. Characterizing the contributions of impaired lexical and conceptual action-processing that result in aphasic verb-retrieval deficits is critical not only for developing theories of disordered language processing, but it is also integral for treatment planning.

3.2 Methods

3.2.1 Participants

Participants were 17 individuals with chronic aphasia due to unilateral left hemisphere stroke and 15 age-matched neurotypical controls. All participants were 1) native English speakers, 2) able to provide informed consent, 3) 25-85 years old, 4) (pre-morbidly) right-handed, and 5) had no history of progressive neurological or psychiatric disease, drug, or alcohol dependence, or significant mood or behavioral disorder. In addition, individuals with aphasia all were more than 6 months post-onset (range: 19-265 months; M=95.8, SD=62 months), had a Comprehensive Aphasia Test (CAT; Swinburn, Porter, & Howard, 2004) Naming Modality T-score ≥ 40, and an overall mean T-score < 70. Demographic participant characteristics are reported in Table 1 for participants with aphasia and Table 2 for age-matched controls.

Table 1. Demographic characteristics of participants with aphasia

Participant ID	Age	Sex	Education Level	Years of Education	Months Post-Onset	Years Post-Onset
7201	59	F	Graduate degree	20	132	11
7202	63	M	Bachelor's degree	14	265	22.08
7203	61	F	Master's degree	17	60	5
7204	55	M	High school	12	53	4.42
7205	52	M	High school	12	136	11.33
7206	78	F	Some graduate	13	114	9.5
7207	70	F	Some college	14	45	3.75
7208	76	M	Some college	14	138	11.5
7209	77	M	Law degree	19	53	4.42
7210	54	M	Bachelor's degree	16	83	6.92
7211	71	M	Some college	14	26	2.17
7212	55	M	Bachelor's degree	16	19	1.58
7213	68	M	High school	12	184	15.33
7214	53	F	Bachelor's degree	17	81	6.75
7215	71	M	Bachelor's degree	16	87	7.25
7216	72	M	Some college	14	60	5
7217	72	M	Some college	15	93	7.75
Summary	M=65.12 SD=9.11	5 F; 12 M		M=15 SD=2.35	M=95.82 SD=62	M=7.99 SD=5.17

Table 2. Demographic characteristics of age-matched control participants

Participant ID	Age	Sex	Education Level	Years of Education
7001	42	M	Tech college	14.5
7002	59	M	High school	12
7003	74	M	Bachelor's degree	16
7004	52	M	Bachelor's degree	16
7005	54	M	Bachelor's degree	16
7006	57	M	High school	12
7007	72	F	Master's degree	18
7008	64	F	Master's degree	18
7010	74	M	Master's degree	20
7011	68	F	Master's degree	22
7012	72	M	Bachelor's degree	16
7013	65	M	Law degree	19
7014	71	F	Master's degree	17
7015	52	M	Master's degree	22
7016	69	F	Master's degree	18
Summary	M=63 SD=9.82	5 F; 10 M		M=17.1 SD=3

Participants who met any of the following criteria were excluded: 1) significant hearing loss or vision impairment that prevented them from completing the experimental tasks, or 2) pre-existing or subsequent brain injury/stroke (e.g., to right-hemisphere regions for individuals with aphasia). Cognitive screening and general language assessment measures, including the CAT, were already available for the participants with aphasia, who all participated in Hula and colleagues' study (Hula et al., in revision). Participants were excluded if their CAT Cognitive Screening recognition memory T scores were under 30, which would be indicative of frank auditory, visual, motor speech, or general cognitive deficits. In addition, neurotypical participants were excluded if they failed a line-bisection visual screening, a binaural pure-tone hearing screening (0.5, 1, 2, and 4 KHz at 40 dB), a Mini-Mental State Examination cognitive screen (required 27/30; Folstein et al., 1975), or Raven's Coloured Progressive Matrices non-linguistic cognitive screen (required 30/36; Raven, 1965).

Institutional Review Board approval was obtained, and all participants provided informed written consent and were compensated for their time.

3.2.2 Materials

All participants completed a set of behavioral language and conceptual knowledge assessments to test verb and action processing. A standardized action knowledge battery (Fiez & Tranel, 1997) was used to probe participants' abilities to retrieve lexical and conceptual information pertaining to actions. The action knowledge battery consisted of (1) a verb production task (action naming), (2) two conceptual, picture-based tasks (picture attribute and picture comparison judgments), and (3) two linguistic, verb-based tasks (word attribute and word comparison judgments). See section 3.2.3 and Fiez and Tranel (1997) for task details. These tasks provide a comprehensive and detailed classification of linguistic versus conceptual verb and action impairments. These will henceforth be referred to as lexical versus conceptual action-processing abilities and impairments.

3.2.3 Testing procedure

The full battery of tasks was presented on a computer monitor, in the same order presented by Kemmerer and colleagues (2012): Naming, Picture Comparison, Picture Attribute, Word Comparison, and Word Attribute. Participants were given detailed instructions and practice items, to ensure they understood each task. Brief descriptions of the tasks are provided below. Further details are reported in Fiez and Tranel (1997) and Kemmerer, Tranel, and Barrash (2001). For a summary of previous studies that have used tests from this battery, see Kemmerer and colleagues (2012). Participants viewed stimuli on computer screen. Participants were allowed an unlimited amount of time to respond to each item. An external microphone recorded naming responses in Audacity® software, and trial-level accuracy was scored by hand for each task.

Naming Task (N = 100 items): For each item, the participant was shown a single colored photograph of a person or animal performing an action. The participant was instructed to provide a single word/verb that describes what the person or animal was doing. The participant's first response was recorded. Following Fiez and Tranel (1997), experimenters prompted participants for a second response if the participant did not provide a verb (e.g. "Can you tell me what the person is *doing*?") or if the participant provided a description (e.g. "Can you give me a *single word* that best describes what the person is doing?"). Target responses provided after a prompt were also scored as correct. Alternate forms of a target verb were accepted as correct (e.g. run, running, ran). Normative data (from Fiez & Tranel, 1997): M = 85.0% correct; SD = 5.0.

Picture Comparison Task (N = 24 items): For each item, the participant was shown three colored photographs depicting actions. The participant was instructed to determine which picture showed an *action* that was most different in meaning from the other two (e.g. cutting a pie, cutting a piece of paper, folding a piece of paper). This task is analogous to the Word Comparison Task. Normative data (from Fiez & Tranel, 1997): M = 83.6% correct; SD = 8.3.

Picture Attribute Task (N = 72 items): For each item, the participant was shown two colored photographs depicting actions and an attribute judgment question. The experimenter read the question aloud. The participant was instructed to indicate which picture best answered the question (e.g., "Which action would make the loudest sound?"). This task is analogous to the Word Attribute Task. Normative data (from Fiez & Tranel, 1997): M = 91.7% correct; SD = 4.8.

Word Comparison Task (N = 44 items): For each item, the participant was shown three printed verbs. The experimenter read the verbs aloud. The participant was instructed to determine which word was most different in meaning from the other two. This task is analogous to the Picture Comparison Task. Normative data (from Fiez & Tranel, 1997): M = 88.7% correct; SD = 8.1.

Word Attribute Task (N = 62 items): For each item, the participant was shown two printed verbs and an attribute judgment question. The experimenter read the question and the verbs aloud. The participant was instructed to indicate which verb best answered the question (e.g., "Which action would make the loudest sound?"). This task is analogous to the Picture Attribute Task. Normative data (from Fiez & Tranel, 1997): M = 94.8% correct; SD = 2.6.

Participant performance on each task is reported in Table 3 for participants with aphasia and Table 4 for age-matched controls.

Table 3. Conceptual and lexical action-processing performance (percent accuracy) for participants with aphasia

Participant ID	Verb Naming	Conceptual Action-Processing		Lexical Action-Processing		CAT Modality Mean T Score
		Picture Comparison	Picture Attribute	Word Comparison	Word Attribute	
7201	0.63	0.88	0.93	0.80	0.82	56.33
7202	0.31	0.58	0.58	0.34	0.53	47.83
7203	0.56	0.50	0.83	0.70	0.92	59.67
7204	0.77	0.79	0.86	0.75	0.84	56
7205	0.44	0.29	0.85	0.73	0.84	48.33
7206	0.89	0.63	0.89	0.86	0.94	66.67
7207	0.52	0.33	0.76	0.77	0.97	59
7208	0.13	0.25	0.69	0.39	0.60	47.83
7209	0.51	0.33	0.85	0.75	0.81	52.83
7210	0.59	0.75	0.81	0.34	0.73	51.33
7211	0.67	0.46	0.79	0.59	0.69	50.33
7212	0.53	0.92	0.88	0.77	0.81	51.17
7213	0.43	0.63	0.78	0.64	0.76	49.83
7214	0.67	0.54	0.86	0.57	0.90	62
7215	0.02	0.29	0.64	0.48	0.56	53.17
7216	0.35	0.54	0.86	0.70	0.82	42.5
7217	0.44	0.46	0.74	0.68	0.94	58.67
M	0.50	0.54	0.80	0.64	0.79	53.73
SD	0.22	0.21	0.09	0.16	0.13	6.13

Notes: CAT = The Comprehensive Aphasia Test (Swinburn et al., 2004) assesses aphasia severity. All other measures come from Fiez & Tranel, 1997.

Table 4. Conceptual and lexical action-processing performance (percent accuracy) for age-matched controls

Participant ID	Verb Naming	Conceptual Action-Processing		Lexical Action-Processing	
		Picture Comparison	Picture Attribute	Word Comparison	Word Attribute
7001	0.9	0.96	0.94	0.93	0.97
7002	0.99	0.83	0.90	0.95	0.98
7003	0.9	0.92	0.92	0.86	0.94
7004	0.86	0.75	0.96	0.98	0.92
7005	0.94	0.88	0.93	0.80	0.98
7006	0.8	0.63	0.82	0.84	0.92
7007	0.92	0.92	0.94	0.95	0.94
7008	0.95	0.92	0.99	1	0.95
7010	0.92	0.79	0.94	0.93	0.98
7011	0.98	0.96	0.94	0.93	0.90
7012	0.95	0.96	0.92	0.91	0.98
7013	0.87	0.79	0.93	0.98	0.97
7014	0.93	1	0.94	0.93	0.95
7015	0.94	0.83	0.93	1	0.95
7016	0.89	0.79	0.94	0.95	0.98
M	0.92	0.86	0.93	0.93	0.95
SD	0.05	0.10	0.04	0.06	0.03

Notes: All measures come from Fiez & Tranel, 1997.

3.2.4 Analyses

Data were analyzed using Bayesian multilevel logistic regression models, which were created in the Stan computational framework (Carpenter et al., 2017; http://mc-stan.org/) and accessed with the brms package (Bürkner, 2017). Ability estimates from Naming, Picture Comparison, Picture Attribute, Word Comparison, and Word Attribute tasks were assessed in terms of the assumptions of normality, homoscedasticity, linearity, and the presence of outliers. Individual task accuracy underwent empirical logit transformations, and empirical logit scores were z-score transformed and averaged to create standardized composite scores for conceptual action-processing performance (Picture Comparison, Picture Attribute) and lexical action-processing performance (Word Comparison, Word Attribute). This model structure allows examination of the effects of conceptual versus lexical action-processing skills on verb retrieval (action naming) ability. Grouping performance on conceptual versus lexical tasks is supported by the design of the standardized battery (Fiez & Tranel, 1997) and the factor analysis reviewed in the introduction (Kemmerer et al., 2001). Furthermore, the current sample of participants with aphasia demonstrated correlations between the conceptual action-processing tasks (Picture Comparison and Picture Attribute: $r = 0.78$, $p < 0.001$) and between the lexical action-processing tasks (Word Comparison and Word Attribute: $r = 0.78$, $p < 0.001$; see Table 5 for full task correlation matrix). Trial-level action-naming performance served as the outcome variable for two models.

Table 5. Correlation matrix for task performance and severity for participants with aphasia

	Naming	Picture Comparison	Picture Attribute	Word Comparison	Word Attribute	CAT Modality Mean
Naming	1					
Picture Comparison	0.54	1				
Picture Attribute	0.73	0.78	1			
Word Comparison	0.56	0.21	0.73	1		
Word Attribute	0.66	0.15	0.69	0.78	1	
CAT Modality Mean	0.62	0.14	0.35	0.42	0.61	1

Notes: All correlations are significant at p<0.001 after Bonferroni corrections for multiple comparisons. Naming, Picture Comparison, Picture Attribute, Word Comparison, and Word Attribute measures are correlated based on percent of correct trials (Fiez & Tranel, 1997). CAT = The Comprehensive Aphasia Test Modality Mean T Score (Swinburn et al., 2004) assesses aphasia severity.

In Model 1, naming performance was compared between participant groups. Fixed effects were group assignment (participants with aphasia coded as 0 vs. neurotypical controls coded as 1), conceptual and lexical action-processing composite z-scores, and a three-way interaction effect (group x conceptual z-scores x lexical z-scores). Random intercepts were included for subjects and items. Random slopes were included for conceptual and lexical z-scores within subjects and group within items. More complex random effects structures failed to converge.

In Model 2, aphasic performance was examined in greater detail. Table 5 summarizes the full correlation matrix across task performance in participants with aphasia. Given the substantial covariance across tasks, as is common among individuals with aphasia and other neurologically impaired populations, additional regression analyses examined the extent to which conceptual versus lexical action-processing performance predicted verb retrieval ability. Fixed effects were aphasia severity (CAT Modality Mean T Score), conceptual and lexical composite z-scores, and a three-way interaction effect (severity x conceptual z-score x lexical z-score). Random intercepts were included for subjects and items. Random slopes were included for conceptual and lexical z-scores within subjects and aphasia severity within items. Models including more complex random slopes failed to converge.

For both models, each parameter was given dispersed starting values and a vague prior, thus allowing the Bayesian estimation process to explore the full parameter space and provide conservative estimates of posterior distributions (McElreath, 2018). For each model, four Hamiltonian Bernoulli family Markov chain Monte Carlo (MCMC) chains were run for 20,000 samples, with half of the iterations discarded as warm-up and 10,000 iterations monitored for convergence and parameter estimation. MCMC convergence was assessed graphically by inspection of the autocorrelation and trace plots (Appendix A) and statistically using the Gelman-Rubin potential scale reduction statistic ($\hat{R}$) and the number of effective samples (ESS; Tables 6 and 7). The $\hat{R}$ statistic is a ratio of the variance within each chain to the variance pooled across chains. $\hat{R}$ values close to 1 indicate satisfactory convergence of the chains to a stable distribution (Gelman et al., 2013). ESS factors out the autocorrelation in the observed MCMC chains and estimates the number of independent samples that would achieve the same degree of precision for the parameter estimates (Carpenter et al., 2017). Large ESS values indicate satisfactory convergence. The posterior distributions are summarized by the estimated parameters and 95% highest density credible intervals (HDI). The HDI is comparable to the frequentist confidence interval and is determined as the narrowest interval containing the assigned proportion of the posterior distribution's probability mass within which all values have a higher probability density than any values outside the interval (see Fergadiotis et al., 2019 for further explanation).

3.3 Results

3.3.1 Model 1: Effect of group on action naming performance

The trace plots for all parameters demonstrated rapid convergence and were stationary relative to the parameter means. There were no divergent transitions. The autocorrelation plots corroborated this assessment and showed minimal autocorrelation. These plots are provided in Appendix A1. The $\hat{R}$ statistic and number of effective samples for each parameter indicated satisfactory convergence and MCMC mixing. These statistics are reported in Table 6. Table 6 also provides the point estimates and 95% high density credible intervals for each parameter. The posterior predictive check is shown in Figure 1. Histograms of the posterior distributions for the estimates discussed below are provided in Figures 2-6.

As expected, group (aphasia versus control) reliably predicted trial-level action naming accuracy ($\beta = 3.26$, EE = 0.38, 95% HDI = [2.54, 4.07]; Figure 2), with participants with aphasia ($M = 0.495$ $SD = 0.208$) performing less well than controls ($M = 0.916$, $SD = 0.047$). Furthermore, the effect of group status was influenced by both conceptual and lexical action-processing ability, such that aphasia amplified the effect of conceptual ($\beta = -0.54$, EE = 0.58, 95% HDI = [-1.77, 0.55]) and lexical ability ($\beta = -0.30$, EE = 0.53, 95% HDI = [-1.32, 0.76]) on action naming. Despite these trends, the posterior probabilities of these effects were not reliably different from zero (Figures 3-4). However, conceptual action-processing ability alone reliably predicted action naming (β = 0.82, EE = 0.39, 95% HDI = [0.09, 1.62]; Figure 5). In addition, conceptual and lexical action-processing abilities interacted, such that higher conceptual ability reduced the effect of lexical impairments on action naming, and vice versa (β = -0.26, EE = 0.44, 95% HDI = [-1.13, 0.60]). Once again, the credible interval of this interaction effect's posterior probability was not reliably different from zero (Figure 6). The full set of results is reported in Table 6.

Table 6. Model 1 population-level effects for participants with aphasia and age-matched control participants

	Estimate	Est. Error	Lower 95% HDI	Upper 95% HDI	$\hat{R}$	Bulk ESS	Tail ESS
(Intercept)	0.05	0.28	-0.49	0.59	1	4048	5900
Group	3.26	0.38	2.54	4.07	1	6655	6545
Conceptual action-processing	0.82	0.39	0.09	1.62	1	4479	5873
Lexical action-processing	0.31	0.38	-0.45	1.03	1	4021	4686
Group : Conceptual	-0.54	0.58	-1.77	0.55	1	4944	5132
Group : Lexical	-0.3	0.53	-1.32	0.76	1	4159	4539
Conceptual : Lexical	-0.26	0.44	-1.13	0.60	1	3284	4700
Group : Conceptual : Lexical	-0.11	0.65	-1.47	1.12	1	3159	4559

Notes: Composite scores for conceptual action-processing and lexical action-processing were calculated by an empirical-logit and z-score transformation per participant. HDI=Highest density interval. $\hat{R}$=The potential scale reduction factor on split chains (at convergence, $\hat{R}$= 1). ESS=Effective sample size.

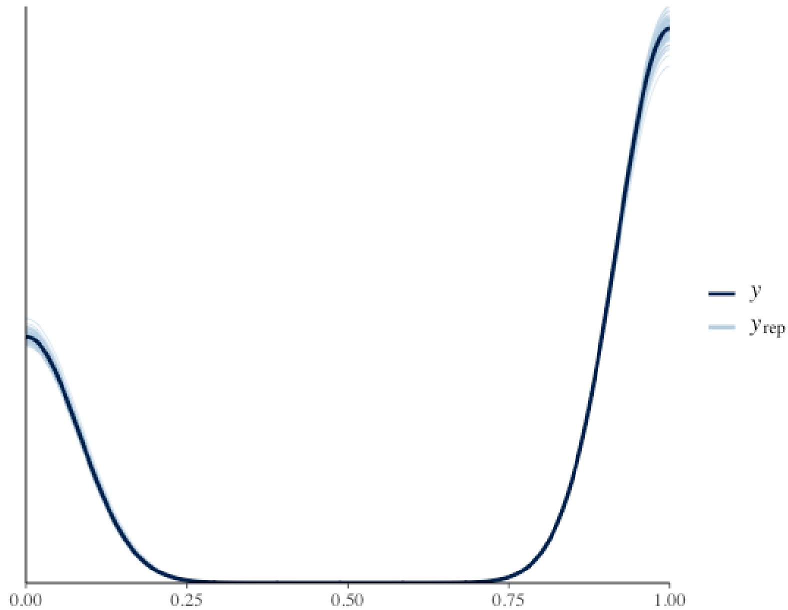


Figure 1. Posterior predictive check for Model 1

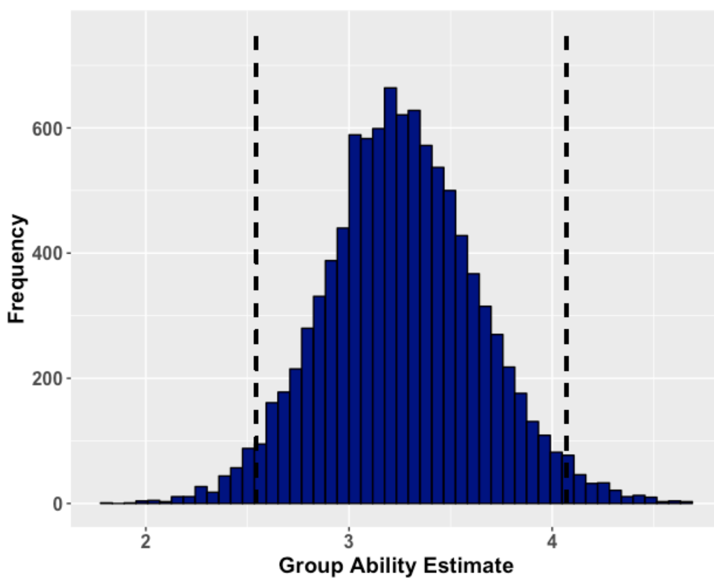


Figure 2. Posterior distributions and 95% highest density intervals (HDIs) of the fixed effect of group from Model 1 (participants with aphasia and healthy controls)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

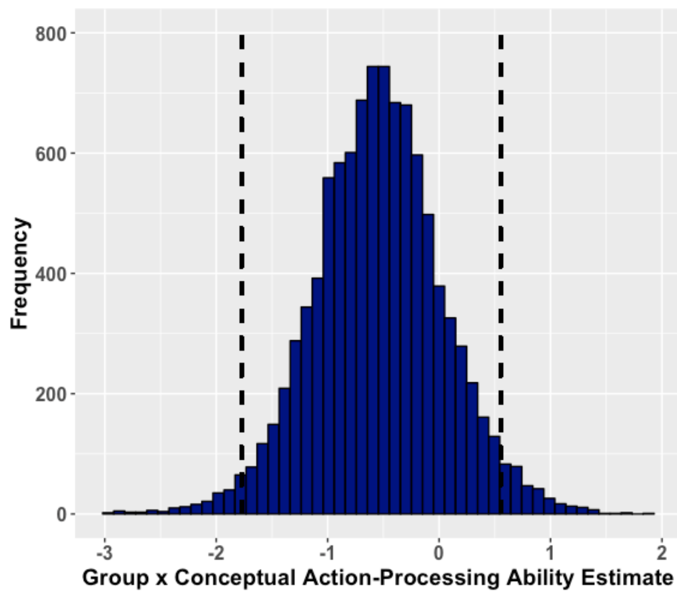


Figure 3. Posterior distributions and 95% highest density intervals (HDIs) of the interaction effect of group and conceptual action-processing Model 1 (participants with aphasia and healthy controls)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

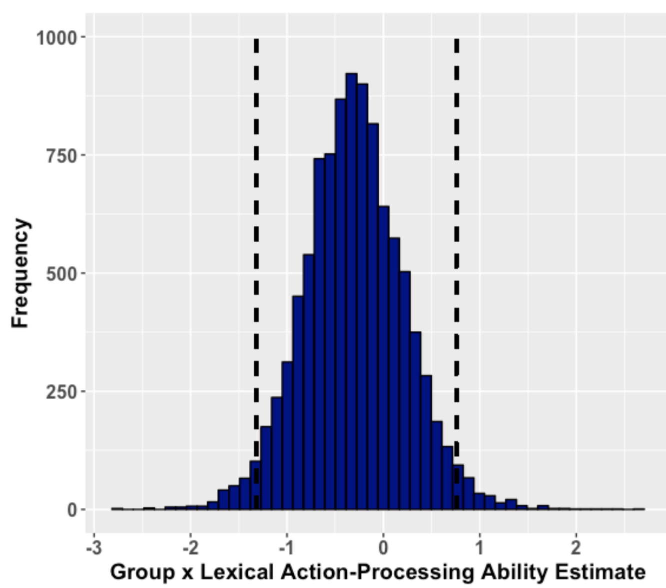


Figure 4. Posterior distributions and 95% highest density intervals (HDIs) of the interaction effect of group and lexical action-processing from Model 1 (participants with aphasia and healthy controls)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

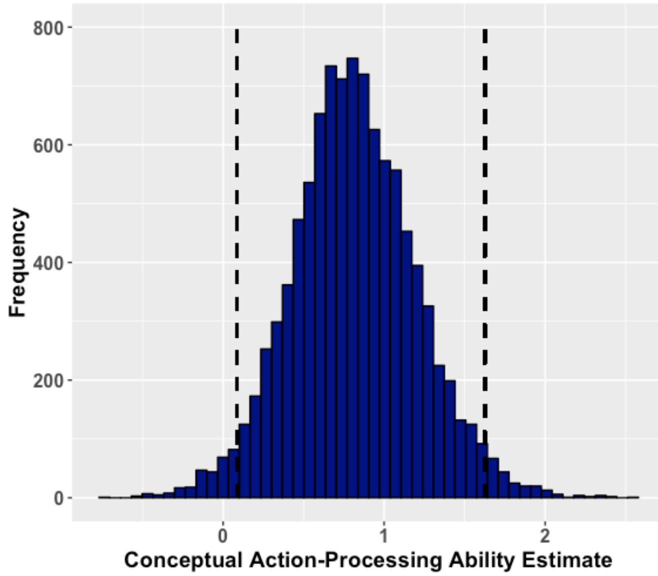


Figure 5. Posterior distributions and 95% highest density intervals (HDIs) of the fixed effect of conceptual action-processing from Model 1 (participants with aphasia and healthy controls)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

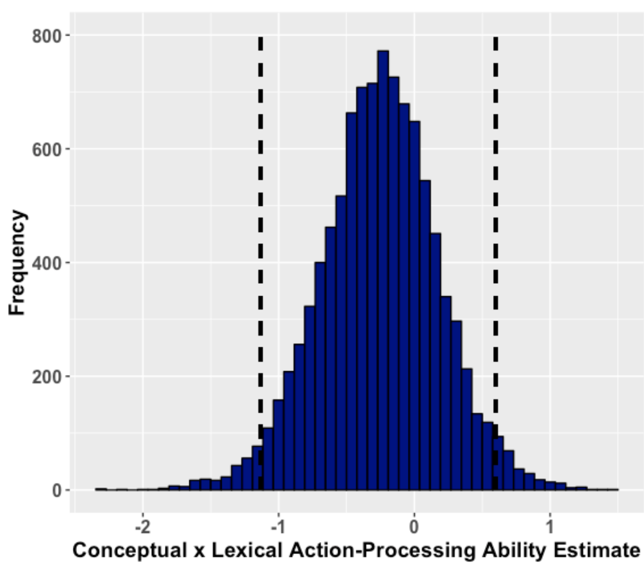


Figure 6. Posterior distributions and 95% highest density intervals (HDIs) of the interaction effect of conceptual and lexical action-processing from Model 1 (participants with aphasia and healthy controls)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

3.3.2 Model 2: Conceptual and lexical action-processing associations with verb naming impairments in adults with aphasia

The trace plots for all parameters demonstrated rapid convergence and were stationary relative to the parameter means. There were no divergent transitions. The autocorrelation plots corroborated this assessment and showed minimal autocorrelation. These plots are provided in Appendix A2. The $\hat{R}$ statistic and number of effective samples for each parameter indicated satisfactory convergence and MCMC mixing. These statistics are reported in Table 7. Table 7 also provides the point estimates and 95% credible intervals for each parameter. The posterior predictive check is shown in Figure 7. Histograms of the posterior distributions for the estimates discussed below are provided in Figures 8-11.

Model 2 results indicate that the degree of aphasia severity (CAT) further interacted with both conceptual and lexical action-processing ability, such that milder aphasia amplified the effect of both conceptual (β = 1.05, EE = 0.82, 95% HDI = [-0.52, 2.76]; Figure 8) and lexical ability (β = 0.42, EE = 0.52, 95% HDI = [-0.69, 1.49]; Figure 9) on action naming. Although the posterior probabilities of these effects overlapped with zero, 91.65 percent of the posterior probability distribution for the interaction effect between severity and conceptual processing exceeded zero, and 82.68 percent of posterior probability distribution for the for the severity and lexical processing interaction exceeded zero. Parallel to results from Model 1, conceptual action-processing ability alone robustly predicted action naming in participants with aphasia (β = 0.93, EE = 0.52, 95% HDI = [-0.07, 2.00]; Figure 10) but lexical action-processing ability did not (β = -0.02, EE = 0.49, 95% HDI = [-1.00, 0.99]). Furthermore, conceptual and lexical action-processing abilities also interacted to predict naming, such that higher conceptual ability reduced the effect of lexical impairments on action naming, and vice versa (β = -1.15, EE = 0.68, 95% HDI = [-2.53, 0.15];

Figure 11). This interaction effect was robust, with 99.98 percent of the posterior probability less than 0. The full set of results is reported in Table 7.

Table 7. Model 2 population-level effects for participants with aphasia

	Estimate	Est. Error	Lower 95% HDI	Upper 95% HDI	$\hat{R}$	Bulk ESS	Tail ESS
(Intercept)	-0.02	0.32	-0.66	0.62	1	1431	1895
Aphasia severity	0.14	0.35	-0.52	0.85	1	1128	1225
Conceptual action-processing	0.93	0.52	-0.07	2.00	1	1455	1601
Lexical action-processing	-0.02	0.49	-1.00	0.99	1	1511	1146
Severity : Conceptual	1.05	0.82	-0.52	2.76	1	1039	942
Severity : Lexical	0.42	0.52	-0.60	1.49	1	1292	1064
Conceptual : Lexical	-1.15	0.68	-2.53	0.15	1	884	1156
Severity : Conceptual : Lexical	-0.03	0.62	-1.25	1.27	1	1671	1784

Notes: Aphasia severity was z-score transformed CAT modality mean score. Composite scores for conceptual action-processing and lexical action-processing were calculated by an empirical-logit and z-score transformation per participant. HDI=Highest density interval. $\hat{R}$=The potential scale reduction factor on split chains (at convergence, $\hat{R}$ = 1). ESS=Effective sample size.

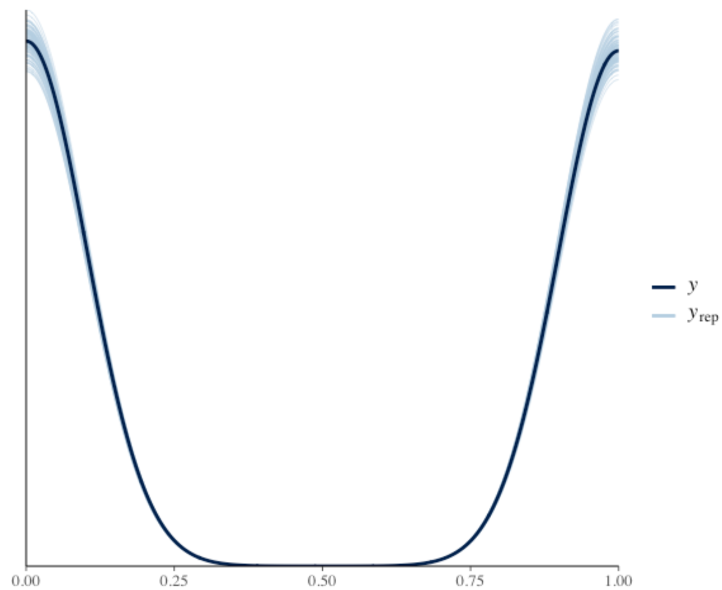


Figure 7. Posterior predictive check for Model 2

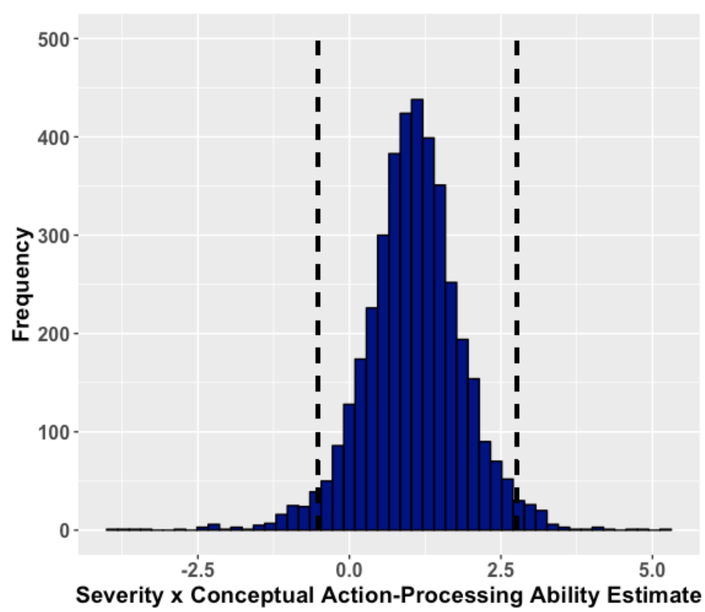


Figure 8. Posterior distributions and 95% highest density intervals (HDIs) of the interaction effect of aphasia severity and conceptual action-processing from Model 2 (participants with aphasia)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

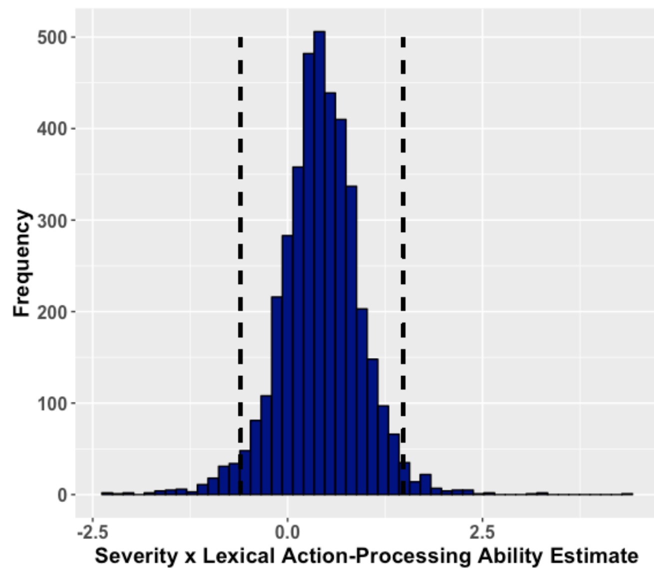


Figure 9. Posterior distributions and 95% highest density intervals (HDIs) of the interaction effect of aphasia severity and lexical action-processing from Model 2 (participants with aphasia)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

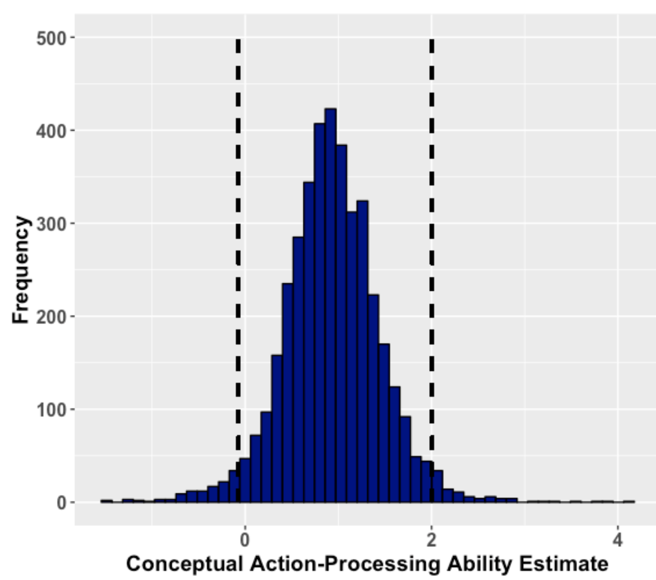


Figure 10. Posterior distributions and 95% highest density intervals (HDIs) of the fixed effect of conceptual action-processing from Model 2 (participants with aphasia)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

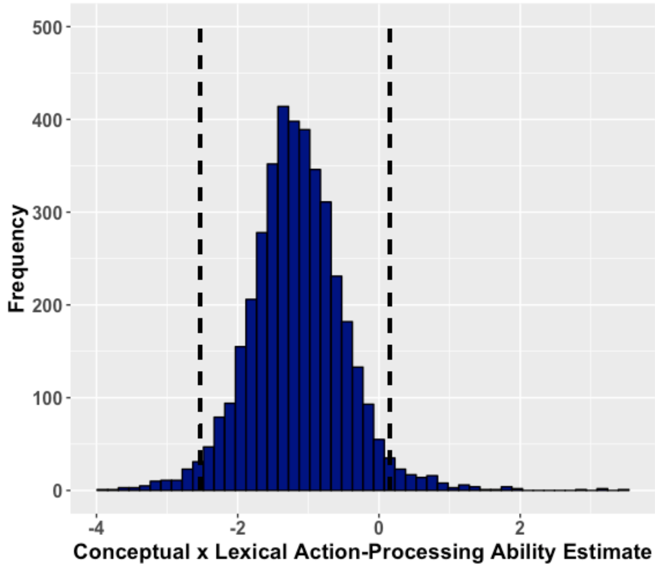


Figure 11. Posterior distributions and 95% highest density intervals (HDIs) of the interaction effect of conceptual and lexical action-processing from Model 2 (participants with aphasia)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

3.4 Discussion

The purpose of this study was to examine the degree to which lexical and conceptual action-processing are distinct or integrally intertwined systems, the extent to which each of these processing systems are impaired in adults with aphasia, and how impairments to each contribute to aphasic verb-retrieval deficits. Findings pertinent to these questions are summarized below and discussed in relation to literature of verb-retrieval deficits, theories of cognition, and potential translation to aphasia treatment.

17 individuals with chronic aphasia due to unilateral left hemisphere stroke and 15 age-matched neurotypical controls completed a standardized action knowledge battery (Fiez & Tranel, 1997) to assess participants' lexical and conceptual action-processing abilities. Each participant

completed (1) a verb production task (action naming), (2) two conceptual, picture-based tasks (picture attribute and picture comparison judgments), and (3) two linguistic, verb-based tasks (word attribute and word comparison judgments).

In this sample, participants with aphasia performed reliably less well than controls in measures of both lexical and conceptual action-processing, as well as action naming. Presence of aphasia amplified the effects of both conceptual and lexical abilities on naming performance. The effect of conceptual processing appeared more robust than the effect of lexical processing on action naming. However, it is possible that this finding could be attributed, in part, to both action naming and conceptual processing tasks relying on cognitive processes involved with picture-based input and mapping of visual information to semantic meaning. Regardless, the effects of both conceptual and lexical abilities on action naming were particularly robust for individuals with more mild aphasia, as measured by the CAT Modality Mean T Score (Swinburn et al., 2004). Critically, lexical processing on its own was not a reliable predictor of verb retrieval in people with aphasia. Rather, both conceptual action-processing and the interaction between lexical and conceptual processing robustly predicted verb-retrieval deficits. Specifically, these results suggest that the interactivity between conceptual and lexical processing systems allows for strong conceptual skills to attenuate and outweigh the effects of lexical impairments on action naming (and vice versa). Taken together, these results suggest that both lexical and conceptual action-processing can be impaired in people with aphasia, and that impairments in both lexical and conceptual abilities contribute to action naming deficits. These findings furthermore highlight the importance of interactions between lexical and conceptual systems to characterizing verb-retrieval performance in aphasia and other neurological conditions (Bak, 2013; Friedemann Pulvermüller, 2018; Vigliocco et al., 2011). This strong interactivity would seem to be at odds with strict cognitive-linguistic accounts that maintain a stark separation between conceptual and linguistic processing.

Classic cognitive-linguistic accounts of aphasia do not predict correlations between conceptual-semantic and language impairments. Traditional cognitive-linguistic accounts treat language and conceptual processing as separate systems, and they assume aphasia results from damage to only language systems, resulting in uniquely linguistic impairments. In contrast, this study found that people with aphasia have impairments that extend beyond language tasks, and that conceptual-semantic ability critically interacts with linguistic impairments to predict verb-retrieval deficits. The results indicate that what are traditionally considered language (naming) impairments in aphasia can in fact reflect deficits that extend beyond the 'language system' and the ability to retrieve or process lexical information. The strong association between conceptual-semantic ability and naming performance is consistent with theories of cognition that emphasize the role of semantic memory and conceptual knowledge in supporting language performance (Dresang et al., 2019; Foygel & Dell, 2000; Levelt, 1989; McRae & Matsuki, 2009; Zwaan, 2016).

These findings may be more consistent with grounded cognition accounts, which predict that language and conceptual processing are intertwined systems that can be similarly damaged by strokes that produce aphasia. Individuals with aphasia in this sample showed correlations between conceptual and lexical action-processing abilities, which is consistent with grounded cognition accounts. Cognitive-linguistic accounts would predict that all individuals with aphasia should have better performance on conceptual than lexical action-processing, but that was not true in the current sample. In addition, conceptual and linguistic performance interacted to predict verb-naming ability, suggesting that deficits in conceptual-semantic and lexical processing each contribute to naming impairments. One possible account of these findings is that conceptual-linguistic representations are commingled and jointly damaged by stroke, as grounded cognition frameworks would suggest (Barsalou, 2008; Barsalou, 2016; Chen et al., 2017; Martin, 2016; Simmons & Barsalou, 2003). However, future work is needed to further investigate the current finding that stronger conceptual abilities attenuate the effect of lexical impairments on action naming. If this interaction effect is replicated in larger samples of people with aphasia, cognitive frameworks will need to characterize the neurocognitive mechanisms underlying this interactivity.

The current study does not definitively test the contrasting predictions of cognitive-linguistic and grounded cognition theories. Although the emerging patterns of results appear consistent with grounded views that emphasize the role of both conceptual-semantic and lexical processing in naming, cognitive-linguistic frameworks may also explain the current the interactions observed between conceptual and lexical performance. This interaction is consistent with cognitive-linguistic predictions that language and conceptual semantics are distinct systems that can be differentially damaged by brain injury, resulting in a wide variety of possible patterns of dissociation and compensation between lexical and conceptual action processing (Kemmerer et al., 2001; Saygin et al., 2004; Study 3).

Regardless of whether cognitive-linguistic or grounded cognition accounts better explain the current findings, the high interactivity between conceptual and lexical ability suggests potential trade-offs between these systems. The precise nature of conceptual-linguistic system interactions could also be explained by other cognitive accounts, such as the information-theoretic principle of *rational adaption*, which predicts that people rely on different information sources as needed to optimize behavior for the specific situation at hand 8/7/2020 4:55:00 PM. In particular, rational adaptation would predict that when the lexical system is more impaired and less reliable, individuals with aphasia should rely more on conceptual-semantic systems to support language tasks like verb retrieval. Although the current findings indicate that conceptual and linguistic systems interact in a way that may be characterized by rational adaptation, it remains unclear under what task- and patient-specific circumstances a tradeoff between these systems is likely to occur.

The predictions of rational adaptation in aphasic verb retrieval are investigated further in Study 3 of this dissertation.

Verb-retrieval deficits are traditionally considered to be disruptions in the ability to retrieve precise lexical representations (Barde et al., 2006; Bastiaanse & Jonkers, 1998; Berndt, Mitchum, et al., 1997; Breedin et al., 1998; Cho-Reyes & Thompson, 2012; Gordon & Dell, 2003). The current findings challenge this view by indicating that breakdowns in conceptual processing also contribute to aphasia's hallmark of naming impairments. These results echo and extend previous findings that people with aphasia have both linguistic and conceptual-semantic impairments (Antonucci & Reilly, 2008; Howard & Gatehouse, 2006; Jefferies & Lambon Ralph, 2006; Saygin et al., 2004; progressive aphasia: Lambon Ralph & Howard, 2000) and that these impairments extend to action processing (Dresang et al., 2019). Dresang, Dickey, and Warren (2019) hypothesized that these co-impairments might results from breakdowns in the dynamics between the conceptual semantic system and functional language processing. The current finding of robust interactions between lexical and conceptual abilities is in line with this hypothesis, and it more specifically predicts that individuals with relatively intact conceptual action-processing may perform well on verb naming despite language impairments at the lexical (functional language) processing stage.

In addition, these results extend findings from Kemmerer, Tranel, and Barrash (2001) who found that linguistic and pictorial tasks in Fiez and Tranel's battery were associated with ('loaded on') separate factors. The current experiment examined the individual contributions of these linguistic (lexical) and pictorial (conceptual) factors in predicting action naming. Our results suggest that verb-retrieval deficits are associated not only with breakdowns at the level of mapping between linguistic representations and meaning (e.g., as measured by successfully selecting whether the word *yawning* or *singing* makes a louder sound; Fiez & Tranel, 1997), but also with breakdowns at the level of non-linguistic conceptual-semantics (e.g., as measured by successfully selecting the image/concept that makes a louder sound; Fiez & Tranel, 1997).

The strong associations between conceptual and lexical action-processing found in this study are largely congruous with neuropsychological investigations comparing conceptual and linguistic action knowledge in individuals with brain damage. Saygin and colleagues (2004) also found that participants with aphasia showed impairments on both conceptual and linguistic tasks, but that performance between the two task types was only correlated in individuals with relatively mild and fluent aphasia profiles. On the other hand, more severe and nonfluent individuals showed disproportionately more impaired linguistic than conceptual performance. The current study design provides deeper insight into this relationship by examining the extent to which these conceptual-linguistic abilities contribute to aphasic naming deficits. In the current sample, individuals with more mild aphasia showed more robust effects of both conceptual and lexical action-processing on naming. Although Kemmerer and colleagues (2012) identified patterns of double dissociations between conceptual action and lexical verb knowledge, the majority of their participants demonstrated associations on their performance of Fiez and Tranel's tasks. Furthermore, it is unclear whether any of the individuals who showed dissociations had stroke aphasia. In contrast to the current study, the behavioral and lesion association studies by Kemmerer and colleagues (2001, 2012), included participants with a variety of brain injuries. These participants had widely distributed lesions in the left and right cerebral hemispheres and were thus likely to display a broader range of cognitive impairments than the subjects in our sample. In addition, the tasks were not grouped by general conceptual versus lexical processing ability, so the reported dissociations may also reflect task-specific skills required for comparison and attribute judgments.

Despite these experimental differences, Kemmerer and colleagues' (2012) lesion-deficit analyses supported the grounded cognition account's predictions that conceptual knowledge is grounded in sensorimotor systems. In particular, they found that impairments on all tasks from the Fiez and Tranel (1997) battery were associated with lesion to the left inferior frontal gyrus, ventral precentral gyrus, and primary motor and premotor areas. The association between primary motor and premotor cortex – which are principal brain regions involved with non-linguistic motor function – has also been reported in numerous functional neuroimaging studies (Kemmerer et al., 2012 for summary), neurostimulation studies (e.g., Gerfo et al., 2008; Pulvermüller, 2005), and neuropsychological studies in patient populations such as amyotrophic lateral sclerosis (e.g., Grossman et al., 2008).

These findings underscore that stronger conceptual action-processing is associated with less impaired verb naming, regardless of lexical action-processing ability. This has a critical message for treatment: improving conceptual-semantic performance should be able to ameliorate action-naming deficits in adults with stroke aphasia. This is consistent with the hypothesized mechanism of action underlying efficacious speech-language treatments like Semantic Feature Analysis (SFA; Boyle, 2010), SFA for Actions (Wambaugh et al., 2014), and Verb Network Strengthening Treatment (VNeST; Edmonds, 2016). These interventions aim to promote improved lexical retrieval abilities beyond items that are explicitly trained, so that participants may be able to improve lexical retrieval across a hierarchy of linguistic contexts, including sentences and discourses. VNeST is a particularly relevant intervention because it depends on the semantic (and syntactic) centrality of verbs in language (Edmonds, 2016). The hypothesis is that systematic activation of conceptually related thematic roles promotes increased activation of semantic "verb networks" (Edmonds, 2016), based on evidence for bidirectional priming and facilitation effects between verbs and their thematic roles (e.g., Ferretti et al., 2001; McRae et al., 2005). Although there is individual variability in response to treatment, VNeST has shown promise in exhibiting robust improvements in noun and verb naming, as well as generalization to lexical retrieval in sentences and discourses (Edmonds, 2016). Although individuals with mild to moderate-to-severe fluent and nonfluent aphasia have shown improvements under these interventions, additional research like the current study is needed to divulge person-specific predictors and neurocognitive mechanisms underlying these treatments.

Future research will examine the effects of person-specific properties on the benefit of conceptual action-processing in language rehabilitation. This study offers preliminary evidence that individuals who have more mild aphasia may exhibit amplified effects of conceptual processing on naming ability compared to participants with greater severity. This suggests that people with more mild language impairments might respond particularly well to treatment that target lexical retrieval via strengthening conceptual-semantic networks (e.g., VNeST, Edmonds, 2016). More detailed individual-level assessments may reveal patient profiles that are most likely to respond to conceptual-semantic interventions for language rehabilitation. It will be critical to explore assessments in greater detail because evidence from patient case studies (Lambon Ralph & Howard, 2000) and computational models (Lambon Ralph et al., 2001) suggests that semantic impairments can contribute to word-retrieval deficits even when they are not detected by conventional comprehension tests. In closing, thorough assessments of conceptual-semantic and lexical processing must be explored to fully characterize verb-retrieval deficits in patients with aphasia, doing so may advance predictors of treatment response and inform candidacy selection processes for language rehabilitation treatments.

3.5 Conclusion

This study found evidence that lexical and conceptual action-processing interact to support verb retrieval. Impairments to both lexical and conceptual action-processing are prevalent in adults with stroke aphasia, and conceptual processing interacts with lexical abilities to contribute to verb-retrieval deficits. Theories of cognition must be able to account for conceptual-semantic impairments in aphasia and high interactivity between lexical and conceptual processing systems. Accounts of grounded cognition might be expanded to model interactions between language and conceptual semantics, but further work is needed to characterize how these systems interact in both healthy and disordered language users. Study 2 begins to do this by evaluating neural predictors of verb retrieval in adults with and without aphasia. Neuroimaging evidence will vitally inform patient-specific predictors and neurocognitive mechanisms that support verb retrieval and enable interactions between conceptual and linguistic systems.

4.0 Study 2: White matter neuroanatomical predictors of aphasic verb retrieval and their consequences for neurolinguistic models

4.1 Introduction

Seventy percent of individuals with aphasia experience verb-retrieval deficits (Mätzig et al., 2009), and speech-language treatments that focus on strengthening verbs elicit increased lexical retrieval of nouns and verbs in sentences, discourses, and untrained items and tasks (e.g., Edmonds, 2016). However, not all individuals achieve these positive treatment outcomes. There is relatively little research on the neurocognitive mechanisms and sources of individual variability underlying verb-retrieval deficits and response to verb treatments. One major source of variability in people with aphasia is the location and extent of neurological damage. Lesion characteristics, including patterns of white matter damage, strongly influence aphasia symptoms and severity (Alyahya et al., 2020; Basilakos et al., 2014; Bates et al., 2003; den Ouden et al., 2019; Marebwa et al., 2017).

The majority of neurolinguistic production models are based on the characterization of cortical substrates of object naming and noun retrieval. Verbs and nouns engage distinct types of knowledge (Baker, 2003; Vigliocco et al., 2011), serve different functions in language (Vigliocco et al., 2011 for review of psycholinguistic models), and can be differentially impaired in aphasia (Caramazza & Hillis, 1990, 1991; Kim & Thompson, 2000, 2004; Miceli et al., 1984, 1988; Zingeser & Berndt, 1988). For these reasons, it is vital to improve our understanding of the neural correlates of action naming and verb-retrieval deficits.

In recent years, more functional neuroimaging and lesion studies have examined action words and concepts, but there remain inconsistent results and theoretical disagreement regarding the role of motor regions in verb processing (see section 4.1.1; Akinina et al., 2019 for discussion). Furthermore, the white matter tracts associated with verb-retrieval deficits are seldom specified. Of note, many neuroimaging studies of verbs that report white matter correlates do not examine or identify specific fiber tracts. For example, lesion-deficit approaches can characterize white matter damage correlated with behavioral impairments, but studies using these approaches seldom describe *specific tracts* that are associated with impaired verb retrieval.

Prominent dual-stream models of language function propose a cortical organization of language consisting of functionally and anatomically differentiated dorsal and ventral processing streams (Hickok & Poeppel, 2004, 2007; Roelofs, 2014; Saur et al., 2008; Ueno et al., 2011). Recent findings offer converging support for a specific set of white matter pathways and their functional contributions to word production (section 4.1.1; c.f., Dick & Tremblay, 2012). However, neuropsychological evidence supporting dual-stream language models predominantly comes from object naming error patterns (Dell et al., 2013; Hula et al., in revision). It is thus unclear whether prevailing neurolinguistic models accurately account for verb processing and action-naming impairments. Addressing this limitation will not only advance neurolinguistic accounts of verbs and verb-retrieval deficits but will also provide novel insight into competing models of human cognition.

Two prominent theories of cognition make distinct predictions about the brain structures recruited during language processing and investigating these contrasting predictions may critically advance neurolinguistic models of verbs and verb-retrieval deficits. On one hand, *cognitive-linguistic accounts* of aphasia view language as a distinct network that engages pathways identified by the dual-stream language model (section 4.1.1.1). On the other hand, *grounded cognition* *accounts* predict that both language pathways and distributed conceptual-motor pathways are critical to action naming. These theoretical frameworks and their implications for healthy and disordered verb retrieval are discussed further in section 4.1.2. This study addresses significant gaps in the literature by identifying specific white matter tracts associated with verb retrieval in a sample of individuals with stroke aphasia and age-matched controls. Specifically, this study examines how the integrity of white-matter fiber tracts in language and conceptual-motor networks predict variation in action-naming performance.

4.1.1 White matter networks underlying verb retrieval

Neuroimaging and neuropsychological studies of verb retrieval often fail to characterize the functional involvement of white matter tracts. In order to understand the neurocognitive networks involved in verb retrieval, it is essential to examine white matter connectivity because robust connections between specific cortical regions are vital to successful language processing (e.g., Catani & Mesulam, 2008; Hula et al., in revision; Saur et al., 2010). Furthermore, tract-based connections enable disparate neural regions to exert strong mutual influences over each other, yielding similar responses to various inputs (Chen et al., 2017 for discussion). Investigating the functional role of white matter tracts and neural connectivity will advance understanding of functional specialization in the brain and disordered language processing (Catani & Mesulam, 2008; Chen et al., 2017).

White matter integrity proves critical in studies of language and speech fluency. Speech and language rely on intact connections between perisylvian language regions and motor and sensory feedback areas (e.g., Hickok & Poeppel, 2004, 2007), and compromised integrity of these tracts results in different types and degrees of impairments (e.g., Basilakos et al., 2014; Catani &

Mesulam, 2008). The integrity of white matter regions has traditionally been underappreciated in aphasia research, but recent studies show promise that white matter characteristics can predict post-stroke speech and language deficits, including chronic aphasia symptoms (Basilakos et al., 2014; Bonilha & Fridriksson, 2009; Fridriksson et al., 2013; Hula et al., in revision; Marebwa et al., 2017; Swiderski et al., 2019). This study therefore focuses its investigation on the integrity of white matter tracts that are associated with verb retrieval in individuals with and without aphasia.

4.1.1.1 White matter networks subserving language: dual-stream models of language function

Theories of brain organization posit that cognitive functions like language are organized in widespread networks consisting of specialized brain regions and their interconnecting white matter fiber tracts (e.g., Hickok & Poeppel, 2004, 2007; Saur et al., 2008). *Dual-stream models* are a prevalent account of functional-anatomical organization that has been applied to multiple cognitive domains including visual (Milner & Goodale, 2008) and auditory processing (Rauschecker & Scott, 2009). Parallel to these models, *dual-stream models of language function* (Hickok & Poeppel, 2004, 2007; Roelofs, 2014; Saur et al., 2008; Ueno et al., 2011) assume that language consists of two cortical interface streams: A ventral semantic stream that maps sound to meaning and a dorsal phonological stream that maps sound to articulation. The ventral stream has a weak left-hemisphere bias and projects ventrolaterally to connect sensory speech input to bilateral middle and inferior temporal cortex (Hickok & Poeppel, 2004, 2007). The dorsal stream is more strongly left-hemisphere dominant and projects dorsoparietally to the posterior frontal lobe and the posterior-dorsal temporal lobe. Critically, these processing streams are bi-directional and thus support both auditory comprehension (e.g., Hickok & Poeppel, 2004) and speech production (e.g., Hula et al., in revision).

The precise neuroanatomical basis and white matter substrates of the dual-stream model of language function are still debated (Dick & Tremblay, 2012; Hula et al., in revision), but general agreement is emerging regarding the involvement of certain tracts. The arcuate fasciculus (AF), which participates in phonological and motor-speech processing, is the primary dorsal stream tract (Fernández-Miranda et al., 2015; Glasser & Rilling, 2008; Roelofs, 2014; Saur et al., 2008; Ueno et al., 2011). In addition, specific portions of the AF may also contribute to semantic processing in language production (Catani et al., 2005; Fernández-Miranda et al., 2015; Glasser & Rilling, 2008; Hula et al., in revision; Roelofs, 2014). Semantic processing in the ventral stream is associated with the middle longitudinal fasciculus (MdLF), the inferior fronto-occipital fasciculus (IFOF), the uncinate fasciculus (UF), and the extreme capsule (Almairac et al., 2015; de Champfleur et al., 2013; Duffau et al., 2013; Han et al., 2013; Hula et al., in revision; Saur et al., 2008; Ueno et al., 2011).

Hula and colleagues (in revision) examined the white matter components of dual-stream language models by investigating structural white matter connectivity associated with semantic and phonological object naming abilities in a sample of 42 individuals with chronic aphasia. Participants first completed the Philadelphia Naming Test (Roach et al., 1996). Next, the SP interactive two-step model, a computational model of word production (Dell et al., 2013), was used to derive s and p parameter values from their naming performance to index semantic and phonological ability. Diffusion spectrum imaging data were collected for each participant, and connectometry analyses (Yeh et al., 2016) examined two multiple regression models to identify the local connectomes associated with s and p parameters. The connectometry results indicated that the structural integrity of both dorsal and ventral tracts was associated with semantic ability, while only dorsal tracts were associated with phonological ability. In particular, semantic processing tracts included the AF, IFOF, UF, and MdLF. Phonological processing tracts included the AF and MdLF. In addition, limbic tracts such as the posterior cingulum and fornix were also associated with both semantic and phonological processing for object naming. These results are largely consistent with dual-stream models of language function, but critically indicate that semantic processing is associated with both dorsal and ventral pathways, the AF is involved in both semantic and phonological processing, and subcortical and limbic structures may also be associated with naming ability.

A significant limitation of Hula and colleagues' study (in revision) is that they only investigated chronic left-hemisphere stroke survivors with aphasia. This is problematic for at least two reasons. First, high lesion overlap in posterior inferior frontal lobe limited the power to detect behavioral associations with fiber tracts in this region. Second, it is unclear whether the identified tracts are associated with object naming only in response to the aphasia-producing lesion or to what extent the findings reflect tracts associated with naming in healthy, pre-stroke brain organization. The current study therefore extends the work of Hula and colleagues by applying the same analytic approach of connectometry in a subset of the Hula et al. (in revision) participants to examine the specific white matter components of *action naming* networks in a sample that also includes healthy control participants without stroke aphasia.

4.1.1.2 White matter networks subserving action naming

There have been very few investigations of white matter fiber tracts associated with verb retrieval. However, Bello and colleagues reported a series of action naming findings from intraoperative language mapping experiments in awake surgery patients (Bello et al., 2006, 2007, 2008). They found that verb processing involved portions of the superior longitudinal fasciculus (SLF), AF, UF, and IFOF. Phonemic paraphasias (word or non-word substitutes that share resemblance to the target word sounds; e.g., dog, gog) were elicited by stimulations to dorsal pathway fiber tracts: SLF, AF, and the subcallosal fasciculus. In contrast, semantic paraphasias (word substitutes related to the target word in meaning; e.g, dog, cat) were produced during stimulation of ventral pathway tracts: UF, IFOF, and ILF. These observations are consistent with dual-stream models of language.

In addition, Akinina and colleagues (2019) were perhaps the first to examine both gray and white matter substrates of the lexical-semantic stages of action naming. Forty native speakers of Russian with stroke-induced aphasia and/or dysarthria were asked to name 80 black-and-white line drawings. Akinina and colleagues (2019) scored and categorized error types that were most likely attributed to lexical-semantic versus phonological deficits. Voxel-based lesion-symptom mapping analyses examined the involvement of gray and white matter regions with lexical-semantic error rate, using phonological error rate as a covariate. The analysis of white matter involvement revealed many white matter fibers that were associated with lexical-semantic processes of action naming. Among these tracts, which were associated with over 80% probability of disconnection, were the frontal aslant tract (FAT), IFOF, SLF II and III, UF, long segment of the AF, fronto-orbital polar and frontal inferior longitudinal tracts, and the fronto-insular tract. In addition, projection fibers were identified that couple the cortex with subcortical regions and the spinal cord, including anterior thalamic projections, corticospinal, frontostriatal and frontopontine tracts. As already discussed, the IFOF, UF, and AF are often implicated in object naming and are consistent with dual-stream models of language function.

On the other hand, the SLF, FAT, and projection fibers are not frequently identified in studies of object naming or dual-stream language models. It is possible that these white matter tracts are uniquely positioned to subserve action naming due to their involvement in action processing and motor control. For example, the SLF, which connects frontal regions to temporo-parietal regions, has been implicated in motor-speech articulation (Duffau et al., 2014; Makris et al., 2005), ideomotor apraxia (Hong et al., 2012; Leiguarda & Marsden, 2000), as well as motor function sequences, semantic action processing, and motor imagery such as mental rotation tasks (Parlatini et al., 2017). In addition, the FAT, which bridges supplementary and pre-supplementary motor areas from the superior frontal gyrus to posterior portions of the inferior frontal gyrus (Catani et al., 2012), has been associated with verbal fluency and motor speech initiation (Catani et al., 2013; Fujii et al., 2015; Kinoshita et al., 2015; Kronfeld-Duenias et al., 2016; Sierpowska et al., 2015; Vassal et al., 2014). Budisavljevic and colleagues (2017) also found associations between the FAT and variation in visually guided hand movements, suggesting that the FAT may contribute to a motor control network that operates beyond the speech and language domain.

Akinina and colleagues (2019) also identified associations between verb retrieval and the fronto-orbital polar tract, frontal inferior longitudinal fasciculus, and fronto-insular tract 4, which are short U-shaped intra-lobar fibers. These fibers tend to connect neighboring gyri by skirting around cortical sulci (Catani & Thiebaut de Schotten, 2012; Catani et al., 2012). Of particular interest, the frontal inferior longitudinal fasciculus connects the precentral gyrus to the ventral middle frontal gyrus and superior inferior frontal gyrus, thus bridging cortex commonly associated with action to language. In addition, the 4^{th} bundle of the fronto-insular tract projects from the precentral gyrus to the anterior insula, which has a role in body representation and emotional experience (Rojkova et al., 2016).

Finally, Akinina and colleagues (2019) also identified projection fibers, which connect cerebral cortex to subcortical regions of the brain and spinal cord. In particular, Akinina and colleagues identified correlations with anterior thalamic projections that are associated with spatial navigation and memory (Jankowski et al., 2013; Molnar et al., 2006), corticospinal projections that are involved in voluntary motor control (Cho et al., 2007; Jang et al., 2008; Lee et al., 2005; Welniarz et al., 2017; Zhu et al., 2010), frontostriatal circuits that modulate motor control and executive function (Haber, 2016; Morris et al., 2016), and frontopontine tracts that connect cortex to the opposite cerebellum for the coordination of planned motor functions (Rea, 2015).

Taken together, these findings indicate that action naming performance is associated with a widely distributed network of cortical regions and underlying white matter pathways. Furthermore, white matter tracts outside of the dual stream model of language may be vital for action naming in patients with verb-retrieval deficits. The specific language functions associated with the identified white matter tracts of projection pathways have yet to be thoroughly investigated, but the functional-anatomical networks identified here suggest that these tracts may be poised to connect the language system to action and affective representations. This broad set of multimodal connections supporting verb processing provides preliminary support for grounded accounts of cognition.

Although there have been limited investigations of white matter tracts involved with verb retrieval, other neuropsychological and neuroimaging experiments offer evidence consistent with grounded cognition accounts of primary motor and premotor cortex (i.e. principal gray matter motor regions) critically supporting verb- and action-knowledge. For example, patients with neurodegenerative diseases affecting primary motor and premotor cortex have shown correlations between degree of damage or atrophy and impairments of both action knowledge and verb retrieval (Bak, 2013; Grossman et al., 2008; Roberts et al., 2017; Chapter 1 for discussion). In addition, primary motor and premotor cortex have been identified in functional neuroimaging studies of verb retrieval (Kemmerer et al., 2012 for summary) and neurostimulation studies facilitating (Pulvermüller et al., 2005) or disrupting action-related semantic processing (Gerfo et al., 2008). These studies do not examine white matter tracts but are consistent with grounded cognition's prediction of the involvement of the corticospinal tract, which is a primary pathway that carries movement-related signals between motor cortices and the spinal cord. Damage to the corticospinal tract has been associated not only with motor impairments (Calautti & Baron, 2003; Jang, 2009, 2011, 2012), but also with action semantics (Vicario et al., 2013) and abstract language processing (Glenberg et al., 2008).

4.1.2 Theoretical frameworks and hypotheses

Grounded cognition accounts state that cognition is rooted in experience-driven multimodal representations that are activated to simulate sensory, motor, and introspective states (e.g., Barsalou, 2008). Critically, grounded cognition proposes that multimodal experiences are stored as distributed memory representations. Under this framework, language processing is accomplished by a general-purpose cognitive system that operates over representations that encode both linguistic and non-linguistic knowledge (e.g., perception, action, and introspection; Altmann, 2017; Barsalou, 2008; Martin, 2016; Zwaan & Madden, 2005).

Although grounded cognition accounts have not been examined in aphasic verb retrieval, preliminary neuropsychological and neurostimulation evidence support a grounded approach to verb processing (Vigliocco et al., 2011 for review of behavioral, electrophysiological, neuropsychological, and imaging evidence related to verbs/actions). For example, Kemmerer and colleagues (2012) found that lesion to left primary motor and pre-motor regions are predictive of impaired retrieval of both linguistic verb and conceptual action knowledge in a large sample of adults with brain injury. In addition, Pulvermüller and colleagues (2005) applied transcranial magnetic stimulation (TMS) to arm and leg areas of motor cortex while participants made lexical decisions about action words. They found that stimulating the arm area of motor cortex led to faster lexical decisions on only arm verbs whereas stimulating the leg area resulted only in faster leg verb processing. Courson, Macoir, and Tremblay (2017) also used repetitive TMS to examine the cortical regions underlying verb processing, finding that verb processing critically depends on supplementary motor area, which has also been linked to motor planning and execution, as well as action-related conceptual tasks like motor imagery. Such TMS evidence supports a causal role of primary motor cortex and prefrontal cortex in retrieving action words, which suggests that people may retrieve non-linguistic motor information when producing or comprehending action words (Vigliocco et al., 2011 for review).

These results demonstrate functional links between action and language systems during verb processing, providing evidence in favor of grounded cognition accounts of verb meaning (Barsalou et al., 2003; Simmons & Barsalou, 2003). Extending grounded cognition accounts to verb-retrieval deficits in aphasia predicts that damage to both primary language *and* motor cortices/pathways will be associated with action-naming impairments. This is because lesion to either motor or language systems can impair access to distributed meaning representations, which support performance in both language and (non-language) conceptual domains. Studies to date have not precisely identified the white-matter fiber tracts associated with verb retrieval, nor have they examined whether a grounded cognition framework could be better suited to account for aphasic impairments than dual-stream language models.

Most theoretical and clinical approaches to aphasia follow traditional *cognitive-linguistic accounts*, which assume cognition is a modular system that maintains linguistic representations separate from conceptual information (Goodglass, 1993; McNeil & Pratt, 2001). Unlike grounded cognition, these accounts assume that conceptual and linguistic processing depend on distinct and dissociable neural substrates: conceptual processing would be associated with modality-specific regions (like motor cortex and subserving white matter pathways), whereas linguistic processing and aphasic language-performance deficits would be associated with perisylvian language cortex and white matter pathways (e.g., Goodglass, 1993). According to cognitive-linguistic accounts, verb retrieval depends on linguistic processes that are supported by perisylvian language cortex, including posterior middle temporal gyrus, posterior superior temporal gyrus, and inferior frontal gyrus (Binder et al., 1997; Geschwind, 1965; Lichteim, 1885; Wernicke, 1874), as well as fiber tracts within the dual-stream model discussed earlier. However, this theoretical prediction has not been directly tested for white matter tracts associated with verb-retrieval deficits in aphasia.

4.1.3 Summary

The purpose of the current study was to examine the relationship between action-naming impairment in aphasia and white matter connectivity. This study addresses the lack of research investigating the neural mechanisms underlying healthy and disordered verb retrieval. Evidence for white matter correlates of verb retrieval to date is largely indirect and inconsistent. However, Akinina and colleagues (2019) identified the involvement of white matter tracts that are not traditionally included in dual-stream models of language.

Cognitive models of language function make distinct predictions about the neural networks involved in action naming and verb-retrieval deficits. To summarize, *grounded cognition accounts* predict that in addition to dual-stream language pathways, conceptual-motor pathways will also contribute to verb-retrieval performance on an action naming task. In contrast, *cognitive-linguistic accounts* of aphasia view language functions as distinct and dissociable from conceptual and motor information as well as the pathways that support them. These latter accounts predict that tracts in the dual-stream stream model of language, but not motor pathways, will be associated with action naming ability.

This study employs diffusion MRI connectometry (Yeh et al., 2016) to study the relationship between action naming and white matter connectivity. Connectometry is a diffusion

MRI analytic approach that uses permutation testing to identify white matter tracts associated with a variable of interest. It has shown a greater sensitivity than conventional voxel-based or tract-based analysis (Yeh et al., 2016). In aphasia, connectometry has only been applied to the study of object naming performance (Hula et al., in revision), and is employed similarly here to identify the white matter correlates of action naming. This analysis tests the theoretical predictions that verb retrieval is associated with the integrity of: (1) both motor and language tracts, as predicted by grounded cognition accounts, or (2) only language tracts, as predicted by cognitive-linguistic accounts. Our specific hypotheses follow from our review of the literature and neuroanatomical findings regarding tracts that underlie the cortical regions identified in our review. These tracts are largely non-overlapping pathways implicated in dual-stream models of language *or* predominantly motor pathways. For example, grounded cognition accounts predict that verb retrieval is associated with integrity of (i) the corticospinal tract, (ii) the frontopontine tract, (iii) the frontal aslant tract, and (iv) the superior longitudinal fasciculus (Akinina et al., 2019; Catani et al., 2012; Lindenberg et al., 2010). In contrast, cognitive-linguistic accounts predict verb retrieval is associated uniquely with (i) the arcuate fasciculus, (ii) the middle longitudinal fasciculus, (iii) the inferior fronto-occipital fasciculus, and (iv) the uncinate fasciculus (Glasser & Rilling, 2008; Hula et al., in revision; Saur et al., 2008).

4.2 Methods

4.2.1 Participants

Participants were 14 individuals with chronic aphasia due to unilateral left hemisphere stroke and 15 age-matched neurotypical controls. All participants were 1) native English speakers, 2) able to provide informed consent, 3) 25-85 years old, 4) (pre-morbidly) right-handed, and 5) had no history of progressive neurological or psychiatric disease, drug, or alcohol dependence, or significant mood or behavioral disorder. In addition, individuals with aphasia all were more than 6 months post-onset (range: 19-265 months; M=88.9, SD=66.5 months), had a Comprehensive Aphasia Test (CAT; Swinburn et al., 2004) Naming Modality T-score ≥ 40, and an overall mean T-score < 70. Demographic participant characteristics are reported in Table 8 for participants with aphasia and Table 9 for age-matched controls.

Table 8. Demographic characteristics of participants with aphasia

Participant ID	Age	Sex	Education Level	Years of Education	Months Post-Onset	Years Post-Onset	CAT Modality Mean T Score	Action Naming
7202	63	M	Bachelor's degree	14	265	22.08	47.83	0.31
7203	61	F	Master's degree	17	60	5	59.67	0.56
7204	55	M	High school	12	53	4.42	56	0.77
7205	52	M	High school	12	136	11.33	48.33	0.44
7207	70	F	Some college	14	45	3.75	59	0.52
7209	77	M	Law degree	19	53	4.42	52.83	0.51
7210	54	M	Bachelor's degree	16	83	6.92	51.33	0.59
7211	71	M	Some college	14	26	2.17	50.33	0.67
7212	55	M	Bachelor's degree	16	19	1.58	51.17	0.53
7213	68	M	High school	12	184	15.33	49.83	0.43
7214	53	F	Bachelor's degree	17	81	6.75	62	0.67
7215	71	M	Bachelor's degree	16	87	7.25	53.17	0.02
7216	72	M	Some college	14	60	5	42.5	0.35
7217	72	M	Some college	15	93	7.75	58.67	0.44
Summary	M=63.9 SD=8.7	3 F; 11 M		M=14.86 SD=2.11	M=88.93 SD=66.45	M=7.41 SD=5.54	M=53.05 SD=5.44	M=0.49 SD=0.18

Notes: CAT = The Comprehensive Aphasia Test (Swinburn et al., 2004) Modality Mean T Score assesses aphasia severity. Action naming assessment (percent accuracy) comes from Fiez & Tranel's standardized battery for the retrieval of lexical and conceptual knowledge for actions (1997).

Table 9. Demographic characteristics of age-matched control participants

Participant ID	Age	Sex	Education Level	Years of Education	Action Naming
7001	42	M	Tech college	14.5	0.90
7002	59	M	High school	12	0.99
7003	74	M	Bachelor's degree	16	0.90
7004	52	M	Bachelor's degree	16	0.86
7005	54	M	Bachelor's degree	16	0.94
7006	57	M	High school	12	0.80
7007	72	F	Master's degree	18	0.92
7008	64	F	Master's degree	18	0.95
7010	74	M	Master's degree	20	0.92
7011	68	F	Master's degree	22	0.98
7012	72	M	Bachelor's degree	16	0.95
7013	65	M	Law degree	19	0.87
7014	71	F	Master's degree	17	0.93
7015	52	M	Master's degree	22	0.94
7016	69	F	Master's degree	18	0.89
Summary	M=63 SD=9.82	5 F; 10 M		M=17.1 SD=3	M=0.92 SD=0.05

Notes: Action naming assessment (percent accuracy) comes from Fiez & Tranel's standardized battery for the retrieval of lexical and conceptual knowledge for actions (1997).

Participants who met any of the following criteria were excluded: 1) significant hearing loss or vision impairment that prevented them from completing the experimental tasks, or 2) pre-existing or subsequent brain injury/stroke (e.g., to right-hemisphere regions for individuals with aphasia). Cognitive screening and general language assessment measures, including the CAT, were already available for the participants with aphasia, who all participated in Hula and colleagues' study (in revision). Participants were excluded if their T scores were less than 30 for the CAT Cognitive Screening semantic memory or recognition memory subtests. T scores under 30 would be indicative of frank auditory, visual, motor speech, or general cognitive deficits. In addition, neurotypical participants were excluded if they failed a line-bisection visual screening, a binaural pure-tone hearing screening (0.5, 1, 2, and 4 KHz at 40 dB), a Mini-Mental State Examination (required 27/30; Folstein et al., 1975), or Raven's Coloured Progressive Matrices (required 30/36; Raven, 1965).

Institutional Review Board approval was obtained, and all participants provided informed written consent and were compensated for their time participating in both behavioral and neuroimaging protocols (described below).

4.2.2 Behavioral language materials & procedures

All participants were administered a standardized action naming task (Fiez & Tranel, 1997) that consists of 100 colored photographs of actions drawn from a variety of semantic categories. See Fiez and Tranel (1997) for task details. The action naming task was administered and scored according to standardized procedures (Fiez & Tranel, 1997; Kemmerer et al., 2001, 2012). Participants were given detailed instructions and practice items, to ensure they understood the task. For each item, a computer displayed a colored photograph of a person or animal performing an action. The participant was instructed to provide a single verb that described what the person or animal was doing. Participants were allowed an unlimited amount of time to name each action.

An external microphone recorded naming responses in Audacity® software, and trial-level accuracy was scored by hand for each task. The participant's first response was recorded. Following Fiez and Tranel (1997), experimenters prompted participants for a second response if the participant did not provide a verb (e.g. "Can you tell me what the person is *doing*?") or if the participant provided a description (e.g. "Can you give me a *single word* that best describes what the person is doing?"). Target responses provided after a prompt were scored as correct. Alternate forms of a target verb were also accepted as correct (e.g. run, running, ran). Normative data from

Fiez and Tranel (1997) reported 85 percent average accuracy, with a standard deviation of 5 percent.

4.2.3 MRI data acquisition and reconstruction

Neuroimaging data were collected at the University of Pittsburgh Medical Center (UPMC) Magnetic Resonance Research Center. The diffusion spectrum imaging (DSI) scans were acquired on a 3T SIEMENS Tim Trio scanner using a 257-direction 2D EPI diffusion sequence (TE=150 ms, TR=3439 ms, voxel size = 2.4 × 2.4 × 2.4 mm, FoV = 231 × 231 mm, b-max = 7000 s/mm2). A diffusion sampling length ratio of 1.25 was used, and the output resolution was 2 mm isotropic. The restricted diffusion was quantified using restricted diffusion imaging (Yeh et al., 2017). The diffusion data were reconstructed in the MNI space using q-space diffeomorphic reconstruction to obtain the spin distribution function (SDF; Yeh & Tseng, 2011). The local connectome fingerprint (Yeh et al., 2016) values were extracted from the data and used in the connectometry analysis. In addition, T1 and T2-weighted images were acquired, lesion masks were constructed, and lesion volumes were calculated for each participant. A lesion overlay map is presented in Figure 12. Please note that this study followed the same MRI data acquisition and reconstruction procedures that are reported in Hula and colleagues (in revision).

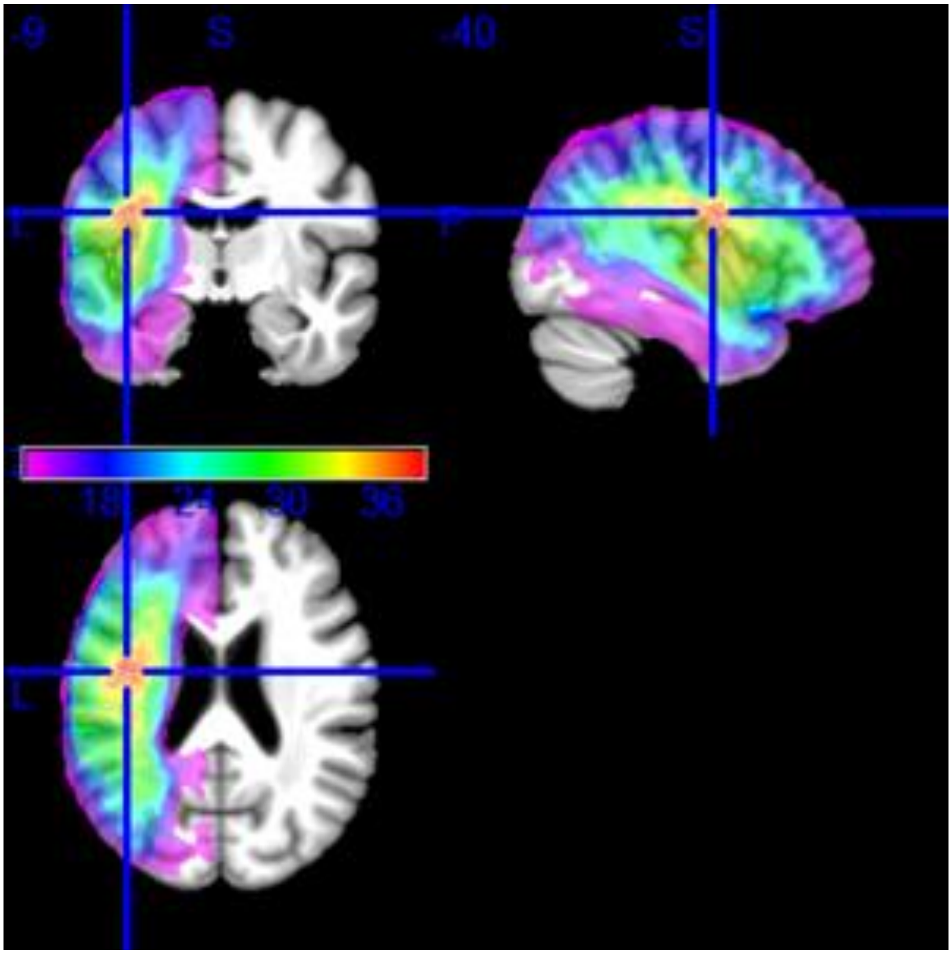


Figure 12. Lesion overlap for participants with aphasia

Notes: This figure depicts the lesion distribution overlap from the larger sample of participants with aphasia reported in Hula et al., in revision. A subset of this sample was included in the current study.

4.2.4 Data analysis

Diffusion MRI connectometry (Yeh et al., 2016) analyses were conducted in DSI Studio (http://dsi-studio.labsolver.org). All 29 subjects' diffusion MRI scans were included in a connectometry database. A multiple regression model was used to identify the local connectome associated with action naming performance, using a deterministic fiber tracking algorithm (Yeh et al., 2013) with an assigned T-score threshold of 3.00 and a fiber length threshold of 30 mm. Lesion volume was included as a covariate, with zero entered for control participants. Topology-informed pruning was conducted to remove false connections (Yeh et al., 2019). All tracks generated from bootstrap resampling were included. The seeding number of each permutation was 50,000. To estimate the false discovery rate, a total of 2,000 randomized permutations were applied to obtain the null distribution of the track length. This analysis approach was previously implemented by Hula and colleagues (in revision), who examined tract fibers associated with object naming in a sample of adults with chronic stroke aphasia.

To examine the extent to which this analysis identified between-group variance or covariance that might obscure the relationship between white matter tracts and the specific verb retrieval behavior of interest, a second connectometry analysis examined tracts associated with verb retrieval only in the participants with aphasia. Lesion volume was again used as a covariate, and all other analysis parameters were the same.

4.3 Results

As shown in Figures 13-14, white matter tracts identified as *positively* associated (false discovery rate [FDR] = 0.000071) with action naming include portions of the left corticothalamic pathway (37%), left inferior fronto-occipital fasciculus (17%), corpus callosum (12%), left frontopontine tract (6.1%), left cingulum (5.1%), left parietopontine tract (4.4%), left inferior longitudinal fasciculus (3.9%), left arcuate fasciculus (3.4%), left corticostriatal pathway (3%), left corticospinal tract (2%), right corticothalamic pathway (1.5%), anterior commissure (1.2%). Percentages reflect the proportion of total streamlines identified in the analysis that were associated with each tract. Figure 15 shows results from the sagittal view, color coded for specific tract assignment. As discussed in section 4.4, these results identify tracts associated with both neurocognitive dual-stream models of language function (Figure 16) as well as projection pathways that connect frontal and parietal cortices to subcortical regions associated with motor programming (Figure 17). Approximately 75 percent of the tracts associated with verb retrieval were projection pathways. The analysis showed no white matter tracts whose connectivity was reliably *negatively* associated with action naming performance (FDR = 1). False fibers are not reported or interpreted.

As expected given the left-hemisphere lateralization of language and patient inclusion criterion of unilateral left-hemisphere stroke, the positive association between action naming and white-matter tract integrity was more prominent in the left than in the right hemisphere. However, the corpus callosum and several right hemisphere tracts were also robustly associated with action naming, suggesting bilateral neural involvement in verb retrieval (Figures 13-14).

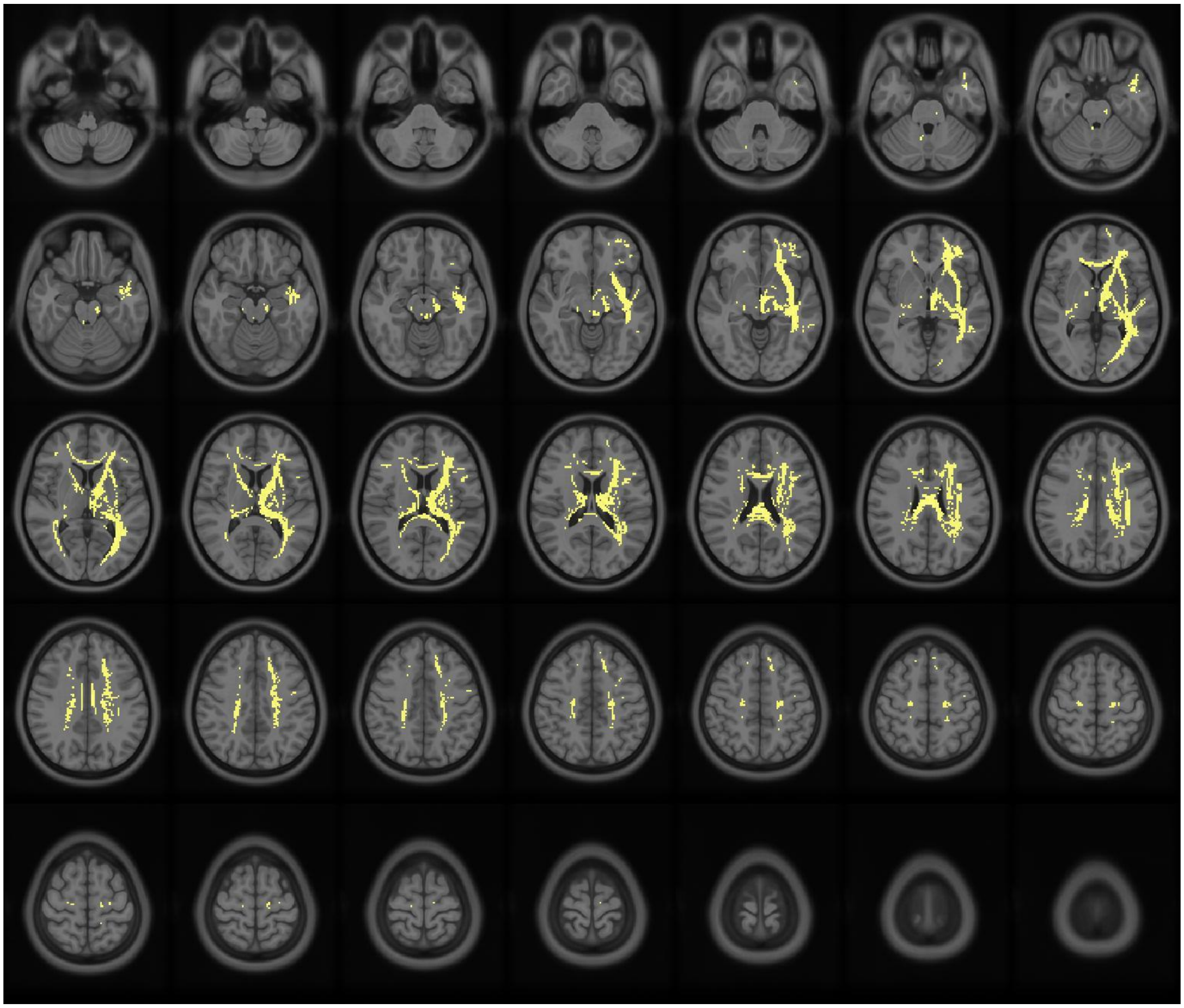


Figure 13. Voxel mapping of white matter fiber tracks with quantitative anisotropy positively correlated with verb naming in all participants

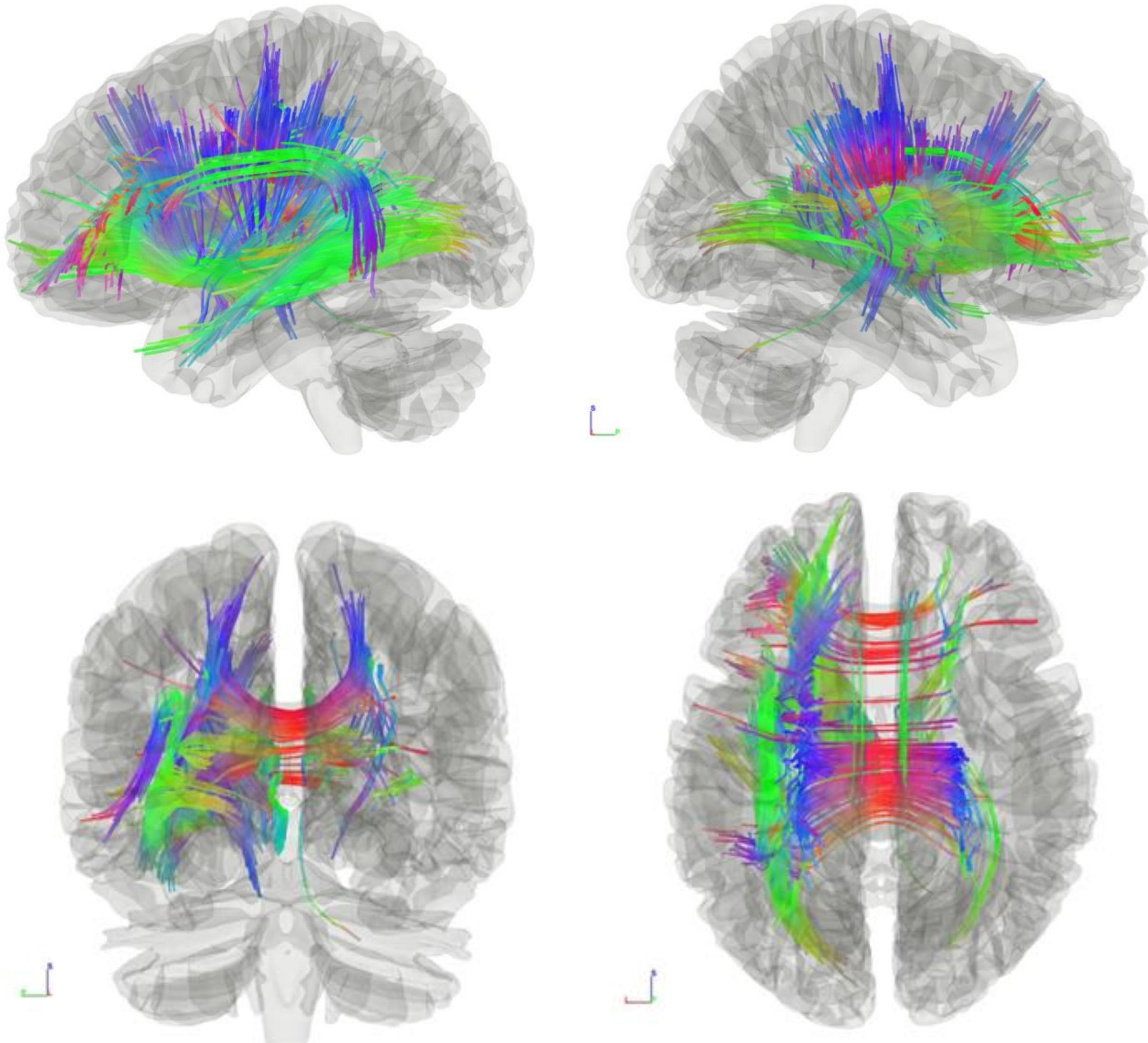


Figure 14. White matter fiber tracks positively correlated with verb naming in all participants

Notes: Colors reflect fiber orientation. Blue: superior–inferior. Green: anterior–posterior. Red: medial–lateral.

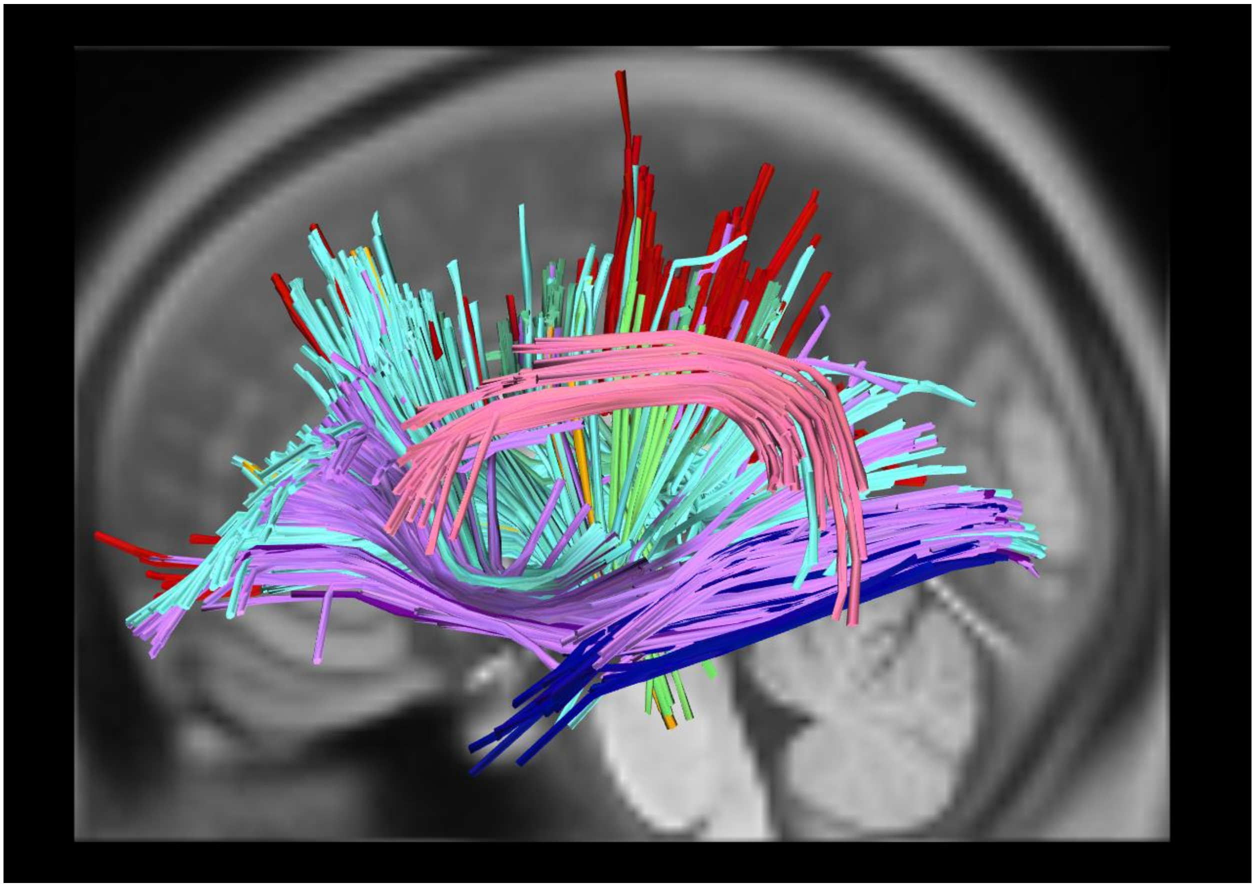


Figure 15. White matter streamlines associated with each tract

Notes: Colors reflect tract assignment. Red – Corpus callosum; Orange – Left frontopontine tract; Pink – Left arcuate fasciculus (AF); Lime green – Left parietopontine tract; Forest green – Left cingulum; Pale blue – Left corticothalamic pathway; Navy – Left inferior longitudinal fasciculus (ILF); Lilac – Left corticostriatal pathway; Violet – Left inferior frontooccipital fasciculus (IFOF); Gray – Left corticospinal tract (CST).

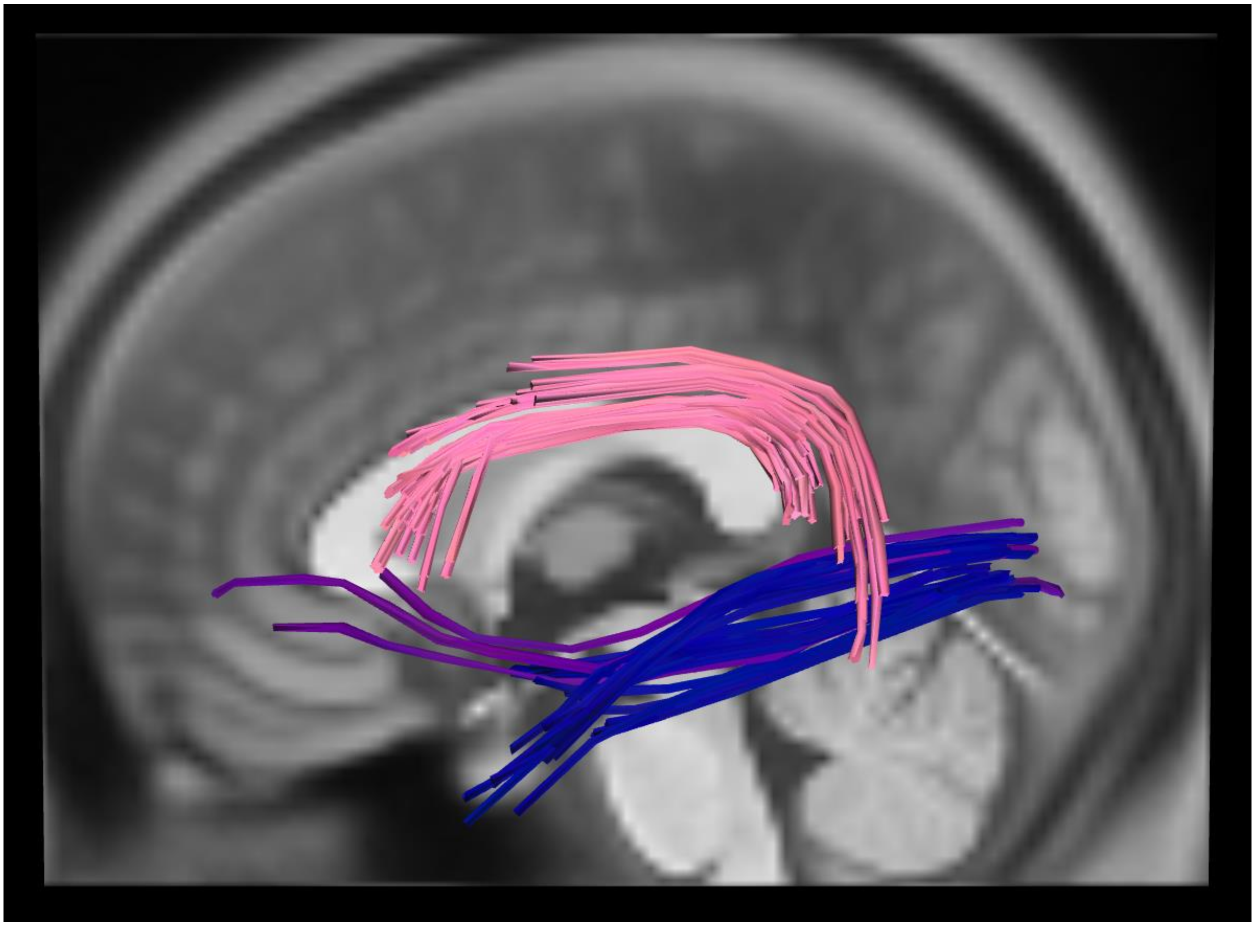


Figure 16. Identified white matter tracts associated with dual-stream models of language function

Notes: Colors reflect tract assignment. *Dorsal stream:* Pink – Left arcuate fasciculus (AF). *Ventral stream:* Navy – Left inferior longitudinal fasciculus (ILF); Violet – Left inferior frontooccipital fasciculus (IFOF).

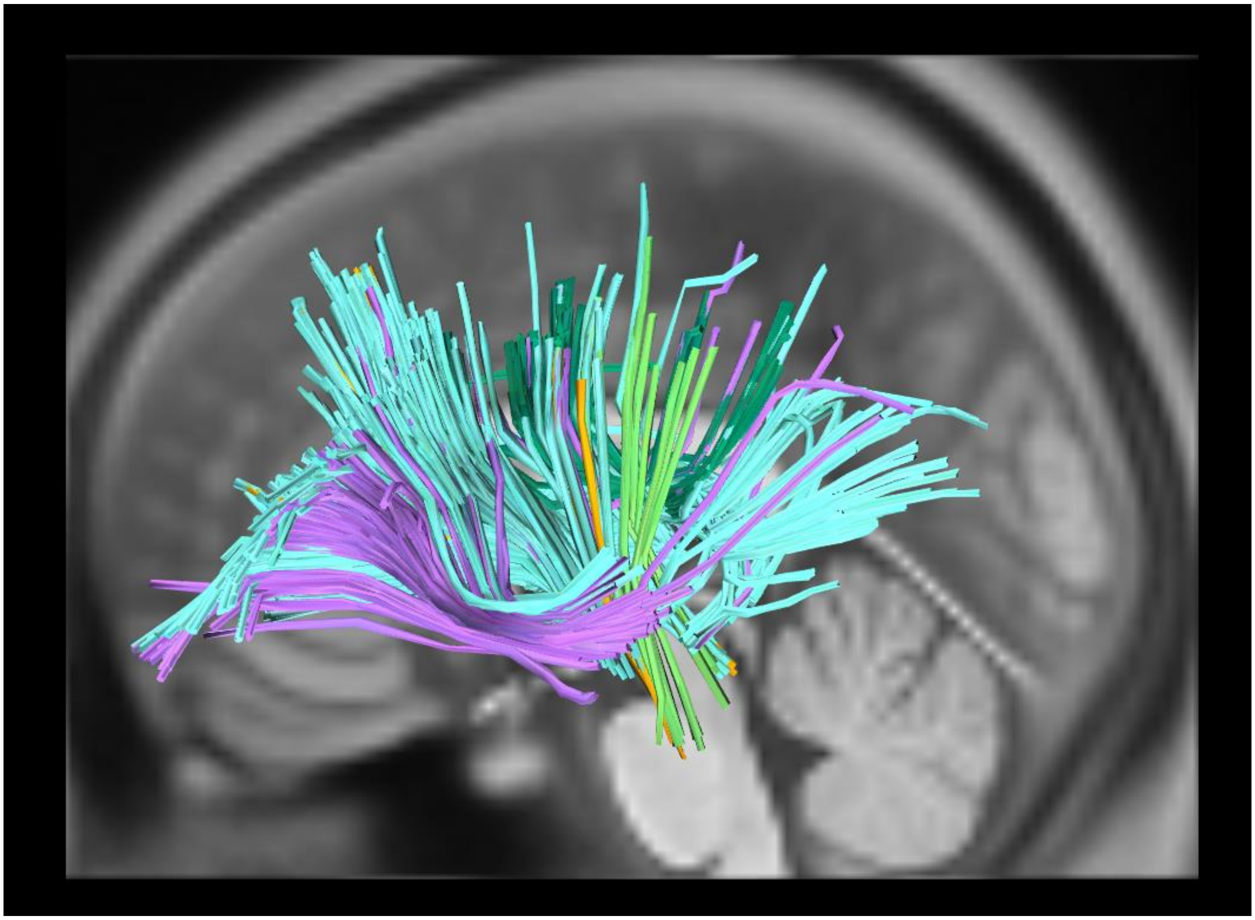


Figure 17. Identified white matter tracts associated with projection motor pathways

Notes: Colors reflect tract assignment. Orange – Left frontopontine tract; Lime green – Left parietopontine tract; Forest green – Left cingulum; Pale blue – Left corticothalamic pathway; Lilac – Left corticostriatal pathway; Gray – Left corticospinal tract (CST).

In the connectometry model only examining the 14 participants with aphasia, similar tracts were positively associated with verb retrieval: corpus callosum (46%), left inferior fronto-occipital fasciculus (9.5%), corticospinal tract (7.6%), left inferior longitudinal fasciculus (7.3%), anterior commissure (7.2%), right cingulum (6.7%), right corticothalamic pathway (4.2%), left corticothalamic pathway (3.8%), and left corticostriatal pathway (1.2%; Figures 18-19; FDR = 0.000826). Again, this analysis showed no white matter tracts whose connectivity was reliably negatively associated with action naming performance (FDR = 0.387755). False fibers are not reported or interpreted.

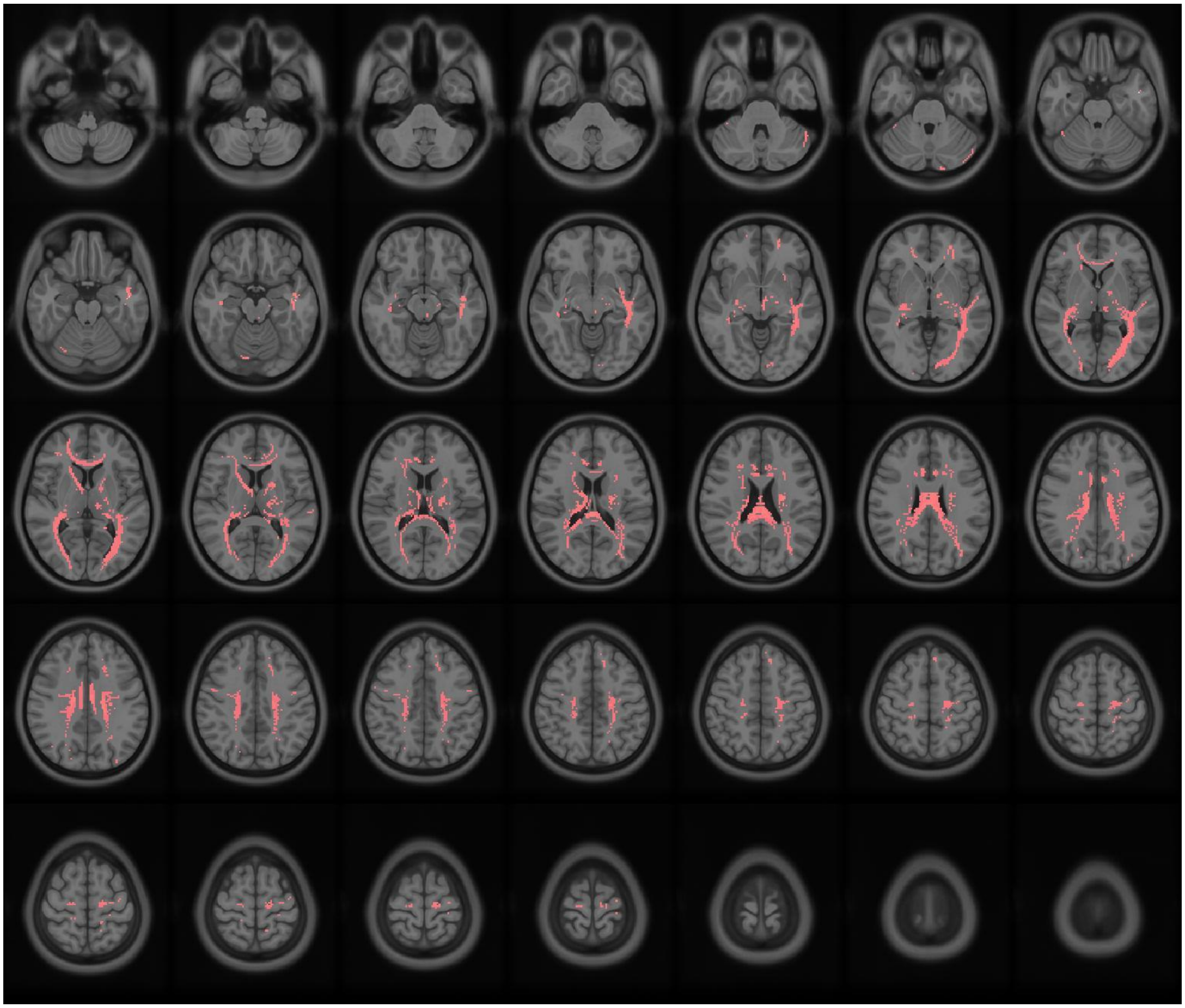


Figure 18. Voxel mapping of white matter fiber tracks with quantitative anisotropy positively correlated with verb naming in only participants with aphasia

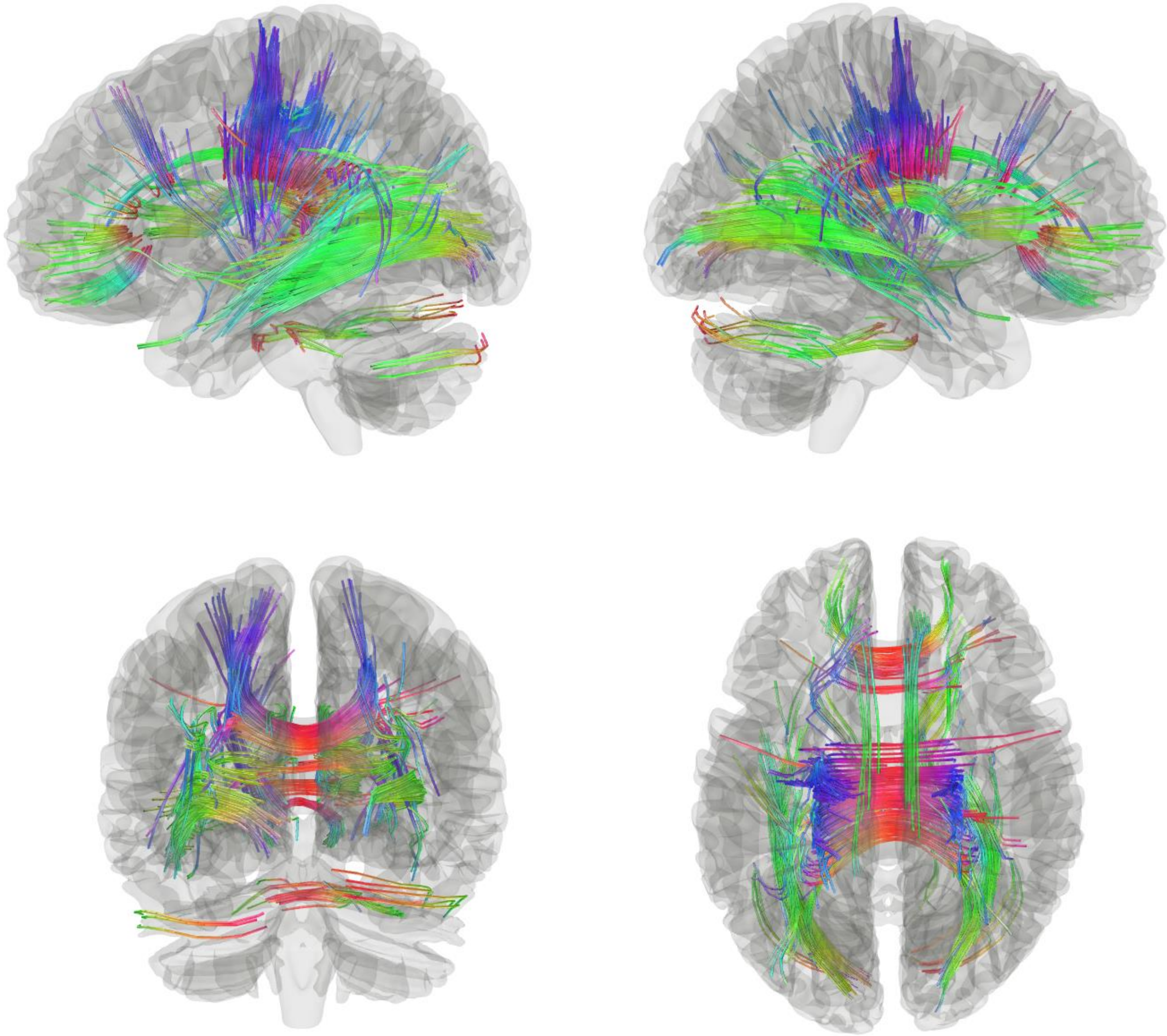


Figure 19. White matter fiber tracks positively correlated with verb naming in only participants with aphasia

Notes: Colors reflect fiber orientation. Blue: superior–inferior. Green: anterior–posterior. Red: medial–lateral.

4.4 Discussion

This study identified white matter tracts associated with verb retrieval (action naming), using high-definition diffusion spectrum MRI connectometry in 14 participants with aphasia due to left-hemisphere stroke and 15 age-matched controls. Previous work characterized white-matter correlates of noun-production deficits (Hula et al., in revision) and found results largely consistent with dual-stream neurocognitive models of language function. Cognitive-linguistic theories and dual-stream language models predict that the same dorsal and ventral pathways underlie (respectively, phonological and lexical-semantic aspects of) verb production. In contrast, grounded cognition accounts predict that distributed pathways supporting both linguistic and non-linguistic conceptual-motor performance critically support action naming.

Verb production and verb-retrieval deficits were assessed by a 100-item standardized task of action picture naming (Fiez & Tranel, 1997). The degree of connectivity between adjacent voxels was used to reconstruct a structural connectome for each participant (Yeh et al., 2016). Verb production ability was then regressed on a connectome matrix for the full group of participants, controlling for total lesion volume. This approach improves upon methods that map pathways between cortical origin and termination points by providing more specific and reliable connectome reconstruction. In comparison, the overlay analysis method for white matter that Akinina and colleagues (2019) employed in their analysis of action naming was limited to detecting intersections between portions of tract probability maps and was not capable of tracking the course of specific fibers.

Connectometry analyses identified tracts associated with verb retrieval that were largely consistent with predictions of grounded cognition accounts: Connectivity of classic linguistic *and* motor pathways were positively associated with verb retrieval ability. First, verb retrieval was positively associated with the integrity of several linguistic tracts, including left AF, IFOF, and ILF. These results are consistent dual-stream models of language function and observations regarding white matter correlates of object naming (Almairac et al., 2015: IFOF; Duffau et al., 2013: IFOF, ILF; Han et al., 2013: IFOF, ALF; Hula et al., in revision; Ueno et al., 2011: AF), action naming (Akinina et al., 2019: AF, IFOF), and verb processing in intraoperative stimulation experiments (Bello et al., 2006, 2007, 2008). The left IFOF and ILF have consistently been associated with the ventral stream, mapping sound to meaning (Almairac et al., 2015; Duffau et al., 2013; Han et al., 2013; Hula et al., in revision; Saur et al., 2008; Ueno et al., 2011). The left AF is considered the predominant dorsal tract in the dual-stream language models, but this was the only dorsal language tract robustly associated with verb retrieval.

The MdLF and UF have both been characterized as language tracts previously but were not identified in the current analyses. The MdLF has been implicated in tractographic studies of language processing (de Champfleur et al., 2013) and has recently been associated with both semantic and phonological stages of object naming in adults with aphasia (Hula et al., in revision). However, evidence from patients with resected MdLF suggests that although this tract may participate in language processing, it is not essential (Hamer et al., 2011). Similarly, the UF was not identified in our analyses but has been characterized as a ventral-stream tract associated with language function and semantic processing (Han et al., 2013; Ueno et al., 2011), including semantic paraphasias in object naming (Hula et al., in revision) and verb naming (Akinina et al., 2019; Bello et al., 2006, 2007, 2008). There is also evidence that the UF is not systematically essential for language and that alternative, perhaps indirect ventral stream pathways may functionally compensate when the UF is damaged or partially resected (Duffau et al., 2009). This possibility and the specific contributions of the MdLF and UF to verb retrieval and broader language function must be explored further.

Second, verb-retrieval deficits were associated with compromised integrity to several motor pathways, including bilateral corticothalamic tracts, and left corticospinal, corticostriatal, frontopontine, and parietopontine tracts. Although these tracts are not traditionally associated with language, frontostriatal, frontopontine, and anterior thalamic projections have been associated with lexical-semantic stages of action naming in a VLSM analysis of individuals with aphasia (Akinina et al., 2019). The current results identified positive associations between verb retrieval and tract integrity connecting both frontal and parietal regions of cortex to the striatum of the basal ganglia, as well as to the thalamus. In particular, the majority of the corticostriatal tracts identified connected left hemisphere cortex to the left putamen, which has been previously associated with movement disorders like Tourette syndrome and Parkinson's disease (DeLong & Wichmann, 2007; Griffiths et al., 1994), as well as motor functions including motor planning, learning, and execution (DeLong, Alexander, et al., 1984; DeLong, Georgopoulos, et al., 1984; Marchand et al., 2008; Turner et al., 2003; Watkins & Jenkinson, 2016). In addition, both Akinina and colleagues (2019) and the current results identified the involvement of corticospinal and corticopontine tracts. As discussed in the introduction, there is a substantial body of work linking this set of projection fibers to voluntary motor control and action-related cognition (Haber, 2016; Rea, 2015; Welniarz et al., 2017 for reviews). The involvement of these motor pathways in verb retrieval is therefore in line with predictions of grounded cognition accounts.

It is unclear why the FAT and SLF were not associated with verb retrieval in our analyses, as they were in Akinina and colleagues' study (2019), but these tracts are not typically identified in picture naming experiments. In addition, the pars opercularis of the inferior frontal gyrus (BA 44) hosts terminations of both the FAT and the SLF III (as well as the AF; Rojkova et al., 2016). This region has a high probability of being damaged in individuals with stroke aphasia and the statistical power to detect meaningful relationships between these tracts and naming performance may therefore be limited. Regardless, it is worth noting that although the result was not robust, approximately 500 fibers of the left SLF were associated with verb naming in our primary analysis. One possibility is that the stronger SLF and FAT relationships identified by Akinina and colleagues (2019) reflect a wider range of articulation and verbal fluency among participants in that study (*articulation/SLF:* Duffau et al., 2014; Makris et al., 2005; *fluency/FAT:* Catani et al., 2013; Fujii et al., 2015; Kinoshita et al., 2015; Kronfeld-Duenias et al., 2016; Vassal et al., 2014). As Akinina and colleagues (2019) discuss, fluency impairments may be partially related to word-retrieval deficits in their sample, and further investigation is needed to characterize white matter tracts associated with fluency's role in word retrieval. If this speculation is correct, it suggests that Akinina and colleagues' results reflected the contribution of the FAT to verbal fluency rather than to verb retrieval. However, Kemmerer and colleagues (2012) also did not find associations between verb retrieval and SLF or FAT in a sample of adults with a wide variety of lesion locations. Future work should continue to assess the roles of these tracts in word retrieval, articulation, and fluency in large samples of diverse patients.

Finally, the corpus callosum and cingulum were also robustly associated with verb retrieval. Hula and colleagues (in revision) similarly found the splenium of the corpus callosum was positively associated with phonological and semantic abilities during object naming. The present study also found associations with bilateral cinguli, although more left than right hemisphere tracts. Cingulum bundles have been related to many functions, including emotion, motivation, executive function, spatial processing, and motor function (Bubb et al., 2018 for review). Bilateral cinguli were associated with both phonological and semantic function in object naming – with an antero-posterior distinction between the two, respectively (Hula et al., in revision). The involvement of the corpus callosum and bilateral cinguli is consistent with aphasia model proposals that the right hemisphere compensates for stroke-related language impairments (Stefaniak et al., 2020 for review).

A complete discussion of each of the identified pathways goes beyond the scope of this study. However, these results emphasize that in addition to cortico-cortical networks of dual-stream language models, cortico-subcortical networks, subcortical substrates, and right-hemisphere tracts may be critically involved in action naming and verb-retrieval deficits in aphasia. Furthermore, the present connectometry methods provide new evidence by tracking each fiber tract along its respective course, rather than simply detecting associations with different portions of tract probability maps, as done by Akinina and colleagues (2019).

This study extended connectometry approaches in aphasia to examine the white matter tracts associated with verb-retrieval deficits, and furthermore addressed a critical limitation by including an age-matched control group. The only previous research that has implemented connectometry in aphasia was Hula and colleagues (in revision), who examined the white matter correlates of semantic and phonological stages of noun production impairments in adults with chronic stroke aphasia. However, as discussed in the Introduction, Hula and colleagues did not include a control group. Perhaps as a result, their analyses found robust negative associations between language behavior and fiber tract connectivity, indicating that individuals with lower white-matter integrity (i.e., higher damage) in certain tracts had better language performance. The lack of negative associations in the current study suggest that this previous pattern of findings is likely an artifact due to the sample bias of only including participants with left-hemisphere lesions. Furthermore, the current results are not limited to ambiguous interpretations driven by high lesion overlap and too few tract observations in posterior inferior frontal lobe.

A potential limitation of this study is the possibility that the connectometry analysis identifies robust between-group variance or covariance that could obscure the relationship between white matter tracts and the specific verb retrieval behavior of interest. To address this concern, a second connectometry analysis was conducted to examine tracts associated with verb retrieval only in participants with varying degrees of language impairment. In the 14 participants with aphasia, similar tracts were positively associated with verb retrieval, including left IFOF, left ILF, bilateral corticothalamic pathways, left corticostriatal and corticospinal pathways, and the corpus callosum. This analysis is likely underpowered to detect reliable differences in specific tracts that experience frequent lesion in aphasia, such as the arcuate fasciculus. In comparison to the full group analysis, a higher proportion of fiber tracts in the corpus callosum, anterior commissure, corticospinal tract, and right hemisphere cingulum and corticothalamic pathways were identified. Verb retrieval in aphasia was also associated with a lower proportion of fiber tracts in the left hemisphere cingulum and corticothalamic pathway, as compared to the full group analysis. These results must be interpreted with extreme caution given the limited statistical power in this analysis. However, these results mitigate concerns about the methods employed in this study. Furthermore, the behavioral performance across participant groups had a large range (range = 0.20 - 0.99, M = 0.51, SD = 0.25) and was generally continuous and linear, which provides an optimal behavioral sample for the connectometry regression methods. Finally, this additional analysis identifies potential neural pathways, including right hemisphere tracts and motor pathways, that might compensate to support verb retrieval in individuals with aphasia.

As predicted by grounded cognition accounts, our findings suggest verb retrieval is associated with a distributed network of tracts supporting both linguistic and non-linguistic conceptual-motor performance. These findings are consistent with language operating as a general-purpose cognitive system that engages distributed, multimodal representations across regions specialized for linguistic, motor, and affective/limbic processing (Altmann, 2017; Barsalou, 2008; Martin, 2016; Zwaan & Madden, 2005). These results are furthermore consonant with previous neuropsychological and neurostimulation studies that found associations between verb/action processing and primary motor, premotor, and supplementary motor cortices (Courson et al., 2017; Kemmerer et al., 2012; Pulvermüller et al., 2005; Vigliocco et al., 2011).

4.5 Conclusion

This study was among the first investigate the white matter connectivity associated with action naming abilities and verb-retrieval deficits in chronic left-hemisphere stroke aphasia. The current findings extend beyond prevailing cognitive-linguistic theories of aphasia and neurocognitive dual-stream models of language function by highlighting associations between verb retrieval and white matter tracts involved in motor pathways. This new evidence is consonant with grounded accounts of cognition, but it remains unclear what neurocognitive principles govern the joint contribution of principal linguistic and motor pathways to verb retrieval and language impairments more broadly. Study 3 investigates one possible principle that may govern these contributions: the principle of rational adaptation.

5.0 Study 3: Rational adaptation in using conceptual versus lexical information in adults with aphasia

5.1 Introduction

The language-processing system has often been viewed as relatively static and context-invariant, particularly by sentence comprehension models (e.g., Bornkessel & Schlesewsky, 2006; Frazier, 1987; Mitchell, 2004). However, recent evidence indicates that successful language processing, including sentence comprehension, is accomplished by an adaptive system (Ellis & Larsen-Freeman, 2009 for review; Gibson et al., 2013). Specifically, the language system flexibly takes advantage of a wide array of potentially informative sources of information to guide performance. These information sources may include linguistic representations (grammatical categories, thematic roles, and lexical co-occurrence probabilities), contextual constraints, and knowledge of the relationships between words and real-world events (e.g., Caramazza & Zurif, 1976; Dresang et al., 2018; Gibson et al., 2013; Kuperberg & Jaeger, 2016; McRae & Matsuki, 2009). There is a substantial body of work investigating the influence and context-sensitive interactivity of different information types in neurotypical adults. Following information theory, the interactivity of information types is governed by *the principle of rational adaptation*, which states that people can change which information sources they rely on in order to optimize behavior under specific circumstances (Anderson, 1991; Caramazza & Zurif, 1976; Gibson et al., 2013; Howes et al., 2009). Accordingly, rational adaptation allows people to process a sentence or name an action as quickly and accurately as possible, and to be able to do so under different experimental conditions (e.g., Gibson et al., 2013) or disease states (Caramazza & Zurif, 1976; Gibson et al., 2015; Warren et al., 2017).

Language performance in individuals with aphasia provides a unique window into adaptive use of multiple information types during language processing. People with aphasia have impairments in accessing and using linguistic information, but their stored conceptual-semantic knowledge is traditionally assumed to be relatively unimpaired and might be relied upon to accomplish language processing. This adaptation is the hypothesized mechanism underlying both aphasic impairments in sentence processing (Caramazza & Zurif, 1976; Goodglass, 1976) and efficacious speech-language treatments (e.g., Boyle, 2010; Edmonds, 2016; Wambaugh et al., 2014). There is long-standing evidence that people with aphasia rely more on world knowledge – like event associations and plausibility information – than syntax when interpreting complex sentences (Caramazza & Zurif, 1976; Grodzinsky, 1986; Schwartz et al., 1980, 1987). Reliance on non-linguistic information, like conceptual representations for actions/events and objects, may function as an effective compensatory strategy during linguistic tasks like sentence comprehension (Gibson et al., 2015; Warren et al., 2017) or word production (Boyle & Coehlo, 1995). And indeed, according to the principle of rational adaptation, people with aphasia should adapt to their linguistic deficits by relying more heavily on these types of spared information.

Previous work has provided evidence that people with aphasia engage in rational adaptation of this kind when accomplishing off-line sentence interpretation tasks. However, it remains unclear whether individuals with aphasia show evidence of rational adaptation during production tasks. To examine whether people with aphasia rely more heavily on conceptual than linguistic knowledge during lexical (verb) retrieval compared to healthy controls, this study contrasted reliance on event-related versus lexical co-occurrence information during successful verb retrieval. This study is among the first to investigate aphasic rational adaptation in reliance on stored representations of linguistic versus conceptual knowledge, rather than in reliance on bottom-up linguistic input (but also see Caramazza & Zurif, 1976). Furthermore, this study focuses on the ability to retrieve wordforms of verbs. This is critical because verb-retrieval deficits are frequently observed in individuals with aphasia, across severity levels and syndrome classification types (Mätzig et al., 2009).

5.1.1 Adaptive behavior in aphasia

The principle of rational adaptation states that individuals optimize their performance by modifying their behavior given the constraints imposed by their environments and neurocognitive architectures (Anderson, 1991; Gibson et al., 2015; Howes et al., 2009; Warren et al., 2017). The rational adaptation principle is key to the noisy channel, or rational inference, account of language comprehension, according to which comprehenders compute the probabilities of possible intended messages given a perceived sentence, and quickly adapt their estimations of these probabilities to changes in the amount of noise or the reliability of cues in the context (Gibson et al., 2013). Gibson and colleagues (2013) demonstrated that increasing the rate of typos in an experiment led participants to rely less on linguistic form during sentence interpretation. Similarly, increasing the proportion of implausible sentences in the experiment led participants to rely less on meaning during sentence interpretation.

Gibson and colleagues (2015) extended this work to adults with aphasia, proposing that during language comprehension, people with aphasia rely more on prior conceptual knowledge than healthy adults, because their impairments are more likely to introduce noise into their representations of the bottom-up linguistic input. Gibson and colleagues examined the effects of plausibility and likelihood of distortion on the interpretation of sentences that, with the addition or deletion of one or two function words, could be transformed into a near neighbor sentence that was plausible if the original sentence had been implausible or implausible if the original sentence had been plausible. The rational adaptation principle posits that people with aphasia are more likely than controls to misinterpret an implausible sentence, “The ball kicked the girl” as its plausible alternative (“The girl kicked the ball”), rather than as the sentence’s literal message. In Gibson and colleagues’ study (2015), participants heard a sentence and were instructed to act out what they heard with figurines. The outcome measure was whether the acted-out event followed the literal form of the sentence provided. Results indicated that in comparison to controls, people with aphasia relied more on plausibility information across all sentence types. In addition, participants demonstrated reliance on syntactic priors, such that more errors were made on less frequent syntactic structures, independent of plausibility. For example, participants both with and without aphasia made more interpretation errors on less frequent double-object sentences (e.g., “The brother gave the bike the sister.”) than prepositional-phrase object sentences (e.g., “The brother gave the sister to the bike.”). These findings are consistent with rational adaptation predictions and demonstrate that like neurotypicals, people with aphasia rationally adapt to event likelihood and distortion likelihood (Gibson et al., 2015). Furthermore, people with aphasia may adapt to their language impairments by relying more on conceptual knowledge (plausibility, event likelihood) than controls do.

Warren, Dickey, and Liburd (2017) expanded on Gibson and colleagues’ (2015) experiment. They examined the same sentence types, but used a sentence-picture matching paradigm, manipulated the severity of the plausibility violation, and tested a larger sample of people with aphasia. Warren and colleagues (2017) replicated Gibson’s findings that adults with aphasia relied more on plausibility information compared to neurotypical controls, as shown by the fact that they were more strongly influenced by semantic coherence. In addition, like in Gibson and colleagues (2015), participants both with and without aphasia were sensitive to the likelihood that a linguistic form would be distorted. Furthermore, people with aphasia relied more on the linguistic form/interpreted sentences more accurately for active and passive sentences than for double-object and prepositional-object sentences. The noisy channel model predicts this because changing an active to a passive or vice versa requires adding or deleting two words ("was" and "by"), whereas changing a double-object sentence to a prepositional-object sentence or vice versa requires only adding or deleting a "to." Other models of aphasic sentence processing do not make this prediction; they would predict that performance on passives (e.g. "The ball was kicked by the girl.") would be worse than double-object sentences (e.g., "The brother gave the sister the bike.") and prepositional-object sentences (e.g., "The brother gave the bike to the sister.") due to the low relative frequency of passive sentence structures (Bock & Loebell, 1990; Gibson et al., 2015 for discussion).

The findings from Gibson (2015) and Warren and colleagues (2017) that support a noisy channel account of language comprehension point to a flexible language processing system that is sensitive to experiment-related or aphasia-related changes in the reliability of cues to interpretation, including the likelihood of input distortion. Other findings provide converging evidence that during language comprehension, people with aphasia rely equally or more heavily on conceptual or world knowledge cues, but less heavily on linguistic cues, than neurotypical controls. For example, Hayes, Dickey, and Warren (2016) used a visual-world task to study the influence of lexical verb-argument information versus plausibility on anticipatory processing of event locations (e.g., "The child put/rode the bicycle in the park/pool."). They found that both linguistic knowledge (specifically, the argument structure requirements of verbs) and the plausibility of the event location guided the anticipatory processing of neurotypical adults across the lifespan, whereas only conceptual knowledge of event plausibility influenced the anticipatory processing of adults with aphasia. Together, the results from Gibson and colleagues (2015), Warren and colleagues (2017), and Hayes and colleagues (2016) are consistent with the hypothesis that people with aphasia rely less on (impaired or noisy) linguistic information and rely more on conceptual event knowledge during language tasks than healthy language users do (see also Caramazza & Zurif, 1976; Saffran et al., 1998).

The evidence for rational adaptation in aphasia to date is limited to auditory sentence comprehension (Caramazza & Zurif, 1976; Gibson et al., 2015; Hayes et al., 2016; Schwartz et al., 1980, 1987; Warren et al., 2017). The current study will break new ground by investigating whether people with aphasia rationally adapt to their impairments during *verb production*, in particular speeded retrieval of wordforms for verbs. Verb naming is critical to investigate because 70 percent of individuals with aphasia experience chronic verb-retrieval deficits (Mätzig et al., 2009). Furthermore, rational adaptation in verb production could potentially be a mechanism behind the apparent efficacy of speech-language therapies that treat verb-retrieval deficits in people with aphasia by strengthening conceptual-semantic networks around verbs (e.g., Verb Network Strengthening Treatment [VNeST]; Edmonds, 2016 for review). Demonstrating rational adaptation in verb production would be a first step in showing that it could underlie these efficacious speech-language treatments and may be leveraged to develop more targeted neurorehabilitation methods by determining what information cue types and experimental (learning) conditions facilitate verb retrieval.

5.1.2 Rational adaptation to language knowledge vs. world knowledge

In order to communicate, people routinely recruit knowledge gleaned from experience with both language and the world (Bornkessel & Schlesewsky, 2006; Chomsky, 1975; Katz, 1972;

McRae & Matsuki, 2009). If people are engaging in rational adaptation, then they should recruit the most informative kind of knowledge to accomplish the task at hand. There are many varieties of language knowledge and world knowledge, and many information types consist of intertwined elements of both (Willits et al., 2015 for discussion). However, Willits and colleagues (2015) demonstrated that at least some types of language and world knowledge can be disentangled. This project follows the foci of Willits and colleagues (2015), who investigated language users' reliance on knowledge of word co-occurrence frequencies (language knowledge) and event-related probabilities (world knowledge of agents, patients, instruments, or locations strongly associated with the event described by the target verb). Specifically, Willits and colleagues (2015) examined how these two information types may facilitate verb-location production and comprehension in neurotypical adults. The current study examines how these same information types facilitate verb production, and tests the hypothesis that individuals with aphasia will rationally adapt to their language deficits and increase their reliance on world knowledge such that they rely more heavily on conceptual knowledge of event probabilities in verb production than neurotypical adults do.

Language knowledge encompasses many kinds of information, including grammatical categories, thematic roles, and verb-argument structure. The specific form of language knowledge examined by Willits and colleagues is word co-occurrence frequency (Hale, 2001; Levy, 2008). Healthy language users utilize their stored knowledge of word co-occurrence in both comprehension and production (Reali & Christiansen, 2007; Wasow, 1997). We know this because high frequency word collocations, which are common word sequences (i.e., lexical bundles), are processed faster (Arnon & Snider, 2010; Durrant & Doherty, 2010; Sonbul, 2015; Wolter & Gyllstad, 2011, 2013) and recalled more accurately than low frequency word collocations (Tremblay et al., 2011). In addition, people make active use of language-specific statistics from prior experience to guide their language use. Information-theoretic studies show that reading times vary as a function of word predictability, derived from word co-occurrence frequencies based on prior linguistic experience (Amato & MacDonald, 2010; Hale, 2001; Levy, 2008; Smith & Levy, 2013). However, it is currently unknown to what degree individuals with aphasia make use of word co-occurrence to facilitate word production (though see discussion of somewhat relevant sentence-comprehension findings by DeDe and Gahl below).

In addition to language statistics, event knowledge gleaned from experiences with the real world also facilitates language processing. Recall from section 5.1.1 that there is robust evidence that adults with aphasia rely strongly on this type of conceptual-semantic knowledge. In healthy adults, priming experiments have demonstrated that generalized event memory is structured to allow immediate access of event knowledge from multiple types of single-word cues (Ferretti et al., 2001; Hare et al., 2009; McRae et al., 2005, 2001; also see Milburn et al., 2016 for visual-world evidence and Amsel et al., 2015 for ERP evidence). In particular, thematic role agent, patient, and instrument nouns are retrieved faster after verbs that denote events in which the nouns are commonly involved (Ferretti et al., 2001). Semantic priming also occurs in the other direction, such that nouns prime both verbs and other event-related nouns. McRae and colleagues (McRae et al., 2001) found that verbs were named more quickly when preceded by an event-related thematic role noun (agents, patients, instruments, and locations) than by an unrelated noun (also see McRae et al., 2005). In addition, Hare, Elman, Tabaczynski, and McRae (2009) found that nouns that denote common events (e.g., trip, accident) primed objects and agents typically involved in that event (trip–luggage; accident–policeman), whereas unrelated nouns did not. Hare and colleagues (2009) also observed priming effects between location and instrument noun primes and typical object and agent targets. Taken together, this evidence indicates that isolated verbs, event nouns, and thematic role/participant nouns activate conceptual event knowledge, resulting in facilitated naming of related concepts.

Word collocations can indirectly reflect event knowledge, due to the fact that language is used to communicate information and ideas about the real world; however, word co-occurrence and event knowledge can also be dissociated. Willits and colleagues (2015) conducted two corpus analyses and found that overall, past progressive verbs co-occur more frequently with locations than do past perfect verbs. However, this varied across individual verbs. Willits and colleagues (2015) capitalized on this variability to create stimuli with three levels: semantically related words with high co-occurrence probability, semantically related words with low co-occurrence probability, and semantically unrelated words with low co-occurrence probability. These stimuli were tested in four behavioral tasks, to investigate whether young neurotypical adults lean more heavily on different sources of information under different task conditions. In their two semantic tasks, plausibility judgment ("Rate how likely it is that the event or action described typically takes place in this location.") and semantic priming ("Is this a location?"), results were driven by event knowledge. But in their two more language-focused tasks, primed verb naming ("Say the target word aloud.") and sentence completion ("Mary was visiting…"), effects were driven by word co-occurrence patterns. This pattern of findings supports the notion that healthy adults prioritize conceptual event versus word co-occurrence information to different degrees depending on the task demands.

The current study extends this work by examining whether people with aphasia adapt to their language impairments by relying more on event knowledge than word co-occurrence during a primed verb-naming task. As such, it is important to note that there is evidence that like neurotypical adults, individuals with aphasia can also use both event knowledge and word co-occurrence information to facilitate language processing. For example, Hayes, Dickey, and Warren (2016) found that people with aphasia relied on event plausibility to guide anticipatory processing of locations in a visual-world experiment. In addition, Dresang, Dickey, and Warren (2019) demonstrated that conceptual knowledge of events was predictive of verb naming and argument structure production impairments in people with aphasia. On the other hand, people with aphasia also make use of lexical frequency and word co-occurrence information. In Gahl (2002), participants with fluent and anomic aphasia types showed sensitivity to lexical verb biases in a sentence plausibility judgment task. In a subsequent set of experiments, Dede (2013a, 2013b) observed that the effects of lexical verb bias were greater in adults with aphasia than controls in an on-line self-paced reading task. Findings from Warren, Dickey, and Lei (2016) could also reflect influences of lexical co-occurrence; they showed that the presence of the word "either" facilitated subsequent processing of a region including the word ”or” for both people with aphasia and neurotypical controls. These results suggest that people with aphasia can rely on both event knowledge and word co-occurrence information. However, it remains unclear which information type is more facilitative of verb retrieval.

5.1.3 Summary

The goal of the current study is to investigate rational adaptation in aphasia by testing the hypothesis that: because language impairment reduces the reliability of linguistic information for people with aphasia, they will rely more heavily on event knowledge and less heavily on linguistic knowledge as compared to unimpaired adults. Given that Willits and colleagues (2015) found that young neurotypical participants relied heavily on linguistic co-occurrence information in a naming task, the current study used a naming task with people with aphasia. We expected to replicate Willits and colleagues' finding that healthy control participants exhibit stronger effects of word collocation than event-relatedness on naming. But we further predicted that people with aphasia would show the opposite pattern and exhibit a larger facilitative effect of event relatedness than linguistic co-occurrence on naming. This project extends our understanding of rational adaptation in aphasia by characterizing whether and to what extent people with aphasia rely more on event knowledge than stored linguistic representations during a verb-naming task.

5.2 Methods

5.2.1 Participants

Participants were 17 individuals with chronic aphasia due to unilateral left hemisphere stroke and 15 age-matched neurotypical controls. All participants were 1) native English speakers, 2) able to provide informed consent, 3) 25-85 years old, 4) (pre-morbidly) right-handed, and 5) had no history of progressive neurological or psychiatric disease, drug, or alcohol dependence, or significant mood or behavioral disorder. In addition, individuals with aphasia all were more than 6 months post-onset (range: 19-265 months; M = 95.8, SD = 62 months), had a Comprehensive Aphasia Test (CAT; Swinburn et al., 2004) Naming Modality T-score ≥ 40, and an overall mean T-score < 70. Demographic participant characteristics are reported in Table 10 for participants with aphasia and Table 11 for age-matched controls.

Table 10. Demographic characteristics of participants with aphasia

Participant ID	Age	Sex	Education Level	Years of Education	Months Post-Onset	Years Post-Onset
7201	59	F	Graduate degree	20	132	11
7202	63	M	Bachelor's degree	14	265	22.08
7203	61	F	Master's degree	17	60	5
7204	55	M	High school	12	53	4.42
7205	52	M	High school	12	136	11.33
7206	78	F	Some graduate	13	114	9.5
7207	70	F	Some college	14	45	3.75
7208	76	M	Some college	14	138	11.5
7209	77	M	Law degree	19	53	4.42
7210	54	M	Bachelor's degree	16	83	6.92
7211	71	M	Some college	14	26	2.17
7212	55	M	Bachelor's degree	16	19	1.58
7213	68	M	High school	12	184	15.33
7214	53	F	Bachelor's degree	17	81	6.75
7215	71	M	Bachelor's degree	16	87	7.25
7216	72	M	Some college	14	60	5
7217	72	M	Some college	15	93	7.75
Summary	M=65.12 SD=9.11	5 F; 12 M		M=15 SD=2.35	M=95.82 SD=62	M=7.99 SD=5.17

Table 11. Demographic characteristics of age-matched control participants

Participant ID	Age	Sex	Education Level	Years of Education
7001	42	M	Tech college	14.5
7002	59	M	High school	12
7003	74	M	Bachelor's degree	16
7004	52	M	Bachelor's degree	16
7005	54	M	Bachelor's degree	16
7006	57	M	High school	12
7007	72	F	Master's degree	18
7008	64	F	Master's degree	18
7010	74	M	Master's degree	20
7011	68	F	Master's degree	22
7012	72	M	Bachelor's degree	16
7013	65	M	Law degree	19
7014	71	F	Master's degree	17
7015	52	M	Master's degree	22
7016	69	F	Master's degree	18
Summary	M=63 SD=9.82	5 F; 10 M		M=17.1 SD=3

Participants who met any of the following criteria were excluded: 1) significant hearing loss or vision impairment that prevented them from completing the experimental tasks, or 2) pre-existing or subsequent brain injury/stroke (e.g., to right-hemisphere regions for individuals with aphasia). Cognitive screening and general language assessment measures, including the CAT, were already available for the participants with aphasia, who all participated in Hula et al. (in revision). Participants were excluded if their T scores were less than 30 for the CAT Cognitive Screening semantic memory or recognition memory subtests. T scores under 30 would be indicative of frank auditory, visual, motor speech, or general cognitive deficits. In addition, neurotypical participants were excluded if they failed a line-bisection visual screening, a binaural pure-tone hearing screening (0.5, 1, 2, and 4 KHz at 40 dB), a Mini-Mental State Examination cognitive screen (required 27/30; Folstein et al., 1975), or Raven's Coloured Progressive Matrices non-linguistic cognitive screen (required 30/36; Raven, 1965).

Institutional Review Board approval was obtained, and all participants provided informed written consent and were compensated for their time.

5.2.2 Materials

Experimental stimuli were adapted from existing normed stimuli for agent-, patient-, instrument-, and location-verb pairs (McRae et al., 2005). We developed items that paired 48 target verbs from McRae et al. (2005) with each of three kinds of noun primes. In the lexical co-occurrence condition, the primes were nouns that co-occurred frequently with the target verbs but were not strongly associated with the target verb's event (*name–WRITE*). Lexical co-occurrence primes were selected from the nouns that most frequently appear within four words of the target verb in COCA's Wikipedia corpus (Davies, 2008). We chose the highest-ranked (M = 7-8th, range: 1st-25th) collocate that: (1) was not a paradigmatic participant in the verb's event, (2) did not form a compound with the verb, and (3) was not a high collocate of many verbs. In the event-related condition, the primes were nouns that were strongly associated with the target verb's event but rarely appeared within four words of the verb in COCA's Wikipedia corpus (*pencil–WRITE*). Event-related primes were drawn from McRae et al. (2005) or from the USF Free Association Norms (Nelson et al., 1998) and consisted of agents, patients, instruments, or locations strongly associated with the target verb's event. Only seven event-related primes were among the top 100 noun collocates for their target verb (Maximum = 50th, M = 65th). In the baseline control condition, the primes were nouns that were neither associated with the verb's event nor often appeared near the verb (*water–WRITE*). They were generated by reassigning event-related primes to targets such that semantic relationships were minimized. Lexical co-occurrence and baseline conditions were matched for lexical-semantic relatedness (Landauer & Dumais, 1997; Mandera et al., 2017). Conditions were counterbalanced and pseudorandomized across three presentation lists. Word length was balanced across the presentation lists. See Appendix B1 for a complete stimulus list that includes individual item properties.

5.2.3 Testing procedures

Each participant completed all three presentation lists, interleaved with other behavioral experiments with different tasks. Every presentation list began with six practice trials, followed by 48 experimental trials. Each trial began with a central fixation cross displayed for 25 milliseconds, followed by a noun prime (in lower-case blue letters) for 450 milliseconds, followed by a central mask (&&&&&&&) for 50 milliseconds, and then the verb naming target (in upper-case black letters) remained on the screen until the participant provided a response or indicated inability to do so. An audio click was presented simultaneously with the target verb for the purpose of manual measurement of naming latencies. Because naming is challenging for people with aphasia and they do not always process incoming linguistic information efficiently (Faroqi-Shah et al., 2010; Goodglass & Wingfield, 1997; Silkes et al., 2020), we used a relatively long prime duration (longer than the standard 200 milliseconds for lexical decision tasks) and we blocked items according to whether the primes most naturally preceded the verb (i.e. event prime agents and instruments; preceding collocates) or followed it (i.e. event prime patients and locations; following collocates). Following McRae and colleagues (2005), trials were separated by a 1500-millisecond blank screen. Participants were instructed to name the target verb aloud as quickly and accurately as possible. An external microphone recorded naming responses in Audacity®, and accuracy and latency measurements coded by hand.

Accuracy and response time were the dependent variables. Trained raters followed procedures outlined by the Philadelphia Naming Test (Roach et al., 1996) in order to determine the first complete attempt, which was then scored for both accuracy and latency. Accuracy was coded as correct or incorrect. Participants with aphasia who had concomitant motor speech impairments (e.g., dysarthria, speech apraxia) were allowed one sound omission, addition, or substitution per response when considering correctness (Roach et al., 1996). Response time (latency) was measured in milliseconds from the time in which the target word was displayed (with audio click) until the participant began to produce their first complete response. These scoring procedures followed the conventional procedures used for the Philadelphia Naming Test (Roach et al., 1996). Two raters measured the critical time points and calculated the naming latency for each trial. They had 93.77 percent agreement on a randomly selected sample of 10 percent of the items (ratings within 50 milliseconds of each other constituted agreement). The raters discussed these discrepancies and reached 100 percent agreement. The amount of priming was calculated by comparing the latency of event and lexically related word pairs to baseline, unrelated trials.

5.2.4 Analyses

Data were analyzed using Bayesian mixed effect regression models, which were created in the Stan computational framework (Carpenter et al., 2017; http://mc-stan.org/) accessed with the brms package (Bürkner, 2017). Trial-level naming accuracy served as the outcome variable for two logit-link bernoulli family models, and trial-level naming response time served as the outcome variable for two ex-gaussian family models. Model 1 examined naming accuracy between participant groups; Model 2 examined naming response time between groups; Model 3 examined accuracy in participants with aphasia; and Model 4 examined response time in participants with aphasia. Estimates of facilitation under each prime condition (baseline, event-related, lexical co-occurrence) were assessed in terms of the assumptions of normality, homoscedasticity, linearity, and the presence of outliers. To address outliers, latency observations above the 95th percentile for each group were trimmed. Finally, only accurate trials were examined in Model 2 and Model 4, for which response time was the dependent variable (Forster, 1976).

The model structures are discussed below. Each parameter was given dispersed starting values and a vague prior, thus allowing the Bayesian estimation process to explore the full parameter space and provide conservative estimates of posterior distributions (McElreath, 2018). For each model, four Hamiltonian Markov chain Monte Carlo (MCMC) chains were run for 20,000 samples, with half of the iterations discarded as warm-up and 10,000 iterations monitored for convergence and parameter estimation. There was no thinning and no divergent transitions for any of the models. For each model, MCMC convergence was assessed graphically by inspection of the autocorrelation and trace plots (Appendix B2-B5) and statistically using the Gelman-Rubin potential scale reduction statistic ($\hat{R}$) and the number of effective samples. The $\hat{R}$ statistic is a ratio of the variance within each chain to the variance pooled across chains. $\hat{R}$ values close to 1 indicate satisfactory convergence of the chains to a stable distribution (Gelman et al., 2013). ESS factors out the autocorrelation in the observed MCMC chains and estimates the number of independent samples that would achieve the same degree of precision for the parameter estimates (Carpenter et al., 2017). Large ESS values indicate satisfactory convergence. The posterior distributions are summarized by the estimated parameters and 95% highest density credible intervals (HDI). The HDI is comparable to the frequentist confidence interval and is determined as the narrowest interval containing the assigned proportion of the posterior distribution's probability mass within which all values have a higher probability density than any values outside the interval (see Fergadiotis et al., 2019 for further explanation).

First, naming accuracy was compared between participant groups with and without aphasia. The outcome variable was trial-level verb naming accuracy. Fixed effects were group assignment (participants with aphasia coded as 0 vs. neurotypical controls coded as 1) and prime condition (event-relatedness vs. baseline; and lexical co-occurrence vs. baseline), and two interaction effects (group x event condition; group x lexical condition). The effect of prime condition was dummy coded with the baseline condition as the reference level. Specifically, the prime condition fixed effect was coded with two contrasts across the three levels of the variable, such that each condition of interest was compared to the baseline prime condition. Random intercepts were included for subjects and items. Random slopes were included for condition within subjects and group within items. More complex random effects structures failed to converge.

Second, naming response time was compared between participant groups with and without aphasia. Fixed effects and random effects structures were the same as for Model 1, but the outcome variable was response time (latency) from word presentation to participant response, in milliseconds.

Third, naming accuracy was examined in greater detail for participants with aphasia. The outcome variable was trial-level verb naming accuracy. Each prime condition was a fixed effect. Prime conditions were coded the same way as for Models 1 and 2. Random intercepts were included for subjects and items. Random slopes were included for condition within subjects and aphasia severity within items.

Fourth, naming response time was examined in greater detail for participants with aphasia. Fixed effects and random effects structures were the same as for Model 3, but the outcome variable was response time (latency) from word presentation to participant response, in milliseconds.

5.3 Results

Descriptive statistics of group level accuracy and response time across each prime condition are reported in Table 12. The trace plots for all parameters demonstrated rapid convergence and were stationary relative to the parameter means. The autocorrelation plots corroborated this assessment and showed minimal autocorrelation for all four models. These plots are provided in Appendix B. The $\hat{R}$ statistic and number of effective samples for each parameter indicated satisfactory convergence and MCMC mixing. These statistics are reported in Tables 13-16. Tables 13-16 also provide the point estimates and 95% credible intervals for each parameter. The posterior predictive checks and histograms of the posterior distributions for the estimates of interest are provided in below.

Table 12. Descriptive statistics of group level accuracy (percent correct) and response time (milliseconds) across prime conditions

Prime Condition		Participants with Aphasia		Control Participants		Grand Total	
		M	SD	M	SD	M	SD
Baseline	Accuracy	0.774	0.419	0.996	0.064	0.885	0.242
	Latency	0.779	0.271	0.598	0.139	0.689	0.205
Event	Accuracy	0.805	0.397	0.990	0.098	0.898	0.248
	Latency	0.822	0.271	0.596	0.159	0.709	0.215
Lexical	Accuracy	0.792	0.406	0.999	0.037	0.896	0.222
	Latency	0.822	0.280	0.589	0.127	0.706	0.204
Grand Total	Accuracy	0.790	0.407	0.995	0.067	0.893	0.237
	Latency	0.814	0.269	0.593	0.132	0.701	0.208

Notes: These values reflect the descriptive statistics after excluding outliers.

5.3.1 Model 1: Primed naming accuracy between participant groups

Group (aphasia versus control) reliably predicted trial-level primed naming accuracy (β = 5.41, EE = 1.22, 95% HDI = [3.06, 7.83]), with participants with aphasia (M = 0.790, SD = 0.407) performing less well than controls (M = 0.995, SD = 0.067). The posterior predictive check is shown in Figure 20. Figure 21 shows the posterior probability for the group effect. Furthermore, group interacted with prime condition in predicting naming accuracy, such that aphasia amplified the facilitation of event-related cues (β = -1.32, EE = 0.88, 95% HDI = [-3.13, 0.37]) but lack of aphasia (i.e., the control group) amplified the effect of lexical co-occurrence cues (β = 1.35, EE = 1.51, 95% HDI = [-1.32, 4.46]). Although both of these credible intervals overlap with zero, there is a 94.57 percent chance that the interaction between group and event facilitation is less than zero (Figure 22), and an 82.62 percent chance that the group and lexical co-occurrence interaction is greater than zero (Figure 23). The full set of results is reported in Table 13.

Table 13. Model 1 primed naming accuracy population-level effects for participants with aphasia and age-matched control participants

	Estimate	Est. Error	Lower 95% HDI	Upper 95% HDI	$\hat{R}$	Bulk ESS	Tail ESS
(Intercept)	1.84	0.54	0.79	2.94	1	1836	3811
Group	5.41	1.22	3.06	7.83	1	3055	4291
Event-related prime	0.3	0.21	-0.14	0.69	1	8274	6879
Lexical co-occurrence prime	0.26	0.26	-0.22	0.80	1	6277	5352
Group : Event prime	-1.32	0.88	-3.13	0.37	1	6724	5599
Group : Lexical prime	1.35	1.51	-1.32	4.46	1	8408	5913

Notes: HDI=Highest density credible interval. $\hat{R}$=The potential scale reduction factor on split chains (at convergence, $\hat{R}$ = 1). ESS=Effective sample size.

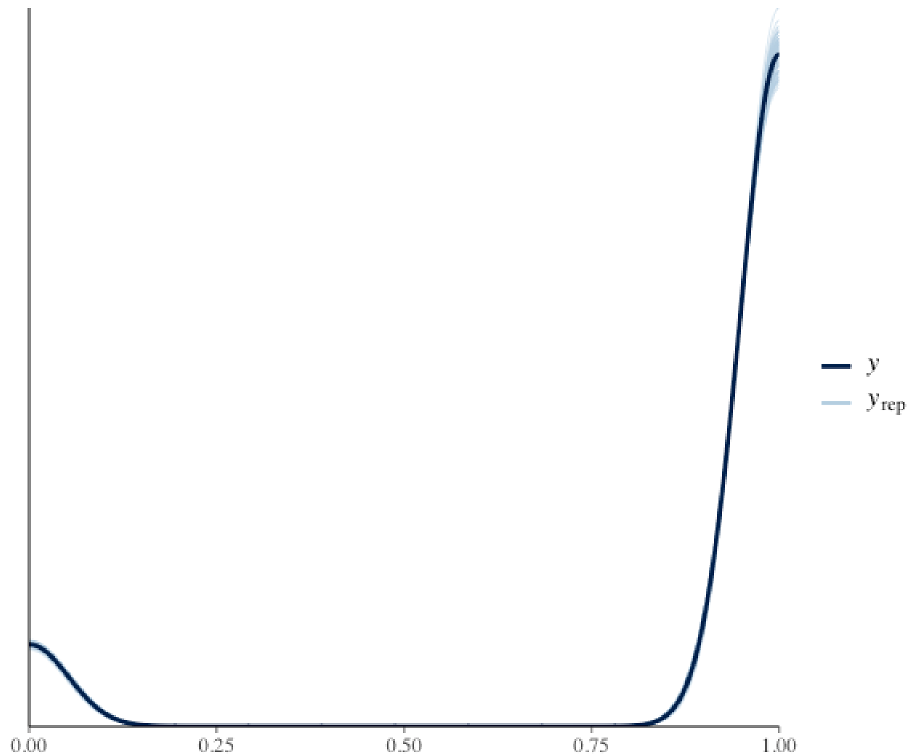


Figure 20. Posterior predictive check for Model 1

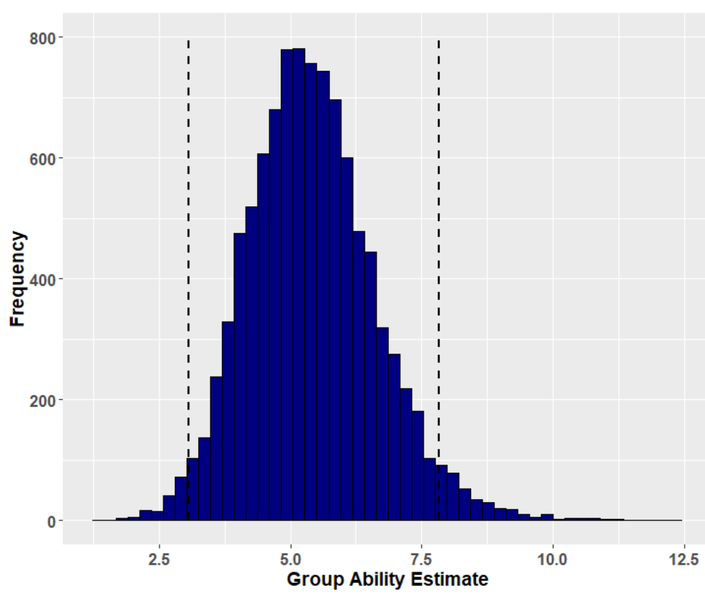


Figure 21. Posterior distribution and 95% highest density intervals (HDIs) of the fixed effect of group from Model 1 (primed accuracy for participants with aphasia and healthy controls)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

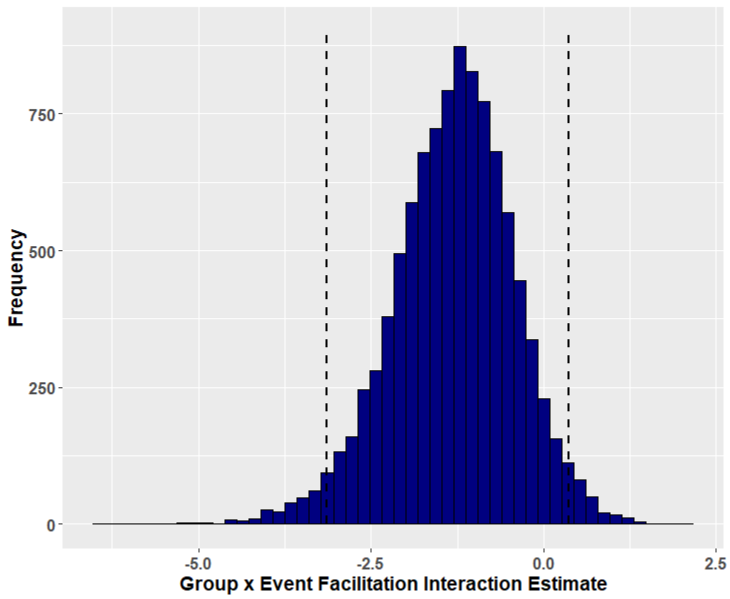


Figure 22. Posterior distribution and 95% highest density intervals of the interaction effect of group and event-related facilitation from Model 1 (primed accuracy for participants with aphasia and healthy controls)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

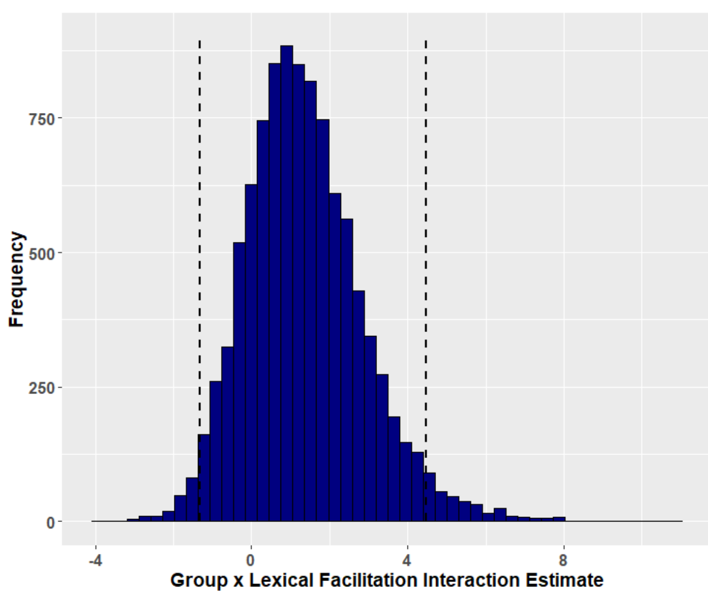


Figure 23. Posterior distribution and 95% highest density intervals of the interaction effect of group and lexical co-occurrence facilitation from Model 1 (accuracy for participants with aphasia and healthy controls)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

5.3.2 Model 2: Primed naming response time between participant groups

The posterior predictive check for Model 2 is shown in Figure 24. Group (aphasia versus control) reliably predicted trial-level primed naming response time (β = -0.274, EE = 0.072, 95% HDI = [-0.415, -0.133]; Figure 25), with participants with aphasia (M = 0.814 seconds, SD = 0.269) performing slower than controls (M = 0.593 seconds, SD = 0.132). Group interacted with prime condition in predicting naming response time, such that aphasia amplified the facilitation of both event-related cues (β = -0.011, EE = 0.015, 95% HDI = [-0.041, 0.016]) and lexical co-occurrence cues (β = -0.009, EE = 0.014, 95% HDI = [-0.036, 0.019]). However, a large proportion of the posterior probability distributions for these interaction effects overlapped with zero: there was a greater than 20 percent probability that the estimates for these interactions did not differ from zero; they were therefore not robust. The full set of results is reported in Table 14.

Table 14. Model 2 naming response time population-level effects for participants with aphasia and age-matched control participants

	Estimate	Est. Error	Lower 95% HDI	Upper 95% HDI	$\hat{R}$	Bulk ESS	Tail ESS
(Intercept)	-0.272	0.052	-0.045	-0.009	1	1928	3531
Group	-0.274	0.072	-0.415	-0.133	1	1795	3438
Event-related prime	0.008	0.018	-0.027	0.0431	1	4452	6071
Lexical co-occurrence prime	0.000	0.018	-0.034	0.036	1	4360	6273
Group : Event prime	-0.011	0.015	-0.041	0.016	1	12723	8405
Group : Lexical prime	-0.009	0.014	-0.036	0.019	1	12647	7708

Notes: HDI=Highest density credible interval. $\hat{R}$ =The potential scale reduction factor on split chains (at convergence, $\hat{R}$ = 1). ESS=Effective sample size.

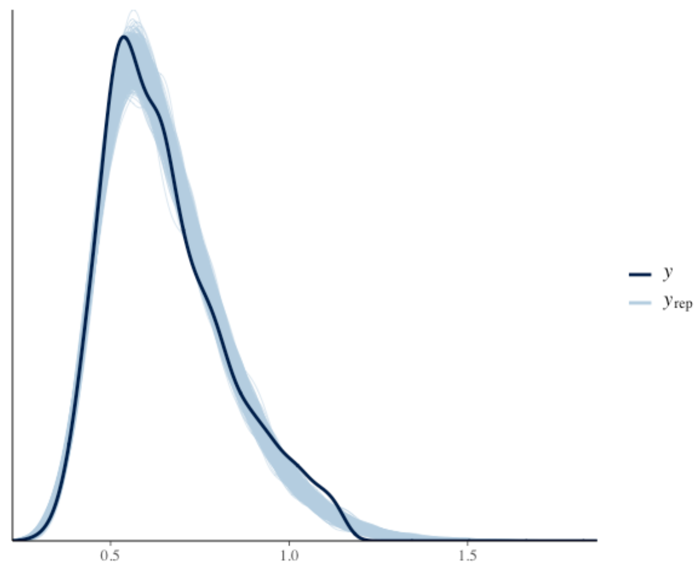


Figure 24. Posterior predictive check for Model 2

Notes: *Y* reflects an expected bimodal distribution between participants with aphasia and controls. The upper tail reflects the fact that the model does well fitting performance except for participants with aphasia at the upper tail of the response time distribution. Further work is required to understand the extent to which this poor fit is due to a lack of data observations of response times at this tail of the distribution.

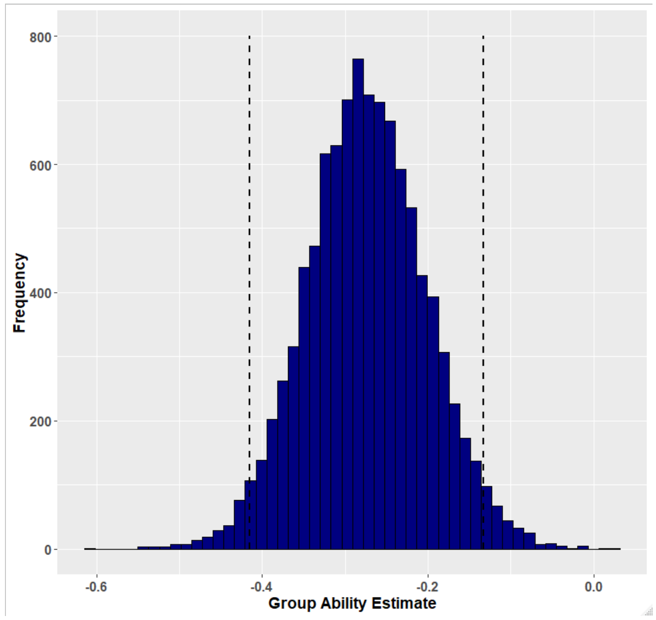


Figure 25. Posterior distribution and 95% highest density intervals (HDIs) of the fixed effect of group from Model 2 (primed response time for participants with aphasia and healthy controls)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

5.3.3 Model 3: Primed naming accuracy in participants with aphasia

The posterior predictive check for Model 3 is shown in Figure 26. Both prime conditions predicted naming accuracy in participants with aphasia, with individuals producing more correct responses after both event-related (M = 0.805, SD = 0.397) and lexical co-occurrence primes (M = 0.792, SD = 0.406), as compared to unrelated baseline (M = 0.774, SD = 0.419). Although the credible intervals for both of these effects overlap with zero, 94.69 percent of the posterior probability for event primes (β = 0.36, EE = 0.23, 95% HDI = [-0.10, 0.78], Figure 27) and 95.02 percent of the posterior probability for lexical primes (β = 0.41, EE = 0.27, 95% HDI = [-0.11, 0.94], Figure 28) exceed zero. The full set of results is reported in Table 15.

Table 15. Model 3 primed naming accuracy population-level effects for participants with aphasia

	Estimate	Est. Error	Lower 95% HDI	Upper 95% HDI	$\hat{R}$	Bulk ESS	Tail ESS
(Intercept)	1.66	0.60	0.47	2.87	1	1347	2349
Event-related prime	0.36	0.23	-0.10	0.78	1	8469	6814
Lexical co-occurrence prime	0.41	0.27	-0.11	0.94	1	5683	5312

Notes: Aphasia severity was z-score transformed CAT modality mean score. HDI=Highest density credible interval.

$\hat{R}$ =The potential scale reduction factor on split chains (at convergence, $\hat{R}$ = 1). ESS=Effective sample size.

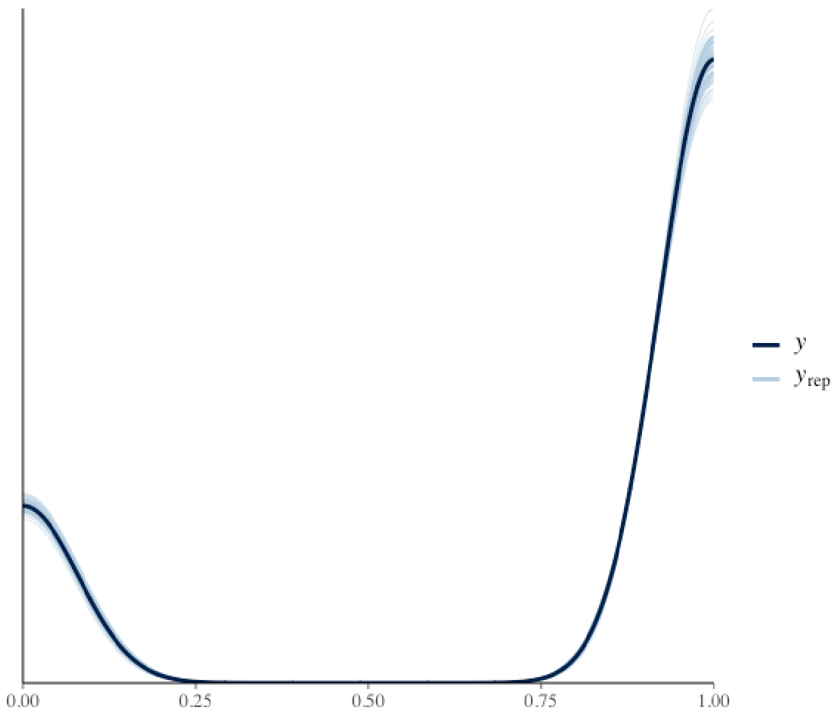


Figure 26. Posterior predictive check for Model 3

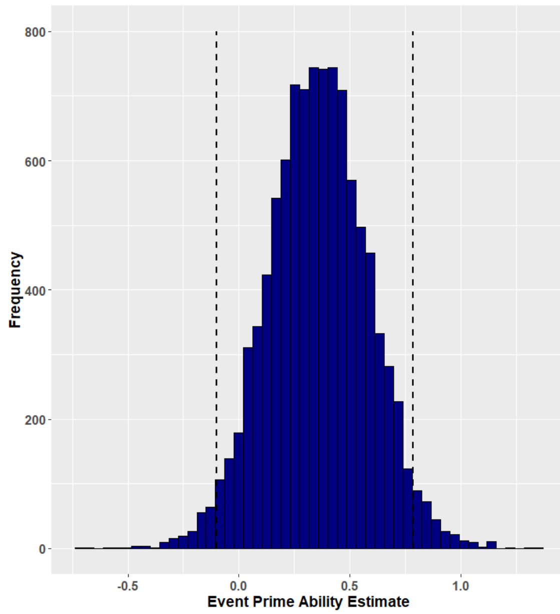


Figure 27. Posterior distribution and 95% highest density intervals (HDIs) of the fixed effect of event-related facilitation from Model 3 (primed accuracy for participants with aphasia)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

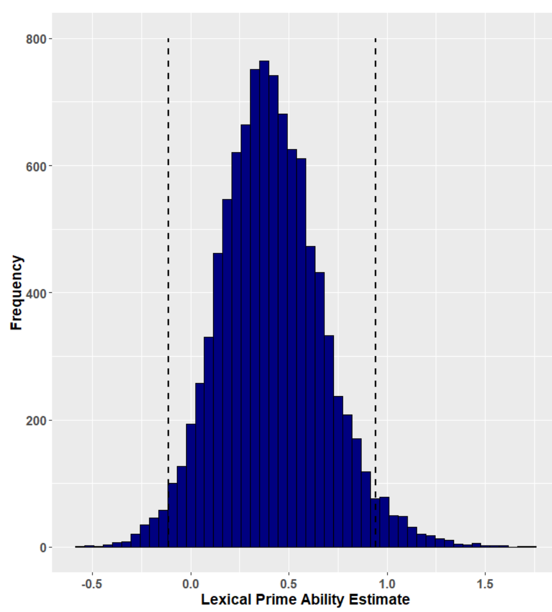


Figure 28. Posterior distribution and 95% highest density intervals (HDIs) of the fixed effect of lexical co-occurrence facilitation from Model 3 (primed accuracy for participants with aphasia)

Notes: Dashed lines mark the 95% highest density intervals (HDIs) for the posterior distribution.

5.3.4 Model 4: Primed naming response time in participants with aphasia.

The posterior predictive check for Model 4 is shown in Figure 29. No reliable priming in response time was observed in participants with aphasia for either event-related (β = 0.017, EE = 0.020, 95% HDI = [-0.024, 0.056]) or lexical co-occurrence conditions (β = 0.010, EE = 0.017, 95% HDI = [-0.024, 0.044]). The full set of results is reported in Table 16.

Table 16. Model 4 naming response time population-level effects for participants with aphasia

	Estimate	Est. Error	Lower 95% HDI	Upper 95% HDI	$\hat{R}$	Bulk ESS	Tail ESS
(Intercept)	-0.155	0.083	-0.048	0.022	1	1613	3030
Event-related prime	0.017	0.020	-0.024	0.056	1	9456	6504
Lexical co-occurrence prime	0.010	0.017	-0.024	0.044	1	10178	7234

Notes: Aphasia severity was z-score transformed CAT modality mean score. HDI=Highest density credible interval.

$\hat{R}$ =The potential scale reduction factor on split chains (at convergence, $\hat{R}$ = 1). ESS=Effective sample size.

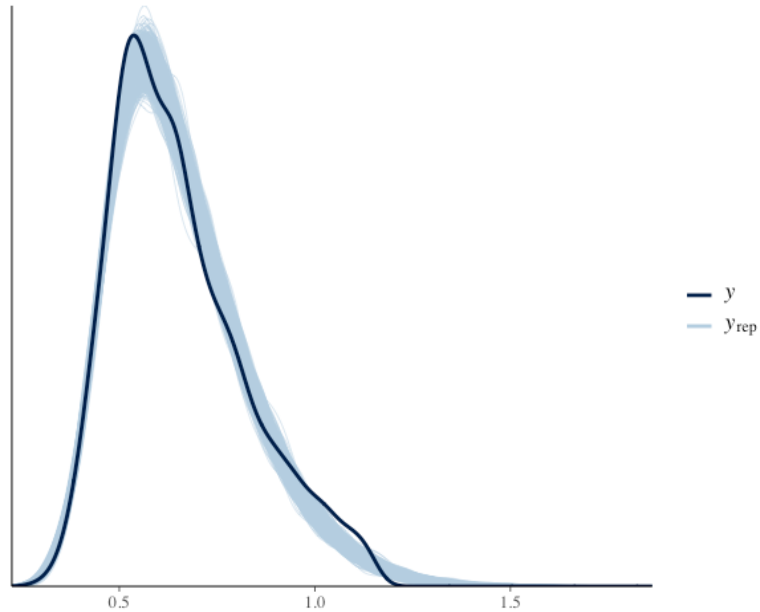


Figure 29. Posterior predictive check for Model 4

Notes: *Y* reflects the fact that the model does well fitting participant performance except for participants with aphasia at the upper tail of the response time distribution. Further work is required to understand the extent to which this poor fit is due to a lack of data observations of response times at this tail of the distribution.

5.4 Discussion

The purpose of this study was threefold. First, it aimed to replicate and extend findings from Willits, Amato, and MacDonald (2015) that indicate naming is a language-focused task in which healthy language users prioritize knowledge of word co-occurrence over conceptual event relatedness. Second, it examined the hypothesis, grounded in rational adaptation, that during verb naming adults with aphasia would rely more heavily on conceptual event-related cues and less heavily on lexical co-occurrence cues, compared to neurotypical controls. Third, aphasic behavior was examined more closely to assess differences in conceptual versus lexical facilitation within the sample of individuals with aphasia. The findings are summarized below, and their implications are discussed in relation to rational adaptation hypotheses and potential clinical directions moving forward.

First, our results from neurotypical controls were broadly consistent with findings from Willits, Amato, and MacDonald (2015), who observed that participants showed robust facilitation from highly related lexical co-occurrence information in naming tasks. Specifically, Willits and colleagues (2015) found participants had faster response times after primes with high co-occurrence probability and high semantic relatedness than primes with low co-occurrence and high relatedness to the target verb. The current sample of older neurotypical adults showed broadly similar patterns to Willits and colleagues' college-aged adults, with greater facilitation of naming in lexical-prime conditions. However, these patterns appeared in accuracy rather than latency measures. This difference may not be surprising, given both the high response-time latency variability in the current sample and the different tradeoffs younger and older adults make between speed and accuracy, with older adults prioritizing accuracy over speed (Ratcliff et al., 2004; Starns & Ratcliff, 2010). These findings suggest that unimpaired language users prioritize linguistic information (specifically, word co-occurrence frequency information) more than conceptual cues when performing naming tasks. This is consistent with findings from language production studies showing that wordform retrieval, which is the specific production task used here, is especially sensitive to lexical frequency effects (e.g., Jescheniak & Levelt, 1994) and that high frequency word collocations speed processing (Arnon & Snider, 2010; McDonald & Shillcock, 2003; Smith & Levy, 2013). These findings are also consistent with the principle of rational adaptation. Specifically, our results add to evidence supporting task-based rational adaptation, which contends that language users rely on the most informative source of knowledge to optimize their behavior on the task at hand (Anderson, 1991; Howes et al., 2009).

Next, we examined the effect of aphasia on primed verb naming (wordform retrieval). As expected, adults with aphasia consistently named verbs more slowly and less accurately than controls for all prime conditions. This is consistent with a large body of literature that demonstrates verb-retrieval deficits in individuals with aphasia (e.g., Berndt et al., 1997; Jonkers & Bastiaanse, 2007; Rofes et al., 2015). Importantly, presence of aphasia interacted with prime condition in predicting verb retrieval accuracy. Participants with aphasia received an amplified facilitation effect, or greater priming, from conceptual event-related cues compared to the control group. In contrast, the control group received greater priming from lexical co-occurrence cues compared to participants with aphasia. Of note, this is not consistent with previous evidence suggesting that aphasia may magnify the effects of lexical frequency on language performance (DeDe, 2013a, 2013b; Gahl, 2002). For naming latencies, presence of aphasia amplified priming from both event-related and lexical co-occurrence cues. This facilitation was less certain in the lexical co-occurrence condition than in the event-related condition, as indicated by wider credible intervals for the lexical co-occurrence condition. This is likely due to high variability in the lexical co-occurrence condition between subjects with aphasia. However, the lexical co-occurrence and event-related cues both showed similar magnitudes of response time priming in people with aphasia, as reflected by similar point estimates for lexical and event facilitation.

Finally, the models that examined performance specifically in participants with aphasia found robust facilitation effects of both conceptual event and lexical co-occurrence cues on verb naming accuracy, but neither cue type reliably influenced naming response time. These results largely echo the pattern of findings discussed above, which indicate that individuals with aphasia showed both event-related and lexical co-occurrence priming in naming accuracy, but no priming effects were evident for response time measures.

Taken together, the findings of this experiment indicate that individuals with aphasia do demonstrate rational adaption. Participants with aphasia showed robust priming from both conceptual event-related and lexical co-occurrence information. Importantly however, individuals with aphasia relied more on conceptual event-relatedness cues and less on lexical co-occurrence cues than neurotypical adults did. These results extend evidence from healthy adults to individuals with aphasia: nouns prime verbs that denote events in which the nouns are commonly involved (e.g., McRae et al., 2005, 2001). This extension is critical because it highlights the importance of conceptual event knowledge in disordered language processing. People with aphasia are not only primed by conceptual event knowledge during verb production, but they appear to be more primed by such information than neurotypical adults are. These findings provide new evidence for the hypothesized involvement of conceptual event-knowledge mechanisms underlying efficacious speech-language treatments targeting verbs (e.g., VNeST: Edmonds, 2016; see further discussion below).

This finding is also consistent with previous evidence of rational adaptation in aphasia, and it extends the evidence base beyond sentence comprehension to verb production. In contrast to previous investigations of rational adaptation in aphasia, this study examined stored knowledge of linguistic representations – specifically, stored knowledge of word co-occurrences – rather than bottom-up linguistic input, such as the literal sentence form (Gibson et al., 2015; Warren et al., 2017). As discussed in the introduction, previous studies investigating off-line comprehension (i.e., the final interpretations reached for a sentence) have reported that people with aphasia can rationally adapt to rely more heavily on conceptual event likelihood cues, and they critically did so to a larger magnitude than neurotypical controls did (Gibson et al., 2015; Warren et al., 2017). Visual world studies investigating online sentence comprehension have also showed that in situations in which neurotypical adults' anticipatory processing was guided by both conceptual event knowledge and linguistic representations, individuals with aphasia only showed anticipatory effects of conceptual event knowledge (Hayes et al., 2016). Integrating the current results with these findings suggests that participants with aphasia may employ rational adaptation to utilize relatively unimpaired conceptual-semantic systems to a greater extent than healthy adults to accomplish not only sentence comprehension, but also verb retrieval. In particular, these findings provide new evidence that people with aphasia adapt to their impairments by weighting conceptual and lexical information types differently than neurotypicals do when performing speeded retrieval of verb wordforms.

Even previous evidence that is consistent with rational adaption in aphasia could be explained by the fact that people with aphasia show less reliance on linguistic knowledge than neurotypicals (Hayes et al., 2016; Warren et al., 2017). This prediction is not unique to rational adaptation, nor is it surprising given that aphasia, by definition, affects language. A critical contribution of this study is that it separately examines automatic facilitatory effects of linguistic and conceptual information types, which are independent of one another in this study design. Linguistic and conceptual knowledge were also independent in the study by Hayes and colleagues (2016), but they only found evidence that people with aphasia relied less on linguistic knowledge than neurotypical controls did. The current study provides new evidence for this finding but furthermore indicates that people with aphasia critically rely more on conceptual event-related information than controls do.

Further work is needed to replicate and extend the current findings in a larger sample of individuals with aphasia. The current study found interactions between group and the two cue contrasts (conceptually associated vs. unrelated baseline; lexically associated vs. unrelated baseline), but future investigations may directly compare conceptual and lexical facilitation. For example, analyzing whether there are robust differences in the magnitude of facilitation between conceptual and lexical conditions could shed light on whether all or certain individuals with aphasia rely more on conceptual cues than lexical cues, and to what extent. The priming effect sizes in the current sample are not large enough to show meaningful or systematic differences between condition cue types, and it is possible that a larger and more diverse sample would enable further exploration of data in this way.

Assessing the mechanisms underlying rational adaptation and potential tradeoffs between conceptual and lexical information will be informative as to what cognitive processes or routes the rational adaptation observed here is operating over. For example, it could be reweighting different routes to lexical access, or alternatively, successive stages of lexical access. If it is reweighting lexical-access routes, the current findings may be evidence that the conceptual system – which some grounded-cognition-inspired models of meaning (Kelter & Kaup, 2012) and highly interactive/interconnected connectionist models of lexical representation (Plaut et al., 1996) have argued provides an indirect, alternate, and typically less efficient route to access lexical wordform information – is a relatively more efficient route to wordform access for people with aphasia. If rational adaptation is re-weighting inputs to successive stages of lexical access, then the nature of people's lexical-access deficits may affect how successful such rational adaptation is. Individuals with aphasia can experience deficits to different stages of lexical access, affecting either conceptual-to-lexical or lexical-to-phonological mapping, or both (Foygel & Dell, 2000). Individuals with more impaired conceptual-to-lexical mapping (s-weight) might receive less priming from conceptual event-related cues than individuals with relatively spared lexical-semantic processing. Of note, the degree of lexical-semantic or lexical-phonological impairment is associated with neurological variability such as lesion site and white-matter connectivity (Dell et al., 2013; Hula et al., in revision; Study 2); this neurological variability may underlie person-level variation in degree of conceptual priming. Further research is needed to assess the potential mechanisms that underlie the role of conceptual information in aphasic language processing.

In addition, rational adaptation predicts that increased damage to the language system would result in increased adaptive reliance on conceptual information types in people with aphasia. Applying this prediction to the current study, we would expect that aphasia severity would interact with information cue type, such that greater severity would amplify the facilitation effects of conceptual event-related cues but reduce the effects of lexical cue facilitation on verb naming. In the current investigation, overall aphasia severity was not included as a covariate predictor due to its multicollinearity with fixed effects of greater theoretical interest, such as the degree of facilitation from different information cue types. Because including aphasia severity in our models attenuated the magnitude of facilitation effects, our analyses were unable to test this prediction in the current (limited) sample. This potential limitation and the relatively small magnitude effects highlight the need for larger samples of participants with aphasia in future studies.

Furthermore, as suggested in Silkes, Baker, and Love (2020), the level of linguistic task complexity could also contribute to whether and to what degree an individual with aphasia might rely on conceptual information. Future work might therefore examine linguistic tasks that vary in complexity, such as comparing rational adaptation during (speeded) primed verb naming to untimed sentence completion tasks (Willits et al., 2015). The mechanisms underlying rational adaptation may be informed by a more thorough characterization of the locus and severity of behavioral and neurological impairments in individuals who receive facilitation from conceptual information during lexical access.

Finally, the current findings may provide new evidence for mechanisms involved in efficacious aphasia interventions. A key finding from this study is that participants with aphasia exhibited a greater degree of naming facilitation from conceptual cues than neurotypical controls did, while controls exhibited a greater degree of facilitation from lexical co-occurrence cues than participants with aphasia did. This result has critical implications because it aligns with the hypothesized mechanism of action for speech-language treatments like Semantic Feature Analysis (SFA; Boyle, 2010), SFA for Actions (Wambaugh et al., 2014), and Verb Network Strengthening Treatment (VNeST; Edmonds, 2016). Specifically, these treatments systematically activate information conceptually related to target words, based on evidence for bidirectional facilitation effects between event-related verbs and thematic roles (Ferretti et al., 2001; McRae et al., 2005). These interventions promote improved lexical retrieval ability for treated nouns (SFA) and verbs (SFA for Actions, VNeST), and there is evidence that improvements can generalize beyond trained items to the lexical retrieval of untreated words, sentences, and performance in connected discourse (e.g., Edmonds, 2016; Quique et al., 2019; Rider et al., 2008). Our rational adaption findings thus demonstrate the likely mechanism driving conceptual/semantic-based aphasia rehabilitation: If people with aphasia already exhibit reliance on conceptual information to retrieve words, then treatment can take advantage of this established mechanism by strengthening conceptually driven activation/retrieval processes. Future efforts to characterize the specific psycholinguistic and neurocognitive systems involved in this adaptation and to identify the types of patients who are most likely to engage adaptive strategies to rely more on conceptual knowledge will advance both our theoretical and clinical approaches to aphasia rehabilitation.

5.5 Conclusion

This study found evidence that individuals with aphasia rationally adapt to their language impairments by relying on conceptual cues to a greater extent than healthy controls do. Participants with aphasia received an amplified facilitation effect from conceptual event-related cues compared to the control group, whereas the control group received a greater facilitation effect from lexical co-occurrence cues compared to participants with aphasia. These findings indicate that adaptation to alternative and relatively unimpaired information types can facilitate successful word retrieval in adults with aphasia. Further work must continue to assess the specific mechanisms underlying rational adaptation in aphasic language, as well as the specific psycholinguistic mechanisms by which conceptual information sources may facilitate verb retrieval. This line of research will ultimately help advance neurorehabilitation and speech-language interventions.

6.0 General Discussion

Verb-retrieval deficits are a prevalent and often permanent symptom for individuals with chronic aphasia (Mätzig et al., 2009; Rofes et al., 2015). Impaired verb retrieval is associated with significant deficits in sentence processing and communicative activities of daily living (Berndt, Haendiges, et al., 1997; Cho-Reyes & Thompson, 2012; Rofes et al., 2015). Verb-retrieval deficits are more frequent and are associated with more variability in terms of severity, clinical diagnostic category, and lesion sites than noun impairments (Mätzig et al., 2009). In their thorough review of the literature, Mätzig and colleagues (2009) speculated that due to this high variability in patient profiles, verb deficits may be caused by a variety of neurocognitive impairments (see future directions/individual difference section below for discussion). However, the preponderance of neurolinguistic and language rehabilitation research has focused on nouns in lexical retrieval. The nature of verb impairments and the mechanisms underlying their rehabilitation remain poorly understood.

Neurolinguistic and neurorehabilitation models must account for verb naming and verb-retrieval deficits. Aim 1 of this dissertation research investigated competing behavioral (Study 1) and neuroanatomical hypotheses (Study 2) from two prominent theories of cognition – cognitive-linguistic accounts and ground cognition theory – with the goal of characterizing conceptual-motor and linguistic components of aphasic verb-retrieval deficits. Aim 2 (Study 3) characterized the types of stored information that support verb retrieval in healthy and disordered populations by testing the prediction that adults with aphasia rationally adapt to language impairments by relying more on conceptual information than neurotypical adults do.

To summarize the results of this research, Study 1 findings emphasized the critical contributions of conceptual-semantic action processing abilities to aphasic verb-retrieval deficits, measured by performance on an action picture naming task. In the present sample, both conceptual and lexical action-processing were impaired in people with aphasia. Furthermore, higher conceptual action-processing ability reduced the effect of lexical-level verb impairments on verb-retrieval ability: Individuals with lower lexical processing ability but relatively high conceptual processing ability exhibited better action naming performance. In Study 2, diffusion spectrum neuroimaging results revealed that in addition to traditional language-related white matter tracts, motor pathways and subcortical networks were also robustly associated with verb retrieval across both healthy and disordered language users. Finally, Study 3 demonstrated that adults with aphasia may rationally adapt to their language impairments by rely more on conceptual event knowledge than lexical co-occurrence knowledge when producing verbs, as compared to healthy controls.

Taken together, these studies show evidence for important contributions of conceptual semantics to verb retrieval for adults with aphasia. Consistent with predictions of grounded cognition, the results from these studies indicate that conceptual action-processing performance (Study 1) and conceptual-motor neural pathways (Study 2) can be impaired in adults with aphasia. These behavioral and neural impairments were both associated with verb retrieval ability, and conceptual deficits were more reliable predictors of verb-retrieval deficits than lexical impairments were (Study 1). Furthermore, individuals with aphasia received robust and roughly equal degrees of priming facilitation from both conceptual event-related cues and lexical co-occurrence cues when retrieving verbs (Study 3). And finally, higher conceptual action-processing attenuated the effect of the lexical processing impairments on verb retrieval (Study 1). In particular, for an individual with lower lexical-processing abilities, stronger conceptual action-processing was associated with more successful verb retrieval. This interaction effect is consistent with the hypothesized mechanism behind aphasia treatments like Verb Network Strengthening Treatment (VNeST; Edmonds, 2016), which propose that patients with aphasia can improve their language skills – like verb retrieval – by strengthening conceptual-semantic networks related to target verbs.

This interaction effect is consistent not only with grounded cognition (see Study 1 discussion), but also with predictions of rational adaptation. Rational adaptation states that people can rely on one information source over another to optimize behavior under different task conditions and disease states (Anderson, 1991; Caramazza & Zurif, 1976; Gibson et al., 2015; Howes et al., 2009; Warren et al., 2017). As such, rational adaptation predicts that people with aphasia can adapt to their lexical/language impairments by relying more on conceptual semantic systems. Following this logic, if an individual has unimpaired (or relatively strong and intact) conceptual semantics, then they should be able to leverage that system to better accomplish tasks like verb retrieval. The interaction in Study 1's findings corroborates this prediction, showing that stronger conceptual action-processing reduced the effect of lexical deficits on the action naming task. It is reasonable to believe that rational adaptation may be driving this interaction because there is significant evidence consistent with the assertion that people with aphasia rationally adapt their behavior in response to changes in their lesioned neurocognitive system (see Study 3 introduction).

Study 3 offers additional evidence for rational adaptation in aphasia, particularly for verb retrieval accuracy. Although the group of participants with aphasia received facilitation from both event-related and lexical co-occurrence cue types compared to unrelated cues, when contrasted with healthy controls, participants with aphasia showed a clear shift in behavior. The presence of aphasia amplified the effect of event-related facilitation, whereas neurotypical participants received more facilitation from lexical co-occurrence cues on naming accuracy. This is consistent with rational adaptation predictions that individuals with aphasia adapt to their language impairments by relying more heavily on relatively intact representations or systems, such as conceptual knowledge.

In contrast to the primed naming accuracy results, rational adaptation predictions were not borne out for the primed naming response times. The only reliable differences in naming latencies showed a significant group difference, whereby participants with aphasia produced verbs more slowly than healthy controls across all prime conditions. However, participants with aphasia performed with high variability both within and across individuals. There is also evidence that individuals employ different speed-accuracy trade-off strategies when completing language tasks (Evans et al., 2019).

6.1 Theoretical implications

This dissertation work examined the theoretical frameworks of grounded cognition, cognitive-linguistic models, and rational adaptation. Evaluating the dissertation project as a whole provides insight into whether and how these accounts might explain healthy and disordered verb retrieval. The set of experiments in this dissertation evaluate the adequacy of classic cognitive-linguistic theory in explaining aphasia. The evidence summarized above suggests that these frameworks should be reevaluated and revised to incorporate conceptual contributions to language impairments (consistent with grounded cognition accounts) and information-based rational adaptation. As described above, the current findings provide novel evidence that rational adaptation affects not only comprehension but production, and that individuals with aphasia rationally adapt to use conceptual information in order to carry out linguistic tasks. This adaptation to rely on conceptual representations is also relevant to the contrasting claims made by the other two theoretical frameworks considered here, grounded cognition and cognitive-linguistic models. Although both models acknowledge the potential importance of conceptual representations to characterizing aphasic language performance, they differ in their view of how conceptual knowledge contributes to language representations and impairments.

In contrast to traditional cognitive-linguistic accounts, grounded cognition accounts assert that as we experience the world around us, our brains integrate information from language (e.g., co-occurrence frequency statistics; see Study 3), sensory, motor, and affective modalities (Barsalou, 2008; Martin, 2016; Pulvermüller, 2018). These multimodal experiences are stored as distributed memory representations that can later be activated by language and retrieved for use. According to grounded cognition, language processing is accomplished by a general-purpose cognitive system that operates over representations encoding both linguistic and non-linguistic (e.g., conceptual, affective, sensorimotor) knowledge (Altmann, 2017; Martin, 2016; Zwaan & Madden, 2005). These predictions are consistent with Study 1 and 2 findings that conceptual processing and conceptual-motor neural systems critically contribute to verb naming performance. Grounded cognition frameworks may also provide a method by which, as seen in Study 3, people with aphasia adapt to their language impairments by retrieving lexical word form information via (multimodal and neurally distributed) conceptual information.

Although this dissertation's findings may be explained by principles of grounded cognition and rational adaptation, the experiments herein do not provide absolute evidence in support of these theories or against cognitive-linguistic frameworks. It remains unclear to what degree prevailing cognitive-linguistic accounts of aphasia require revisions to explain the current set of findings. However, it will be important moving forward that clinical rehabilitation frameworks consider alternative approaches to aphasia that acknowledge the critical contribution of conceptual systems to linguistic disorders and interventions.

Recall that cognitive-linguistic accounts of aphasia assume cognition is a modular and symbolic system that maintains neuroanatomical and functional separation between linguistic and conceptual information/processes (Goodglass, 1993; Hickok & Poeppel, 2004, 2007; Lichteim, 1885; McNeil & Pratt, 2001; Wernicke, 1874). Following this perspective, verb-retrieval deficits result from damage to linguistic processes that are supported by perisylvian language regions, while conceptual knowledge systems remain relatively intact and unimpaired, at least in comparison to language. Cognitive-linguistic accounts thus do not naturally predict findings from Study 1 that individuals with aphasia exhibited both conceptual and lexical action-processing impairments, and that both types of impairments were associated with verb-retrieval deficits. These results might be accounted for by additional assumptions that are not inconsistent with cognitive-linguistic models. For instance, these individuals might display comorbid deficits of conceptual action representations that are separate from aphasia but nonetheless disrupt the retrieval of conceptual information that is required prior to lexical access, thereby resulting in the manifestation of verb-retrieval deficits stemming from a locus outside of the language system. However, cognitive-linguistic accounts also do not predict Study 2's findings that white matter tracts from principal motor pathways predict verb retrieval performance. Study 2 suggests that action-motor pathways are associated with action naming in both individuals with aphasia and neurotypical controls. Although individuals with aphasia may rely on motor pathways for compensatory or adaptive strategies, cognitive-linguistic accounts offer no direct explanation for motor tract involvement in healthy language users, who could presumably rely on language-specialized networks to accomplish verb naming (see Ripollés et al., 2017 for related findings).

These findings may be better accounted for by alternative theoretical frameworks like grounded cognition. As predicted by grounded cognition accounts, Study 2 indicates that verb retrieval is associated with a distributed white matter network that is involved in both linguistic and non-linguistic conceptual-motor performance. This could be accomplished by grounded cognition's hypothesis that language operates as a general-purpose cognitive system that engages representations across regions specialized for linguistic, motor, and affective/limbic processing (Altmann, 2017; Barsalou, 2008; Martin, 2016; Zwaan & Madden, 2005).

The debate in grounded cognition theory has traditionally focused on the format of concepts (abstract/symbolic vs. modality-specific; Mahon, 2015 for review). However, the focus is moving toward how activity spreads between representations, for instance between amodal and sensory/motor representations. The specific issues at hand include which neurocognitive systems are involved in verb processing, how these systems are involved (e.g., their respective roles and possible interactions), and in what (linguistic) contexts these systems are engaged. The current findings might be most consonant with weak embodied cognition models, which suggest that concepts are grounded in, and interact with sensorimotor systems. This weak, hybrid, or pluralistic perspective has been referred to by many names, including cross-modal conjunctive representations, action perception circuits, neural cell assemblies, hub-and-spoke models, sensory/motor models, and grounding by interaction (Barsalou, 1999; Binder & Desai, 2011; Chao & Martin, 2000; Hauk & Tschentscher, 2013; Kiefer & Pulvermüller, 2012; Lambon Ralph, 2014; Martin, 2007, 2009; Meteyard et al., 2012; Patterson et al., 2007; Pulvermüller, 2005; Zwaan, 2014). Despite differences among these specific models, these accounts all theoretically allow for interactivity between conceptual, motor, and linguistic systems. However, the precise nature of these interactions and the role of language remain elusive. Further work is needed to determine what mechanisms gate information flow within and between these interacting systems, and in what linguistic contexts sensorimotor systems are usefully engaged.

Despite these open questions regarding weakly grounded models, such accounts would naturally explain the current findings, indicating a strong influence of action-conceptual and sensorimotor information on verb retrieval. These findings are also consistent with a large body of psycholinguistic and neuropsychological evidence suggesting that conceptual-semantic information is intimately connected to language performance. As reviewed in Study 3's introduction, priming experiments have demonstrated that conceptual-semantic memory allows for immediate access of event knowledge from multiple types of single-word cues, resulting in facilitated naming of event-related concepts (Ferretti et al., 2001; Hare et al., 2009; McRae et al., 2005, 2001). These findings have been corroborated by visual-world (Milburn et al., 2016) and ERP studies (Amsel et al., 2015). In addition, neuropsychological studies have documented comorbidities between conceptual and language performance for objects (Jefferies & Ralph, 2006) and actions (Kemmerer et al., 2012). This evidence is consistent with claims that conceptual and linguistic representations may in fact be commingled, as claimed by both strong and weakly grounded views of cognition.

Future work should also investigate similarities and differences between retrieval of verbs and other word types. The current findings suggest that verb retrieval is critically supported by both language and conceptual representations, with deficits or lesions impacting either system predicting the degree of verb-retrieval impairments among individuals with aphasia. This pattern is somewhat different from that seen for noun retrieval. In the neuropsychological and aphasiological literature, object naming and object knowledge impairments are commonly seen as being dissociated: people with aphasia consistently have noun-retrieval difficulties (anomia), but relatively rarely have object-related conceptual impairments (Goodglass, & Wingfield, 1997; McNeil & Pratt, 2001). It is unclear whether this apparent difference between noun retrieval and verb retrieval stems from a smaller number of case study examples focused on verb retrieval (see related discussion in Section 6.4), poor characterization of verb anomia versus agrammatic aphasia symptoms, or the possibility that lexical and conceptual systems may fractionate differently for nouns and verbs. However, it is possible that nouns and verbs might be grounded to modality-specific (or specialized) systems in different manners, which could help explain the strong contribution of both conceptual and language impairments to verb-retrieval performance in the current study. Nouns are traditionally considered to be grounded in physical component properties (e.g. *an apple* is shiny, round, crunchy, sweet, etc.; Martin, 2016). In contrast, verbs may have a broader grounding that relies both on sensorimotor properties (represented in action-related motor and pre-motor regions) and on relational knowledge (e.g. *eating* typically involves an animate agent [eater], an inanimate patient [food], and sometimes an instrument [fork/spoon]). Accordingly, verbs could be grounded in distributed neural systems that extend beyond the primary sensorimotor regions, including regions that are commonly affected in left MCA stroke (the most common cause of aphasia; Quandt et al., 2017; Wurm & Caramazza, 2019). In contrast, object knowledge is commonly represented in inferotemporal regions and anterior temporal regions that are less likely to be affected by left MCA stroke (Damasio, 1989; Martin, 2016). This hypothesis remains to be investigated but would be consistent with psycholinguistic evidence for bidirectional priming between action verbs and thematic role agents, patients, instruments, and locations related to the actions the verbs denote (see McRae & Matsuki, 2009). This hypothesis would also be consistent with findings from Study 2, which identified associations between action naming and a network of white matter tracts that have not been implicated in similar studies of object naming (e.g. Akinina et al., 2019; Hula et al., in revision).

The focus of this dissertation is on characterizing aphasic language-processing deficits – specifically, verb retrieval deficits. The current findings appear to be most naturally consistent with grounded cognition accounts. However, grounded cognition theories of language processing and language impairment remain underspecified. One grounded perspective on language is described by Zwaan (2016) and Barsalou (2016), who claim that words are distributed linguistic representations that are the sum of their visual, auditory, and motor patterns. They propose that words function as symbolic placeholders that enable efficient processing for completing tasks, such as verb retrieval. Consistent with this perspective (Barsalou, 2016; Zwaan, 2016), the activated content of these distributed representations can be more colored by collocation statistics (e.g., lexical co-occurrence information, as in Study 3) or by multimodal simulations (e.g., action-conceptual processing in Study 1; motor white-matter tracts in Study 2) based on the task demands, or perhaps whether the language system is noisy or impaired. The current work extends this grounded view of language to aphasia by hypothesizing that words may engage conceptual information not only to different extents under different experimental or linguistic task conditions but will also critically vary as a function of aphasic deficits. This view provides a new and potentially useful way of understanding aphasic language deficits: it recasts them as a special case of a more general phenomenon, varying degrees of engagement of different components of distributed representations. Such an approach to aphasic language deficits remains to be fully specified, but it may provide a useful alternative to or extension of classical cognitive-linguistic models of aphasia.

6.2 Clinical implications

Characterizing the contributions of impaired lexical and conceptual action-processing that result in aphasic verb-retrieval deficits is critical not only for developing theories of disordered language processing, but it is also integral for treatment planning. This dissertation research informs verb-treatment strategies by identifying the critical contribution of conceptual processing in verb retrieval in individuals with aphasia. Study 1 highlights the need to assess both lexical and conceptual action-processing ability in individuals with verb-retrieval deficits. Furthermore, the interaction between conceptual and lexical processing described in Study 1 is consonant with hypothesized mechanisms behind efficacious verb treatment strategies (e.g., VNeST; Edmonds, 2016) and supports strengthening conceptual semantics to improve verb naming in adults with aphasia. Similarly, Study 2 results suggest that in addition to classic dual-stream language pathways, it will be critical to characterize the involvement of conceptual and motor pathways, as well as subcortical and right-hemisphere regions in verb processing and aphasic impairments. Although these findings are preliminary, they could lead to development of neurorehabilitation techniques like paired stimulation of conceptual-motor tracts with behavioral interventions like VNeST (Edmonds, 2016). Finally, since participants with aphasia received more conceptual cue facilitation than controls, Study 3 indicates that individuals with aphasia might adapt to their language disorder by relying more heavily on conceptual information in contexts where neurotypicals preferentially rely on lexical information (Willits et al., 2015). This suggests that speech-language treatments should incorporate conceptually related cues for lexical retrieval therapy. Together these findings highlight that assessing (Mätzig et al., 2009; Rofes et al., 2015) the cognitive and neural bases of verb-retrieval deficits in people with aphasia will be essential to formulating efficacious verb treatments.

6.3 Limitations

Several empirical limitations of the studies reported in this dissertation should be considered. First, despite many advantages of the Fiez and Tranel (1997) battery, there are also task-specific limitations (see Kemmerer et al., 2012 for further discussion). In the lexical action-processing and verb naming tasks, the verb stimuli were not carefully controlled for potentially confounding ‘nuisance’ variables like age of acquisition, frequency, length, imageability, noun/verb homophony, transitivity, or the range of possible argument structure constructions. In addition, across all of the Fiez and Tranel tasks (1997), potentially confounding conceptual nuisance variables were not carefully controlled for, including the body part(s) involved in the action, the number or type of core entities involved, whether the action was causal or required an entity to undergo physical changes, and so forth. Furthermore, the tasks involve various combinations of verbal and non-verbal processing, including verbal instructions of varying complexity and different degrees of response burden, which may contribute to the variability seen in performance across tasks. As such, these measures do not assess pure lexical or conceptual processing abilities. Nonetheless, these tasks have important and desirable advantages. For example, Fiez and Tranel (1997) provided normative data for all items, including two measures of target verb name agreement, and measures for visual complexity and familiarity for the pictorial stimuli (see Kemmerer & Tranel, 2000 for further consideration). In addition, all the tasks were carefully normed to avoid ceiling effects, which captures nuances in performance and enables discrimination between mild, moderate, and severe impairments (and permitting significant variability to be observed even for neurotypical participants). Finally, this battery is unique in that a wide range of tasks are included and multiple action categories are represented in every task, providing a comprehensive assessment of both conceptual and lexical knowledge of actions.

A second limitation to this research is the modest sample size. Sample size was limited in these experiments due to recruitment, funding, and timeline constraints. A larger sample size would have been desirable, particularly for Study 3, which yielded several results with wide credible intervals that were likely attributed to high variability in the sample. In addition, more participants and higher variability in lesion site may identify additional tracts that were not robustly associated with verb naming in Study 2. Limited sample sizes preclude generalization of the current findings beyond the present sample to more diverse samples of individuals with aphasia. Replication of these dissertation studies in a larger, more diverse sample would help determine the applicability of these results to the broader aphasia population. Larger sample sizes may also permit the use of more robust and sophisticated statistical techniques such as exploratory factor analyses and voxel-based lesion-symptom mapping to further characterize associations within and between patient behavioral and neurological variables.

Finally, these studies are far from comprehensive examinations of the theoretical models under investigation, and the evidence provided here does not definitively support one framework over another. Rather, the purpose of this work is to call attention to shortcomings of prominent cognitive-linguistic accounts of aphasia, with a particular focus on traditionally understudied verb-retrieval deficits. In addition, it is unclear to what degree the observed data should be credited to inherent properties of neurocognitive architecture or to the processing strategies implemented in service of verb retrieval tasks. This is known as the *architecture–strategy credit assignment problem*, which is common in cognitive science experiments and makes findings difficult to interpret without caution (Howes & Young, 1997; Kieras & Meyer, 2000).

6.4 Future directions

The findings emerging from this set of studies promote interesting directions for further research. Lesions that induce aphasia, particularly in anterior brain regions, are interwoven with proximate cortical areas supporting upper limb and hand movements as well as action processing (Wortman-Jutt & Edwards, 2019). The behavioral reciprocity and functional specializations of these language and motor regions may give rise to new theoretical insights and clinical innovations for aphasia treatment. Therefore, it is vital to further evaluate the extent to which neurocognitive mechanisms underlying these linguistic and conceptual-motor systems are associated with verb retrieval during action naming. Future studies should test a larger sample of patient participants with a more diverse battery of neuroimaging and behavioral assessments.

In addition, it remains unknown whether individuals with aphasia can permanently adapt to rely on conceptual semantics in response to training. Future work is needed to determine the viability of lexical (verb) retrieval treatments seeking to target this specific type of adaptation deficit. As discussed, there is promising evidence supporting this possibility given that rational adaptation to conceptual semantic information is the hypothesized mechanism of action for treatments like VNeST (Edmonds, 2016). Additional evidence is needed to rigorously test this hypothesis.

Furthermore, it will be important to carefully assess and characterize the sources of individual differences in the trade-off dynamics between conceptual and lexical processing. Individuals are likely to differ in their ability to rationally adapt to, or rely on, either conceptual-semantic or lexical processing to accomplish tasks like verb retrieval. For example, underlying processes, such as cognitive control, or specific levels of language impairment could influence these individual differences (Evans et al., 2019 for related discussion). Individuals with different cognitive and linguistic impairment profiles may be more or less equipped to engage adaptive strategies. Similarly, the integrity of certain neural pathways may be vital to (or at least predictive of) the ability to adapt to alternative types of information. Future research can shed light on the degree to which rational adaptation to rely on conceptual semantics is under volitional control or can be trained as a compensation strategy. There are many potential sources of individual differences in rational adaptation that should be characterized to inform neurocognitive mechanisms at play and to potentially yield new options for personalized interventions.

Neurological factors are a potential source of individual variability in rational adaptation, as well as conceptual and lexical action-processing, among people with aphasia. Study 2 examined the neurological factor of white matter connectivity that was associated with verb retrieval. Future research may further examine associations between both white matter fiber tracts and grey matter lesion variables that are associated with a broad range of conceptual and lexical action-processing tasks (Fiez & Tranel, 1997; Kemmerer et al., 2012). Larger sample sizes and more diverse patient samples are desirable to answer these questions, but recent variants of lesion-symptom mapping techniques using regions of interest (rather than individual voxels) and permutation test methods may permit statistically robust analyses for modest sample sizes (Behroozmand et al., 2018). Pursuing these questions will reveal vital information about the neurological mechanisms involved in verb-retrieval deficits and aphasic adaptations to such deficits. Characterizing person level neurological predictors of rational adaptation ability can also be used to inform selection of treatment candidates most likely to respond to conceptual-semantic language interventions.

Verb-retrieval deficits likely reflect multiple cognitive processes, including conceptual-semantic, lexical, grammatical processing, and potentially motor/action programs as well. Patients may have impairments in any combination of these domains. For example, patients have shown dissociations between action picture naming deficits and impaired verb production in connected speech (Druks & Carroll, 2005; Mätzig et al., 2009). Case studies have reported patients with noun-verb double dissociations that manifest in picture naming, word repetition, and sentence completion tasks (Shapiro et al., 2000; Shapiro & Caramazza, 2003). In such cases, the double dissociation is likely to occur at the level of the lexicon and grammatical-class morphology (Mätzig et al., 2009). We have focused our investigation on conceptual-semantic and lexical aspects of action processing and spoken verb retrieval. Future work will also need to target grammatical and sentence processing levels as well as language tasks that assess other modalities.

Case studies have also documented patients who present with modality specific naming deficits, either in the visual modality (naming action pictures) or in the motor modality (naming actions acted out by a clinician or the patient), even when the patients had excellent access to semantics (Druks & Shallice, 2000; Yoon et al., 2005). Furthermore, Yoon and colleagues (2005) presented a case study in which verb retrieval during action picture naming was preserved, despite impaired action semantics, as reflected by the ability to read nonwords and nouns but not verbs. This evidence indicates that unimpaired access to action programs (e.g., via a direct visual route to action that bypasses semantics) may support not only actions but also action naming, perhaps via a route involving the right hemisphere (as speculated by Yoon et al., 2005). Together, these findings suggest that action programs are involved in action naming (Mätzig et al., 2009). Consistent with the conjectures in the Study 3 discussion above, this case-study evidence and related connectionist models (Yoon et al., 2002) suggest that conceptual representations provide (direct) access to wordforms, at least in cases where damage has forced the system to adapt to use this typically ill-favored route. The connections between action-program representations and the output lexicon might be differentially damaged by brain injury, creating important variability in whether individuals will benefit from action-program cues (like gestures) to facilitate verb retrieval. It will be important for future research and clinical assessments to assess individual variation across multiple cognitive processes and language domains, in an effort to improve personalized treatment.

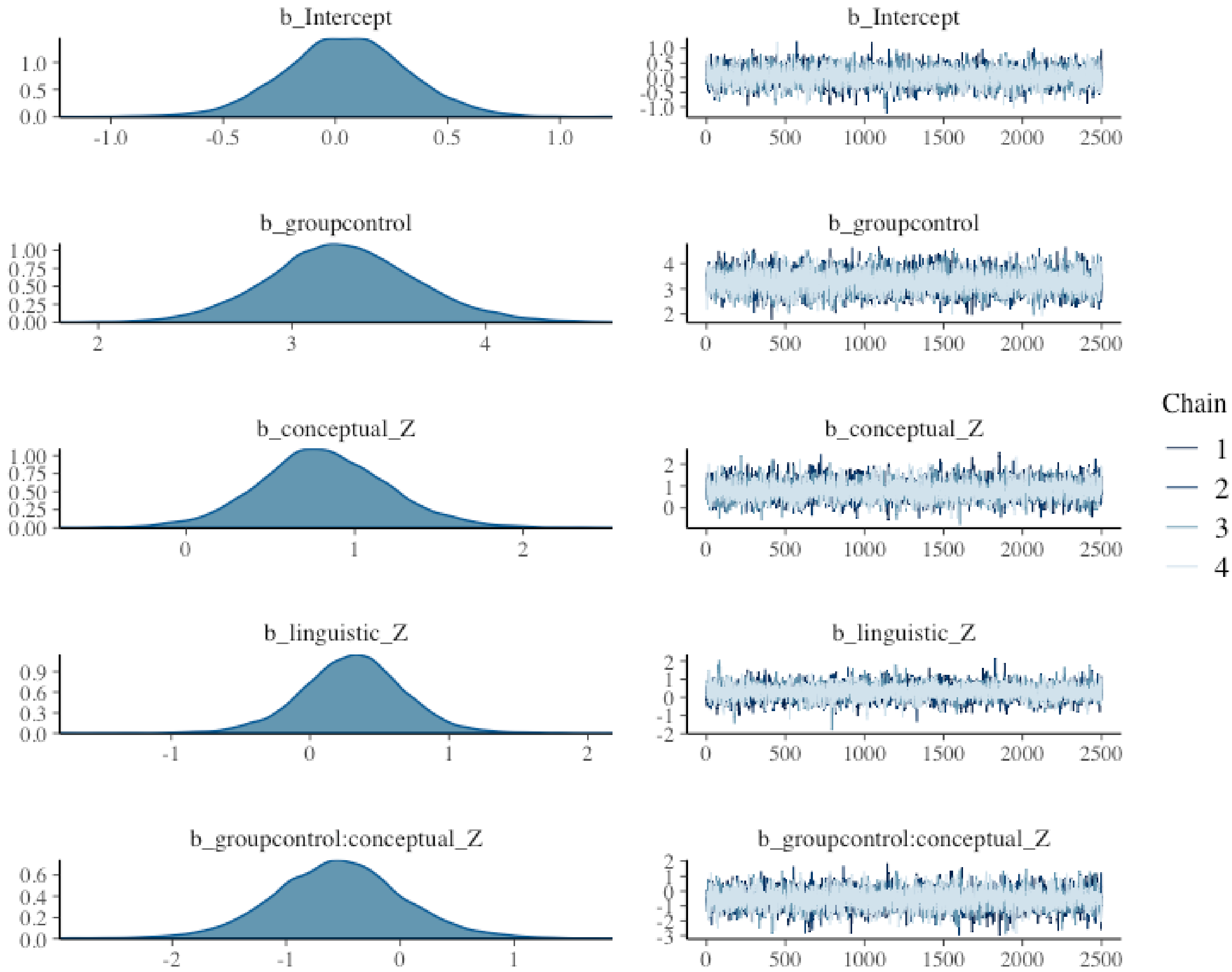
7.0 Conclusion

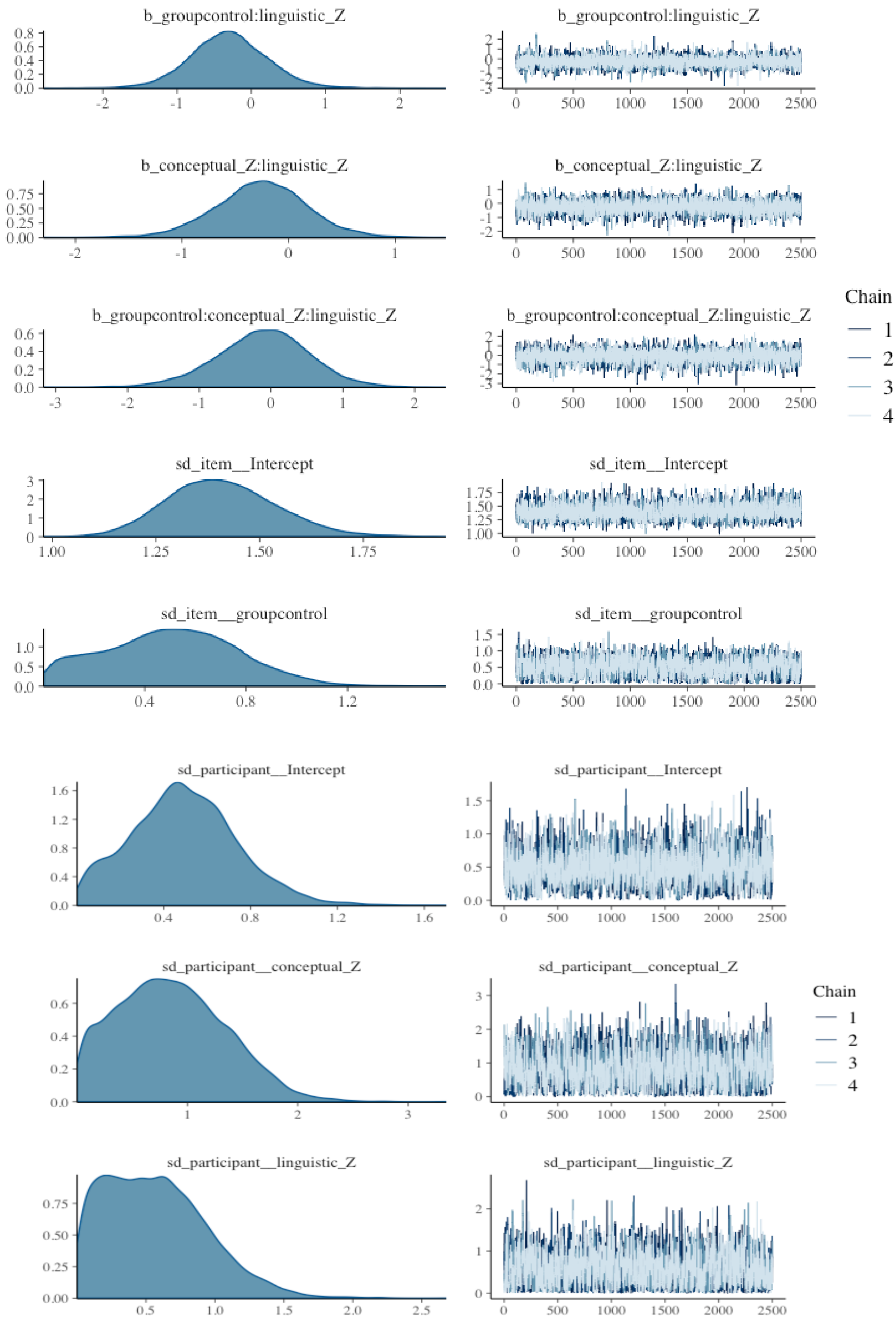
This dissertation project provides the first examination of grounded cognition and rational information-based adaptation in aphasia, integrating individual differences on validated behavioral measures (Study 1) and neuroanatomical network variables (Study 2). It also provides preliminary evidence regarding the types of cues that are most facilitative of verb-retrieval (Study 3), informing future design and selection of verb-retrieval interventions.

Findings from this dissertation contribute to current knowledge of the mechanisms driving differential impairments and recovery patterns in aphasic verb-retrieval and anomia treatment. The results across these studies largely support hypotheses of grounded cognition and rational adaptation theories, and together they emphasize the critical contributions of conceptual action/event semantics and motor pathways to verb-retrieval deficits. In particular, Study 1 demonstrated the involvement of conceptual action-processing in verb retrieval, Study 2 revealed the involvement of conceptual-motor neural pathways in verb retrieval, and Study 3 showcased facilitation from stored conceptual knowledge representations for verb retrieval. These neurocognitive aspects of conceptual semantics are important variables to consider when evaluating patient abilities, designing and implementing treatments, and researching the predictors of aphasia recovery. Aphasia theories and treatment models must account for the complex interactions between language and conceptual-semantic systems. Future work to advance our understanding of these interactions will be vital to aphasia treatment and improving patient outcomes.

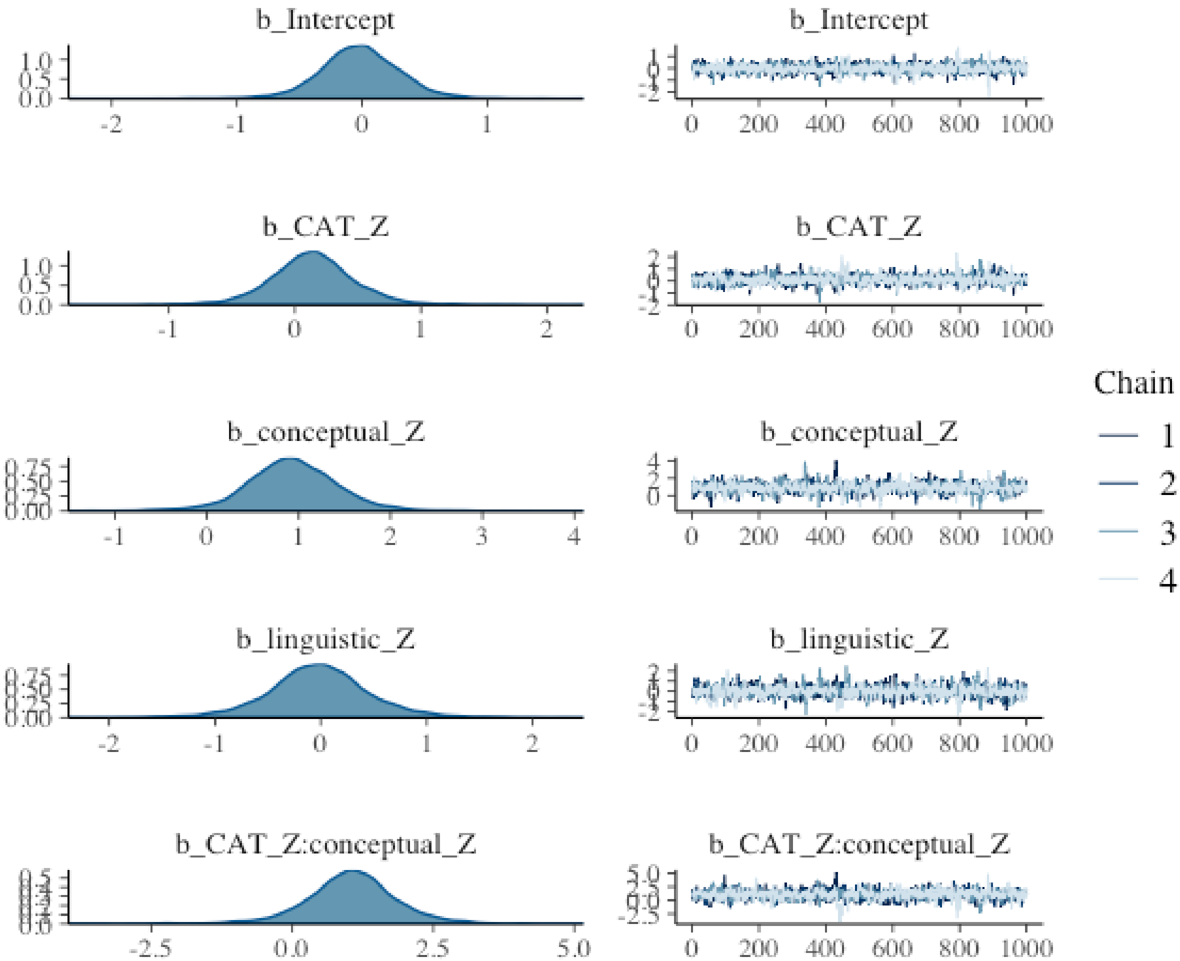
Appendix A Study 1

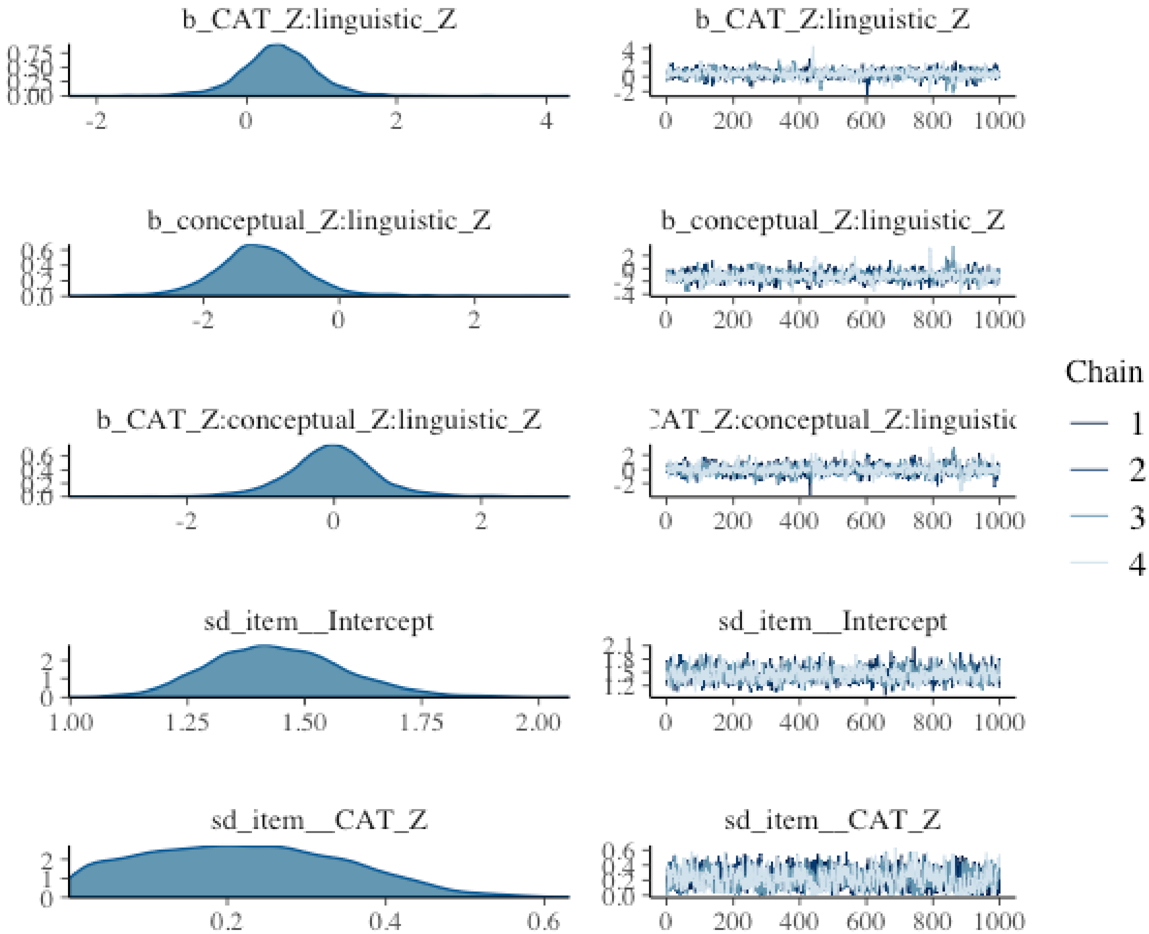
Appendix A.1 Trace and density plots for MCMC samples for Model 1

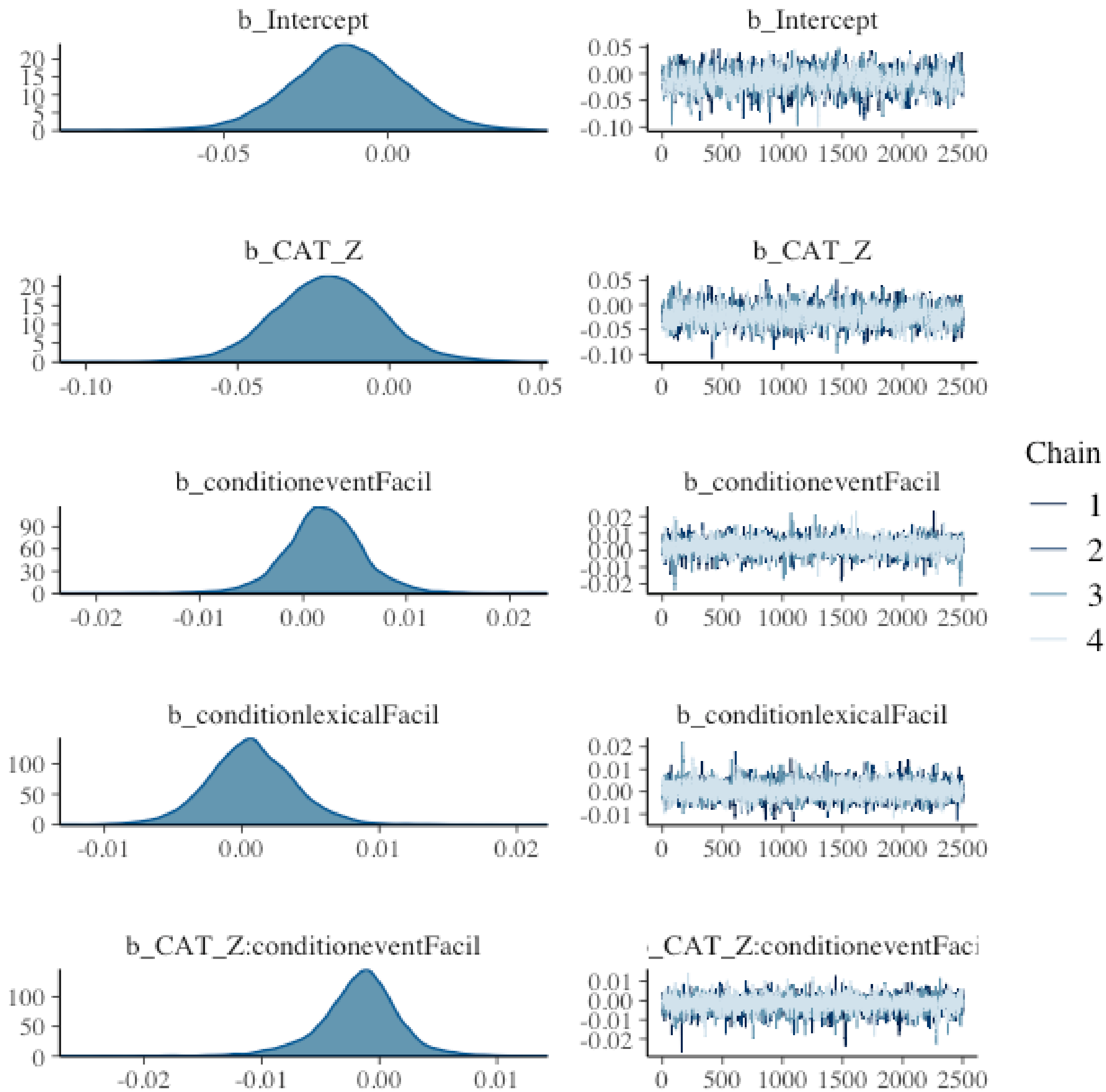


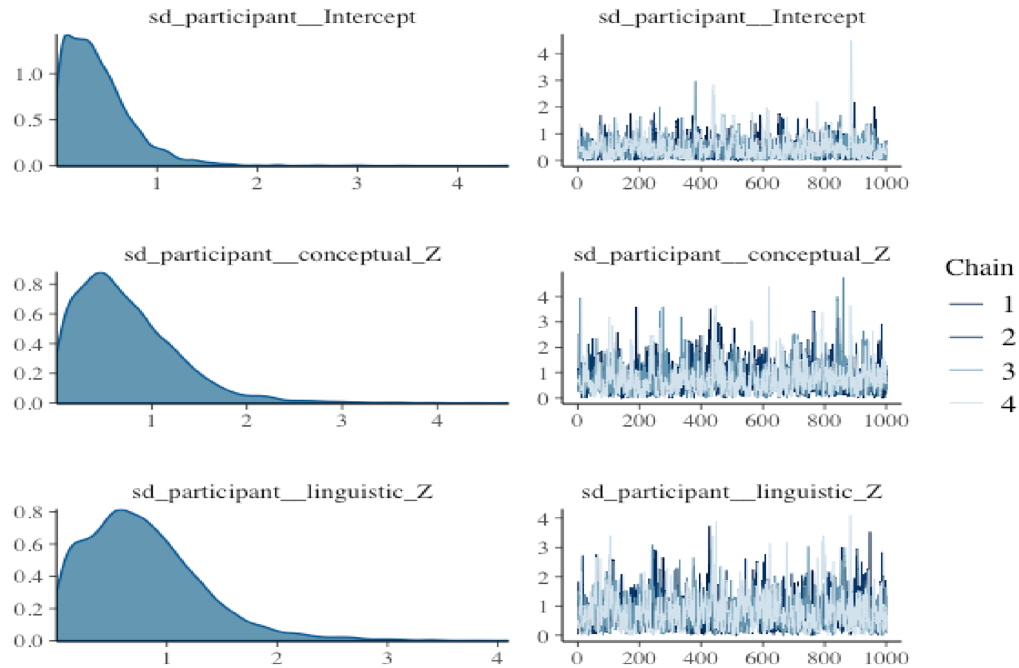

b_groupcontrol:linguistic_Z
b_groupcontrol:linguistic_Z
b_conceptual_Z:linguistic_Z
b_conceptual_Z:linguistic_Z
b_groupcontrol:conceptual_Z:linguistic_Z
b_groupcontrol:conceptual_Z:linguistic_Z
Chain
1
2
3
4
sd_item__Intercept
sd_item__Intercept
sd_item__groupcontrol
sd_item__groupcontrol
sd_participant__Intercept
sd_participant__Intercept
sd_participant__conceptual_Z
sd_participant__conceptual_Z
Chain
1
2
3
4
sd_participant__linguistic_Z
sd_participant__linguistic_Z

Appendix A.2 Trace and density plots for MCMC samples for Model 2




b_CAT_Z:linguistic_Z
b_CAT_Z:linguistic_Z
b_conceptual_Z:linguistic_Z
b_conceptual_Z:linguistic_Z
b_CAT_Z:conceptual_Z:linguistic_Z
sd_item__Intercept
sd_item__Intercept
sd_item__CAT_Z
sd_item__CAT_Z
Chain
1
2
3
4


b_Intercept
b_CAT_Z
b_conditioneventFacil
b_conditionlexicalFacil
b_CAT_Z:conditioneventFacil
Chain
1
2
3
4


sd_participant__Intercept
sd_participant__Intercept
sd_participant__conceptual_Z
sd_participant__conceptual_Z
sd_participant__linguistic_Z
sd_participant__linguistic_Z
Chain
1
2
3
4

Appendix B Study 3

Appendix B.1 Stimulus list and properties

verb target	conceptual event related prime						
	noun cue	**noun type**	**COCA rank**	**COCA freq**	**USF norms FSG**	**USF norms BSG**	**semantic distance**
ANSWER	knock	patient	>100	n/a	0.02	0	0.734
BET	*racetrack*	location	>100	n/a	n/a	n/a	0.661
CHASE	*fugitive*	patient	>100	n/a	n/a	n/a	0.726
CHEER	spectator	agent	>100	n/a	n/a	n/a	0.928
CHOP	*ax*	instrument	>100	n/a	0.09	0	0.667
CLEAN	*maid*	agent	>100	n/a	0.19	0	0.653
CUT	*butcher*	agent	>100	n/a	0.05	0	0.684
DELIVER	mailman	agent	>100	n/a	0.03	0.011	0.863
DIG	*sandbox*	location	>100	n/a	n/a	n/a	0.851
DRAW	marker	instrument	>100	n/a	0.03	0	0.836
DRINK	cocktail	patient	>100	n/a	0.45	0	0.550
DRIVE	parkway	location	>100	n/a	0.07	0	0.729
DUST	*rag*	instrument	>100	n/a	0.02	0.041	0.764
EXERCISE	*gym*	location	>100	n/a	0.06	0.02	0.547
FLY	*airport*	location	29	165	0.06	0	0.600
HAMMER	*carpenter*	agent	>100	n/a	0.13	0	0.707
HEAT	radiator	instrument	>100	n/a	0.19	0.02	0.698
HUNT	*rifle*	instrument	>100	n/a	0.04	0	0.748
INVESTIGATE	*detective*	agent	>100	n/a	n/a	n/a	0.637
LEARN	university	location	>100	n/a	0.04	0	0.864
LOCK	latch	instrument	>100	n/a	0.14	0	0.505
MEASURE	*ruler*	instrument	>100	n/a	0.41	0.169	0.712
OPEN	jar	patient	>100	n/a	0.06	0	0.799
PAY	toll	patient	>100	n/a	0.14	0	0.801
PERFORM	*actor*	agent	>100	n/a	n/a	n/a	0.770
PRAY	preacher	agent	>100	n/a	0.01	0	0.660
RECYCLE	aluminum	patient	38	14	0.06	0.099	0.844

RENT	lot	patient	>100	n/a	0.01	0	0.771
RESCUE	*hero*	agent	>100	n/a	n/a	n/a	0.638
RIDE	sleigh	patient	>100	n/a	0.12	0	0.612
ROLL	marble	patient	>100	n/a	0.03	0	0.893
SERVE	*customer*	patient	27	352	0.09	0.034	0.784
SHAVE	blade	instrument	82	7	0.02	0	0.736
SHOP	plaza	location	>100	n/a	0.12	0	0.854
SLEEP	*bedroom*	location	45	118	0.18	0	0.650
STAB	pitchfork	instrument	>100	n/a	0.02	0	0.626
STEAL	*burglar*	agent	>100	n/a	0.09	0	0.649
SWEAT	*sauna*	location	>100	n/a	n/a	n/a	0.705
THROW	dart	patient	>100	n/a	0.08	0	0.812
TYPE	*secretary*	agent	>100	n/a	0.11	0	0.918
WAIT	lobby	location	>100	n/a	0.11	0	0.741
WALK	cane	instrument	>100	n/a	0.02	0	0.708
WATCH	*audience*	agent	>100	n/a	0.03	0	0.776
WEAR	outfit	patient	49	213	0.03	0	0.469
WORK	*factory*	location	>100	n/a	0.11	0	0.600
WORSHIP	synagogue	location	>100	n/a	0.02	0	0.690
WRAP	*tinfoil*	instrument	>100	n/a	0.15	0.017	0.632
WRITE	pencil	instrument	>100	n/a	0.07	0.022	0.623

verb target	lexical collocate prime					
	noun cue	COCA rank	COCA frequency	USF norms FSG	USF norms BSG	semantic distance
ANSWER	research	11	287	n/a	n/a	0.873
BET	investors	34	73	n/a	n/a	0.867
CHASE	dreams	5	85	n/a	n/a	0.687
CHEER	football	17	25	n/a	n/a	0.711
CHOP	pieces	13	16	n/a	n/a	0.663
CLEAN	air	7	277	n/a	n/a	0.757
CUT	pieces	3	2336	n/a	n/a	0.606
DELIVER	speech	4	372	n/a	n/a	0.834
DIG	roots	25	64	n/a	n/a	0.772
DRAW	line	1	2978	n/a	n/a	0.678
DRINK	drugs	25	180	n/a	n/a	0.707
DRIVE	prices	8	454	n/a	n/a	0.916
DUST	top	9	19	n/a	n/a	0.796
EXERCISE	diet	2	626	n/a	n/a	0.609
FLY	sparks	16	238	n/a	n/a	0.665
HAMMER	details	3	35	n/a	n/a	0.907
HEAT	cheeks	94	19	n/a	n/a	0.813
HUNT	food	4	139	n/a	n/a	0.715
INVESTIGATE	research	3	390	n/a	n/a	0.748
LEARN	mistakes	15	1050	n/a	n/a	0.763
LOCK	eyes	3	203	n/a	n/a	0.772
MEASURE	sensors	36	110	n/a	n/a	0.735
OPEN	markets	20	519	n/a	n/a	0.924
PAY	attention	1	15511	n/a	n/a	0.691
PERFORM	tasks	1	1090	n/a	n/a	0.701
PRAY	peace	8	202	n/a	n/a	0.617
RECYCLE	water	2	78	n/a	n/a	0.854
RENT	month	19	81	n/a	n/a	0.544
RESCUE	fire	5	179	n/a	n/a	0.598
RIDE	storm	16	165	n/a	n/a	0.727
ROLL	hall	33	117	n/a	n/a	0.811
SERVE	purpose	1	1844	n/a	n/a	0.605
SHAVE	strokes	7	65	n/a	n/a	0.798
SHOP	antiques	10	77	n/a	n/a	0.695
SLEEP	night	1	3601	n/a	n/a	0.381

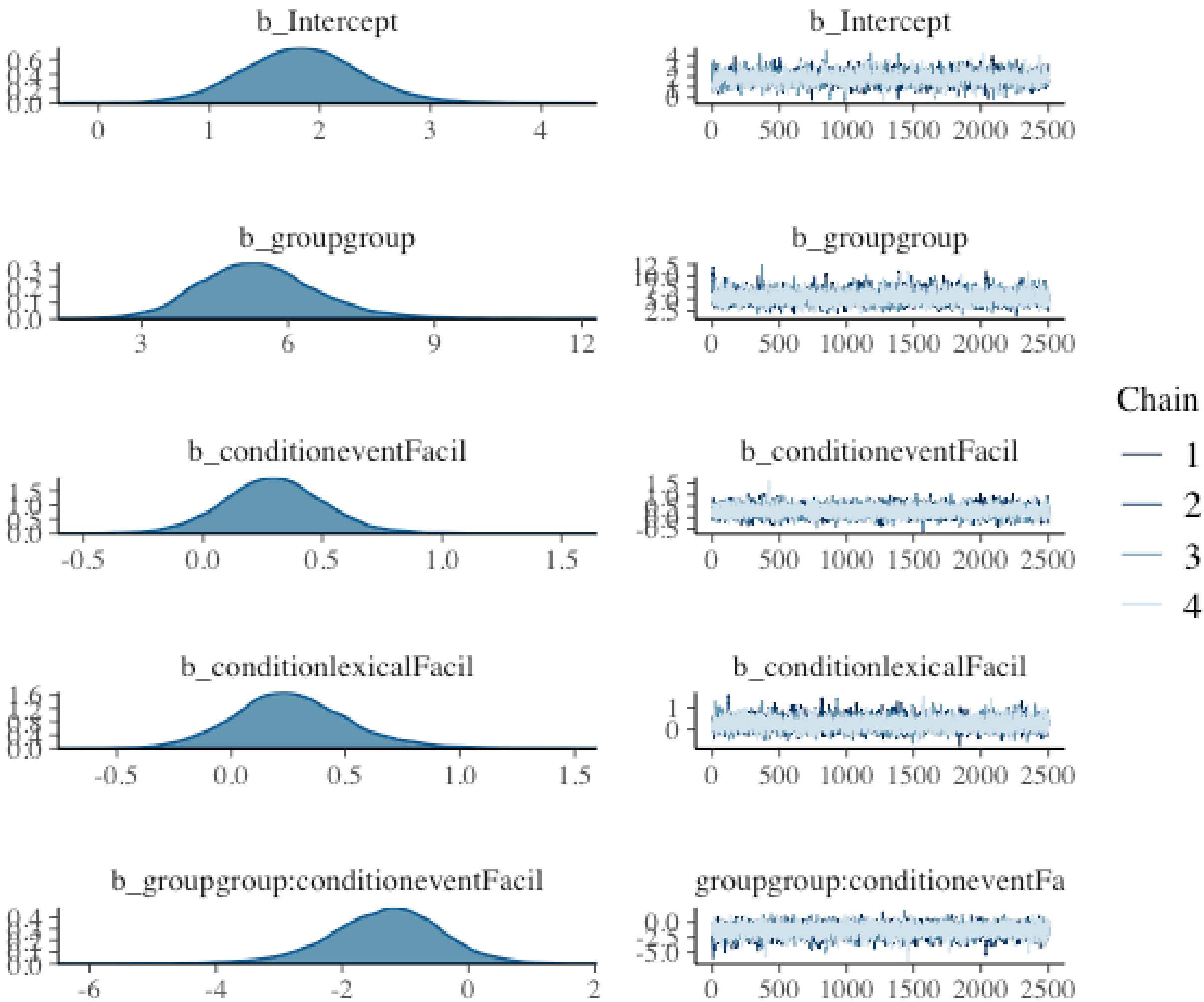
STAB	back	1	223	n/a	n/a	0.630
STEAL	election	4	295	n/a	n/a	0.944
SWEAT	palms	5	84	n/a	n/a	0.760
THROW	money	4	838	n/a	n/a	0.670
TYPE	commands	10	34	n/a	n/a	0.938
WAIT	second	2	5807	n/a	n/a	0.430
WALK	door	1	2136	n/a	n/a	0.612
WATCH	television	7	1682	n/a	n/a	0.542
WEAR	hair	13	557	n/a	n/a	0.647
WORK	system	9	1916	n/a	n/a	0.827
WORSHIP	freedom	6	79	n/a	n/a	0.787
WRAP	boots	6	222	n/a	n/a	0.867
WRITE	name	18	904	n/a	n/a	0.698

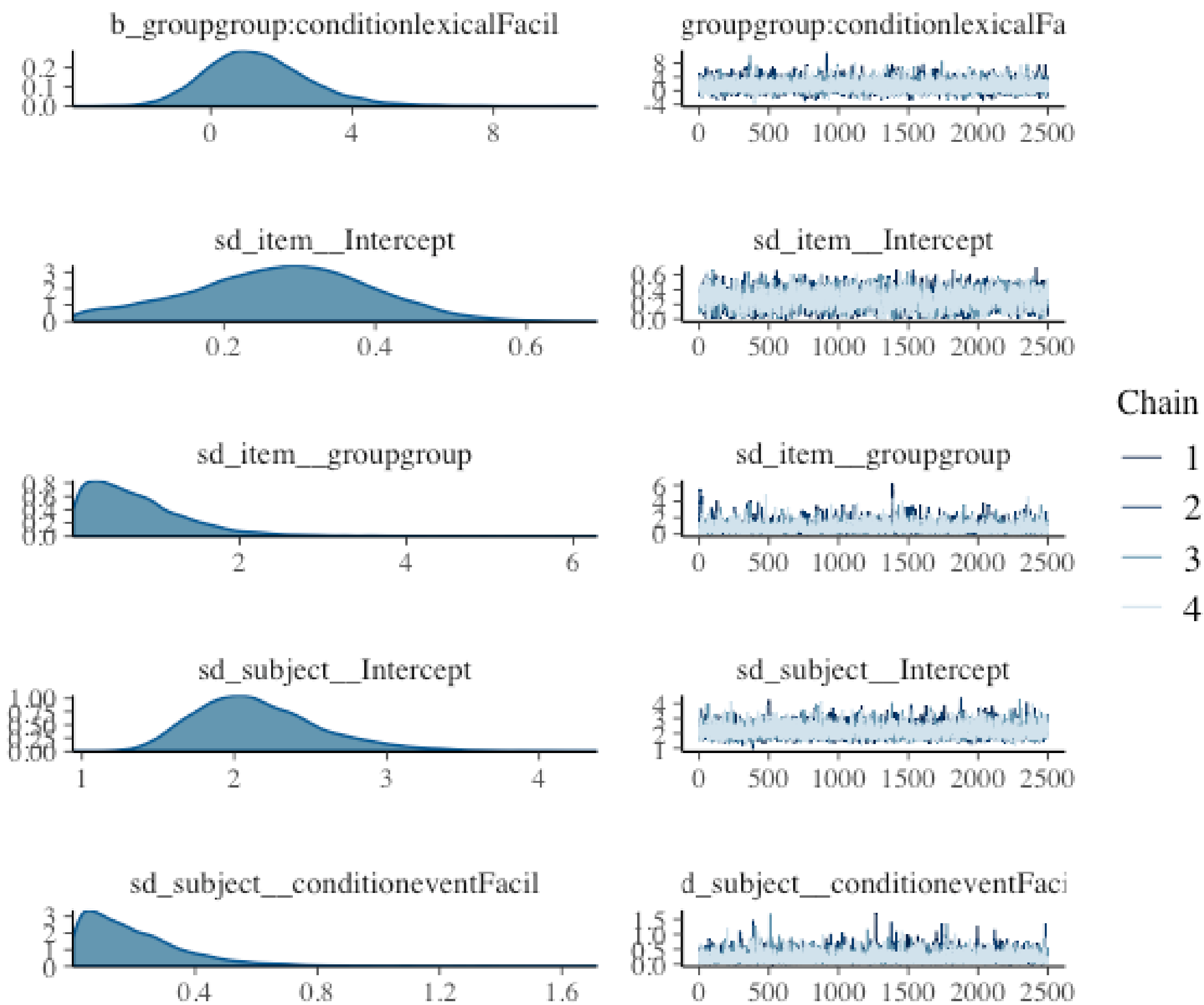
verb target	unrelated baseline prime					
	noun cue	COCA rank	COCA frequency	USF norms FSG	USF norms BSG	semantic distance
ANSWER	food	>100	n/a	n/a	n/a	0.869
BET	air	>100	n/a	n/a	n/a	0.823
CHASE	strokes	>100	n/a	n/a	n/a	0.832
CHEER	antiques	>100	n/a	n/a	n/a	0.972
CHOP	attention	>100	n/a	n/a	n/a	0.956
CLEAN	sparks	>100	n/a	n/a	n/a	0.818
CUT	freedom	>100	n/a	n/a	n/a	0.865
DELIVER	diet	>100	n/a	n/a	n/a	0.966
DIG	speech	>100	n/a	n/a	n/a	0.962
DRAW	storm	>100	n/a	n/a	n/a	0.907
DRINK	back	>100	n/a	n/a	n/a	0.596
DRIVE	fire	>100	n/a	n/a	n/a	0.811
DUST	money	>100	n/a	n/a	n/a	0.805
EXERCISE	research	>100	n/a	n/a	n/a	0.911
FLY	details	>100	n/a	n/a	n/a	0.944
HAMMER	second	>100	n/a	n/a	n/a	0.873
HEAT	purpose	>100	n/a	n/a	n/a	0.896
HUNT	hall	>100	n/a	n/a	n/a	0.900
INVESTIGATE	night	>100	n/a	n/a	n/a	0.816
LEARN	peace	>100	n/a	n/a	n/a	0.841
LOCK	month	>100	n/a	n/a	n/a	0.877
MEASURE	markets	>100	n/a	n/a	n/a	0.983
OPEN	pieces	>100	n/a	n/a	n/a	0.856
PAY	eyes	>100	n/a	n/a	n/a	0.853
PERFORM	roots	>100	n/a	n/a	n/a	0.932
PRAY	prices	>100	n/a	n/a	n/a	0.842
RECYCLE	line	>100	n/a	n/a	n/a	1.039
RENT	boots	>100	n/a	n/a	n/a	0.865
RESCUE	palms	>100	n/a	n/a	n/a	0.924
RIDE	name	>100	n/a	n/a	n/a	0.774
ROLL	door	>100	n/a	n/a	n/a	0.841
SERVE	sensors	>100	n/a	n/a	n/a	1.013
SHAVE	drugs	>100	n/a	n/a	n/a	0.922
SHOP	football	>100	n/a	n/a	n/a	0.898
SLEEP	pieces	>100	n/a	n/a	n/a	0.870

STAB	hair	>100	n/a	n/a	n/a	0.899
STEAL	system	>100	n/a	n/a	n/a	0.856
SWEAT	tasks	>100	n/a	n/a	n/a	0.915
THROW	top	>100	n/a	n/a	n/a	0.817
TYPE	investors	>100	n/a	n/a	n/a	1.011
WAIT	commands	>100	n/a	n/a	n/a	0.783
WALK	research	>100	n/a	n/a	n/a	0.977
WATCH	mistakes	>100	n/a	n/a	n/a	0.789
WEAR	cheeks	>100	n/a	n/a	n/a	0.829
WORK	television	>100	n/a	n/a	n/a	0.773
WORSHIP	election	>100	n/a	n/a	n/a	0.930
WRAP	dreams	>100	n/a	n/a	n/a	0.834
WRITE	water	>100	n/a	n/a	n/a	0.877

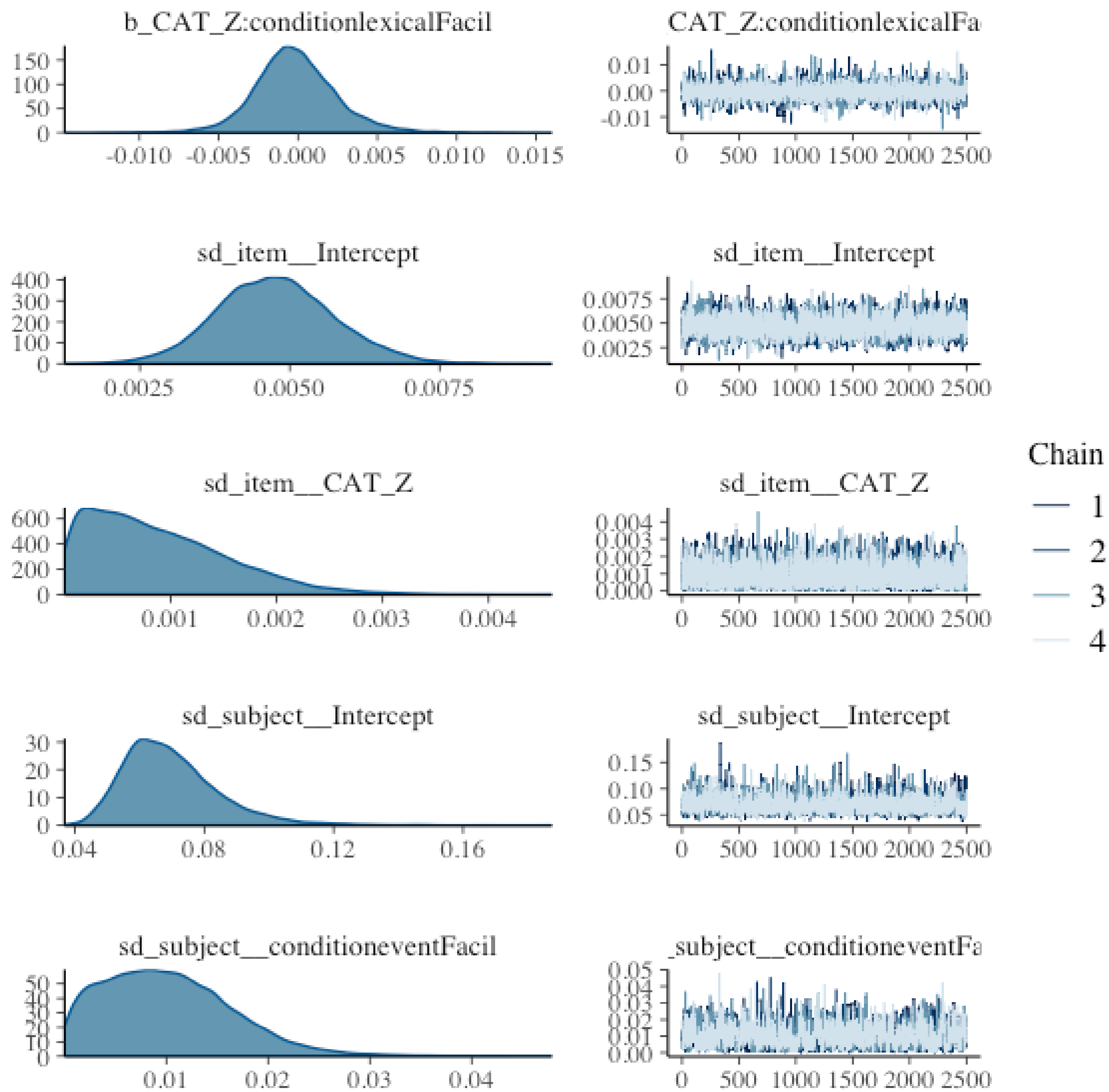
Notes: Italics denote items used by McRae and colleagues (2005). COCA is the Corpus of Contemporary American English (COCA), a corpus with more than 560 million words (Davies, 2008). USF FSG and BSG norms are forward strength and backward strength measures from cue-to-target or target-to-cue, these are calculated by dividing the number of participants producing a particular response by the number of participants serving in the group norming the word (Nelson et al., 1998). Semantic distance between cue and target words was calculated by snaut (Landauer & Dumais, 1997; Mandera et al., 2017).

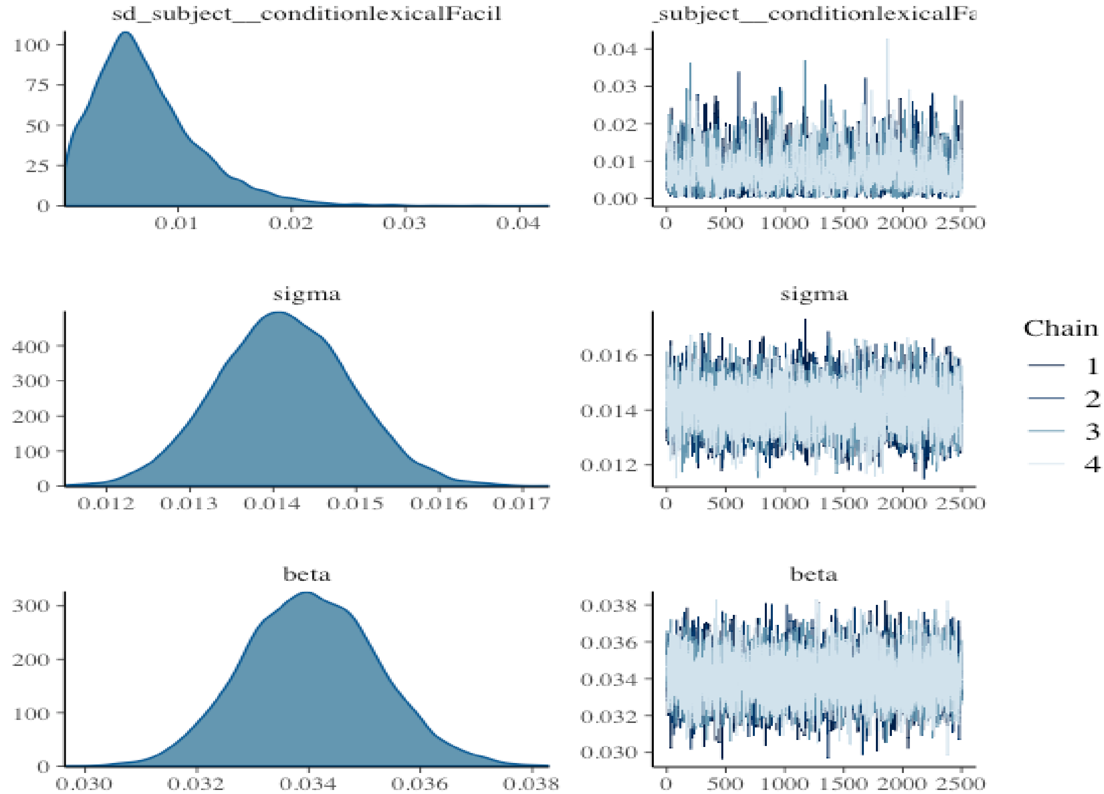
Appendix B.2 Trace and density plots for MCMC samples for Model 1




b_groupgroup:conditionlexicalFacil
groupgroup:conditionlexicalFa
sd_item__Intercept
sd_item__Intercept
sd_item__groupgroup
sd_item__groupgroup
sd_subject__Intercept
sd_subject__Intercept
sd_subject__conditioneventFacil
d_subject__conditioneventFaci
0 500 1000 1500 2000 2500
Chain
1
2
3
4

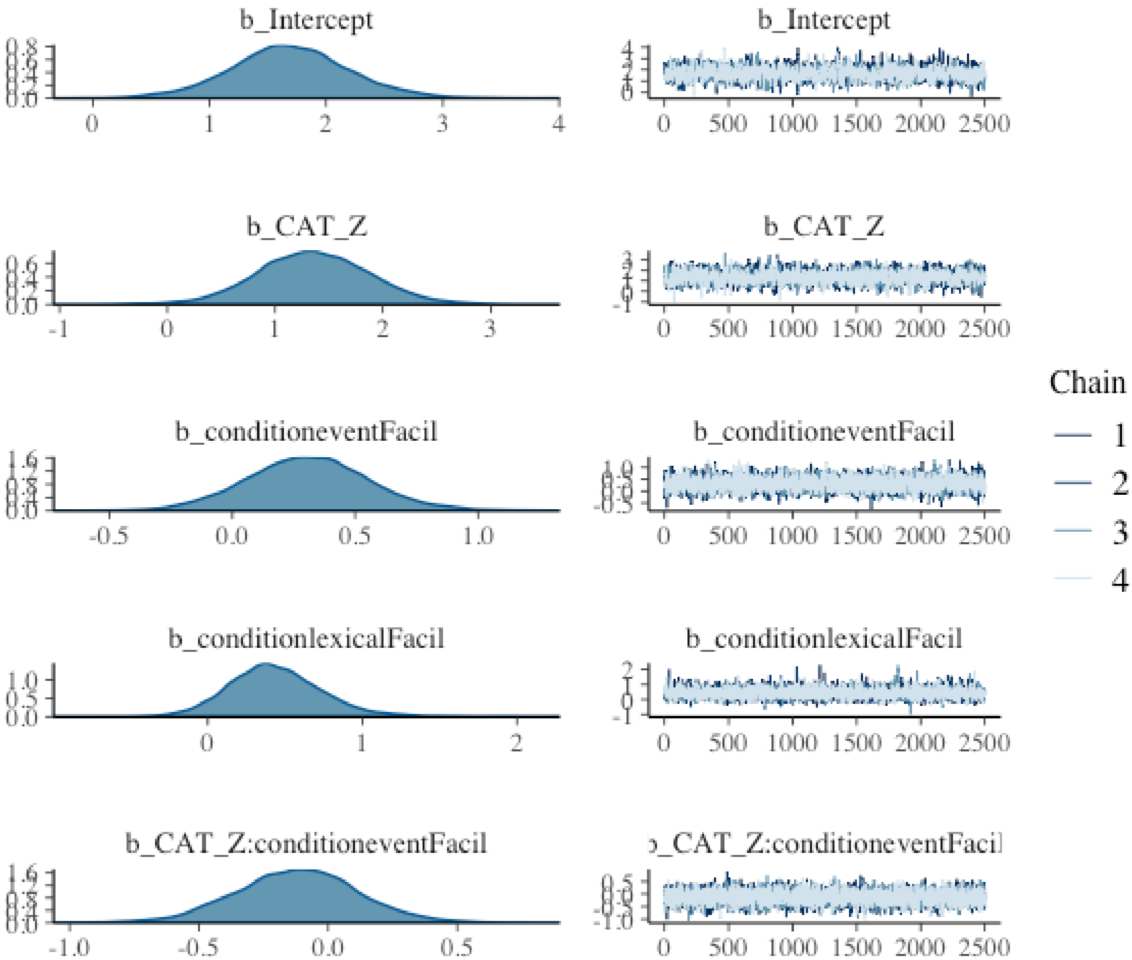
Appendix B.3 Trace and density plots for MCMC samples for Model 2

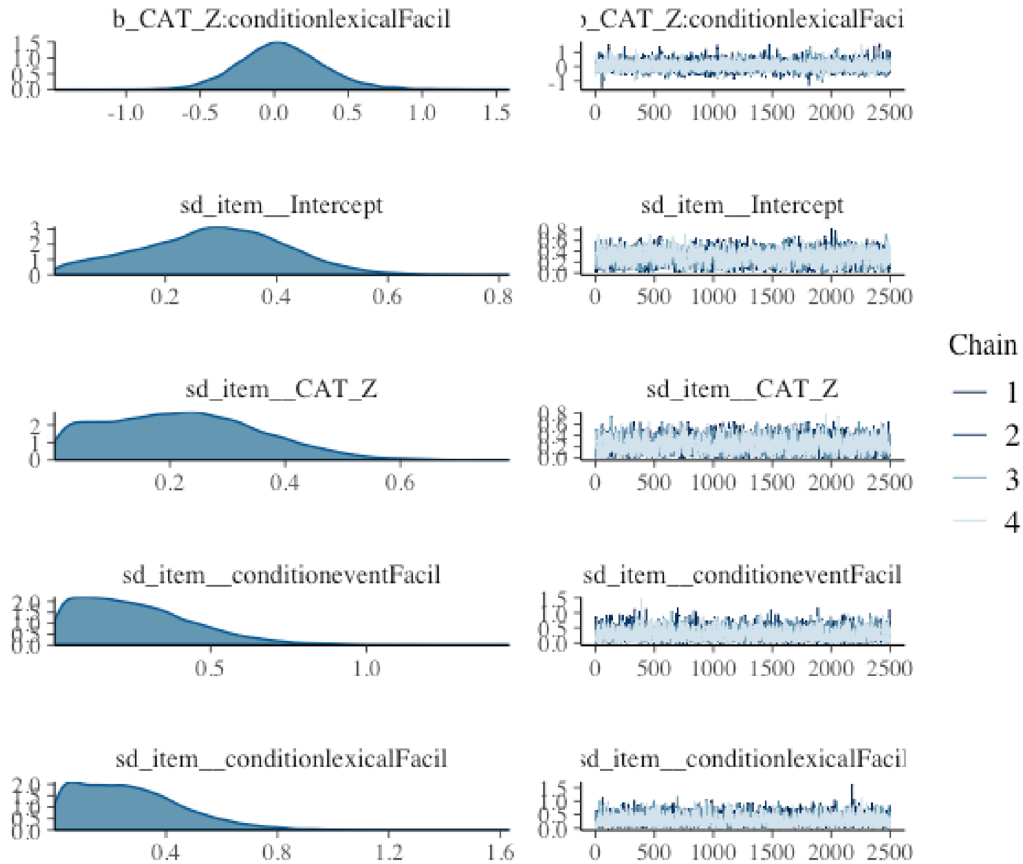


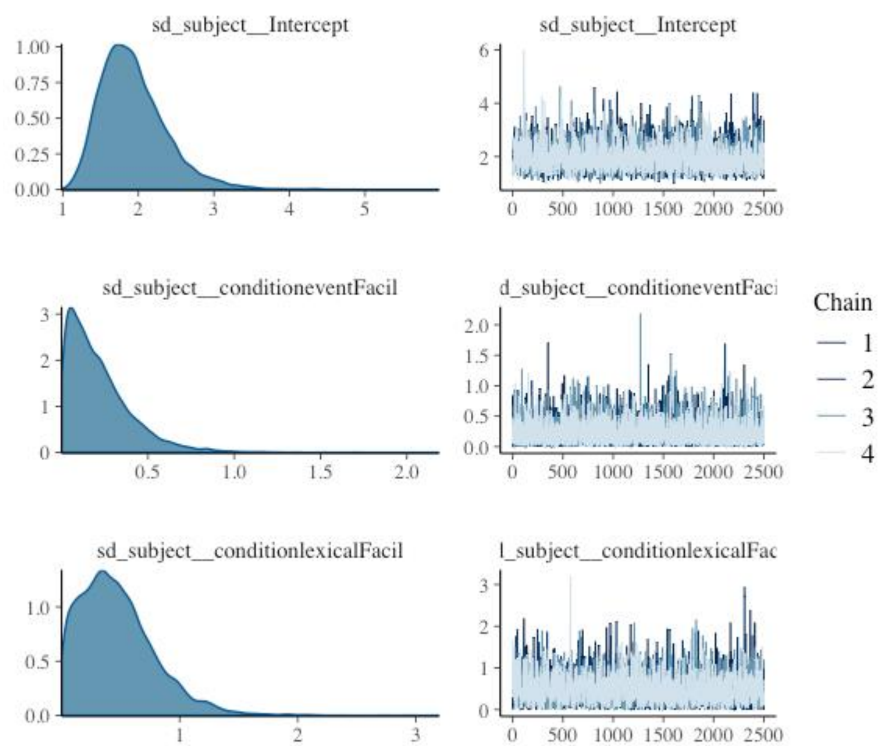


sd_subject__conditionlexicalFacil
_subject__conditionlexicalFa
sigma
sigma
beta
beta
Chain
1
2
3
4

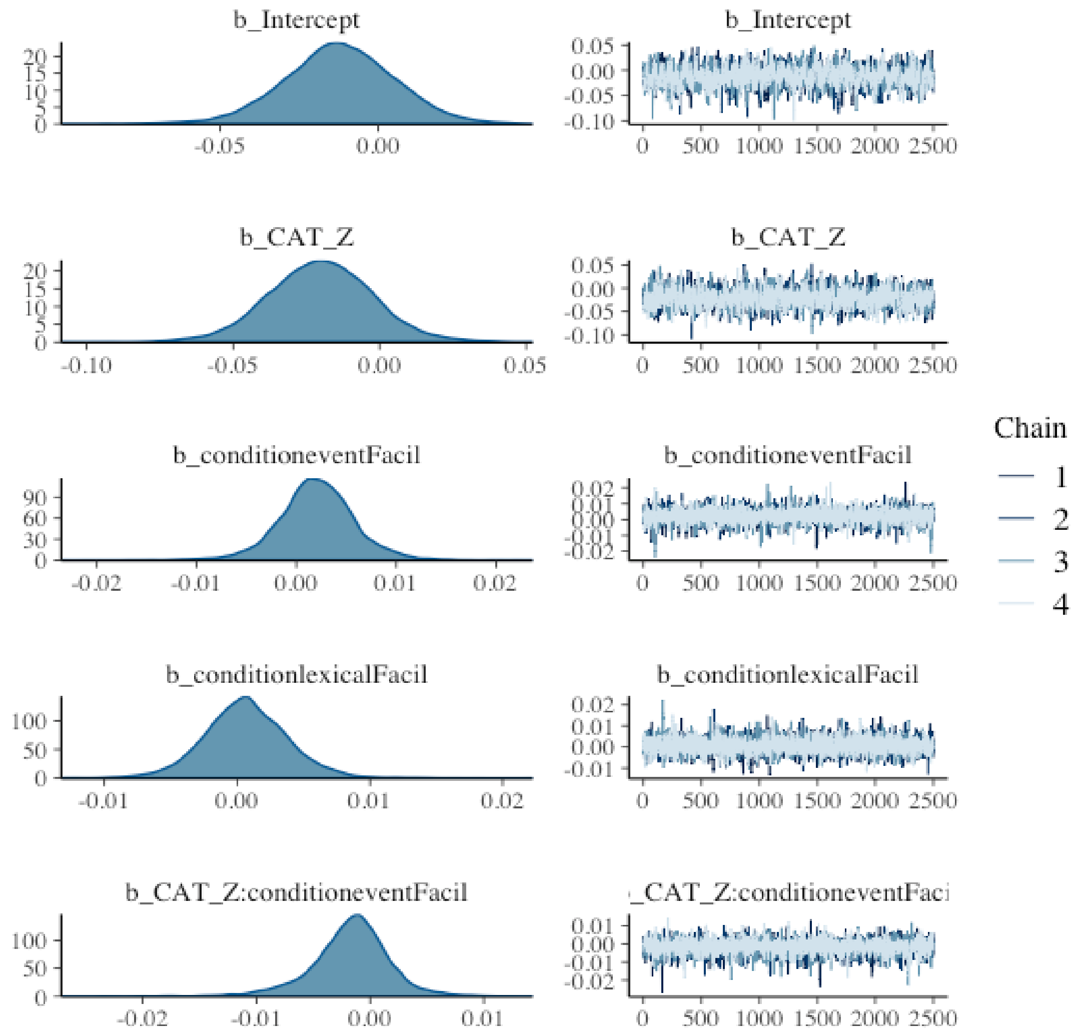
Appendix B.4 Trace and density plots for MCMC samples for Model 3

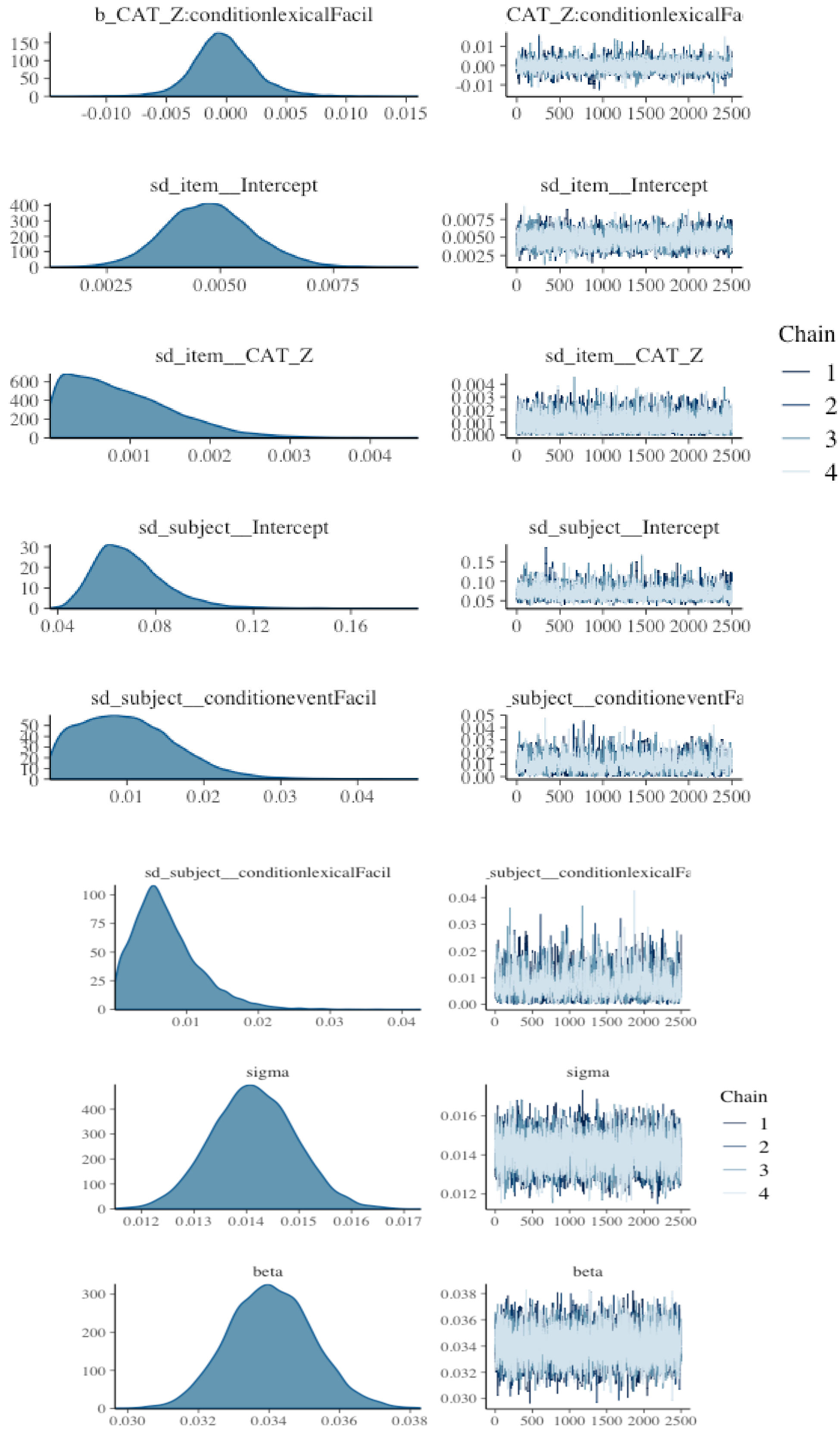



b_CAT_Z:conditionlexicalFacil
_CAT_Z:conditionlexicalFaci
sd_item__Intercept
sd_item__Intercept
sd_item__CAT_Z
sd_item__CAT_Z
sd_item__conditioneventFacil
sd_item__conditioneventFacil
sd_item__conditionlexicalFacil
d_item__conditionlexicalFacil
Chain
1
2
3
4


sd_subject__Intercept
sd_subject__Intercept
sd_subject__conditioneventFacil
d_subject__conditioneventFaci
sd_subject__conditionlexicalFacil
_subject__conditionlexicalFac
Chain
1
2
3
4

Appendix B.5 Trace and density plots for MCMC samples for Model 4




b_CAT_Z:conditionlexicalFacil
CAT_Z:conditionlexicalFa
sd_item__Intercept
sd_item__Intercept
sd_item__CAT_Z
sd_item__CAT_Z
sd_subject__Intercept
sd_subject__Intercept
sd_subject__conditioneventFacil
_subject__conditioneventFa
Chain
1
2
3
4
sd_subject__conditionlexicalFacil
_subject__conditionlexicalFa
sigma
sigma
Chain
1
2
3
4
beta
beta

Bibliography

Akinina, Y., Dragoy, O., Ivanova, M. V., Iskra, E. V., Soloukhina, O. A., Petryshevsky, A. G., Fedina, O. N., Turken, A. U., Shklovsky, V. M., & Dronkers, N. F. (2019). Grey and white matter substrates of action naming. *Neuropsychologia*, *131*, 249–265. https://doi.org/10.1016/j.neuropsychologia.2019.05.015

Alexander, G. E., & Crutcher, M. D. (1990). Functional architecture of basal ganglia circuits: Neural substrates of parallel processing. *Trends in Neurosciences*, *13*(7), 266–271. https://doi.org/10.1016/0166-2236(90)90107-l

Almairac, F., Herbet, G., Moritz-Gasser, S., de Champfleur, N. M., & Duffau, H. (2015). The left inferior fronto-occipital fasciculus subserves language semantics: A multilevel lesion study. *Brain Structure & Function*, *220*(4), 1983–1995. https://doi.org/10.1007/s00429-014-0773-1

Altmann, G. T. M. (2017). Abstraction and generalization in statistical learning: Implications for the relationship between semantic types and episodic tokens. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *372*(1711). https://doi.org/10.1098/rstb.2016.0060

Altmann, G. T. M., & Mirković, J. (2009). Incrementality and Prediction in Human Sentence Processing. *Cognitive Science*, *33*(4), 583–609. https://doi.org/10.1111/j.1551-6709.2009.01022.x

Alyahya, R. S. W., Halai, A. D., Conroy, P., & Lambon Ralph, M. A. (2020). Mapping psycholinguistic features to the neuropsychological and lesion profiles in aphasia.

Cortex; a Journal Devoted to the Study of the Nervous System and Behavior, *124*, 260–273. https://doi.org/10.1016/j.cortex.2019.12.002

Amato, M. S., & MacDonald, M. C. (2010). Sentence processing in an artificial language: Learning and using combinatorial constraints. *Cognition*, *116*(1), 143–148. https://doi.org/10.1016/j.cognition.2010.04.001

Amsel, B. D., DeLong, K. A., & Kutas, M. (2015). Close, but no garlic: Perceptuomotor and event knowledge activation during language comprehension. *Journal of Memory and Language*, *82*, 118–132. https://doi.org/10.1016/j.jml.2015.03.009

Anderson, J. (1991). Is human cognition adaptive? *Behavioral and Brain Sciences*, *14*, 471–517. https://doi.org/10.1017/s0140525x00070801

Anderson, J. R., & Milson, R. (1989). Human memory: An adaptive perspective. *Psychological Review*, *96*(4), 703–719. https://doi.org/10.1037/0033-295X.96.4.703

Anderson, J. R., & Schooler, L. J. (1991). Reflections of the Environment in Memory. *Psychological Science*, *2*(6), 396–408. https://doi.org/10.1111/j.1467-9280.1991.tb00174.x

Antonucci, S. M., & Reilly, J. (2008). Semantic memory and language processing: A primer. *Seminars in Speech and Language*, *29*(1), 5–17. https://doi.org/10.1055/s-2008-1061621

Arnon, I., & Snider, N. (2010). More than words: Frequency effects for multi-word phrases. *Journal of Memory and Language*, *62*(1), 67–82. https://doi.org/10.1016/j.jml.2009.09.005

Bak, T. H. (2013). The neuroscience of action semantics in neurodegenerative brain diseases: *Current Opinion in Neurology*, *26*(6), 671–677. https://doi.org/10.1097/WCO.0000000000000039

Baker, M. C. (2003). *Lexical Categories: Verbs, Nouns and Adjectives*. Cambridge University Press.

Barde, L. H., Schwartz, M. F., & Boronat, C. B. (2006). Semantic weight and verb retrieval in aphasia. *Brain and Language*, *97*(3), 266–278.

Barsalou, L. W. (1999). Perceptual symbol systems. *The Behavioral and Brain Sciences*, *22*(4), 577–660.

Barsalou, Lawrence W. (2008). Grounded cognition. *Annu. Rev. Psychol.*, *59*, 617–645.

Barsalou, Lawrence W. (2016). On Staying Grounded and Avoiding Quixotic Dead Ends. *Psychonomic Bulletin & Review*, *23*(4), 1122–1142. https://doi.org/10.3758/s13423-016-1028-3

Barsalou, Lawrence W., Kyle Simmons, W., Barbey, A. K., & Wilson, C. D. (2003). Grounding conceptual knowledge in modality-specific systems. *Trends in Cognitive Sciences*, *7*(2), 84–91. https://doi.org/10.1016/s1364-6613(02)00029-3

Basilakos, A., Fillmore, P. T., Rorden, C., Guo, D., Bonilha, L., & Fridriksson, J. (2014). Regional White Matter Damage Predicts Speech Fluency in Chronic Post-Stroke Aphasia. *Frontiers in Human Neuroscience*, *8*. https://doi.org/10.3389/fnhum.2014.00845

Bastiaanse, R., & Jonkers, R. (1998). Verb retrieval in action naming and spontaneous speech in agrammatic and anomic aphasia. *Aphasiology*, *12*(11), 951–969.

Bates, E., Wilson, S. M., Saygin, A. P., Dick, F., Sereno, M. I., Knight, R. T., & Dronkers, N. F. (2003). Voxel-based lesion–symptom mapping. *Nature Neuroscience*, *6*(5), 448–450.

Behroozmand, R., Phillip, L., Johari, K., Bonilha, L., Rorden, C., Hickok, G., & Fridriksson, J. (2018). Sensorimotor impairment of speech auditory feedback processing in aphasia. *NeuroImage*, *165*, 102–111. https://doi.org/10.1016/j.neuroimage.2017.10.014

Bello, L., Acerbi, F., Giussani, C., Baratta, P., Taccone, P., Songa, V., Fava, M., Stocchetti, N., Papagno, C., & Gaini, S. M. (2006). Intraoperative language localization in multilingual patients with gliomas. *Neurosurgery*, *59*(1), 115–125; discussion 115-125. https://doi.org/10.1227/01.NEU.0000219241.92246.FB

Bello, L., Gallucci, M., Fava, M., Carrabba, G., Giussani, C., Acerbi, F., Baratta, P., Songa, V., Conte, V., Branca, V., Stocchetti, N., Papagno, C., & Gaini, S. M. (2007). Intraoperative subcortical language tract mapping guides surgical removal of gliomas involving speech areas. *Neurosurgery*, *60*(1), 67–80; discussion 80-82. https://doi.org/10.1227/01.NEU.0000249206.58601.DE

Bello, L., Gambini, A., Castellano, A., Carrabba, G., Acerbi, F., Fava, E., Giussani, C., Cadioli, M., Blasi, V., Casarotti, A., Papagno, C., Gupta, A. K., Gaini, S., Scotti, G., & Falini, A. (2008). Motor and language DTI Fiber Tracking combined with intraoperative subcortical mapping for surgical removal of gliomas. *NeuroImage*, *39*(1), 369–382. https://doi.org/10.1016/j.neuroimage.2007.08.031

Berndt, R. S., Haendiges, A. N., Mitchum, C. C., & Sandson, J. (1997). Verb Retrieval in Aphasia. 2. Relationship to Sentence Processing. *Brain and Language*, *56*(1), 107–137. https://doi.org/10.1006/brln.1997.1728

Berndt, R. S., Mitchum, C. C., & Wayland, S. (1997). Patterns of sentence comprehension in aphasia: A consideration of three hypotheses. *Brain and Language*, *60*(2), 197–221.

Binder, J. R., & Desai, R. H. (2011). The neurobiology of semantic memory. *Trends in Cognitive Sciences*, *15*(11), 527–536. https://doi.org/10.1016/j.tics.2011.10.001

Binder, J. R., Frost, J. A., Hammeke, T. A., Cox, R. W., Rao, S. M., & Prieto, T. (1997). Human Brain Language Areas Identified by Functional Magnetic Resonance Imaging. *Journal of Neuroscience*, *17*(1), 353–362.

Bock, K., & Levelt, W. (1994). *Language production: Grammatical encoding. Handbook of psycholinguistics, ed. By Morton Ann Gernsbacher, 945-84*.

Bock, K., & Loebell, H. (1990). Framing sentences. *Cognition*, *35*(1), 1–39. https://doi.org/10.1016/0010-0277(90)90035-I

Boehme, A. K., Martin-Schild, S., Marshall, R. S., & Lazar, R. M. (2016). Effect of aphasia on acute stroke outcomes. *Neurology*, *87*(22), 2348–2354. https://doi.org/10.1212/WNL.0000000000003297

Bonilha, L., & Fridriksson, J. (2009). Subcortical damage and white matter disconnection associated with non-fluent speech. *Brain: A Journal of Neurology*, *132*(Pt 6), e108. https://doi.org/10.1093/brain/awn200

Bornkessel, I., & Schlesewsky, M. (2006). The extended argument dependency model: A neurocognitive approach to sentence comprehension across languages. *Psychological Review*, *113*(4), 787.

Boyle, M. (2010). Semantic feature analysis treatment for aphasic word retrieval impairments: What's in a name? *Topics in Stroke Rehabilitation*, *17*(6), 411–422.

Boyle, M., & Coehlo, C. A. (1995). Application of Semantic Feature Analysis as a Treatment for Aphasic Dysnomia. *American Journal of Speech Language Pathology*, *4*, 94–98.

Breedin, S. D., Saffran, E. M., & Schwartz, M. F. (1998). Semantic factors in verb retrieval: An effect of complexity. *Brain and Language*, *63*(1), 1–31. https://doi.org/10.1006/brln.1997.1923

Bubb, E. J., Metzler-Baddeley, C., & Aggleton, J. P. (2018). The cingulum bundle: Anatomy, function, and dysfunction. *Neuroscience and Biobehavioral Reviews*, *92*, 104–127. https://doi.org/10.1016/j.neubiorev.2018.05.008

Budisavljevic, S., Dell'Acqua, F., Djordjilovic, V., Miotto, D., Motta, R., & Castiello, U. (2017). The role of the frontal aslant tract and premotor connections in visually guided hand movements. *NeuroImage*, *146*, 419–428. https://doi.org/10.1016/j.neuroimage.2016.10.051

Burgess, C. (1998). From simple associations to the building blocks of language: Modeling meaning in memory with the HAL model. *Behavior Research Methods, Instruments, & Computers, 30*(2), 188–198.

Bürkner, P. (2017). brms: An R Package for Bayesian Multilevel Models Using Stan. *Journal of Statistical Software*, *80*(1), 1–28. http://dx.doi.org/10.18637/jss.v080.i01

Calautti, C., & Baron, J.-C. (2003). Functional neuroimaging studies of motor recovery after stroke in adults: A review. *Stroke*, *34*(6), 1553–1566. https://doi.org/10.1161/01.STR.0000071761.36075.A6

Caramazza, A., & Hillis, A. E. (1990). Spatial representation of words in the brain implied by studies of a unilateral neglect patient. *Nature*, *346*(6281), 267–269. https://doi.org/10.1038/346267a0

Caramazza, A., & Hillis, A. E. (1991). Lexical organization of nouns and verbs in the brain. *Nature*, *349*(6312), 788–790. https://doi.org/10.1038/349788a0

Caramazza, Alfonso, & Zurif, E. B. (1976). Dissociation of algorithmic and heuristic processes in language comprehension: Evidence from aphasia. *Brain and Language*, *3*(4), 572–582. https://doi.org/10.1016/0093-934X(76)90048-1

Carpenter, B., Gelman, A., Hoffman, M. D., Lee, D., Goodrich, B., Betancourt, M., Brubaker, M., Guo, J., Li, P., & Riddell, A. (2017). Stan: A Probabilistic Programming Language. *Journal of Statistical Software, 76*(1), 1–32. https://doi.org/10.18637/jss.v076.i01

Catani, M, & Thiebaut de Schotten, M. (2012). *Atlas of human brain connections*. Oxford University Press.

Catani, M., Dell'acqua, F., Vergani, F., Malik, F., Hodge, H., Roy, P., Valabregue, R., & Thiebaut de Schotten, M. (2012). Short frontal lobe connections of the human brain. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *48*(2), 273–291. https://doi.org/10.1016/j.cortex.2011.12.001

Catani, M., Jones, D. K., & Ffytche, D. H. (2005). Perisylvian language networks of the human brain. *Annals of Neurology*, *57*(1), 8–16. https://doi.org/10.1002/ana.20319

Catani, M., & Mesulam, M. (2008). The arcuate fasciculus and the disconnection theme in language and aphasia: History and current state. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *44*(8), 953–961. https://doi.org/10.1016/j.cortex.2008.04.002

Catani, M., Mesulam, M. M., Jakobsen, E., Malik, F., Martersteck, A., Wieneke, C., Thompson, C. K., Thiebaut de Schotten, M., Dell'Acqua, F., Weintraub, S., & Rogalski, E. (2013). A novel frontal pathway underlies verbal fluency in primary progressive aphasia. *Brain*, *136*(8), 2619–2628. https://doi.org/10.1093/brain/awt163

Chao, L. L., & Martin, A. (2000). Representation of Manipulable Man-Made Objects in the Dorsal Stream. *NeuroImage*, *12*(4), 478–484. https://doi.org/10.1006/nimg.2000.0635

Chater, & Oaksford. (1999). Ten years of the rational analysis of cognition. *Trends in Cognitive Sciences*, *3*(2), 57–65. https://doi.org/10.1016/s1364-6613(98)01273-x

Chen, L., Lambon Ralph, M. A., & Rogers, T. T. (2017). A unified model of human semantic knowledge and its disorders. *Nature Human Behaviour*, *1*(3), 0039. https://doi.org/10.1038/s41562-016-0039

Cho, S.-H., Kim, D. G., Kim, D.-S., Kim, Y.-H., Lee, C.-H., & Jang, S. H. (2007). Motor outcome according to the integrity of the corticospinal tract determined by diffusion tensor tractography in the early stage of corona radiata infarct. *Neuroscience Letters*, *426*(2), 123–127. https://doi.org/10.1016/j.neulet.2007.08.049

Chomsky, N. (1975). *The Logical Structure of Linguistic Theory*. Springer US. https://books.google.com/books/about/The_Logical_Structure_of_Linguistic_Theo.html?id=1D66ktXOITAC

Cho-Reyes, S., & Thompson, C. K. (2012). Verb and sentence production and comprehension in aphasia: Northwestern Assessment of Verbs and Sentences (NAVS). *Aphasiology*, *26*(10), 1250–1277.

Coltheart. (1999). Modularity and cognition. *Trends in Cognitive Sciences*, *3*(3), 115–120. https://doi.org/10.1016/s1364-6613(99)01289-9

Courson, M., Macoir, J., & Tremblay, P. (2017). Role of medial premotor areas in action language processing in relation to motor skills. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *95*, 77–91. https://doi.org/10.1016/j.cortex.2017.08.002

Davies, M. (2008). *The Corpus of Contemporary American English (COCA): 560 million words, 1990-present*. https://corpus.byu.edu/coca/

de Aguiar, V., Bastiaanse, R., Capasso, R., Gandolfi, M., Smania, N., Rossi, G., & Miceli, G. (2015). Can tDCS enhance item-specific effects and generalization after linguistically motivated aphasia therapy for verbs? *Frontiers in Behavioral Neuroscience, 9*. https://doi.org/10.3389/fnbeh.2015.00190

de Champfleur, N. M., Maldonado, I. L., Moritz-Gasser, S., Machi, P., Le Bars, E., Bonafé, A., & Duffau, H. (2013). Middle longitudinal fasciculus delineation within language pathways: A diffusion tensor imaging study in human. *European Journal of Radiology*, *82*(1), 151–157.

DeDe, G. (2012). Effects of word frequency and modality on sentence comprehension impairments in people with aphasia. *American Journal of Speech-Language Pathology*, *21*(2), S103–S114.

DeDe, G. (2013a). Verb transitivity bias affects on-line sentence reading in people with aphasia. *Aphasiology*, *27*(3), 326–343.

DeDe, G. (2013b). Effects of verb bias and syntactic ambiguity on reading in people with aphasia. *Aphasiology*, *27*(12), 1408–1425. https://doi.org/10.1080/02687038.2013.843151

Dell, G. S., Schwartz, M. F., Nozari, N., Faseyitan, O., & Coslett, H. B. (2013). Voxel-based lesion-parameter mapping: Identifying the neural correlates of a computational model of word production. *Cognition*, *128*(3), 380–396.

DeLong, M. R., Alexander, G. E., Georgopoulos, A. P., Crutcher, M. D., Mitchell, S. J., & Richardson, R. T. (1984). Role of basal ganglia in limb movements. *Human Neurobiology*, *2*(4), 235–244.

DeLong, M. R., Georgopoulos, A. P., Crutcher, M. D., Mitchell, S. J., Richardson, R. T., & Alexander, G. E. (1984). Functional organization of the basal ganglia: Contributions of single-cell recording studies. *Ciba Foundation Symposium*, *107*, 64–82. https://doi.org/10.1002/9780470720882.ch5

DeLong, M. R., & Wichmann, T. (2007). Circuits and Circuit Disorders of the Basal Ganglia. *Archives of Neurology*, *64*(1), 20–24. https://doi.org/10.1001/archneur.64.1.20

den Ouden, D.-B., Malyutina, S., Basilakos, A., Bonilha, L., Gleichgerrcht, E., Yourganov, G., Hillis, A. E., Hickok, G., Rorden, C., & Fridriksson, J. (2019). Cortical and structural-connectivity damage correlated with impaired syntactic processing in aphasia. *Human Brain Mapping*. https://doi.org/10.1002/hbm.24514

Dick, A. S., & Tremblay, P. (2012). Beyond the arcuate fasciculus: Consensus and controversy in the connectional anatomy of language. *Brain: A Journal of Neurology*, *135*(Pt 12), 3529–3550. https://doi.org/10.1093/brain/aws222

Dowty, D. (1982). Grammatical Relations and Montague Grammar. In *The Nature of Syntactic Representation* (pp. 79–130). Springer, Dordrecht. https://doi.org/10.1007/978-94-009-7707-5_4

Dresang, H. C., Dickey, M. W., & Warren, T. (2018). *Event-referent activation in the visual world: Persistent activation is guided by both lexical and event representations*. 31st Annual CUNY Sentence Processing Conference, Davis, CA. https://osf.io/3dp4a/

Dresang, H. C., Dickey, M. W., & Warren, T. C. (2019). Semantic memory for objects, actions, and events: A novel test of event-related conceptual semantic knowledge. *Cognitive Neuropsychology*, *36*(7–8), 313–335. https://doi.org/10.1080/02643294.2019.1656604

Druks, J., & Carroll, E. (2005). The crucial role of tense for verb production. *Brain and Language*, *94*(1), 1–18. https://doi.org/10.1016/j.bandl.2004.11.003

Druks, J., & Shallice, T. (2000). Selective Preservation of Naming from Description and the “Restricted Preverbal Message.” *Brain and Language*, *72*(2), 100–128. https://doi.org/10.1006/brln.1999.2165

Duffau, H. (2015). Stimulation mapping of white matter tracts to study brain functional connectivity. *Nature Reviews. Neurology*, *11*(5), 255–265. https://doi.org/10.1038/nrneurol.2015.51

Duffau, H., Gatignol, P., Moritz-Gasser, S., & Mandonnet, E. (2009). Is the left uncinate fasciculus essential for language? A cerebral stimulation study. *Journal of Neurology*, *256*(3), 382–389. https://doi.org/10.1007/s00415-009-0053-9

Duffau, H., Herbet, G., & Moritz-Gasser, S. (2013). Toward a pluri-component, multimodal, and dynamic organization of the ventral semantic stream in humans: Lessons from stimulation mapping in awake patients. *Frontiers in Systems Neuroscience*, *7*. https://doi.org/10.3389/fnsys.2013.00044

Duffau, H., Moritz-Gasser, S., & Mandonnet, E. (2014). A re-examination of neural basis of language processing: Proposal of a dynamic hodotopical model from data provided by brain stimulation mapping during picture naming. *Brain and Language*, *131*, 1–10. https://doi.org/10.1016/j.bandl.2013.05.011

Durrant, P., & Doherty, A. (2010). Are high-frequency collocations psychologically real? Investigating the thesis of collocational priming. *Corpus Linguistics and Linguistic Theory*, *6*(2), 125–155. https://doi.org/10.1515/cllt.2010.006

Edmonds, L. A. (2016). A Review of Verb Network Strengthening Treatment: Theory, Methods, Results, and Clinical Implications. *Topics in Language Disorders*, *36*(2), 123–135.

Ellis, N. C., & Larsen-Freeman, D. (2009). *Language as a Complex Adaptive System*. John Wiley & Sons.

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

Elman, J. L. (1991). Distributed representations, simple recurrent networks, and grammatical structure. *Machine Learning*, *7*, 195–225.

Evans, W. S., Hula, W. D., & Starns, J. J. (2019). Speed–Accuracy Trade-Offs and Adaptation Deficits in Aphasia: Finding the “Sweet Spot” Between Overly Cautious and Incautious

Responding. *American Journal of Speech-Language Pathology*, *28*(1 Suppl), 259–277. https://doi.org/10.1044/2018_AJSLP-17-0156

Faroqi-Shah, Y., & Graham, L. E. (2011). Treatment of semantic verb classes in aphasia: Acquisition and generalization effects. *Clinical Linguistics & Phonetics*, *25*(5), 399–418. https://doi.org/10.3109/02699206.2010.545964

Faroqi-Shah, Y., Wood, E., & Gassert, J. (2010). Verb impairment in aphasia: A priming study of body-part overlap. *Aphasiology*, *24*(11), 1377–1388.

Fergadiotis, G., Hula, W. D., Swiderski, A. M., Lei, C.-M., & Kellough, S. (2019). Enhancing the Efficiency of Confrontation Naming Assessment for Aphasia Using Computer Adaptive Testing. *Journal of Speech, Language, and Hearing Research: JSLHR*, *62*(6), 1724–1738.

Fernández-Miranda, J. C., Wang, Y., Pathak, S., Stefaneau, L., Verstynen, T., & Yeh, F.-C. (2015). Asymmetry, connectivity, and segmentation of the arcuate fascicle in the human brain. *Brain Structure and Function*, *220*(3), 1665–1680.

Ferreira, F. (2003). The misinterpretation of noncanonical sentences. *Cognitive Psychology*, *47*(2), 164–203.

Ferretti, T. R., McRae, K., & Hatherell, A. (2001). Integrating verbs, situation schemas, and thematic role concepts. *Journal of Memory and Language*, *44*(4), 516–547.

Fiez, J. A., & Tranel, D. (1997). Standardized stimuli and procedures for investigating the retrieval of lexical and conceptual knowledge for actions. *Memory & Cognition*, *25*(4), 543–569. https://doi.org/10.3758/BF03201129

Flombaum, J. I., Santos, L. R., & Hauser, M. D. (2002). Neuroecology and psychological modularity. *Trends in Cognitive Sciences*, *6*(3), 106–108. https://doi.org/10.1016/s1364-6613(02)01872-7

Flowers, H. L., Skoretz, S. A., Silver, F. L., Rochon, E., Fang, J., Flamand-Roze, C., & Martino, R. (2016). Poststroke Aphasia Frequency, Recovery, and Outcomes: A Systematic Review and Meta-Analysis. *Archives of Physical Medicine and Rehabilitation*, *97*(12), 2188-2201.e8. https://doi.org/10.1016/j.apmr.2016.03.006

Fodor, J. A. (1983). *The modularity of mind*. MIT Press.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*(3), 189–198.

Forster, K. I. (1976). Accessing the mental lexicon. In R. J. Walker & F. Wales (Eds.), *New approaches to language mechanisms*. North-Holland.

Foygel, D., & Dell, G. S. (2000). Models of Impaired Lexical Access in Speech Production. *Journal of Memory and Language*, *43*(2), 182–216. https://doi.org/10.1006/jmla.2000.2716

Frazier, L. (1987). Sentence processing: A tutorial review. In *Attention and performance 12: The psychology of reading* (pp. 559–586). Lawrence Erlbaum Associates, Inc.

Fridriksson, J., Guo, D., Fillmore, P., Holland, A., & Rorden, C. (2013). Damage to the anterior arcuate fasciculus predicts non-fluent speech production in aphasia. *Brain: A Journal of Neurology*, *136*(Pt 11), 3451–3460. https://doi.org/10.1093/brain/awt267

Fujii, M., Maesawa, S., Motomura, K., Futamura, M., Hayashi, Y., Koba, I., & Wakabayashi, T. (2015). Intraoperative subcortical mapping of a language-associated deep frontal tract connecting the superior frontal gyrus to Broca's area in the dominant hemisphere of patients with glioma. *Journal of Neurosurgery*, *122*(6), 1390–1396. https://doi.org/10.3171/2014.10.JNS14945

Gahl, S. (2002). Lexical biases in aphasic sentence comprehension: An experimental and corpus linguistic study. *Aphasiology*, *16*(12), 1173–1198.

Garrett, M. F. (1975). Syntactic processes in sentence production. *New Approaches to Language Mechanisms*, *30*, 231–256.

Gelman, A., Carlin, J., Stern, H., Dunson, D., Vehtari, A., & Rubin, D. (2013). *Bayesian data analysis* (3rd ed.). CRC Press.

Gentsch, A., Weber, A., Synofzik, M., Vosgerau, G., & Schütz-Bosbach, S. (2016). Towards a common framework of grounded action cognition: Relating motor control, perception and cognition. *Cognition*, *146*, 81–89. https://doi.org/10.1016/j.cognition.2015.09.010

Gerfo, E. L., Oliveri, M., Torriero, S., Salerno, S., Koch, G., & Caltagirone, C. (2008). The influence of rTMS over prefrontal and motor areas in a morphological task: Grammatical vs. semantic effects. *Neuropsychologia*, *46*(2), 764–770. https://doi.org/10.1016/j.neuropsychologia.2007.10.012

Geschwind, N. (1965). Disconnexion Syndromes in Animals and Man. *Brain*, *88*(2), 237–237. https://doi.org/10.1093/brain/88.2.237

Geschwind, N. (1972). Language and the Brain. *Scientific American*, *226*(4), 76–83. https://doi.org/10.1038/scientificamerican0472-76

Gialanella, B., Bertolinelli, M., Lissi, M., & Prometti, P. (2011). Predicting outcome after stroke: The role of aphasia. *Disability and Rehabilitation*, *33*(2), 122–129. https://doi.org/10.3109/09638288.2010.488712

Gibson, E., Bergen, L., & Piantadosi, S. T. (2013). Rational integration of noisy evidence and prior semantic expectations in sentence interpretation. *Proceedings of the National Academy of Sciences*, *110*(20), 8051–8056. https://doi.org/10.1073/pnas.1216438110

Gibson, E., Sandberg, C., Fedorenko, E., Bergen, L., & Kiran, S. (2015). A rational inference approach to aphasic language comprehension. *Aphasiology*, 1–20.

Glasser, M. F., & Rilling, J. K. (2008). DTI tractography of the human brain's language pathways. *Cerebral Cortex*, *18*(11), 2471–2482.

Glenberg, A. M., Sato, M., Cattaneo, L., Riggio, L., Palumbo, D., & Buccino, G. (2008). Processing abstract language modulates motor system activity. *Quarterly Journal of Experimental Psychology (2006)*, *61*(6), 905–919. https://doi.org/10.1080/17470210701625550

Goodglass, H. (1976). Agrammatism. *Studies in Neurolinguistics*, *1*, 237–260.

Goodglass, H. (1993). *Understanding aphasia.* Academic Press.

Goodglass, H., & Wingfield, A. (1997). *Anomia: Neuroanatomical and Cognitive Correlates*. Elsevier. https://doi.org/10.1016/B978-0-12-289685-9.X5000-5

Gordon, J. K., & Dell, G. S. (2003). Learning to divide the labor: An account of deficits in light and heavy verb production. *Cognitive Science*, *27*(1), 1–40. https://doi.org/10.1016/S0364-0213(02)00111-8

Graham, J. R., Pereira, S., & Teasell, R. (2011). Aphasia and return to work in younger stroke survivors. *Aphasiology*, *25*(8), 952–960. https://doi.org/10.1080/02687038.2011.563861

Grawburg, M., Howe, T., Worrall, L., & Scarinci, N. (2013a). A qualitative investigation into third-party functioning and third-party disability in aphasia: Positive and negative experiences of family members of people with aphasia. *Aphasiology*, *27*(7), 828–848. https://doi.org/10.1080/02687038.2013.768330

Grawburg, M., Howe, T., Worrall, L., & Scarinci, N. (2013b). Third-party disability in family members of people with aphasia: A systematic review. *Disability and Rehabilitation*, *35*(16), 1324–1341. https://doi.org/10.3109/09638288.2012.735341

Griffiths, P. D., Perry, R. H., & Crossman, A. R. (1994). A detailed anatomical analysis of neurotransmitter receptors in the putamen and caudate in Parkinson's disease and Alzheimer's disease. *Neuroscience Letters*, *169*(1), 68–72. https://doi.org/10.1016/0304-3940(94)90358-1

Grodzinsky, Y. (1986). Language deficits and the theory of syntax. *Brain and Language*, *27*(1), 135–159.

Grodzinsky, Y. (2000). The neurology of syntax: Language use without Broca's area. *Behavioral and Brain Sciences*, *23*(01), 1–21.

Grossman, M., Anderson, C., Khan, A., Avants, B., Elman, L., & McCluskey, L. (2008). Impaired action knowledge in amyotrophic lateral sclerosis. *Neurology*, *71*(18), 1396–1401. https://doi.org/10.1212/01.wnl.0000319701.50168.8c

Haber, S. N. (2016). Corticostriatal circuitry. *Dialogues in Clinical Neuroscience*, *18*(1), 7–21.

Hale, J. (2001). A Probabilistic Earley Parser as a Psycholinguistic Model. *Second Meeting of the North American Chapter of the Association for Computational Linguistics*. NAACL 2001. https://www.aclweb.org/anthology/N01-1021

Hamer, P. C. D. W., Moritz-Gasser, S., Gatignol, P., & Duffau, H. (2011). Is the human left middle longitudinal fascicle essential for language? A brain electrostimulation study. *Human Brain Mapping*, *32*(6), 962–973. https://doi.org/10.1002/hbm.21082

Han, Z., Ma, Y., Gong, G., He, Y., Caramazza, A., & Bi, Y. (2013). White matter structural connectivity underlying semantic processing: Evidence from brain damaged patients. *Brain: A Journal of Neurology*, *136*(Pt 10), 2952–2965. https://doi.org/10.1093/brain/awt205

Hare, M., Jones, M., Thomson, C., Kelly, S., & McRae, K. (2009). Activating event knowledge. *Cognition*, *111*(2), 151–167. https://doi.org/10.1016/j.cognition.2009.01.009

Hauk, O., & Tschentscher, N. (2013). The Body of Evidence: What Can Neuroscience Tell Us about Embodied Semantics? *Frontiers in Psychology*, *4*. https://doi.org/10.3389/fpsyg.2013.00050

Hayes, R. A., Dickey, M. W., & Warren, T. (2016). *Looking for a location: Dissociated effects of event-related plausibility and verb-argument information on predictive processing in aphasia*.

Hickok, G., & Poeppel, D. (2004). Dorsal and ventral streams: A framework for understanding aspects of the functional anatomy of language. *Cognition*, *92*(1), 67–99.

Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience*, *8*(5), 393–402.

Hilari, K. (2011). The impact of stroke: Are people with aphasia different to those without? *Disability and Rehabilitation*, *33*(3), 211–218. https://doi.org/10.3109/09638288.2010.508829

Hong, J. H., Lee, J., Cho, Y. W., Byun, W. M., Cho, H. K., Son, S. M., & Jang, S. H. (2012). Limb apraxia in a patient with cerebral infarct: Diffusion tensor tractography study. *NeuroRehabilitation*, *30*(4), 255–259. https://doi.org/10.3233/NRE-2012-0753

Howard, D., & Gatehouse, C. (2006). Distinguishing semantic and lexical word retrieval deficits in people with aphasia. *Aphasiology*, *20*(9–11), 921–950. https://doi.org/10.1080/02687030600782679

Howes, A., Lewis, R. L., & Vera, A. (2009). Rational adaptation under task and processing constraints: Implications for testing theories of cognition and action. *Psychological Review*, *116*(4), 717–751. https://doi.org/10.1037/a0017187

Howes, A., & Young, R. M. (1997). The Role of Cognitive Architecture in Modeling the User: Soar's Learning Mechanism. *Human–Computer Interaction*, *12*(4), 311–343. https://doi.org/10.1207/s15327051hci1204_2

Hula, W. D., Panesar, S., Gravier, M., Yeh, F.-C., Dresang, H. C., Dickey, M. W., & Fernandez-Miranda, J. C. (in revision). Structural White Matter Connectometry of Word Production in Aphasia. *Brain*.

Hula, W., Fernandez-Miranda, J., Yeh, F., Fernandes-Cabral, D., Dickey, M., Gravier, M., Panesar, S., Rowthu, V., & Doyle, P. (2017). *Left Ventral Stream White Matter Connectivity Predicts Response to Semantic Feature Analysis Treatment in Chronic Aphasia*. Academy of Aphasia.

Isenberg, A. L., Vaden, K. I., Saberi, K., Muftuler, L. T., & Hickok, G. (2012). Functionally distinct regions for spatial processing and sensory motor integration in the planum temporale. *Human Brain Mapping*, *33*(10), 2453–2463. https://doi.org/10.1002/hbm.21373

Jackendoff, R. (1978). Grammar as evidence for conceptual structure. In M. Hale, J. Bresnan, & G. Miller (Eds.), *Linguistic theory and psychological reality* (pp. 209–228). MIT Press.

Jang, S. H. (2009). The role of the corticospinal tract in motor recovery in patients with a stroke: A review. *NeuroRehabilitation*, *24*(3), 285–290. https://doi.org/10.3233/NRE-2009-0480

Jang, S. H. (2011). A review of diffusion tensor imaging studies on motor recovery mechanisms in stroke patients. *NeuroRehabilitation*, *28*(4), 345–352. https://doi.org/10.3233/NRE-2011-0662

Jang, S. H. (2012). Motor Recovery Mechanisms in Patients with Middle Cerebral Artery Infarct: A Mini-Review. *European Neurology; Basel*, *68*(4), 234–239. http://dx.doi.org.pitt.idm.oclc.org/10.1159/000342026

Jang, S. H., Bai, D., Son, S. M., Lee, J., Kim, D.-S., Sakong, J., Kim, D. G., & Yang, D. S. (2008). Motor outcome prediction using diffusion tensor tractography in pontine infarct. *Annals of Neurology*, *64*(4), 460–465. https://doi.org/10.1002/ana.21444

Jankowski, M. M., Ronnqvist, K. C., Tsanov, M., Vann, S. D., Wright, N. F., Erichsen, J. T., Aggleton, J. P., & O'Mara, S. M. (2013). The anterior thalamus provides a subcortical circuit supporting memory and spatial navigation. *Frontiers in Systems Neuroscience*, *7*, 45. https://doi.org/10.3389/fnsys.2013.00045

Jefferies, E. (2006). Semantic impairment in stroke aphasia versus semantic dementia: A case-series comparison. *Brain*, *129*(8), 2132–2147. https://doi.org/10.1093/brain/awl153

Jefferies, E., & Ralph, M. A. L. (2006). Semantic impairment in stroke aphasia versus semantic dementia: A case-series comparison. *Brain*, *129*(8), 2132–2147.

Jescheniak, J. D., & Levelt, W. J. M. (1994). Word frequency effects in speech production: Retrieval of syntactic information and of phonological form. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *20*(4), 824–843. https://doi.org/10.1037/0278-7393.20.4.824

Jonkers, R., & Bastiaanse, R. (2007). Action naming in anomic aphasic speakers: Effects of instrumentality and name relation. *Brain and Language*, *102*(3), 262–272. https://doi.org/10.1016/j.bandl.2007.01.002

Katz, J. (1972). *Semantic theory: Studies in language*. Harper & Row. https://books.google.com/books/about/Semantic_theory.html?id=x_RYAAAAMAAJ

Kauhanen, M.-L., Korpelainen, J., Hiltunen, P., Määttä, R., Mononen, H., Brusin, E., Sotaniemi, K., & Myllylä, V. (2000). Aphasia, depression, and non-verbal cognitive impairment in ischaemic stroke. *Cerebrovascular Diseases, 10*(6), 455–461.

Kelter, S., & Kaup, B. (2012). Conceptual knowledge, categorization, and meaning. In C. Maienborn, K. von Heusinger, & P. Portner (Eds.), *Semantics: An International Handbook of Natural Language Meaning* (pp. 2775–2804). Walter de Gruyter.

Kemmerer, D., Rudrauf, D., Manzel, K., & Tranel, D. (2012). Behavioral patterns and lesion sites associated with impaired processing of lexical and conceptual knowledge of actions. *Cortex*, *48*(7), 826–848. https://doi.org/10.1016/j.cortex.2010.11.001

Kemmerer, D., & Tranel, D. (2000). Verb Retrieval in Brain-Damaged Subjects: 1. Analysis of Stimulus, Lexical, and Conceptual Factors. *Brain and Language*, *73*(3), 347–392. https://doi.org/10.1006/brln.2000.2311

Kemmerer, D., Tranel, D., & Barrash, J. (2001). Patterns of dissociation in the processing of verb meanings in brain-damaged subjects. *Language and Cognitive Processes*, *16*(1), 1–34. https://doi.org/10.1080/01690960042000175

Kiefer, M., & Pulvermüller, F. (2012). Conceptual representations in mind and brain: Theoretical developments, current evidence and future directions. *Cortex*, *48*(7), 805–825. https://doi.org/10.1016/j.cortex.2011.04.006

Kieras, D. E., & Meyer, D. E. (2000). The role of cognitive task analysis in the application of predictive models of human performance. In *Cognitive task analysis* (pp. 237–260). Lawrence Erlbaum Associates Publishers.

Kim, M., & Thompson, C. K. (2000). Patterns of comprehension and production of nouns and verbs in agrammatism: Implications for lexical organization. *Brain and Language*, *74*(1), 1–25.

Kim, M., & Thompson, C. K. (2004). Verb deficits in Alzheimer’s disease and agrammatism: Implications for lexical organization. *Brain and Language*, *88*(1), 1–20.

Kinoshita, M., de Champfleur, N. M., Deverdun, J., Moritz-Gasser, S., Herbet, G., & Duffau, H. (2015). Role of fronto-striatal tract and frontal aslant tract in movement and speech: An axonal mapping study. *Brain Structure and Function*, *220*(6), 3399–3412. https://doi.org/10.1007/s00429-014-0863-0

Kronfeld-Duenias, V., Amir, O., Ezrati-Vinacour, R., Civier, O., & Ben-Shachar, M. (2016). The frontal aslant tract underlies speech fluency in persistent developmental stuttering. *Brain Structure and Function*, *221*(1), 365–381. https://doi.org/10.1007/s00429-014-0912-8

Kuperberg, G. R., & Jaeger, T. F. (2016). What do we mean by prediction in language comprehension? *Language, Cognition and Neuroscience*, *31*(1), 32–59. https://doi.org/10.1080/23273798.2015.1102299

Lam, J., & Wodchis, W. (2010). The relationship of 60 disease diagnoses and 15 conditions to preference-based health-related quality of life in Ontario hospital-based long-term care residents. *Medical Care*, *48*, 380–387.

Lambon Ralph, M. A., McClelland, J. L., Patterson, K., Galton, C. J., & Hodges, J. R. (2001). No right to speak? The relationship between object naming and semantic impairment: neuropsychological evidence and a computational model. *Journal of Cognitive Neuroscience*, *13*(3), 341–356. https://doi.org/10.1162/08989290151137395

Lambon Ralph, M. A. (2014). Neurocognitive insights on conceptual knowledge and its breakdown. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1634). https://doi.org/10.1098/rstb.2012.0392

Landauer, T. K., & Dumais, S. T. (1997). A solution to Plato's problem: The Latent Semanctic Analysis theory of the acquisition, induction, and representation of knowledge. *Psychological Review*, *104*, 211–240.

Lee, J. S., Han, M.-K., Kim, S. H., Kwon, O.-K., & Kim, J. H. (2005). Fiber tracking by diffusion tensor imaging in corticospinal tract stroke: Topographical correlation with clinical symptoms. *NeuroImage*, *26*(3), 771–776. https://doi.org/10.1016/j.neuroimage.2005.02.036

Lei, C.-M., Dresang, H. C., Holcomb, M. B., Warren, T., & Dickey, M. W. (2016, August). *Neural bases of semantic-memory deficits for events*. Cognitive Science Society, Philadelphia, PA.

Leiguarda, R. C., & Marsden, C. D. (2000). Limb apraxias: Higher-order disorders of sensorimotor integration. *Brain: A Journal of Neurology*, *123 (Pt 5)*, 860–879. https://doi.org/10.1093/brain/123.5.860

Levelt, W. J. M. (1989). *Speaking: From intention to articulation*. The MIT Press.

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

Lichteim, L. (1885). On Aphasia. *Brain*, *7*(4), 433–484. https://doi.org/10.1093/brain/7.4.433

Lindenberg, R., Renga, V., Zhu, L. L., Betzler, F., Alsop, D., & Schlaug, G. (2010). Structural integrity of corticospinal motor fibers predicts motor impairment in chronic stroke. *Neurology*, *74*(4), 280–287. https://doi.org/10.1212/WNL.0b013e3181ccc6d9

Links, P., Hurkmans, J., & Bastiaanse, R. (2010). Training verb and sentence production in agrammatic Broca's aphasia. *Aphasiology*, *24*(11), 1303–1325. https://doi.org/10.1080/02687030903437666

Loverso, F. L., Prescott, T. E., & Selinger, M. (1988). Cueing verbs: A treatment strategy for aphasic adults (CVT). *Journal of Rehabilitation Research and Development*, *25*(2), 47–60.

Lund, K., & Burgess, C. (1996). Producing high-dimensional semantic spaces from lexical co-occurrence. *Behavior Research Methods, Instruments, & Computers*, *28*(2), 203–208.

Mahon, B. Z. (2015). What is embodied about cognition? *Language, Cognition and Neuroscience*, *30*(4), 420–429. https://doi.org/10.1080/23273798.2014.987791

Makris, N., Kennedy, D. N., McInerney, S., Sorensen, A. G., Wang, R., Caviness, V. S., & Pandya, D. N. (2005). Segmentation of subcomponents within the superior longitudinal fascicle in humans: A quantitative, in vivo, DT-MRI study. *Cerebral Cortex (New York, N.Y.: 1991)*, *15*(6), 854–869. https://doi.org/10.1093/cercor/bhh186

Mandera, P., Keuleers, E., & Brysbaert, M. (2017). Explaining human performance in psycholinguistic tasks with models of semantic similarity based on prediction and counting: A review and empirical validation. *Journal of Memory and Language*, *92*, 57–78. https://doi.org/10.1016/j.jml.2016.04.001

Marchand, W. R., Lee, J. N., Thatcher, J. W., Hsu, E. W., Rashkin, E., Suchy, Y., Chelune, G., Starr, J., & Barbera, S. S. (2008). Putamen coactivation during motor task execution. *NeuroReport*, *19*(9), 957–960. https://doi.org/10.1097/WNR.0b013e328302c873

Marebwa, B. K., Fridriksson, J., Yourganov, G., Feenaughty, L., Rorden, C., & Bonilha, L. (2017). Chronic post-stroke aphasia severity is determined by fragmentation of residual white matter networks. *Scientific Reports*, *7*(1), 8188. https://doi.org/10.1038/s41598-017-07607-9

Martin, A. (2007). The Representation of Object Concepts in the Brain. *Annual Review of Psychology*, *58*(1), 25–45. https://doi.org/10.1146/annurev.psych.57.102904.190143

Martin, A. (2009). Circuits in mind: The neural foundations for object concepts. In *The cognitive neurosciences, 4th ed* (pp. 1031–1045). Massachusetts Institute of Technology.

Martin, A. (2016). GRAPES-Grounding representations in action, perception, and emotion systems: How object properties and categories are represented in the human brain.

Psychonomic Bulletin & Review, *23*(4), 979–990. https://doi.org/10.3758/s13423-015-0842-3

Mätzig, S., Druks, J., Masterson, J., & Vigliocco, G. (2009). Noun and verb differences in picture naming: Past studies and new evidence. *Cortex*, *45*(6), 738–758.

McDonald, S. A., & Shillcock, R. C. (2003). Eye movements reveal the on-line computation of lexical probabilities during reading. *Psychological Science*, *14*(6), 648–652. https://doi.org/10.1046/j.0956-7976.2003.psci_1480.x

McElreath, R. (2018). *Statistical rethinking: A Bayesian course with examples in R and Stan*. Chapman and Hall/CRC.

McNeil, M. R., & Pratt, S. R. (2001). Defining aphasia: Some theoretical and clinical implications of operating from a formal definition. *Aphasiology*, *15*(10–11), 901–911.

McRae, K., Hare, M., Elman, J. L., & Ferretti, T. (2005). A basis for generating expectancies for verbs from nouns. *Memory & Cognition*, *33*(7), 1174–1184.

McRae, K., Hare, M., Ferretti, T., & Elman, J. L. (2001). *Activating verbs from typical agents, patients, instruments, and locations via event schemas*. 617–622.

McRae, K., & Matsuki, K. (2009). People Use their Knowledge of Common Events to Understand Language, and Do So as Quickly as Possible. *Language and Linguistics Compass*, *3*(6), 1417–1429. https://doi.org/10.1111/j.1749-818X.2009.00174.x

Meteyard, L., Cuadrado, S. R., Bahrami, B., & Vigliocco, G. (2012). Coming of age: A review of embodiment and the neuroscience of semantics. *Cortex*, *48*(7), 788–804. https://doi.org/10.1016/j.cortex.2010.11.002

Miceli, G., Silveri, M. C., Villa, G., & Caramazza, A. (1984). On the basis for the agrammatic's difficulty in producing main verbs. *Cortex; a Journal Devoted to the Study of the*

Nervous System and Behavior, *20*(2), 207–220. https://doi.org/10.1016/s0010-9452(84)80038-6

Miceli, Gabriele, Silveri, M. C., Nocentini, U., & Caramazza, A. (1988). Patterns of dissociation in comprehension and production of nouns and verbs. *Aphasiology*, *2*(3–4), 351–358. https://doi.org/10.1080/02687038808248937

Milburn, E., Warren, T., & Dickey, M. W. (2016). World knowledge affects prediction as quickly as selectional restrictions: Evidence from the visual world paradigm. *Language, Cognition and Neuroscience*, *31*(4), 536–548.

Milner, A. D., & Goodale, M. A. (2008). Two visual systems re-viewed. *Neuropsychologia*, *46*(3), 774–785.

Mirman, D., & Britt, A. E. (2014). What we talk about when we talk about access deficits. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1634). https://doi.org/10.1098/rstb.2012.0388

Mitchell, D. C. (2004). On-line methods in language processing: Introduction and historical review. In M. Carreiras & C. E. Clifton (Eds.), *The on-line study of sentence comprehension: Eye-tracking, ERP and beyond* (pp. 15–32). Routledge.

Molnar, G. F., Sailer, A., Gunraj, C. A., Cunic, D. I., Wennberg, R. A., Lozano, A. M., & Chen, R. (2006). Changes in motor cortex excitability with stimulation of anterior thalamus in epilepsy. *Neurology*, *66*(4), 566–571. https://doi.org/10.1212/01.wnl.0000198254.08581.6b

Morris, L. S., Kundu, P., Dowell, N., Mechelmans, D. J., Favre, P., Irvine, M. A., Robbins, T. W., Daw, N., Bullmore, E. T., Harrison, N. A., & Voon, V. (2016). Fronto-striatal organization: Defining functional and microstructural substrates of behavioural flexibility. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *74*, 118–133. https://doi.org/10.1016/j.cortex.2015.11.004

Nelson, D. L., McEvoy, C. L., & Schreiber, T. A. (1998). *The University of South Florida word association, rhyme, and word fragment norms*. http://www.usf.edu/FreeAssociation/

Nickels, L. (2002). Therapy for naming disorders: Revisiting, revising, and reviewing. *Aphasiology*, *16*(10–11), 935–979. https://doi.org/10.1080/02687030244000563

Oaksford, M., & Chater, N. (1994). A rational analysis of the selection task as optimal data selection. *Psychological Review*, *101*(4), 608–631. https://doi.org/10.1037/0033-295X.101.4.608

Ovbiagele, B., Goldstein, L. B., Higashida, R. T., Howard, V. J., Johnston, S. C., Khavjou, O. A., Lackland, D. T., Lichtman, J. H., Mohl, S., Sacco, R. L., Saver, J. L., Trogdon, J. G., & American Heart Association Advocacy Coordinating Committee and Stroke Council. (2013). Forecasting the future of stroke in the United States: A policy statement from the American Heart Association and American Stroke Association. *Stroke*, *44*(8), 2361–2375. https://doi.org/10.1161/STR.0b013e31829734f2

Parlatini, V., Radua, J., Dell’Acqua, F., Leslie, A., Simmons, A., Murphy, D. G., Catani, M., & Thiebaut de Schotten, M. (2017). Functional segregation and integration within fronto-parietal networks. *NeuroImage*, *146*, 367–375. https://doi.org/10.1016/j.neuroimage.2016.08.031

Patterson, K. (2007). The Reign of Typicality in Semantic Memory. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *362*(1481), 813–821.

Patterson, K., Nestor, P. J., & Rogers, T. T. (2007). Where do you know what you know? The representation of semantic knowledge in the human brain. *Nature Reviews Neuroscience*, *8*(12), 976–987. https://doi.org/10.1038/nrn2277

Pedersen, P. M., Vinter, K., & Olsen, T. S. (2004). Aphasia after stroke: Type, severity and prognosis. The Copenhagen aphasia study. *Cerebrovascular Diseases (Basel, Switzerland)*, *17*(1), 35–43. https://doi.org/10.1159/000073896

Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review*, *103*(1), 56–115. https://doi.org/10.1037/0033-295X.103.1.56

Pulvermüller, F. (2003). *The Neuroscience of Language: On Brain Circuits of Words and Serial Order*. Cambridge University Press.

Pulvermüller, F. (2005). Brain mechanisms linking language and action. *Nature Reviews Neuroscience*, *6*(7), 576–582. https://doi.org/10.1038/nrn1706

Pulvermüller, F. (2018). Neural reuse of action perception circuits for language, concepts and communication. *Progress in Neurobiology*, *160*, 1–44. https://doi.org/10.1016/j.pneurobio.2017.07.001

Pulvermüller, F., Hauk, O., Nikulin, V. V., & Ilmoniemi, R. J. (2005). Functional links between motor and language systems. *The European Journal of Neuroscience*, *21*(3), 793–797. https://doi.org/10.1111/j.1460-9568.2005.03900.x

Quandt, L. C., Lee, Y.-S., & Chatterjee, A. (2017). Neural bases of action abstraction. *Biological Psychology*, *129*, 314–323. https://doi.org/10.1016/j.biopsycho.2017.09.015

Quique, Y. M., Evans, W. S., & Dickey, M. W. (2019). Acquisition and Generalization Responses in Aphasia Naming Treatment: A Meta-Analysis of Semantic Feature Analysis Outcomes. *American Journal of Speech-Language Pathology*, *28*(1S), 230–246.

Ralph, M. A., & Howard, D. (2000). Gogi aphasia or semantic dementia? Simulating and assessing poor verbal comprehension in a case of progressive fluent aphasia. *Cognitive Neuropsychology*, *17*(5), 437–465. https://doi.org/10.1080/026432900410784

Ratcliff, R., Thapar, A., Gomez, P., & McKoon, G. (2004). A diffusion model analysis of the effects of aging in the lexical-decision task. *Psychology and Aging*, *19*(2), 278–289. https://doi.org/10.1037/0882-7974.19.2.278

Rauschecker, J. P., & Scott, S. K. (2009). Maps and streams in the auditory cortex: Nonhuman primates illuminate human speech processing. *Nature Neuroscience*, *12*(6), 718–724.

Raven, J. C. (1965). *Guide to using the coloured progressive matrices: Sets A, Ab, B*. William Grieve & Sons.

Rea, P. (2015). *Essential Clinical Anatomy of the Nervous System*. Academic Press.

Reali, F., & Christiansen, M. H. (2007). Processing of relative clauses is made easier by frequency of occurrence. *Journal of Memory and Language*, *57*(1), 1–23. https://doi.org/10.1016/j.jml.2006.08.014

Rech, F., Herbet, G., Moritz-Gasser, S., & Duffau, H. (2016). Somatotopic organization of the white matter tracts underpinning motor control in humans: An electrical stimulation study. *Brain Structure & Function*, *221*(7), 3743–3753. https://doi.org/10.1007/s00429-015-1129-1

Rider, J. D., Wright, H. H., Marshall, R. C., & Page, J. L. (2008). Using Semantic Feature Analysis to Improve Contextual Discourse in Adults With Aphasia. *American Journal of Speech-Language Pathology*, *17*(2), 161. https://doi.org/10.1044/1058-0360(2008/016)

Ripollés, P., Biel, D., Peñaloza, C., Kaufmann, J., Marco-Pallarés, J., Noesselt, T., & Rodríguez-Fornells, A. (2017). Strength of Temporal White Matter Pathways Predicts Semantic Learning. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *37*(46), 11101–11113. https://doi.org/10.1523/JNEUROSCI.1720-17.2017

Roach, A., Schwartz, M. F., Martin, N., Grewal, R. S., & Brecher, A. (1996). The Philadelphia naming test: Scoring and rationale. *Clinical Aphasiology*, *24*, 121–134.

Roberts, A., Nguyen, P., Orange, J. B., Jog, M., Nisbet, K. A., & McRae, K. (2017). Differential impairments of upper and lower limb movements influence action verb processing in Parkinson disease. *Cortex*, *97*, 49–59. https://doi.org/10.1016/j.cortex.2017.09.022

Roelofs, A. (2014). A dorsal-pathway account of aphasic language production: The WEAVER++/ARC model. *Cortex*, *59*, 33–48. https://doi.org/10.1016/j.cortex.2014.07.001

Rofes, A., Capasso, R., & Miceli, G. (2015). Verb production tasks in the measurement of communicative abilities in aphasia. *Journal of Clinical and Experimental Neuropsychology*, *37*(5), 483–502. https://doi.org/10.1080/13803395.2015.1025709

Rojkova, K., Volle, E., Urbanski, M., Humbert, F., Dell'Acqua, F., & Thiebaut de Schotten, M. (2016). Atlasing the frontal lobe connections and their variability due to age and education: A spherical deconvolution tractography study. *Brain Structure and Function*, *221*(3), 1751–1766. https://doi.org/10.1007/s00429-015-1001-3

Rose, M., & Sussmilch, G. (2008). The effects of semantic and gesture treatments on verb retrieval and verb use in aphasia. *Aphasiology*, *22*(7–8), 691–706.

Saffran, E. M., Schwartz, M. F., & Linebarger, M. C. (1998). Semantic influences on thematic role assignment: Evidence from normals and aphasics. *Brain and Language*, *62*(2), 255–297.

Saur, D., Kreher, B. W., Schnell, S., Kümmerer, D., Kellmeyer, P., Vry, M.-S., Umarova, R., Musso, M., Glauche, V., & Abel, S. (2008). Ventral and dorsal pathways for language. *Proceedings of the National Academy of Sciences*, *105*(46), 18035–18040.

Saur, D., Schelter, B., Schnell, S., Kratochvil, D., Küpper, H., Kellmeyer, P., Kümmerer, D., Klöppel, S., Glauche, V., Lange, R., Mader, W., Feess, D., Timmer, J., & Weiller, C. (2010). Combining functional and anatomical connectivity reveals brain networks for auditory language comprehension. *NeuroImage*, *49*(4), 3187–3197. https://doi.org/10.1016/j.neuroimage.2009.11.009

Saygin, A. P., Wilson, S. M., Dronkers, N. F., & Bates, E. (2004). Action comprehension in aphasia: Linguistic and non-linguistic deficits and their lesion correlates. *Neuropsychologia*, *42*(13), 1788–1804. https://doi.org/10.1016/j.neuropsychologia.2004.04.016

Schwartz, M. F., Linebarger, M. C., Saffran, E. M., & Pate, D. (1987). Syntactic transparency and sentence interpretation in aphasia. *Language and Cognitive Processes*, *2*(2), 85–113.

Schwartz, M. F., Saffran, E. M., & Marin, O. S. (1980). The word order problem in agrammatism: I. Comprehension. *Brain and Language*, *10*(2), 249–262.

Shapiro, K., Shelton, J., & Caramazza, A. (2000). Grammatical class in lexical production and morhpological processing: Evidence from a case of fluent aphasia. *Cognitive Neuropsychology*, *17*(8), 665–682. https://doi.org/10.1080/026432900750038281

Shapiro, K., & Caramazza, A. (2003). Grammatical processing of nouns and verbs in left frontal cortex? *Neuropsychologia*, *41*(9), 1189–1198. https://doi.org/10.1016/S0028-3932(03)00037-X

Sierpowska, J., Gabarrós, A., Fernandez-Coello, A., Camins, À., Castañer, S., Juncadella, M., de Diego-Balaguer, R., & Rodríguez-Fornells, A. (2015). Morphological derivation overflow as a result of disruption of the left frontal aslant white matter tract. *Brain and Language*, *142*, 54–64. https://doi.org/10.1016/j.bandl.2015.01.005

Silkes, J. P., Baker, C., & Love, T. (2020). The Time Course of Priming in Aphasia. *Topics in Language Disorders*, *40*(1), 54–80. https://doi.org/10.1097/TLD.0000000000000205

Simmons, W. K., & Barsalou, L. W. (2003). The similarity-in-topography principle: Reconciling theories of conceptual deficits. *Cognitive Neuropsychology*, *20*(3), 451–486. https://doi.org/10.1080/02643290342000032

Simmons-Mackie, N., & Cherney, L. R. (2018). Aphasia in North America: Highlights of a White Paper. *Archives of Physical Medicine and Rehabilitation*, *99*(10), e117. https://doi.org/10.1016/j.apmr.2018.07.417

Simmons-Mackie, N., & Kagan, A. (2007). Application of the ICF in Aphasia. *Seminars in Speech and Language*, *28*(4), 244–253. https://doi.org/10.1055/s-2007-986521

Smith, N. J., & Levy, R. (2013). The effect of word predictability on reading time is logarithmic. *Cognition*, *128*(3), 302–319. https://doi.org/10.1016/j.cognition.2013.02.013

Sonbul, S. (2015). Fatal mistake, awful mistake, or extreme mistake? Frequency effects on off-line/on-line collocational processing. *Bilingualism: Language and Cognition*, *18*(3), 419–437. https://doi.org/10.1017/S1366728914000674

Starns, J. J., & Ratcliff, R. (2010). The effects of aging on the speed-accuracy compromise: Boundary optimality in the diffusion model. *Psychology and Aging*, *25*(2), 377–390.

Stefaniak, J. D., Halai, A. D., & Lambon Ralph, M. A. (2020). The neural and neurocomputational bases of recovery from post-stroke aphasia. *Nature Reviews. Neurology*, *16*(1), 43–55. https://doi.org/10.1038/s41582-019-0282-1

Swiderski, A., Dresang, H., Hula, W., Dickey, M., Yeh, F.-C., Fernandez-Miranda, J., & Doyle, P. (2019). Structural fragmentation of linguistic brain networks predicts aphasia severity, but not response to treatment. *Frontiers in Human Neuroscience*, *13*. https://doi.org/10.3389/conf.fnhum.2019.01.00116

Swinburn, K., Porter, G., & Howard, D. (2004). *CAT: comprehensive aphasia test*. Psychology Press.

Tabor, W., & Tanenhaus, M. K. (1999). Dynamical models of sentence processing. *Cognitive Science*, *23*(4), 491–515.

Thomas, S. A., & Lincoln, N. B. (2008). Predictors of emotional distress after stroke. *Stroke*, *39*(4), 1240–1245. https://doi.org/10.1161/STROKEAHA.107.498279

Tremblay, A., Derwing, B., Libben, G., & Westbury, C. (2011). Processing advantages of lexical bundles: Evidence from self-paced reading and sentence recall tasks. *Language Learning*, *61*(2), 569–613. https://doi.org/10.1111/j.1467-9922.2010.00622.x

Tsouli, S., Kyritsis, A. P., Tsagalis, G., Virvidaki, E., & Vemmos, K. N. (2009). Significance of aphasia after first-ever acute stroke: Impact on early and late outcomes. *Neuroepidemiology*, *33*(2), 96–102. https://doi.org/10.1159/000222091

Turner, R. S., Desmurget, M., Grethe, J., Crutcher, M. D., & Grafton, S. T. (2003). Motor Subcircuits Mediating the Control of Movement Extent and Speed. *Journal of Neurophysiology*, *90*(6), 3958–3966. https://doi.org/10.1152/jn.00323.2003

Ueno, T., Saito, S., Rogers, T. T., & Ralph, M. A. L. (2011). Lichtheim 2: Synthesizing aphasia and the neural basis of language in a neurocomputational model of the dual dorsal-ventral language pathways. *Neuron*, *72*(2), 385–396.

Vassal, F., Boutet, C., Lemaire, J.-J., & Nuti, C. (2014). New insights into the functional significance of the frontal aslant tract: An anatomo–functional study using intraoperative electrical stimulations combined with diffusion tensor imaging-based fiber tracking. *British Journal of Neurosurgery*, *28*(5), 685–687. https://doi.org/10.3109/02688697.2014.889810

Vicario, C. M., Candidi, M., & Aglioti, S. M. (2013). Cortico-spinal embodiment of newly acquired, action-related semantic associations. *Brain Stimulation*, *6*(6), 952–958. https://doi.org/10.1016/j.brs.2013.05.010

Vigliocco, G., Vinson, D. P., Druks, J., Barber, H., & Cappa, S. F. (2011). Nouns and verbs in the brain: A review of behavioural, electrophysiological, neuropsychological and imaging studies. *Neuroscience & Biobehavioral Reviews*, *35*(3), 407–426. https://doi.org/10.1016/j.neubiorev.2010.04.007

Wambaugh, J. L., Mauszycki, S., & Wright, S. (2014). Semantic feature analysis: Application to confrontation naming of actions in aphasia. *Aphasiology*, *28*(1), 1–24. https://doi.org/10.1080/02687038.2013.845739

Warren, T., Dickey, M. W., & Lei, C.-M. (2016). Structural prediction in aphasia: Evidence from either. *Journal of Neurolinguistics*, *39*, 38–48.

Warren, T., Dickey, M. W., & Liburd, T. L. (2017). A rational inference approach to group and individual-level sentence comprehension performance in aphasia. *Cortex*, *92*, 19–31. https://doi.org/10.1016/j.cortex.2017.02.015

Wasow, T. (1997). End-Weight from the Speaker’s Perspective. *Journal of Psycholinguistic Research*, *26*(3), 347–361. https://doi.org/10.1023/A:1025080709112

Watkins, K. E., & Jenkinson, N. (2016). Chapter 8—The Anatomy of the Basal Ganglia. In G. Hickok & S. L. Small (Eds.), *Neurobiology of Language* (pp. 85–94). Academic Press. https://doi.org/10.1016/B978-0-12-407794-2.00008-0

Welniarz, Q., Dusart, I., & Roze, E. (2017). The corticospinal tract: Evolution, development, and human disorders. *Developmental Neurobiology*, *77*(7), 810–829. https://doi.org/10.1002/dneu.22455

Wernicke, C. (1874). *Der aphasische Symptomenkomplex*. Springer Berlin Heidelberg.

WHO | World Health Organization. (n.d.). Retrieved December 7, 2017, from http://www.who.int/en/

Willits, J. A., Amato, M. S., & MacDonald, M. C. (2015). Language knowledge and event knowledge in language use. *Cognitive Psychology*, *78*, 1–27. https://doi.org/10.1016/j.cogpsych.2015.02.002

Wolter, B., & Gyllstad, H. (2011). Collocational Links in the L2 Mental Lexicon and the Influence of L1 Intralexical Knowledge. *Applied Linguistics*, *32*(4), 430–449. https://doi.org/10.1093/applin/amr011

Wolter, B., & Gyllstad, H. (2013). Frequency of input and l2 collocational processing: A Comparison of Congruent and Incongruent Collocations. *Studies in Second Language Acquisition*, *35*(3), 451–482. https://doi.org/10.1017/S0272263113000107

Wortman-Jutt, S., & Edwards, D. (2019). Poststroke Aphasia Rehabilitation: Why All Talk and No Action? *Neurorehabilitation and Neural Repair*, *33*(4), 235–244. https://doi.org/10.1177/1545968319834901

Wurm, M. F., & Caramazza, A. (2019). Distinct roles of temporal and frontoparietal cortex in representing actions across vision and language. *Nature Communications*, *10*(1), 289. https://doi.org/10.1038/s41467-018-08084-y

Yeh, F.-C., Badre, D., & Verstynen, T. (2016). Connectometry: A statistical approach harnessing the analytical potential of the local connectome. *Neuroimage*, *125*, 162–171.

Yeh, F.-C., Liu, L., Hitchens, T. K., & Wu, Y. L. (2017). Mapping immune cell infiltration using restricted diffusion MRI. *Magnetic Resonance in Medicine*, *77*(2), 603–612. https://doi.org/10.1002/mrm.26143

Yeh, F.-C., Panesar, S., Barrios, J., Fernandes, D., Abhinav, K., Meola, A., & Fernandez-Miranda, J. C. (2019). Automatic Removal of False Connections in Diffusion MRI Tractography Using Topology-Informed Pruning (TIP). *Neurotherapeutics: The Journal of the American Society for Experimental NeuroTherapeutics*, *16*(1), 52–58.

Yeh, F.-C., Tang, P.-F., & Tseng, W.-Y. I. (2013). Diffusion MRI connectometry automatically reveals affected fiber pathways in individuals with chronic stroke. *NeuroImage: Clinical*, *2*, 912–921. https://doi.org/10.1016/j.nicl.2013.06.014

Yeh, F.-C., & Tseng, W.-Y. I. (2011). NTU-90: A high angular resolution brain atlas constructed by q-space diffeomorphic reconstruction. *NeuroImage*, *58*(1), 91–99. https://doi.org/10.1016/j.neuroimage.2011.06.021

Yoon, E. Y., Humphreys, G. W., & Ridoch, M. J. (2005). Action naming with impaired semantics: Neuropsychological evidence contrasting naming and reading for objects and verbs. *Cognitive Neuropsychology*, *22*, 753–767.

Yoon, E. Y., Heinke, D., & Humphreys, G. W. (2002). Modelling direct perceptual constraints on action selection: The Naming and Action Model (NAM). *Visual Cognition*, *9*(4–5), 615–661. https://doi.org/10.1080/13506280143000601

Zhu, L. L., Lindenberg, R., Alexander, M. P., & Schlaug, G. (2010). Lesion load of the corticospinal tract predicts motor impairment in chronic stroke. *Stroke*, *41*(5), 910–915. https://doi.org/10.1161/STROKEAHA.109.577023

Zingeser, L. B., & Berndt, R. S. (1988). Grammatical class and context effects in a case of pure anomia: Implications for models of language production. *Cognitive Neuropsychology*, *5*(4), 473–516. https://doi.org/10.1080/02643298808253270

Zwaan, R. A., & Madden, C. J. (2005). Embodied sentence comprehension. In D. Pecher & R. A. Zwaan (Eds.), *Grounding cognition: The role of perception and action in memory, language, and thinking* (pp. 224–245). Cambridge University Press.

Zwaan, R. A. (2014). Embodiment and language comprehension: Reframing the discussion. *Trends in Cognitive Sciences*, *18*(5), 229–234. https://doi.org/10.1016/j.tics.2014.02.008

Zwaan, R. A. (2016). Situation models, mental simulations, and abstract concepts in discourse comprehension. *Psychonomic Bulletin & Review*, *23*(4), 1028–1034. https://doi.org/10.3758/s13423-015-0864-x