SPEECH-GESTURE INTEGRATION IN ADULTS WITH MODERATE-SEVERE TRAUMATIC BRAIN INJURY

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

Communication is multimodal. When people talk, they gesture, and these gestures often convey unique information that is not present in speech. For example, a speaker might say, “I searched for a new recipe,” while making a typing gesture, conveying only in gesture that the speaker searched online (rather than through a cookbook). When people listen, they receive information from multiple sources, including speech and gesture, generating an integrated representation of the message (Cassell et al., 1999; McNeill et al., 1994). Gesture facilitates communication and cognition: Gesture improves comprehension and memory for spoken information (Dargue et al., 2019; Hostetter, 2011), helps organize thinking for speaking (Hostetter et al., 2007; Kita, 2000; Kita et al., 2017), improves working memory by reducing cognitive load (Cook et al., 2012; Goldin-Meadow et al., 2001; Ping & Goldin-Meadow, 2010), and facilitates retention and transfer of new learning (Broaders et al., 2007; Cook et al., 2013; Cook et al., 2008; Goldin-Meadow et al., 2009). Although the benefits of gesture for communication and cognition are well-documented in neurotypical indviduals, these functions have been understudied in adults with neurogenic communication disorders. In particular, it is unclear if the benefits of gesture extend to clinical populations with cognitive-communication disorders or if the very nature of their deficits prevent gesture’s facilitatory role in communication and cognition.

Traumatic brain injury (TBI) is one example of a cognitive-communication disorder. TBI is very common, and the incidence is rising globally (Dewan et al., 2019; Roozenbeek et al., 2013). In the US alone, one person sustains a TBI every 21 seconds (Center for Disease Control and Prevention, 2015). Cognitive-communication deficits result from domain general cognitive deficits, rather than a primary language disorder. In moderate-severe TBI, these deficits are attributed to diffuse brain injury, reducing the integrity of white matter pathways and overall brain connectivity (Hayes et al., 2016). TBI is linked to poor communication, which is in turn associated with reduced social participation (Ownsworth & McKenna, 2004), difficulty maintaining employment (Meulenbroek & Turkstra, 2016) and friends (Shorland & Douglas, 2010), and reduced opportunities for positive social interactions (Ylvisaker & Feeney, 1998). Although we have seen a reduction in TBI-related deaths, we have seen no parallel reduction in TBI-related disability over the past 20 years despite considerable research (Roozenbeek et al., 2013). This limited progress necessitates critical evaluation of current practices for assessment and rehabilitation of cognitive-communication disorders. Critically, much of the current research on TBI has privileged evaluation of spoken communication, and when nonverbal communication cues are examined, they are typically studied in isolation from other verbal and nonverbal behaviors (e.g., facial affect recognition (Radice-Neumann et al., 2007; Rigon et al., 2016), eye gaze (Mutlu et al., 2019; Turkstra, 2005)). This provides an incomplete assessment of the abilities of people with TBI to process and integrate co-occuring cues in rich communication contexts. Indeed, theoretical accounts of cognitive-communication deficits in TBI posit that communication success requires integration of multiple skills in rich dynamic contexts (MacDonald, 2017), and communication deficits in TBI may reflect impaired perception and integration of verbal and nonverbal cues (Byom & Mutlu, 2013; McDonald et al., 2019). By studying speech and gesture together, the current research more closely approximates the real-world communication contexts that characterize and enrich everyday life and provides more ecologically valid assessments of complex communicative demands which may in turn inform new treatment targets to improve the communicative lives of people with TBI.

This thesis investigates the ability of adults with moderate-severe TBI to integrate co-occurring information from speech and gesture. It is composed of three chapters. All chapters are adapted from articles developed for publication. Chapter 1 is an interdisciplinary narrative review of the benefits of gesture for communication and cognition. I review the literature of the functions of gesture for both listeners and speakers and the role of gesture in learning and memory in neurotypical individuals. Then I describe the extent to which these functions have been understudied in populations of adult neurogenic communication disorders, including aphasia, right hemisphere damage, traumatic brain injury, and Alzheimer's disease. This review provides a theoretical and conceptual framework for the remaining chapters and serves as motivation for studying multimodal communication in acquired brain injury. One conclusion from the review is that gesture has been largely understudied in individuals with TBI. As a first effort to address this gap in the literature, I designed two studies with complementary methods to assess speech-gesture integration in TBI. In Chapter 2, I examined whether participants with TBI integrated information from a narrator's gesture into their narrative retellings and memory for stories over time. The narrator provided some information only in gesture, and I examined whether participants reported information from gesture in their speech retellings. In Chapter 3, I use eye-tracking in a visual world paradigm to examine the timecourse of participants' speech-gesture integration in real time. In this experiment, the speaker sometimes produced meaningful information in gesture before the target referent occurred in speech and I examined whether participants made anticipatory eye movements toward the pictured target item. Collectively, these studies increase our understanding of the communicative abilities of people with TBI in multimodal language contexts. Following Chapter 3, I provide a general discussion synthesizing findings across the two experiments and their implications for the study and treatment of cognitive-communication disorders.

CHAPTER 1

The Role of Gesture in Communication and Cognition: Implications for Understanding and Treating Neurogenic Communication Disorders

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When people talk, they move their hands. Spontaneous hand movements produced in rhythm with speech are called co-speech gestures and naturally accompany all spoken language. People from all known cultures and linguistic backgrounds gesture (Feyereisen & de Lannoy, 1991), and gesture is fundamental to communication. Indeed, babies gesture before they produce their first words (Bates, 1976). Congenitally blind speakers who have never seen gesture even gesture to blind listeners (Iverson & Goldin-Meadow, 1997, 1998). Our hands help us talk, think, and remember, sometimes revealing unique knowledge that cannot yet be verbalized (Goldin-Meadow et al., 1993). Everybody gestures, but despite its ubiquity, gesture is often seen as secondary to spoken language, receiving less attention in language research. Gesture is often reduced to a subcategory of non-verbal communication. However, non-verbal does not mean non-language, and theoretical approaches of gesture suggest that speech and gesture arise from the same representational system (McNeill, 1992). In this view, rich conceptual representations contain both imagistic and symbolic information that give rise to gesture and speech, respectively. Both these modalities have communicative functions and originate from the same communicative intention (de Ruiter, 2000).

Gesture serves a variety of functions and overlaps with speech in both time and meaning. However, gesture differs from speech in notable ways. Gesture conveys information holistically, spatially, and often simultaneously in a single event whereas speech is made up of discrete units that unfold incrementally and sequentially over time to create a cumulative meaning (McNeill, 1992). Throughout this review, we highlight findings that demonstrate that speech and gesture, though integrally related, each have their own unique advantages and affordances; for example, gesture is particularly well-suited for communicating visuo-spatial information which is often omitted from speech entirely. Thus, language research is strengthened by considering both speech and gesture together. The data demonstrate that when taken together, speech and gesture provide a rich communicative context that reflects the cognitive processes that underlie language production, manifesting thought into communication. The study of language has a long history; however, despite proposals that spoken language and gesture either co-evolved (Kendon, 2017) or even that language might have emerged from an earlier gestural communication system (Corballis, 2010, 2012), much of linguistic and psycholinguistic theory has privileged spoken language over multimodal communication. The formal study of gesture in communication is a more recent discipline, gaining traction with the seminal work of McNeill (1992) and since accumulating a robust literature, described below, that details the role of co-speech gesture in a variety of functions in healthy adults for both communication and cognition. However, following the course of linguistics and psycholinguistics, researchers studying language disorders have focused primarily on spoken language, and consequently, we know very little about gesture in these disorders.

Here we provide an interdisciplinary narrative review of the communicative benefits of gesture for both speakers and listeners and its interactions with cognition. Gesture does not only contribute essential information to a message but also actively facilitates the cognitive formation of messages and supports learning and memory. We provide an overview of co-speech gesture theory and describe behavioral evidence of the functions of gesture for communication and cognition across the lifespan. We then discuss the application of this research for studying patient populations with neurogenic communication disorders and identify several gaps for future research. While this review takes great interest in the neurologic representation of gesture in the brain, and specifically the insights that may be revealed by studying gesture in neurogenic communication disorders, studies using electrophysiological and neuroimaging methods are largely excluded and outside of the scope of this review. Rather, we focus on empirical behavioral studies that examine the benefits of gesture on communication, learning, and memory. Thus, this paper aims to highlight the status of gesture in its role for shaping language, cognition, and communication. In doing so, we raise awareness of the extent to which gesture has been understudied in people with neurogenic communication disorders. We review existing literature on the study of gesture in aphasia, for which language impairments are primary, as well as in populations where language impairments are secondary to cognitive deficits, including right hemisphere damage (RHD), traumatic brain injury (TBI), and Alzheimer's disease (AD). We explore ways in which applying the psychological literature of gesture to neurogenic communication disorders can help us better understand these disorders and leverage gesture for rehabilitation. Such work contributes to our understanding of the neural correlates of gesture to advance theories of co-speech gesture that are psychologically and biologically plausible.

1.1 Theoretical Underpinnings of Speech and Gesture

There has been much theoretical interest in describing the relationship between speech and gesture. These theories either posit that speech and gesture arise from a single conceptual system or that they represent two separate, but tightly integrated systems. One of the first and most influential accounts of gesture production is The Growth Point Theory (McNeill, 1992, 2005, 2013; McNeill & Duncan, 2000). To summarize, the growth point is the conceptual starting point of a sentence. It is the initial unit of thought that combines linguistic and imagistic information together to initiate the dynamic cognitive processes that organize thinking for speech and results in co-speech gesture. This theory proposes that speech and gesture originate from a single system where an utterance contains both a linguistic and visuo-spatial structure that cannot be separated. Both speech and gesture, therefore, reflect characteristics of the underlying idea, and one cannot be fully interpreted without considering the other. Speech and gesture are integrated not only at a speaker's thought conception, but also in perception; listeners integrate information from speech and gesture into a single mental representation. For example, after having watched a storyteller narrate a story, listeners report information from both the storyteller's speech and gesture in their later retelling (McNeill et al., 1994; Cassell et al., 1999).

Although the majority of speech models do not include gesture, many gesture models are based on Levelt's (1989) model of speech production where spoken language production occurs in three stages: (1) Representations from long-term memory and knowledge of the communicative context feed into a conceptualizer and forms a communicative intention. At this conceptual level, the speaker prepares what they want to communicate and generates a preverbal plan. (2) This information then is passed to a message formulator where the lexicon is accessed and grammatical, phonological, and phonetic components are encoded into a linguistic structure. (3) Finally, the message reaches the articulator level to produce the planned speech. The message is monitored and refined through feedback mechanisms at various levels. Although speech and gesture take very distinct forms of communication, the pathway that produces them may not be all that different. Both arise from a communicative thought, are shaped and planned, and then motorically executed.

The Sketch Model (de Ruiter, 2000) for gesture and speech production is an expansion of Levelt's classical speech production model and differs from McNeill's Growth Point Theory in that speech and gesture are described as integrated but separate systems. The Sketch Model proposes that gesture and speech follow parallel but separate routes of production, but each originating from one common communicative intention. The conceptualizer includes both a preverbal message for speech and spatiotemporal sketch for gesture that captures aspects of the idea's size, speed, and location. Thus, speech and gesture are planned together before linguistic formulation occurs. These conceptualizations then diverge, taking one of two routes: the speech formulator or the gesture planner, each of which then develops a motor program to produce overt movement via speech and gesture, respectively. This model would predict that impairments at the conceptual level or communicative intention may affect both speech and gesture production while impairments downstream may have differential effects on speech and gesture production, with either modality able to compensate for the other. This is important because it suggests that gesture may be preserved and therefore, retains its communicative and cognitive functions even in the presence of language or speech disorders. This model was recently revised and renamed the Asymmetric Redundancy Sketch Model with modified assumptions that speech is the dominant modality and iconic gestures are mostly redundant with speech content (de Ruiter, 2017; de Beer et al., 2019).

The Interface Model (Kita & Özyürek, 2003) is also an extension of Levelt's (1989) speech production model but proposes that in addition to generating a communicative intention and preverbal plan, the conceptualizer also selects modalities of expression. Speech and gesture then are generated from two separate systems: an action generator that activates action schemata for spatial and motor imagery and a message generator which formulates a verbal proposition. Critically, these two systems communicate bi-directionally during the conceptualization and formulation of utterances. Thus, gesture is shaped by how information is organized and packaged for speech production as well as the spatial and motoric properties of the referent. Additionally, the Gesture for Conceptualization Hypothesis (Kita et al., 2017) proposes that gesture's base in action schemata has functions beyond organizing utterances for speaking and also mediates cognitive processes, through the activation, manipulation, packaging, and exploring of spatio-motoric information, and thus, has self-oriented functions for both speaking and thinking.

Whether speech and gesture form a single or two tightly integrated systems, it is clear that they are tightly coupled in time (Morrel-Samuels & Krauss, 1992), meaning (McNeill, 1992), and function (Wagner et al., 2014) and are integral parts of the language system. A critical question, then, is how this meaning reaches our fingertips. One possibility arises from the embodied-cognition framework which proposes that all language is grounded in sensorimotor experiences (Zwaan & Madden, 2005; Glenberg & Gallese, 2012). In this view, the gestures we produce reflect sensorimotor experiences and arise from rich memory representations of the world around us. Convergent evidence from behavioral, neuroimaging, and lesion studies support this embodied framework, demonstrating that conceptual representations in the brain are flexible and distributed and dependent on prior perceptual and motor experiences (Kiefer & Pulvermüller, 2012). Motor representations in the brain interact with language; for example, reading action words related to the face, arm, or leg results in activation of the corresponding area of the motor cortex (Hauk et al., 2004), and transcortical magnetic stimulation to motor areas of the arm or leg can increase processing speeds for words like "pick" or "kick," respectively (Pulvermüller et al., 2005). This link between action and language has important implications for gesture which is motoric in nature and, like speech, stems from rich memory representations and experiences. The Gesture as Simulated Action framework (Hostetter & Alibali, 2008, 2010, 2019) proposes that gestures are automatically generated by the mental activations that occur when people think about motor actions and perceptual states and predicts that speakers gesture at higher rates when they activate visuospatial or motor simulations. Indeed, speakers gesture more when retelling a story after watching an animation compared to only having heard it (Hostetter & Skirving, 2011). This model also acknowledges that individual and situational differences in gesture production depend on the speaker's gesture threshold which can change based on the speaker's disposition to produce gesture in a particular context. Together, these theories provide compelling support for including gesture in any framework that describes the linguistic system. Next, we consider the broad functions of gesture for communication for both listener and speaker.

1.2 Gesture for Communication

Like the study of spoken language, which can be characterized by its parts (e.g., phonemes, morphemes), the study of gesture has also identified different subtypes of gesture (McNeill, 1992). Broadly, these can be classified as representative or non-representative gestures. Following McNeill's classification system, representative gestures include iconic gestures, which depict the shape, size, action, or position of an object (e.g., the trajectory of a baseball). They also include metaphoric gestures which give concrete form to abstract ideas (e.g., a grabbing motion when talking about gaining a run) and deictic gestures which are used to refer to the location of an object in space (e.g., pointing to home base while recapping a close play). Non-representative gestures are often called beat gestures which are brief, repetitive movements that occur in rhythm with speech but without substantive meaning, serving instead to stress or emphasize certain words (e.g., marking the word "runner" with a wrist flick). Representational gestures are symbolic and can only be interpreted within the context of speech, in contrast to other non-gesture hand movements such as emblems which are conventionalized signs (e.g., an umpire crossing and extending his arms to indicate the runner is "safe") or pantomimes which are imitations of motor actions and can replace speech entirely. Representational gestures are the focus of this paper for the meaningful role they play in spoken language.

1.2.1 Gesture for the Listener

Perhaps the most obvious communication benefits of gesture are those produced for the listener. While listeners receive much of a message in speech alone, gestures may be particularly communicative in difficult listening situations such as listening in noise (Drijvers & Özyürek, 2017), listening in a second language (Dahl & Ludvigsen, 2014), or listening with hearing loss (Obermeier et al., 2012). However, even in typical listening situations, gestures often communicate unique information that is not present in the speech signal. For example, a speaker might say, "The batter hit the ball," while gesturing a high arching trajectory, uniquely communicating the ball's path. In this case, the message cannot be fully understood without integrating speech and gesture. Listeners attend to this unique information in gesture and later report information from both speech and gesture in their retellings (e.g., reporting, "The batter hit a fly ball"). Healthy people integrate information from both speech and gesture into a single memory representation, even when they contain conflicting information (McNeill et al., 1994; Cassell et al., 1999; Smith & Kam, 2012). This is done without explicit awareness or attention to the gestures. In fact, interviewers can mislead eyewitnesses when they gesture during a seemingly open question (e.g., asking, "What was the man wearing?" while producing a hat gesture; Broaders & Goldin-Meadow, 2010).

However, not all gestures are created equal. Although, meta-analyses have found an overall moderate beneficial effect of gesture on listener comprehension (Hostetter, 2011; Dargue et al., 2019), some gestures were more beneficial than others. Gestures improved comprehension most when they were iconic and supplemented speech with unique information. Hostetter (2011) found that child listeners benefited more from gesture than adult listeners; however, a more recent meta-analysis by Dargue et al. (2019) found no significant difference in the benefits of gesture for comprehension between adult and child listeners, indicating that gesture robustly facilitates comprehension across the lifespan. Gesture seems to be particularly important for comprehension when listeners are learning language. Children understand complex syntactic structures (e.g., object-cleft-construction) better when the speaker gestures to help them track referents (Theakston et al., 2014), and children are sensitive to referential gestures, using them to disambiguate pronouns (Smith & Kam, 2015). Adult English-as-second-language learners also demonstrate improved comprehension of lecture material when given access to the teacher's facial and gesture cues compared to audio-only information (Sueyoshi & Hardison, 2005). Gestures in this study were more helpful for language learners of lower proficiency than high English proficiency speakers, highlighting an important function of gesture in scaffolding language access for both child and adult learners.

Furthermore, speakers design their spoken communication for the listener (Clark & Murphy, 1982), and there is evidence that they intend their gestures to be communicative as well (Goldin-Meadow & Alibali, 2013). Speakers gesture more when their listener can see them (Alibali et al., 2001; Mol et al., 2011), and when explicitly asked to communicate specific information to a listener, speakers frequently provide some of the required information only in gesture (Melinger & Levelt, 2004). Speakers are also sensitive to their listener's knowledge state and use both more words and gestures when their listener does not share common ground with them (Campisi & Özyürek, 2013; Galati & Brennan, 2013; Hoetjes et al., 2015; Hilliard & Cook, 2016) and produce more iconic gestures to child than adult listeners (Campisi & Özyürek, 2013). When they do share knowledge with a listener, their gestures are less complex and informative (Gerwing & Bavelas, 2004); smaller and less precise (Galati & Brennan, 2013; Hoetjes et al., 2015); and lower in the visual field (Hilliard & Cook, 2016). Thus, speakers design their gestures to illustrate information that is novel or important for the listener, emphasizing the communicative function of gesture.

1.2.2 Gesture for the Speaker

While it may seem intuitive that gesture has functions for the listener, gesture also has important benefits for the speaker. Although speakers gesture more when their listener can see them (Alibali et al., 2001; Mol et al., 2011), they also produce gestures when the listener cannot. For example, people gesture when talking on the phone (Wei, 2006), and blind speakers even gesture to blind listeners (Iverson & Goldin-Meadow, 1997, 1998). Here we explore the functions of gesture for the speaker.

One view proposes that in addition to communicating information to the listener, gesture plays an active role in speech production. The Lexical Retrieval Hypothesis (Krauss, 1998; Krauss et al., 2000) posits that cross-modal priming via gesture increases neural activation and makes words easier to access. Indeed, people gesture more when word retrieval is difficult such as when speaking spontaneously or recalling objects from memory (Chawla & Krauss, 1994; Krauss, 1998; Morsella & Krauss, 2004). The temporal nature of speech and gesture supports this idea as well in that the onset of gesture usually precedes the word with which it is associated (Morrel-Samuels & Krauss, 1992). Furthermore, when gesture is prohibited, people are more dysfluent, exhibiting increased pause time, more filler pauses, and slower speech rate (Graham & Heywood, 1975; Rauscher et al., 1996; Morsella & Krauss, 2004). Krauss et al. (2000) propose that the facilitative effect of gesture happens at the level of the phonological encoder of Levelt's speech model, where a word's phonological form is planned for articulation. This proposed mechanism for cross-modal priming is based on "tip-of-the-tongue" studies that have found that word retrieval difficulties are more often phonological rather than semantic in nature (e.g., Jones & Langford, 1987) and that participants experience word retrieval failures when gesture is restricted (Frick-Horbury & Guttentag, 1998; although see Beattie & Coughlan, 1999). Understanding the mechanism of this facilitative effect is critical to applying gesture theory to language interventions for people with neurogenic communication disorders, particularly aphasia for which word finding difficulties are hallmark, a point we will return to later. The Lexical Retrieval Hypothesis proposes that to facilitate word retrieval, gestures should be iconic, representing a generalized semantic feature of the target word (Krauss et al., 2000), for example, gesturing whiskers to retrieve the word "cat." However, it is unclear how producing gestures related to the conceptual features of a word might directly retrieve the phonological word form. The tip-of-the-tongue phenomenon occurs when a speaker is unable to access stored information in memory but has a "feeling of knowing" (Brown, 1991). During retrieval failure, the speaker often has access to incomplete information about the target word such as the first letter, number of syllables, stress pattern, or part of speech and may be able to identify other words that are phonologically or semantically similar (Brown, 1991). This represents the more abstract lexical representation stage in Levelt's speech model called the "lemma" which may be a more likely beneficiary of cross-modal priming, where semantic information encoded in gesture may boost specification of the lemma and result in spreading activation for retrieval of phonological form. In contrast to the Lexical Retrieval Hypothesis, other studies have found that speakers gesture more during fluent than disfluent speech and that when speech stops, so does gesture (Mayberry & Jaques, 2000; Graziano & Gullberg, 2018), suggesting that the function of gesture is not compensatory or supportive, but rather it co-produces language together with speech.

Differences between speech and gesture suggest that these modalities may not lend themselves equally well to communicating different kinds of ideas. Given its visual nature, gesture is particularly well-suited to convey spatial information. For example, describing the location of furniture in a room would require more complex descriptions in speech (e.g., “the chair is at a 45-degree angle to the right of couch and facing inward”) than simply demonstrating these relative positions with our hands. Indeed, people gesture more when communicating spatial imagery (Rauscher et al., 1996; Krauss, 1998; Alibali et al., 2001; Alibali, 2005) and describing how to complete motor tasks such as how to wrap a present (Feyereisen & Havard, 1999; Hostetter & Alibali, 2007). It can be difficult to describe such motor tasks at all without moving your hands. In these cases, information is often provided uniquely in the gesture modality and absent from speech. Thus, when communicating complex locations and movements, it is easier to show than tell.

There is also evidence to suggest that gesture facilitates the planning and organization of speech. The Information Packaging Hypothesis (Kita, 2000) proposes that gesture plays a role in language production by helping the speaker package visuospatial information into units that are compatible with speech. Indeed, people gesture more when linguistic and processing demands are challenging (Melinger & Kita, 2007; Kita & Davies, 2009). For example, when tasked to describe a complex array of dots, people gestured more when they had to organize the dots themselves in their descriptions compared to people whose dot arrays were “pre-packaged” with connected lines (Hostetter et al., 2007b). Direct evidence for this idea that gesture shapes speech production is demonstrated by manipulating gesture and examining its influence on speech (Kita et al., 2017). Mol and Kita (2012) had participants describe actions involving both manner (e.g., roll) and path (e.g., down) components. In one condition they asked participants to gesture manner and path simultaneously (e.g., making a downward spiraling motion) while in the other condition participants made a separate, sequential gestures for each component (e.g., a turning motion for “roll” and a downward motion for “down”). When participants simultaneously gestured path and manner, they were more likely to verbally produce the information in a single clause (e.g., “It rolled down the hill”) whereas when producing two separate gestures, participants were more likely to produce two clauses (e.g., “It rolled and went down the hill”). Therefore, gestures help to organize spatial information in a way that directly influences how ideas are translated into speech.

In summary, gesture is fundamental to communication, tightly integrated with speech in the formulation and perception of utterances, and often communicates unique information not present in the speech signal, especially about spatial and motoric properties of referents. Thus, speech and gesture each have their own advantages but work together to enrich the language context. Gestures have benefits for both listeners and speakers. Gesture facilitates comprehension, and listeners integrate information from both modalities in their mental representations. Gesture may also facilitate word retrieval and fluency for the speaker and is integrally involved in the process of producing spoken language by helping the speaker package thoughts into units that are compatible with the constraints of speech for a given language system. These same communicative functions of gesture that robustly enrich and facilitate communication in healthy individuals may also extend to people with neurogenic communication disorders as well. Next, we review the functions of gesture for cognition.

1.3 Gesture for Cognition

Unlike speech, the spontaneous gestures that speakers produce have no standardized form, but rather, are idiosyncratic. Because they are free to take a variety of forms, they uniquely reveal the speaker's thoughts in a way speech cannot. The form of our gestures reflects our knowledge and experiences, and increasingly, gesture has been shown to have self-oriented cognitive functions that extend benefits of gesture beyond speaking into cognition more broadly; the Gesture-for-Conceptualization Hypothesis (Kita et al., 2017) proposes that gesture facilitates conceptualization by activating, manipulating, packaging, and exploring spatio-motoric information. In other words, gesture helps thinking as well as speaking. Here, we explore some of the ways gesture interacts with cognition.

1.3.1 Gesture Reduces Cognitive Load

Given that speakers gesture more when a task is cognitively or linguistically complex (Melinger & Kita, 2007; Kita & Davies, 2009), it is critical to understand how gesture confers cognitive benefits. One theory is that producing co-speech gesture improves working memory by reducing the cognitive load (Goldin-Meadow et al., 2001). Direct evidence for this hypothesis comes from a dual-task paradigm in which participants are asked to memorize a series of items (such as a string of letters) and then are asked to explain something (e.g., how to solve a math problem) during which gesture is either allowed or prohibited. Afterward, they are tested on recall of the initially learned items. In this task, recall is better for both children and adults when they are allowed to gesture during the explanation phase, suggesting that producing gesture reduces the cognitive load during speaking so that speakers can devote more cognitive resources to rehearsal of the target stimuli (Goldin-Meadow et al., 2001; Wagner et al., 2004; Ping & Goldin-Meadow, 2010). This is especially true when the gestures participants produce are meaningful (Cook et al., 2012). An alternative explanation is that the act of inhibiting gesture production increases cognitive load and reduces performance. Indeed, evidence suggests that inhibiting gestures is more cognitively costly for people with low working memory capacity relative to those with high working memory capacity (Marstaller & Burianová, 2013), and individual differences in working memory abilities predict gesture rate in a story retell task, providing further evidence for a facilitative role of gesture on language production and recall when verbal working memory is taxed (Gillespie et al., 2014). These results highlight the potential benefit of gesture for freeing up cognitive resources, and importantly, suggest potential negative ramifications for restricting gesture use, particularly in special populations that may have reduced working memory or attentional capacities, which is an important consideration in neurogenic communication disorders.

1.3.2 Spontaneous Gestures Predict Readiness to Learn

Our hands not only reveal what we know but also what we are about to know. Gesture precedes language learning. Children produce their first gesture (typically deictic gestures) between 8 and 12 months prior to their first word at about 12 months (Bates, 1976). Furthermore, the gestures children produce predict which words will enter that child's vocabulary first (Iverson & Goldin-Meadow, 2005). Before creating multiple-word combinations, babies first combine words with gestures (e.g., pointing at a ball and saying "mine" to communicate "my ball"). Children who produce gesture-word combinations first also produce two-word combinations first (Iverson & Goldin-Meadow, 2005). These early gestures have distal effects on children's communication as well; gesture use at 14 months predicts vocabulary size at 42 months (Rowe et al., 2008) and 54 months of age (Rowe & Goldin-Meadow, 2009a), and babies who produce more gesture-speech combinations at 18 months of age produce more complex sentences when they are 3-years-old (Rowe & Goldin-Meadow, 2009b).

Gesture continues to predict cognitive development throughout childhood and serves as a cue for when the child is ready to learn (Goldin-Meadow et al., 1993). This insight comes from studying young children explaining Piagetian conservation tasks. When explaining these tasks, children gesture frequently. Sometimes, they produce similar explanations in both speech and gesture, but other times, they present an incorrect explanation in speech but convey partial knowledge in gesture (Goldin-Meadow, 2005; Goldin-Meadow & Alibali, 2013). When speech and gesture express different ideas, they are called gesture-speech mismatches. Those who produce these mismatches were more likely to benefit from instruction (Church & Goldin-Meadow, 1986). 3rd and 4th graders who produce gesture-speech mismatches when solving mathematical equivalence problems at pretest and learning phases also performed significantly better at post-test than children who did not (Goldin-Meadow & Singer, 2003). In these cases, children convey knowledge with their hands that they may not be able to fully articulate verbally. These gestures reflect transitional knowledge and may reveal that the child is on the cusp of grasping the concept (Perry et al., 1988; Pine et al., 2004). When encouraged to gesture while solving math problems, children produce an even wider range of strategies (Broaders et al., 2007). Similarly, when encouraged to gesture during the Alternative Uses Test, children produced more novel uses for target objects (Kirk & Lewis, 2017); gesture helped them conceptualize different features and uses for objects, some of which could then be verbalized. Thus, gesture use may facilitate creative problem solving and the exploration of ideas (Kita et al., 2017).

Importantly, gesture does not only predict learning in children. Adults produce gesture-speech mismatches during complex spatial and reasoning problems such as when explaining the Tower of Hanoi puzzle (Garber & Goldin-Meadow, 2002), gear movement (Perry and Elder, 1997), algebra (Alibali et al., 1999), and during moral reasoning (Church et al., 1995). Gestures also reveal transitional knowledge during learning of organic chemistry (Ping et al., 2019); when naive adults were asked to solve a set of stereoisomer problems and explain their solutions, all participants produced problem solving strategies in both speech and gesture. However, the researchers found that the participants' explanations predicted post-test performance only when they demonstrated gesture-speech mismatches in which the relevant strategy was conveyed in gesture. The authors conclude that gesture predicts learning because it reveals implicit knowledge and promotes change. Therefore, gesture depicts transitional knowledge and predicts future learning.

1.3.3 Gesture Facilitates Memory

Gesture not only depicts a readiness to learn but also makes learning last. Studies of classroom learning have revealed that children learn better (Valenzeno et al., 2003; Singer & Goldin-Meadow, 2005) and show better retention and transfer of new learning (Cook et al., 2013) when their teacher gestures. Furthermore, when teachers gesture a particular strategy during math instruction, children were more likely to produce that gesture themselves during the learning period (Cook & Goldin-Meadow, 2006), possibly mediating or enhancing the effect of teacher gesture on learning. Indeed, although viewing gestures improves learning, producing gestures has an even larger effect on comprehension and memory (Dargue et al., 2019); children learn and remember better when they produce gestures during learning compared to children who spoke only during a lesson (Broaders et al., 2007; Cook et al., 2008; Goldin-Meadow et al., 2009). Therefore, encouraging teachers to gesture improves both children's access to the information and changes the ways in which they engage and interact with the material themselves.

Gesture facilitates learning and memory in other ways, too. Producing meaningful gestures during foreign language learning (Macedonia & von Kriegstein, 2012; Macedonia, 2014; Sweller et al., 2020) and novel word-learning tasks (Krönke et al., 2013) improves subsequent retrieval. Gesture also seems to facilitate recall of mappings from linguistic representations; when explaining the meaning of metaphors, participants used more detail when allowed to gesture (Argyriou & Kita, 2013; Argyriou et al., 2017), suggesting that gesture helped participants retrieve literal and abstract meanings (Kita et al., 2017). In spatial learning for navigation, participants had better recall for a learned route when they gestured during study phase compared to both mental rehearsal and drawing (So et al., 2014). Furthermore, these same participants demonstrated better learning when they were allowed to gesture during their descriptions at recall. These studies highlight a role of gesture in both linguistic tasks such as word learning as well as non-linguistic tasks such as spatial learning. Thus, gesture leaves lasting traces that affect our representations for language and the world around us.

In sum, in addition to demonstrating benefits for communication, gesture has been shown to serve a variety of cognitive functions, reducing cognitive load to benefit working memory, facilitating the exploration of ideas through transitional knowledge, increasing access to lexical and mental representations, and leading to lasting benefits in learning and memory. Less is known, however, about the neural mechanisms of gesture or how the benefits of gesture for communication and cognition are instantiated in the brain. Likewise, the functions of gesture have been explored to a much more limited degree in individuals with neurologic disorders of language and communication, or neurogenic communication disorders. Yet, the study of gesture in such populations provides a key opportunity to establish, and test, neurobiological models of co-speech gesture. Next we review the existing literature on gesture in these populations.

1.4 Gesture in Neurogenic Communication Disorders

So far, we have reviewed evidence that gesture has robust functions for both communication and cognition. Our hands provide a modality for communicating unique kinds of information, benefiting both listeners and speakers, and they reflect and shape our knowledge and experiences. Despite a rich literature that highlights the benefits of gesture and theorizes a tightly integrated relationship with speech, gesture has received substantially less attention in our efforts to understand and treat neurogenic communication disorders. Here, neurogenic communication disorder is an umbrella term that refers to communication impairments with neurological origin including damage from relatively focal lesions from stroke or diffuse neuropathology from insult or degeneration. The four neurogenic communication disorders reviewed here are aphasia, RHD, TBI, and AD. Of these, aphasia is considered a primary language impairment, often due to focal damage to the canonical language network whereas RHD, TBI, and AD are considered cognitive-communication disorders, where communication deficits are secondary, resulting from primary cognitive deficits (e.g., memory, attention, executive function). Differences among these disordered populations provide key context for testing theories of the relationship between speech and gesture and examining gesture's role in communication and cognition.

1.4.1 Aphasia

Aphasia most often occurs after left hemisphere stroke and is defined as a selective and primary language impairment that can result in word-finding deficits (i.e., anomia), impaired grammatical formulation (i.e., agrammatism), and fluency disruptions. Aphasia can affect both expressive and receptive language, and several aphasia subtypes and classification systems exist. However, while there is large variability in aphasia presentation, aphasia has been defined as a disorder of the linguistic system, leaving other forms of cognition intact (although see Martin & Reilly, 2012; Murray, 2012; Fonseca et al., 2017 for examples where cognitive impairments have been identified). Furthermore, people with aphasia (PwA) generally have intact communication, meaning that they know what they want to say, and their intents are pragmatically appropriate. In this case, when people with aphasia are unable to communicate verbally, they continue attempts, often through other modalities, including writing, drawing, and gesture. These forms of communication are encouraged in therapeutic approaches prioritizing functional communication.

Gesture research in aphasia has largely examined gesture in three ways: characterizing gesture use, inhibiting gesture use to rehabilitate spoken language, and encouraging gesture use to facilitate functional communication. As reviewed above, healthy adults produce rich spontaneous gestures that take a variety of forms and communicate unique information that supplements the speech signal. These gestures depict spatio-motoric properties that are not easily expressed in language. Gesture is a ubiquitous and natural part of communication, and it is worth exploring how gesture is affected by language disorders and whether it can support, or hinder, recovery.

1.4.1.1 Characterizing Gesture Production

Early studies have primarily characterized gesture production of PwA to see whether language deficits extended to a similar disruption in the manual modality (see Rose, 2006, for a historical review). These studies confirmed that PwA do indeed gesture (e.g., Herrmann et al., 1988; McNeill, 1992; Goodwin, 2000). However, their gestures seem to differ from those of non-brain-damaged individuals. While people with aphasia produce a lower rate of gestures per minute than healthy comparison participants (Cicone et al., 1979; McNeill, 1992), likely due to also producing fewer words per minute, they produce a higher rate of gestures per word (Feyereisen, 1983; Carlomagno & Cristilli, 2006; Sekine et al., 2013; de Beer et al., 2019) and a larger variety of gesture types than healthy participants (Sekine & Rose, 2013). Gesture production also seems to vary by type of aphasia and on the dimension of fluency; Cicone et al. (1979) found that gesture form parallels verbal output where people with non-fluent aphasia produced fewer but clear and informative gestures, and people with fluent aphasia produced frequent but vague gestures. In contrast, other studies have found that people with non-fluent aphasia gesture at higher rates than those with fluent aphasia (Kong et al., 2017). In a story retell task, people with non-fluent Broca's aphasia produced almost twice as many gestures per 100 words as people with fluent Wernicke's aphasia, and they also differed by gesture type; people with Broca's aphasia were more likely to produce meaningful gestures such as iconic gestures whereas those with Wernicke's aphasia produced more beat and metaphoric, or abstract, gestures (Sekine et al., 2013). However, while people with Broca's aphasia seem to produce more iconic gestures per word, those with Wernicke's aphasia produce more iconic gestures per unit of time (Carlomagno & Cristilli, 2006). Critically, brain lesions resulting in aphasia also frequently produce contralateral hemiparesis or limb apraxia, restricting limb use and thus potentially impacting gesture (see Rose, 2006, for a review of the impact of limb apraxia on gesture production). However, studies comparing people with aphasia with and without hemiparesis have found no difference in the number of gestures per word produced (Kong et al., 2015) or the comprehensibility of the gestures produced (Hogrefe et al., 2012, 2017).

One explanation for the increased gesture use by PwA is that it is used to replace speech, serving a compensatory function when verbal communication fails, which accords with theoretical models of speech and gesture that posit highly integrated prelinguistic origins of speech and gesture (for a discussion, see de Ruiter & de Beer, 2013). Behrmann and Penn (1984) found that the functions of gesture production also differed by fluency; people with non-fluent aphasia primarily used gesture to substitute verbal communication while those with fluent aphasia used it to support verbal communication. In conversational speech, 20% of the gestures made by PwA were considered essential (i.e., conveyed information not present in speech) compared to a minimal number of essential gestures produced by healthy comparison participants (van Nispen et al., 2017). Furthermore, Dipper et al. (2015) examined the narrative retellings of PwA and comparison participants describing key motion events from a cartoon depicting the actions "swing" and "roll." PwA were more likely than healthy comparisons to produce gesture-speech mismatches with a semantically light verb in speech (e.g., "go" for "swing") and a semantically richer verb in gesture (e.g., gesturing an arc-shaped trajectory), carrying more weight in the gesture modality. Thus, the use of gestures by PwA has a clear communicative function. In fact, listeners more accurately interpret PwAs' message when provided both speech and gesture video compared to an audio only signal (De Beer et al., 2017; Rose et al., 2017), suggesting that PwA rely more on gestures to communicate their message relative to healthy adults.

Another explanation for increased gesture use is that, consistent with the Lexical Retrieval Hypothesis (Krauss, 1998; Krauss et al., 2000), PwA gesture to resolve anomia. Analyzing the frequency of gesture production, Cocks et al. (2013) found that although PwA produced more iconic gestures than control participants, the frequency of iconic gesture did not differ between the two groups when gestures produced during word retrieval difficulties were removed. In conversational samples, PwA produced significantly more gestures during word retrieval difficulty (69%) compared to fluent speech production (31%), and 93.8% of the gestures PwA produced during word retrieval were meaningful (e.g., iconic, pantomime, emblems; Lanyon & Rose, 2009). Although there is evidence that PwA are more successful at word retrieval when producing iconic gestures compared to other gesture types or no gesture (Akhavan et al., 2018), Lanyon and Rose (2009) found that not all PwA benefited from gesture during lexical retrieval, but those who did had phonological impairments (Lanyon & Rose, 2009). Another alternative explanation for the increased gesture use by PwA is that it serves a pragmatic function to signal to the listener that they are still searching to maintain their conversational turn (Beattie & Coughlan, 1999). Indeed, PwA produced more interactive gestures (i.e., gestures that coordinate dialogue such as flipping a hand to "pass" the turn to your interlocutor; Bavelas et al., 1992) than comparison participants both during spontaneous conversation and narrative retellings (de Beer et al., 2019).

1.4.1.2 Constraining Gesture

While some aphasia interventions encourage functional communication, others take a strict impairment-based approach in which they discourage forms of communication that may be compensatory in order to rehabilitate the target deficit (i.e., speech). One notable example of this is Constraint-Induced Aphasia Therapy (CIAT; Pulvermüller et al., 2001). In CIAT, communication is constrained to the spoken modality in an attempt to maximize spoken language recovery. CIAT aims to promote cortical reorganization (Taub et al., 2014) and is based on studies of limb rehabilitation in monkeys which found that constraining use of an unaffected limb forces use of a deafferented limb and improves mobility (Taub, 1976, 1980). Without intervention, the subjects developed "learned non-use" of the affected arm. This treatment was successfully extended to humans with impaired motor damage and limb use after neurological damage (Taub et al., 1993; Wolf et al., 2006, 2008) and termed Constraint-Induced Movement Therapy (CIMT). CIMT consists of four key components including (1) an intensive training schedule, (2) training behaviors through shaping, (3) a transfer package designed to generalize results beyond the research setting, and (4) discouraging compensatory behaviors (Taub et al., 2014). In theoretical extensions of this approach to aphasia, "learned non-use" results from compensatory or avoidance behaviors that include non-speech communication such as gestures and non-verbal sounds or the PwA remaining silent or allowing a caregiver to speak for them (Pulvermüller et al., 2001; Johnson et al., 2014).

Under the first constraint-induced aphasia protocol, people with chronic aphasia received 3 h of therapy every weekday for 2 weeks in a group-based language card game that resembles "Go Fish" and constrains communication to the verbal modality through the use of a barrier separating communication partners, the difficulty of stimuli used, explicit game rules provided by the therapist, and reinforcement of adherence to constraint rules (Pulvermüller et al., 2001). This protocol was subsequently modified to include a larger variety of expressive language exercises (e.g., repetition drills, picture description, role playing), increased intensity for verbal targets, and inclusion of a "transfer package" (Johnson et al., 2014), termed CIAT II. In a pilot of this most recent version of the intervention with four participants with moderate Broca's aphasia, gesture was strongly discouraged, and therapists and caregivers were instructed not to respond to them. Overall, the participants reported improvement in their amount of verbal activity pre-to post-treatment and achieved large effect sizes for improvement in WAB-R aphasia quotients but without statistical significance for the small sample (Johnson et al., 2014).

Many versions of CIAT have been tested by different research groups with an overall positive impact on expressive communication (see Rose, 2013, for a summary of outcomes of constraint-induced language interventions); however, it is unclear whether the active ingredients of its success are related to gesture suppression or other factors such as the high intensity of treatment, group participation, caregiver training, and transfer package. Indeed, these studies are highly variable in the extent to which they constrain gesture and often not well described (Pierce et al., 2017). Some studies prohibited gesture use (Pulvermüller et al., 2001) and even strictly enforced spoken language by asking patients to sit on their hands if necessary (Maher et al., 2006; Kirmess & Maher, 2010; Martin et al., 2014). Others allowed gesture use as long as it was used to facilitate verbal language output (i.e., for self-cueing; Meinzer et al., 2007a,b; Difrancesco et al., 2012; Wilssens et al., 2015; Ciccone et al., 2016; Nickels & Osborne, 2016). In this view, PwA may use gesture to complement but not replace speech.

Thus, the use of gesture constraint has been interpreted and implemented very differently across CIAT studies, and it is important to consider its implications. While use of a barrier in the language game does not prevent the speaker from using gestures, it may implicitly decrease the amount of gestures they produce as people gesture less when their listener cannot see them (Alibali et al., 2001; Mol et al., 2011), and it prevents any gestures they do produce from being communicative to the listener. While it is a goal of CIAT for all communicative intentions to be completed verbally, this ignores the robust gesture literature on healthy adults that shows that gesture often naturally supplements speech, with people expressing unique information only in gesture, especially when talking about motor or spatial relations (Rauscher et al., 1996; Krauss, 1998; Feyereisen & Havard, 1999; Alibali et al., 2001; Hostetter & Alibali, 2007; Hostetter et al., 2007b). These gestures communicate to the listener but also may benefit the speaker in their organization, packaging, and conceptualization of information (Kita, 2000; Kita et al., 2017), beyond the self-cueing function described above. Furthermore, the act of consciously inhibiting gesture use may increase the cognitive load, especially for those with lower working memory capacity (Marstaller & Burianová, 2013; Gillespie et al., 2014) with implications for PwA for whom working memory deficits are common (Martin & Reilly, 2012).

Theoretical perspectives that propose that speech and gesture are tightly integrated processes predict that speech production might actually be hindered by gesture suppression. Indeed, in healthy adults, restricting gesture use has direct negative consequences on speech production; prohibiting gesture leads to impoverished speech content, resulting in less semantically rich descriptions of motor tasks (Hostetter et al., 2007a), decreased imagery (Rimé et al., 1984), fewer descriptions of perceptual-motor information (Alibali & Kita, 2010), and reduced speech fluency (Graham and Heywood, 1975; Rauscher et al., 1996; Morsella & Krauss, 2004). Conversely, explicitly encouraging gesture in healthy people improves recall (Goldin-Meadow et al., 2009), visuo-spatial problem solving (Chu & Kita, 2011) and perspective-taking in moral reasoning (Beaudoin-Ryan and Goldin-Meadow, 2014), highlighting the facilitative role of gesture production on various aspects of memory and reasoning. Importantly, two CIAT participants expressed frustration at being constrained to the verbal modality only (Maher et al., 2006), and the way gesture is treated in patient and caregiver training, a critical component of the intervention, may have long-term effects on how gesture is used with that communication partner. For example, training caregivers not to respond to communication attempts via gesture (e.g., Johnson et al., 2014) may result in increased communication breakdowns and frustration if gesture is taught as a mal-adaptive strategy. When gesture is allowed as a self-cueing mechanism for word retrieval, PwA may receive some benefit from spontaneous gesture; however, at best, this approach attenuates the potential of gesture for cognitive and communicative functions and at worst, may actually deny PwA access to the benefits of gesture in communication which may be critical ingredients of their language recovery. More research is needed to explore whether gesture can actually be leveraged to support language recovery in aphasia. The idea that gesture contributes to verbal “learned non-use” in aphasia is not empirically founded. Furthermore, constraining gesture has no theoretical support in current models of gesture production which propose that gesture and language represent an integrated (McNeill, 1992) or tightly coordinated system with both spoken language (de Ruiter, 2000; Kita, 2000) and cognition (Kita et al., 2017).

1.4.1.3 Encouraging Gesture

In contrast, other aphasia interventions encourage gesture use with the aim of either compensating for or restoring verbal communication (Rose, 2006). Recognition of aphasia as a disorder across modalities of communication (Hallowell & Chapey, 2001) has led to interventions incorporating the use of multiple modalities to facilitate recovery in which strengths in one modality may be leveraged to improve communication in another (Pierce et al., 2019). Indeed, many established aphasia intervention techniques take advantage of multiple modalities of communication including melodic intonation therapy (MIT; Sparks et al., 1974), Supported Conversation for Adults with Aphasia (SCA; Kagan et al., 2001), Promoting Aphasic Communicative Effectiveness (PACE; Davis, 2005), and Multiple-Modality Aphasia Treatment (M-MAT; Rose et al., 2013a). In addition to speech, these interventions may use drawing, music, symbol boards, and importantly, gesture. However, other treatments containing word-based cuing beyond speech (e.g., orthography) are also common and are not considered a multi-modality treatment by this definition (Pierce et al., 2019). Mutli-modality treatment approaches are thought to cue word retrieval and stimulate language and often take one of two aims: (a) improving speech or (b) improving total communication in which successful communication through any modality is encouraged (for a review, see Pierce et al., 2019). This latter approach trains functional communication tools that reduce communication breakdowns when word retrieval fails.

M-MAT and CIAT take different theoretical approaches to the potential interference or facilitation of gesture and other non-verbal modalities (see Rose, 2013 for a comparison of features of constraint vs. multi-modality interventions). However, functionally these two interventions share many common features that may help drive response to treatment (Pierce et al., 2017). Both interventions use group-based language games, are highly intensive, and rely on shaping to approximate desired communicative behaviors. However in M-MAT, there are no visual barriers, participants are given paper and pencil, and therapists provide cues and shaping for both verbal and multi-modal responses (Rose et al., 2019). M-MAT involves a cueing hierarchy where when naming pictures, participants make a verbal attempt first and if incorrect, the participant is next cued to produce an iconic gesture and re-attempt naming. Subsequent steps of the hierarchy involve clinician modeling of gesture, drawing, orthographic cues, and verbal repetitions (Rose et al., 2013a).

Direct comparisons of these interventions in a two-participant single-case design pilot study found a marginal advantage of M-MAT for the primary outcome measure of confrontation naming (Attard et al., 2013), but comparable effect sizes were found for both treatments in a group study of 11 PwA (Rose et al., 2013a). A systematic review of multi-modal and constraint-induced intervention approaches found limited empirical support for the superiority of either, although a meta-analysis of single-case experimental design studies favored multi-modal treatments (Pierce et al., 2017). The authors called for a more rigorous, direct comparison of these two approaches with explicitly described protocol for use of constraints or the types of multi-modality cueing used. This work is currently being undertaken by Rose and colleagues in a randomized controlled trial of constraint-induced or multi-modal personalized aphasia rehabilitation (COMPARE Trial; 2019). Currently, there is not enough evidence to support the use of gesture constraint, and its use should be cautioned against until more empirical evidence can evaluate any potential negative effects suppressing gesture may have on spoken language recovery in aphasia.

Likewise, more work is needed to explore the facilitatory effect that gesture may have in aphasia and the extent to which it corresponds to the functions of gesture observed in healthy adults. One obvious application is to study the effect of gesture on lexical retrieval in PwA. Murteira et al. (2019) report a lexical or semantic priming effect of observing congruent gestures on improved action picture naming in people without language impairments relative to observing an unrelated gesture or neutral stimulus prior to naming trials. In extending this study to PwA, this group found significant group differences for a facilitatory effect of observing congruent gestures for action verb naming for both naming accuracy and naming latencies (Murteira & Nickels, 2020). However, group results were more robust for naming latencies, and the effect of gesture varied considerably by individual. Studies looking at a role of gesture production for lexical retrieval of verb forms have had mixed results. A systematic review of gesture treatments for aphasia (Rose et al., 2013b) found that training gestures with verbal targets does improve word retrieval for trained stimuli. However, when comparing the effects of gesture + verbal treatment to verbal-only treatment on naming, some studies showed no advantage of gesture (Rodriguez et al., 2006; Rose & Sussmilch, 2008; Boo & Rose, 2011), but these studies had small samples of 2–4 participants. In contrast, Rose and Douglas (2001) did find a benefit for a subgroup of PwA: PwA had significantly improved picture naming when instructed to make a related iconic gesture but only if they had a primary phonological impairment as opposed to semantic or phonetic impairment. Similarly, in a study of 18 PwA, five produced more gestures during resolved word retrieval difficulties than unresolved, all of whom had phonological level impairments (Lanyon & Rose, 2009). These findings suggest that the facilitatory effect of gesture on lexical retrieval may depend on the individual PwA's profile of relative strengths and deficits, and further work is needed to identify the participant and word-level factors that predict responsiveness to gesture in naming tasks in this heterogeneous patient population.

The large majority of gesture studies in aphasia have focused on using gesture to facilitate word retrieval but have left unexplored the many other communicative and cognitive functions of gesture. To our knowledge, at the time of this writing, no experimental studies in aphasia have examined how encouraging or constraining gesture affects the fluency of verbal output or whether listener perceptions of fluency are influenced by gesture use. Other open questions pertain to whether gesture facilitates planning or working memory capacity in the face of increased linguistic or processing demands, and whether gesture can be leveraged to improve learning and memory in aphasia which could lead to better retention for functional treatment stimuli. Importantly, in healthy people, producing gesture during learning not only improves recall of learned material but also leads to improved transfer of learning (Cook et al., 2013), the ultimate goal of successful language treatment. A single study examined the effect of producing gesture on word learning and memory in aphasia; 14 people with chronic mild aphasia learned novel labels for 30 manipulable objects by either gesturing and repeating target words or just repeating the words over 4 days (Kroenke et al., 2013). Recall was better for words that were encoded with gesture but only for people with phonological and working memory impairments. In fact, those with semantic impairments actually performed worse when producing gesture. These results accord with previous findings (Lanyon & Rose, 2009) that suggest that the benefits and function of gesture may depend on the individual's aphasia profile, where those with phonological impairments rather than semantic impairments may have greater potential to benefit from gestural intervention. Indeed, intact semantic knowledge may be required to produce iconic gestures (Hadar & Butterwork, 1997; Cocks et al., 2013). These studies have important implications for the Lexical Retrieval Hypothesis (Krauss et al., 2000) which posits that gesture facilitates word retrieval through cross-modal priming at the phonological encoding stage. It may be more likely that iconic gesture operates on the cognitive processes involved in word retrieval by strengthening associations between preserved semantic representations. This is similar to the mechanism that underlies semantic approaches to language therapy such as semantic feature analysis (Efstratiadou et al., 2018) where words are retrieved via spreading activation of semantic associations, activating the lemma stage and, subsequently, the corresponding phonological representation (Maher & Raymer, 2004). Iconic gestures contain semantic features of their referents and reflect the distributed and experience-dependent conceptual representations in the brain (Kiefer & Pulvermüller, 2012). Thus, it may be this interaction between gesture and semantic memory that facilitates lexical retrieval. More work is needed to specify this mechanism to better predict treatment response and improve specificity of aphasia intervention. Future work should focus on exploring the cognitive and communicative functions of gesture in larger group studies of PwA to better identify individual and linguistic factors that may modulate the benefits of gesture.

1.4.2 Cognitive-Communication Disorders

Cognitive-communication disorders are those for which domain general deficits in cognition such as attention, memory, problem solving, information processing, or executive function result in communication deficits. Given both the cognitive and communicative functions of gesture, it seems natural to study gesture in the context of cognitive-communication disorders and consider the ways in which gesture might uniquely reveal communication deficits or be leveraged to facilitate communication outcomes of people with brain injury and neurodegenerative diseases. However, cognitive-communication research has focused primarily on spoken language. It is an open question whether people with cognitive-communication disorders use gesture and benefit from gesture in the same way that healthy people do. Here we provide a brief overview of the deficits associated with RHD, TBI, and AD before reviewing the literature on gesture across these disorders.

1.4.2.1 Right Hemisphere Damage

Right hemisphere damage, often acquired after stroke, frequently results in a cognitive-communication disorder affecting pragmatics and discourse including a reduced ability to produce or comprehend emotional prosody, flat or monotone speech production, impaired comprehension of abstract or non-literal language, and impaired turn taking, topic maintenance, or eye contact (Blake, 2007, 2018; Blake et al., 2013). It is estimated that 50–68% of people with RHD exhibit at least one communication deficit (Blake et al., 2002; Côte et al., 2007). Critically, people with RHD also commonly experience visuospatial neglect (Kaplan & Hier, 1982; Bowen et al., 2013), which could impair their perception and production of gesture use.

1.4.2.2 Traumatic Brain Injury

Traumatic brain injury results from an external force that causes damage to the brain. In addition to anoxia, hemorrhages, edema, and seizures, the hallmark injury in TBI is diffuse axonal injury which decreases the integrity of white matter pathways, affecting the brain's overall connectivity (Hayes et al., 2016). This diffuse neural injury results in heterogenous patterns of cognitive impairment across individuals with TBI. However, injury is common in the frontal and temporal lobes, producing deficits in executive functioning, processing speed, social cognition, and memory (Stuss, 2011). People with both mild (Leh et al., 2017) and moderate-severe TBI (Rigon et al., 2019, 2020) frequently demonstrate memory deficits. People with TBI also often have poor social outcomes (Wehman et al., 1993; Engberg & Teasdale, 2004; Kelly et al., 2008) which create barriers to community reintegration. Thus, assessment and treatment of cognitive-communication deficits is critical. Researchers have focused discourse analyses on documenting language impairments in coherence, cohesion, turn-taking, topic maintenance, and appropriateness (Bond and Godfrey, 1997; Coelho et al., 2002; Hough & Barrow, 2003; Davis & Coelho, 2004) and pragmatic skills (McDonald, 1993; McDonald and van Sommers, 1993; Turkstra et al., 1996; Bara et al., 2001). In addition to difficulties using and understanding language appropriately, people with TBI can also demonstrate impaired social cognition such as theory of mind and perspective taking deficits (Martín-Rodríguez & León-Carrión, 2010) and difficulty understanding irony (Martin & McDonald, 2005), sarcasm (Channon et al., 2005), and emotional affect (McDonald & Flanagan, 2004). Thus, people with TBI commonly have difficulty using non-verbal and extralinguistic cues to understand their communication partner's needs and intentions. While some aspects of non-verbal communication including eye gaze (Turkstra, 2005) and facial affect recognition (Radice-Neumann et al., 2007; Rigon et al., 2017, 2018; Byom et al., 2019) have received independent attention, gesture has been relatively understudied.

1.4.2.3 Alzheimer's Disease

Alzheimer's disease is a neurogenerative disease characterized by gradually declining abilities in learning and memory and more observable impairments in connected speech and language as the disease progresses (Mueller et al., 2018). Although neuropathology is distributed throughout the brain in AD, the earliest and most severe pathology occurs in the medial temporal lobe, including the hippocampus (Hyman et al., 1990; Braak & Braak, 1991). This hippocampal atrophy has been linked to decreased memory performance in AD (Deweer et al., 1995; Laakso et al., 1995; Small et al., 1999; Kramer et al., 2004). Furthermore, hippocampal pathology in TBI has been linked to increased risk for later developing AD (Fleminger et al., 2003; Li et al., 2017). Given that memory deficits are hallmark to both TBI and AD, these populations provide a unique test of the reach of gesture in facilitating learning and memory. However, the diffuse nature of injury in these populations also make it difficult to isolate the effects of memory deficits alone.

Relative to aphasia, there has been significantly less research on gesture across these cognitive-communication disorders. The research that does exist has focused largely on characterizing gesture production in each population relative to healthy, non-injured comparison participants. In the next sections, we will review how researchers have examined gesture across cognitive-communication disorders by characterizing gesture production as well as work examining its functions in social communication and memory.

1.4.2.4 Characterizing Gesture Production

Given the prevalence of pragmatic deficits in RHD affecting paralinguistic (e.g., prosody) and non-verbal aspects of communication (e.g., eye contact), there has been some interest in whether RHD affects gesture production. Indeed, early case studies report a loss of emotional gesturing with two patients presenting with an "agestural state" (Ross & Mesulam, 1979). Further, there is evidence that people with RHD produce fewer iconic gestures overall than both healthy adults and people with aphasia (Hadar et al., 1998; Hogrefe et al., 2016) and that they produce fewer gestures in discourse samples with high emotional content compared to healthy adults (Cocks et al., 2007). Other studies have found an increase in self-touching movements such as grooming and scratching in RHD (Blonder et al., 1995; Cocks et al., 2007). One study found no difference in overall gesture production frequency between people with RHD and healthy adults in narrative discourse; however, significant positive correlations between the amount of gestures people with RHD produce and overall narrative competence suggest that gesture production may facilitate performance through domain general processes of attention and working memory (Akbıyık et al., 2018), lending support to the idea that gesture facilitates speaking and thinking by lightening the cognitive load (Goldin-Meadow et al., 2001).

Initial attempts to characterize gesture production in people with TBI have grouped gesture together with other aspects of non-verbal communication. These have mostly used rating scales to describe gesture as a subset of pragmatic communication. Aubert et al. (2004) used the Prutting and Kirchner: Pragmatic Aspects of Language (Prutting & Kirchner, 1987) qualitative scale to measure paralinguistic and non-verbal aspects of communication and found that facial expression, gaze functioning, and referential gesture were often impaired, especially in conversational discourse. Rousseaux et al. (2010) used a quantitative rating scale to measure aspects of non-verbal language and found that people with TBI in the rehabilitation stage (2–12 months post injury), but not the chronic stage (after 2 years), were globally impaired on non-verbal communication as well as understanding gestures (specifically relating to object shapes), but neither TBI group had deficits in producing gestures. Sainson et al. (2014) also used a rating scale to quantify gesture production in spontaneous conversation. They found that people with TBI were impaired in their frequency of gesture use relative to controls. Their gesture production was rated on a six-point scale from 0 (no impairment) to 5 (very severe impairment), however, this scale did not specify the direction of disruption (i.e., over-or under-production of gestures). In a case study examining gesture use and classifying gesture type in a single patient with multiple severe TBIs, the participant produced much fewer overall gestures and lower gesture rates than two healthy comparison participants, using only two iconic gestures in conversation (Sainson, 2007). These studies provide a cursory characterization of gesture production in TBI but lack a more quantitative approach and provide little insight into the types and communicative functions of gesture in this very heterogeneous population.

Considering gesture's proposed role in lexical retrieval (Krauss et al., 2000), Kim et al. (2015) investigated the use of gesture by people with TBI who, though typically without aphasia, often demonstrate anomia (King et al., 2006; Hough, 2008). They analyzed the type and frequency of gestures that people with TBI produced during a confrontation naming task and found that people with TBI produced three times more co-speech gestures and hand movements than healthy comparison participants. Importantly, these hand movements included non-gesture movements that were unrelated to speech such as tapping, touching, and scratching. A significant negative correlation was also found where those with poorer performance on the word retrieval test produced more gestures and hand movements. This study provides an initial exploration of the association between gesture production and word retrieval in TBI but does not provide evidence for whether hand gesture has a facilitative function in resolving anomia.

There is a sparse literature exploring functions of gesture in pediatric TBI. Landry et al. (2004) found that infants (age 3–23 months) with history of severe TBI demonstrated reduced initiation of social interactions during play as well as reduced responsiveness to interactions initiated by the examiner compared to comparison participants; however, both groups were similar on indices of gestural and verbal communication. In contrast, Ewing-Cobbs et al. (2012) found that for children who had sustained a TBI before age 7, those children with moderate-severe TBI gestured more than those with mild TBI, possibly reflecting a developmental lag. Although much more work is needed to characterize gesture in pediatric TBI, there is additional support for a role of gesture for predicting and supporting language development from studies of children with pre-or perinatal unilateral brain lesions. The gesture use of children with these brain lesions at 18 months predicted later language development; those whose gesture use was in the typically developing range at 18 months developed vocabularies that did not differ from their typically developing peers whereas those whose gestures were below the typical developing range showed expressive and receptive vocabulary delay (Sauer et al., 2010). Thus, gesture could serve as in important diagnostic and therapeutic consideration for children at risk for communication disorders (Capone & McGregor, 2004). Furthermore, similar to healthy children (Rowe and Goldin-Meadow, 2009b), gesture-speech mismatches of children with these brain lesions later predicted simple (but not complex) sentence construction in speech (Özçaliskan et al., 2013). An additional study of children with perinatal unilateral brain lesions in kindergarten found that they benefited from seeing gesture, producing better structured narratives when retelling stories told by a narrator who used co-speech gestures compared to having seen and heard a story without gesture (Demir et al., 2014). These findings highlight an important role of gesture for scaffolding language and memory and evoking linguistic change for children with brain injuries.

Studies characterizing spontaneous gesture production in AD are also limited. An initial study found that the gestures of people with AD are more ambiguous and less complex with fewer semantic features, paralleling the use of empty speech in this population (Glosser et al., 1998). Similarly, Carlomagno et al. (2005) found that although people with AD produced a similar gesture rate to healthy comparison participants, they produced fewer iconic gestures. In contrast, Schiaratura et al. (2015) found that while people with AD had decreased quantity and quality of speech, their gestures were relatively unaffected.

In sum, the bulk of the work on gesture in cognitive-communication disorders has focused on characterizing gesture production in term of quantity and form and across different types of discourse elicitation tasks. While these disorders all have in common deficits in communication and cognition, there is variability as to the specific profiles across disorders and even within individuals who share the same diagnostic label. To better understand the shared and unique patterns of gesture production in individuals with neurogenic communication disorders we need considerably more gesture research and with larger samples sizes to account for known variability across and within disorders. Furthermore, use of experimental designs and protocols to examine gesture's role in thinking, speaking, and remembering from the broader gesture literature in psychology and psycholinguistics would facilitate connection across literatures which is needed to advance understanding of the neural correlates of gesture in communication and cognition.

1.4.2.5 Gesture and Social Communication

Disruptions in social communication are common to all neurogenic communication disorders, but these impairments have perhaps been most studied and well-documented in TBI. Successful communication involves the integration and interpretation of both verbal and non-verbal signals. Healthy people automatically integrate information from a speaker's speech and gesture (McNeill et al., 1994; Cassell et al., 1999) and use information from gesture to improve pragmatic understanding (Kelly et al., 1999). However, while gesture is an integral and often essential part of the communicative message, only a couple studies have examined the perception of gesture by people with TBI. Bara et al. (2001) examined whether people with TBI could use gestures to interpret communication acts of varying levels of complexity. Participants watched short silent movies in which the actors communicated only through gesture. Participants then chose a photograph representing the appropriate conclusion from a field of four. People with TBI were as successful as controls at using gesture to interpret simple and complex standard communication acts. However, people with TBI were significantly worse at interpreting gestures communicating deceit or irony. Evans and Hux (2011) examined whether people with TBI could integrate information from gesture with speech to accurately interpret indirect requests. Participants made predictions and interpretations after watching videos in which indirect requests were given verbally, with gesture-only, or with both speech and gesture together. Both people with TBI and healthy comparison participants interpreted indirect requests with greater accuracy when provided verbal and gesture information together than in either condition alone. However, people with TBI performed significantly worse than comparison participants on all conditions. These results indicate that people with TBI may be able to leverage gesture to reduce the deficit in their social communication performance and improve everyday communication, but more work is needed to understand this relationship. Furthermore, while people with TBI can successfully integrate verbal and non-verbal cues in a laboratory setting (Mutlu et al., 2019), little is known about how people with TBI rapidly integrate multiple cues, such as speech and gesture, for social interaction and decision-making in rich complex environments.

Studies examining listener perception of the gestures of people with TBI suggest that producing gesture may also facilitate social communication in this population. When judges rated a speaker with TBI on measures of pragmatic and communicative competence, "gesture appropriateness" was positively correlated with message effectiveness and ease of understanding, and hand/arm movements positively correlated with overall competence (Cannizzaro et al., 2011). Similarly, Jones and Turkstra (2011) found that when speakers with TBI narrated their accident stories, listeners perceived them as more charismatic when they gestured and indicated an increased likelihood of wanting to engage with them in a future conversation. These studies highlight gesture as a potential contributor to social communication outcomes in TBI. Given that neurogenic communication disorders more broadly disrupt social communication, research examining gesture's role in social communication outcomes in RHD and AD is also warranted.

1.4.2.6 Gesture and Memory

Examining a link between gesture and memory in cognitive-communication disorders is important for several reasons: gesture plays a special role in promoting memory and learning; deficits in memory and learning are common across cognitive-communication disorders, and the success of all behavioral therapeutic interventions depends critically on memory and learning. Memory is not a unitary function but rather provides an account of our experiences and knowledge and includes the processes that support our encoding, consolidation, and retrieval of information with both temporary and long-term storage capacities. Memory is often divided into functionally and biologically distinct systems (Cohen & Squire, 1980; Eichenbaum & Cohen, 2001; Henke, 2010). Two primary systems that support long-term memory are the declarative and procedural memory systems. The declarative memory system, mediated by the hippocampus, supports acquisition of facts and world knowledge (semantic memory), and episodic events (episodic memory). In contrast, procedural memory, an aspect of non-declarative memory mediated by the basal ganglia, supports the acquisition of rules, habits, and skills. Both declarative and non-declarative memory interact closely with language acquisition (Ullman et al., 1997) and use (Brown-Schmidt & Duff, 2016; Duff & Brown-Schmidt, 2017). While not traditionally considered a cognitive-communication disorder, the study of a rare population of people with acquired bilateral hippocampal damage and amnesia who have severe declarative memory impairment but intact non-declarative memory has provided unique insights into understanding how memory systems support language use. The hippocampal declarative memory system supports relational binding and representational flexibility (Cohen & Eichenbaum, 1993) and has been found to underlie a variety of aspects of language use and processing (Duff & Brown-Schmidt, 2012, 2017). Only recently, there is a growing body of work characterizing the role of hippocampal declarative memory in gesture production. Hippocampal pathology is common to both AD (Hyman et al., 1984) and TBI (Bigler et al., 1996). Unlike AD, hippocampal pathology and memory deficits in amnesia are not progressive, but the results of these studies have important implications for cognitive-communication disorders resulting from memory deficits.

To test the role of the declarative memory system in gesture production, Hilverman et al. (2016) looked at spontaneous gesture production in a narrative task by people with focal, non-progressive, bilateral hippocampal damage and severe amnesia. They found that even though people with amnesia and healthy adults produced a similar amount of words in procedural and autobiographical narratives, people with amnesia had reduced gesture rates, producing significantly fewer gestures per word than their demographically healthy comparison participants. Critically, hippocampal amnesia does not produce motoric deficits that would interfere with the physical ability to produce gesture. However, while impoverished memory representations may not always affect the amount of speech produced, it does often impact its content: People with amnesia produce fewer episodic details relating to perceptual, temporal, and spatial information (Kurczek et al., 2015), and the words they produce are less imageable and concrete when producing narratives than healthy adults (Hilverman et al., 2017). These findings suggest that the declarative memory system contributes to rich and imageable information conveyed in both speech and gesture and that when impaired, in any population, may result in impoverished speech and gesture.

While these findings suggest that declarative memory impairments lead to impoverished gesture production, other studies demonstrate that the spontaneous gestures people with amnesia produce are communicative and uniquely reveal information about their knowledge and experiences. For example, when healthy people share knowledge (i.e., common ground) with a communication partner, they attenuate both their speech and gesture use in parallel, producing both fewer words and gestures (Campisi & Özyürek, 2013; Galati & Brennan, 2013; Hoetjes et al., 2015; Hilliard & Cook, 2016; but see Jacobs & Garnham, 2007; Holler & Wilkin, 2009 for two exceptions). There is evidence that multiple memory systems support the acquisition and use of common ground (Brown-Schmidt & Duff, 2016). When designing communication for a child compared to an adult listener, people with amnesia adapt more in gesture than speech relative to healthy adults; healthy adults increased both the number of words and gestures they produced when demonstrating how to do everyday tasks to a child (e.g., how to change a lightbulb) whereas people with amnesia increased their gesture use for the child above and beyond the changes they made in the number of words produced (Clough et al., 2022). People with amnesia also reflect shared knowledge in gesture but somewhat inconsistently in speech; in a collaborative referential barrier game in which the participant accrues incremental common ground with a partner through multiple rounds of a matching game, people with amnesia arrived at concise shared spoken labels with the partners (Duff et al., 2006); however, they did not consistently use definite references like the healthy adults (Duff et al., 2011). In gesture, people with amnesia signaled common ground by producing fewer visible gestures above the barrier over the course of the game as shared knowledge and familiarity increased (Hilverman et al., 2019). This parallels research in healthy adults that shows that when speakers share common ground with a listener, their produce gestures that are lower in the visual field (Hilliard & Cook, 2016). Thus, despite greatly reduced explicit recall for episodic information, the gestures of people with declarative memory impairments can reflect their knowledge and experiences.

These studies provide important evidence that speech and gesture can dissociate and, under certain conditions, may be differentially supported by distinct memory systems. Although people with amnesia produce fewer gestures during narrative discourse, indicating that gestures stem from declarative memory representations, their gestures uniquely communicate information about their knowledge states and experiences, even for information they may be unable to verbalize and declare. This supports the idea that gesture reflects implicit knowledge (Broaders et al., 2007), and therefore, may engage the non-declarative memory system in some contexts. Indeed, the gestures of people with Parkinson's disease, which affects the basal ganglia system supporting non-declarative, or procedural memory, do not reflect their prior experiences performing a motor task (Klooster et al., 2015). Gestures themselves may also be considered implicit in that both speakers and listeners rarely consciously attend to them, and yet, both healthy adults and people with amnesia integrate information from co-speech gesture into their narrative retellings of a story, suggesting that gesture-speech integration does not depend on the hippocampal declarative memory system (Hilverman et al., 2018a). Furthermore, gesture often reflects implicit transitional knowledge states by communicating information that is not yet verbally accessible (Goldin-Meadow et al., 1993). If non-declarative memory supports gesture, then it is possible that gesture can be leveraged to improve recall in people with declarative memory impairments. To test this idea, participants with amnesia completed a novel word-learning task (a task they are profoundly impaired on) by learning word-object associations while producing gesture, observing gesture, or without gesture; although the participants were unable to freely recall the labels when tested, they demonstrated above chance recognition memory for labels but only when they produced gesture during learning (Hilverman et al., 2018b). This research in individuals with hippocampal amnesia offers exciting new insights into the relationship between memory and gesture, however, as of yet, it has largely unexplored implications for people with cognitive-communication disorders.

1.5 Discussion

Gesture provides a unique window into a speaker's mind and provides a direct link between cognition and communication. However, despite a robust literature on the functions of gesture for thinking, speaking, and remembering in healthy adults, gesture has been relatively underexplored in populations with neurogenic communication disorders. Here we assert that gesture is not just an accessory to the language system, but rather an integral partner in communication. A broader approach to the study of language provides insights into these rich communicative contexts. Here, language is a dynamic process that is locally constructed between communication partners and leverages multiple modalities of information, including gesture. Minimally, we have reviewed literature showing that gesture has essential communicative functions above and beyond speech, and therefore, researchers studying neurogenic communication disorders should work to also characterize the consequences of these disorders on the gestural modality. Indeed, as a field, we know much less about gesture than spoken language in these disorders as well as knowing less about gesture than even other non-verbal aspects of communication such as eye-gaze or facial affect recognition. Much of the research that exists on gesture in these populations has focused on characterizing spontaneous gesture production but often from an atheoretical perspective. Studying gesture in populations with impairments in language and cognition provides a unique opportunity to test hypotheses generated by various theoretical accounts in the gesture literature in healthy adults which suggests that gesture provides cognitive and linguistic benefits. Indeed, despite well-documented deficits in memory and social communication after cognitive-communication disorders, researchers have not explored whether patterns of brain injury or cognitive deficit predict gesture use or if gestures can improve memory and communicative function in these individuals.

Of all the functions of gesture described here, perhaps the most exciting is the potential benefit of gesture on learning and memory and the implications that this might have for clinical practice. The success of all behavioral therapy depends on the ability of the patient to learn and remember the targeted skills. Yet, rather than incorporating gesture into our interventions, some therapy protocols have inhibited it. This seems counterproductive in light of the potent role of gesture in learning and memory. Rather than discouraging gesture production, it may be more useful to consider the synergistic nature of speech and gesture and explore ways to leverage gesture to achieve various intervention goals across disciplines. To date, the bulk of the theoretical and empirical work on co-speech gesture has been from a cognitive or psychological perspective rather than a neural correlates perspective. Thus, while we know a lot about the cognitive and communicative benefits of gesture, we know less about the neural mechanisms that support them. Applying the psychological literature of gesture to neurogenic communication disorders not only has the potential to improve treatment, but also provides an opportunity to generate and advance theories of co-speech gesture that are psychologically and biologically plausible.

While this review identifies several gaps in the neurogenic communication disorder literature, it highlights an exciting opportunity to consider neurogenic communication disorders from a new perspective. Our hands shape and actively alter our own learning and display traces of that learning in conversation, reflecting our prior experiences and depicting knowledge even for things the speaker may not be explicitly aware of or cannot yet communicate in speech. In addition to supporting learning and memory, gesture facilitates the exploration of ideas especially when it comes to visuo-spatial problem solving and complex reasoning. Yet, we know little about how gesture interacts with cognition in clinical populations, and this is critical to fully understand language, cognition, and communication, and its disorders. Thus, gesture deserves more of our attention in the study of neurogenic communication disorders. Future research should systematically assess the impact of cognitive and communication disorders on gesture production in larger group studies as well as empirically testing the functions of gesture for language use and social cognition. Such research would shed light on the untapped potential of gesture in understanding and rehabilitating neurogenic communication disorders.

1.5.1 Thesis Aims

Although gesture warrants more attention across all populations with adult neurogenic communication disorders, one clear gap in the literature is characterizing the multimodal communication abilities of people with TBI. TBI frequently impairs social communication and cognition, but little attention has been given to how these deficits might manifest in multimodal language processing and use, giving us an incomplete understanding of their communicative abilities. As a first exploration in this space, this thesis examines whether adults with moderate-severe TBI can integrate information from co-occurring speech and gesture, across two experiments. If adults with TBI demonstrate disruptions in speech-gesture integration, these findings could provide new insights into the mechanisms the underlie their social communication deficits in rich real-world communication contexts. On the other hand, if adults with TBI show intact speech-gesture integration, it would suggests that they may have access to the communicative and cognitive benefits of gesture, opening up new avenues for treatment and rehabilitation in which gesture might be leveraged to support learning and memory. Chapter 2 presents the first of these two experiments. In the following chapter, I examine whether adults with TBI can integrate information from a speaker's gestures into their mental representation and memory for stories.

CHAPTER 2

Intact Speech-Gesture Integration in Narrative Recall by Adults with Moderate-Severe Traumatic Brain Injury

This manuscript is under review at *Neuropsychologia* (Clough, Padilla, Brown-Schmidt, & Duff, submitted).

2.1 Introduction

Language is multimodal, containing both speech and gesture. Gesture plays an important role in language comprehension, contributing to the listener's understanding and memory of a message. To achieve this benefit, listeners must bind linguistic information from speech and visuospatial information from gesture to generate an integrated representation of a message. Studying speech-gesture integration in clinical populations can reveal unique insights into how this process might be disrupted and the cognitive and neural resources that support it. In the current study, we examined speech-gesture integration in narrative retellings of adults with and without moderate-severe traumatic brain injury (TBI). We examined whether information presented uniquely in the gesture modality is reported in participants' retellings of stories and if it persists over time across delays. We aimed to better understand the impact of brain injury on comprehension in everyday multimodal communication contexts, as well as the potential benefit of gesture for supporting communication and memory after TBI.

Although there are many kinds of gestures, iconic gestures have a well-documented role in language comprehension. Iconic gestures are representative, visually depicting attributes of a referent such as its size, shape, position, or movement (McNeill, 1992) and have been shown to have an overall moderate beneficial effect on language comprehension (Dargue et al., 2019; Hostetter, 2011). Although these spontaneous movements of the hands and arms are semantically and temporally linked to the information in speech, they offer unique affordances and contributions to communication. For example, the onset of gesture often proceeds its semantic affiliates in speech (Fritz et al., 2021; Morrel-Samuels & Krauss, 1992), and gestures commonly convey meaning that is not present in the speech signal, especially when communicating visuospatial information and actions (Alibali, 2005; Feyereisen & Havard, 1999; Hostetter & Alibali, 2019; Melinger & Levelt, 2004). Speech-gesture integration has been described as an implicit cognitive process that combines semantically related audiovisual information into a single representation (Green et al., 2009). Although multimodal language processing often occurs without overt attention to the speaker's gestures (Gullberg & Holmqvist, 2006; Gullberg & Kita, 2009), the automaticity of speech-gesture integration may be moderated by a variety of factors (Kandana Arachchige et al., 2021). In a recent review, Kandana Arachchige and colleagues summarized several methodological factors that influence speech-gesture integration, including the method of investigation (e.g., behavioral, electrophysiology, functional magnetic resonance imaging, eye-tracking), the relationship of speech and gesture (redundant, complementary, incongruent), the stimuli content (e.g., single words, sentences, narration), the task demands on the participant (e.g., passive observation, attentional task, dual task paradigm, decision or judgement task), and more. We briefly summarize the evidence for speech-gesture integration across methodological approaches below.

Behavioral approaches to studying speech-gesture integration have used story retelling and reaction time tasks in which the gestures communicate information that is additional or contradictory to the information in speech. For example, a speaker might say, “He searched for a new recipe,” while making a *typing* gesture, conveying only in gesture the manner of searching (i.e., online as opposed to a physical cookbook). These are often referred to as *complementary* gestures. To examine the impact of complementary gestures on comprehension, studies have looked for evidence of the gestures in participants’ retelling of narratives (e.g., reporting, “He searched for a new recipe *online*”). Indeed, when participants watched videos of a narrator telling a story with complementary gestures, their retellings often reflected the gestures they saw (Cassell et al., 1999; McNeill et al., 1994). In this case, not only did participants attend to information in gesture, but also, information encoded through gesture crossed modalities at recollection, reappearing in their speech. Another method used to study speech-gesture integration has been to examine the effect of incongruent gestures on language comprehension. These mismatching gestures are contradictory to the information provided in speech (e.g., pairing “I searched for a new recipe online” with a *page-turning* gesture). When listeners view incongruent gestures in stories, they report more inaccuracies in their retellings (Cassell et al., 1999; McNeill et al., 1994). In another study, participants were asked to identify whether information presented in speech or gesture was related to action primes viewed earlier; they were faster and more accurate when speech and gesture were congruent compared to incongruent, and reaction time was moderated by the degree of the incongruency (Kelly et al., 2010). Gestures can also serve a pragmatic function, facilitating the comprehension of indirect requests beyond speech alone (Kelly et al., 1999). Thus, bimodal information from speech and gesture interacts during language comprehension to form an integrated representation of a message. In the first study of speech-gesture integration in TBI, we build on this prior work to examine the influence of complementary gestures on their narrative retellings.

Neuroimaging approaches to studying speech-gesture integration have used electroencephalography and functional magnetic resonance imaging to identify the timecourse and neural correlates of multimodal language comprehension (For a review, see Kandana Arachchige et al., 2021 and Özyürek, 2014). Event-related potentials display a negative deflection consistent with the N400 effect indicative of semantic processing when the listener views gestures that are semantically incongruent with the linguistic context (Holle & Gunter, 2007; Kelly et al., 2004; Kutas & Hillyard, 1980; Özyürek et al., 2007). Manipulating the timing of speech-gesture synchrony disrupts the N400 effect, suggesting that speech-gesture integration is most efficient when speech and gesture onsets are closely linked in time (Habets et al., 2011). Obermeier and colleagues (2011) proposed that while temporally synchronous speech and gesture are integrated automatically, more active memory processes are required to combine temporally asynchronous speech and gesture. However, speech-gesture asynchrony may not impede semantic integration when the proceeding linguistic context constrains the gesture's meaning (Fritz et al., 2021). Patterns of fMRI activation also indicate that speech-gesture integration shares neural resources with semantic processing of speech. Studies have consistently identified patterns of activation recruiting the left-lateralized frontal-posterior temporal network, including the left inferior frontal gyrus, middle temporal gyrus, posterior superior temporal sulcus, and motor cortex (Dick et al., 2009; Green et al., 2009; Holle et al., 2008; Straube et al., 2012; Willems et al., 2007, 2009).

These studies increase our understanding of how and where in the brain semantic processing of speech and gesture occurs. However, less is known about individual differences in speech-gesture integration or whether this process is disrupted in populations with cognitive and neural differences. Toward this aim, an increased number of studies have begun to examine speech-gesture integration in clinical populations. For example, studies have highlighted impaired speech-gesture integration abilities in children with specific language impairment (Botting et al., 2010; Wray et al., 2016) and autism (Perrault et al., 2019; Silverman et al., 2010). Studying adults with acquired neurogenic communication disorders also offers a unique opportunity to understand the neural and cognitive mechanisms of speech-gesture integration; however, to date, investigation into the speech-gesture integration abilities of these populations is limited (See Clough & Duff, 2020 for a review). Within acquired neurogenic communication disorders, the bulk of attention has been on people with aphasia. Eye-tracking studies have shown that people with aphasia were more likely to fixate on gestures than healthy comparison participants (Eggenberger et al., 2016; Preisig et al., 2018) and received a boost in comprehension when speech and gesture were congruent compared to the baseline and incongruent conditions (Eggenberger et al., 2016). In contrast, Cocks and colleagues (Cocks et al., 2009, 2018) found that people with aphasia were less able to integrate speech and gestures than healthy comparison participants, showing reduced accuracy identifying a corresponding picture cue for the target sentence when presented speech and gesture together than in either modality alone. The authors propose that disrupted speech-gesture integration in aphasia is most likely due to difficulties with attention allocation or reduced cognitive resources (Cocks et al., 2018). This suggests that when cognitive resources are limited or cognitive demands are high, individuals may weight audiovisual signals differently. More work is needed to identify whether neuroanatomical profile (i.e., lesion location, size), aphasia-type syndrome, or cognitive-linguistic abilities moderate a benefit of gesture comprehension in aphasia.

Other populations of adults with neurogenic communication disorders have received much less attention and less is known about whether the cognitive and communicative benefits of gesture extend to adults with cognitive-communication disorders, such as traumatic brain injury, dementia, and right hemisphere brain damage (Clough & Duff, 2020). These populations not only provide a unique opportunity to identify the cognitive resources that support speech-gesture integration, but also may yield insights into the therapeutic utility of gesture to support comprehension, learning, and memory in rehabilitation. For example, our group has examined the relationship between gesture and declarative memory in a rare group of patients with hippocampal amnesia and found that they successfully integrate information from complementary gestures into their immediate retellings of stories at higher likelihoods than non-brain injured and brain-damage control participants with focal injury to the ventromedial prefrontal cortex (Hilverman, Clough, et al., 2018). Gesture has also been shown to improve word learning performance in individuals with hippocampal amnesia (Hilverman, Cook, et al., 2018) and facilitate memory encoding in amnestic mild cognitive impairment (Sgard et al., 2020). Although these studies point to a benefit of gesture, even in populations with profound memory impairment, the enduring nature of those benefits is unknown. In fact, very little is known about the duration of those benefits more broadly in typical populations. Thus, studying the relationship between gesture and memory in clinical populations, over time, has the potential to advance both basic science and clinical translation.

Although converging evidence from behavioral, electrophysiological, fMRI, and clinical methods support an interaction between speech and gesture in language comprehension, more work is needed to understand when and for whom gesture benefits, the long-term effects of gesture on learning and memory, and the cognitive and neural mechanisms that support speech-gesture integration. One population that has the potential to yield novel insights into these processes is TBI. To our knowledge, only a couple of studies have examined gesture comprehension in adults with TBI. Bara and colleagues (2001) asked people with TBI to watch silent movies containing only gestures and found that they were as successful as non-injured adults at interpreting simple and complex standard communication acts (e.g., gesturing for someone to take a seat) but significantly worse at interpreting gestures communicating deceit or irony (e.g., a child pointing blame to another child after breaking a vase). Evans and Hux (2011) provide evidence that people with TBI can benefit from gesture to improve comprehension of indirect requests (e.g., pointing to their partner's sandwich while saying, "I'm still pretty hungry"). Despite having overall reduced accuracy interpreting indirect requests, participants with TBI interpreted indirect requests with greater accuracy when provided both speech and gesture combined compared to either modality alone. These two studies provide mixed evidence as to whether people with TBI might be able to leverage gesture to improve comprehension of non-literal language (e.g., irony, sarcasm, indirect messages), for which they have well-documented deficits (Channon et al., 2005; Martin & McDonald, 2005). Further, although the above studies focused mostly on the use of deictic or pointing gestures and at a single timepoint, it is unknown how people with TBI integrate iconic gestures with co-occurring speech context over time.

We hypothesized that disruptions in the ability to process and integrate multimodal signals may underlie social communication deficits in individuals with TBI. Diffuse axonal injury is a frequent result of rapid acceleration, deceleration, and rotational injuries that occur during TBI, leading to overall reduced brain connectivity (Hayes et al., 2016) which may disrupt white matter pathways supporting multimodal processing and integration (McDonald et al., 2019). Indeed, communication requires integration of perceptual, emotional, and situational cues with shared world knowledge in rich dynamic contexts (MacDonald, 2017). Studying communication in such rich dynamic contexts is critical for advancing assessment and treatment of language deficits in TBI. We propose that studying speech alongside gesture in more naturalistic paradigms can enhance our understanding of communication abilities after TBI. The current study examined whether people with TBI successfully integrate unique information conveyed through complementary gestures in their narrative retellings of short stories and whether information from gesture persists in memory after short and long delays. We predicted that individuals with TBI will be less likely to report information from gesture in their narrative retellings than non-brain injured peers.

2.2 Materials and Methods

2.2.1 Participants

Participants were 60 adults with chronic moderate-severe TBI (30 male, 30 female), at least six months post injury (M time since injury = 74.62 months, SD = 74.23) and 60 non-injured comparison (NC) participants (30 male, 30 female). TBI and NC participants were matched pairwise on sex, age (MTBI = 40.13 years, SDTBI = 10.60 years; MNC = 39.95 years, SDNC = 10.39), and education (MTBI = 14.93 years, SDTBI = 2.51 years; MNC = 14.97 years, SDNC = 2.43). All participants were recruited from the Vanderbilt Brain Injury Patient Registry (Duff et al., 2022). All participants with TBI sustained their injuries in adulthood and met inclusion criteria for moderate-severe TBI using the Mayo Classification System (Malec et al., 2007) verified through medical records and intake interviews. Participants were classified as moderate-severe if at least one of the following criteria were met: (1) Glasgow Coma Scale (GCS) <13 within 24 hours of acute care admission, (2) positive neuroimaging findings (acute CT findings or lesions visible on a chronic MRI), (3) loss of consciousness (LOC) >30 minutes, or (4) post-traumatic amnesia PTA >24 hours. Table 2.1 shows demographic and injury details for participants with TBI.

Table 2.1: Demographic and injury information for participants with TBI

ID	Age	Edu	Etiology	TSO	LOC	Neuroimaging	GCS	PTA
5002	41-45	16	Non-motorized vehicle accident	250	LOC >30 minutes	ICH	3	>24 hours
5003	26-30	18	Ped vs. auto	46	N/A	SDH	11	>24 hours
5014	51-55	16	MVA	207	LOC >30 minutes	N/A	N/A	>24 hours
5016	18-25	16	MVA	39	LOC >30 minutes	SAH	13	>24 hours
5017	31-35	16	Ped vs. auto	191	LOC >30 minutes	SAH; IVH	4	>24 hours
5021	41-45	18	MVA	52	LOC >30 minutes	EDH; SAH	3	>24 hours
5027	31-35	16	Ground-level fall	35	LOC >30 minutes	SAH	9	>24 hours
5029	31-35	14	Non-motorized vehicle accident	34	LOC <30 minutes	SDH: IPH; SAH	14	<24 hours
5034	36-40	16	MVA	61	LOC >30 minutes	SAH	3	>24 hours
5038	41-45	16	Ground-level fall	41	LOC >30 minutes	SDH; multifocal hemorrhages; post-traumatic hemorrhagic contusions	N/A	>24 hours
5041	31-35	16	MVA	76	No LOC	No acute intracranial findings	10	>24 hours
5046	46-50	18	Non-motorized vehicle accident	68	LOC <30 minutes	SAH	14	>24 hours
5047	26-30	16	Assault	40	LOC <30 minutes	SDH	15	<24 hours
5048	46-50	16	MVA	366	LOC >30 minutes	N/A	N/A	>24 hours
5050	31-35	18	Ground-level fall	36	LOC >30 minutes	SAH; IPH	15	<24 hours
5051	51-55	16	MVA	21	LOC <30 minutes	SAH; SDH	14	<24 hours
5058	36-40	12	MCC	135	LOC <30 minutes	SAH; SDH; PCH	8	>24 hours
5062	18-25	12	MVA	85	LOC <30 minutes	SDH	15	<24 hours
5068	26-30	16	Fall from height	55	LOC <30 minutes	ICH	3	>24 hours
5070	46-50	16	Fall from height	69	LOC <30 minutes	SAH; hemorrhagic contusions	15	>24 hours
5071	26-30	12	MVA	59	LOC >30 minutes	SDH	3	>24 hours
5073	31-35	14	Non-motorized vehicle accident	127	LOC >30 minutes	EDH	14	>24 hours
5079	36-40	18	MVA	102	LOC >30 minutes	PCH; SAH	5	>24 hours
5082	46-50	12	Assault	89	LOC >30 minutes	SDH; SAH; bifrontal contusions	14	<24 hours
5091	46-50	12	MVA	34	LOC >30 minutes	SDH; SAH; hemorrhagic shear injuries	6	>24 hours
5095	41-45	12	Other	50	LOC >30 minutes	ICH; parenchymal contusions, SAH; SDH	3	>24 hours
5098	51-55	14	Struck by object	165	LOC <30 minutes	front-temporal contusion; IPH; SAH; ICH	N/A	<24 hours
5099	31-35	20	Assault	46	LOC >30 minutes	SDH	13	<24 hours
5100	51-55	18	Other	30	LOC >30 minutes	IVH; IPH	3	>24 hours
5104	36-40	20	Struck by object	22	LOC <30 minutes	SDH; scattered SAH; right temporal hemorrhage	15	<24 hours
5109	26-30	14	MVA	102	LOC >30 minutes	SDH; IPH; IVH	5	>24 hours
5111	26-30	16	MVA	72	LOC <30 minutes	Shear Injury; DAI	N/A	>24 hours
5112	51-55	16	MVA	49	LOC >30 minutes	frontal hematoma; IPH; IVF	10	>24 hours
5115	36-40	12	MVA	206	No LOC	SAH	N/A	>24 hours
5117	46-50	12	MCC	115	LOC <30 minutes	DAI	15	>24 hours
5118	26-30	18	MVA	45	LOC >30 minutes	SDH	10	>24 hours
5119	36-40	16	MVA	222	LOC >30 minutes	SAH; Possible right frontal contusion	N/A	>24 hours
5121	51-55	12	MCC	13	LOC <30 minutes	SAH; SDH; PCH	12	>24 hours
5122	51-55	18	Non-motorized vehicle accident	20	LOC <30 minutes	SAH	15	>24 hours
5123	51-55	12	MCC	21	LOC <30 minutes	IPH; SDH; SAH	14	>24 hours
5124	18-25	12	Fall from height	30	LOC >30 minutes	ICH; IVH	3	>24 hours
5125	51-55	12	Ground-level fall	9	No LOC	SDH; SAH	15	No
5127	51-55	12	Fall from height	10	LOC <30 minutes	SAH; SDH	10	<24 hours
5128	36-40	16	MVA	185	LOC >30 minutes	N/A	N/A	>24 hours
5129	51-55	12	Other	9	LOC <30 minutes	SDH; SAH	12	<24 hours
5131	41-45	12	MVA	9	LOC >30 minutes	SDH	12	>24 hours
5133	18-25	12	MCC	22	LOC <30 minutes	contusions; SDH; IVH	15	<24 hours
5134	46-50	16	MCC	8	LOC <30 minutes	IPH	12	<24 hours
5137	26-30	16	Ped vs. auto	11	LOC >30 minutes	EDH; SDH: SAH	3	>24 hours
5141	26-30	12	MVA	8	LOC >30 minutes	SDH	13	<24 hours
5145	31-35	20	MVA	129	LOC >30 minutes	No acute intracranial findings	12 (est.)	>24 hours
5146	51-55	12	Fall from height	17	LOC <30 minutes	ICH; SDH; SAH; IPH	15	>24 hours
5147	51-55	16	MVA	118	LOC >30 minutes	Diffuse Shear Injury	N/A	>24 hours
5149	18-25	14	MVA	12	LOC <30 minutes	IPH; SAH; DAI	3	>24 hours
5150	36-40	12	MVA	13	LOC >30 minutes	SAH	10	>24 hours
5151	36-40	12	MVA	11	N/A	IPH; SDH; SAH	13	>24 hours
5152	51-55	18	MCC	175	LOC >30 minutes	SDH; SAH; Shear injuries	7	>24 hours
5153	46-50	16	MVA	155	LOC >30 minutes	PCH; IPH; ICH; SAH	3	>24 hours
5156	51-55	12	MVA	42	LOC >30 minutes	SDH	15	No
5157	51-55	16	MCC	8	LOC <30 minutes	SDH; SAH; IPH	15	No

Note: ID = participant ID number. Education (Edu) reflects years of highest degree obtained. MVA = motor vehicle accident. MCC includes both motorcycle and snowmobile accidents. Non-motor = non-motorized vehicle accident. Ped vs. auto = participant was hit by car while walking or running. Time since onset (TSO) is presented in months. Loss of consciousness (LOC) is presented in minutes. SDH = subdural hematoma. SAH = subarachnoid hemorrhage. IPH = intraparenchymal hemorrhage. IVH = intraventricular hemorrhage. ICH= intracranial hemorrhage. EDH = epidural hematoma. DAI = diffuse axonal injury. PCH = parenchymal hemorrhage. Glasgow Coma Scale (GCS) is total score at time of first post-injury measurement. PTA = post-traumatic amnesia. N/A = information was not available.

2.2.2 Stimuli

We used the same stimulus materials as Hilverman et al. (2018). Participants watched videos of a narrator telling four stories in North American English about an unlucky man named Carl (See Appendix A). The stores were about 30 seconds long, consisted of six sentences, contained four iconic gestures, and were made up of 10-12 story details. Each story contained four gestures: Two gestures were redundant with speech, depicting overlapping information with speech (e.g., "He formed the meat into balls" paired with a meatball-patting motion), and the other two gestures were complementary to speech, providing unique information (e.g., "He searched for a new recipe" paired with a typing motion). Each story had two versions in which the narrator produced different complementary gestures (e.g., "He searched for a new recipe" paired with a typing motion in one version and a page-turning motion in the other). Participants were randomly assigned to one of the versions for the set of four stories. Figure 2.1 displays examples of redundant and complementary gestures that participants saw.

Figure 2.1: An example of a redundant (left) and complementary gesture (right) produced by the narrator during one of the Carl stories. In the redundant gesture example, the narrator says, "He formed the meat into balls," while producing a meatball-patting movement. In the complementary gesture example, the narrator says, "He searched and searched for a new recipe," while producing a typing movement.

2.2.3 Procedure

Data collection sessions were conducted via Zoom conference call. Participants were instructed to sit away from the camera to maximize the view of their gesture space. Participants were not told explicitly that their gestures might be examined but were told the purpose was to simulate a more full-body view, characteristic of face-to-face communication. Participants were also instructed to hide their self-view to reduce distractions from their own video. Due to limitations with space, setting, equipment, and personal comfort, there was variability in how much of the participants' gesture space was captured on the Zoom call. See the exploratory analysis results section below for more details. The videos of the narrator were presented using Gorilla Experiment Builder (Anwyl-Irvine et al., 2020), played on the participants' personal computer. Participants shared their screen with the experimenter who controlled the screen remotely. The experimenter played a sample audio file during which participants were able to adjust their volume controls until they self-reported the signal was loud enough. To ensure they understood the task, participants first watched a practice video of an unrelated story about a different character (Suzy). Then they watched the four Carl stories in a set order. Each video started with a picture prompt displaying a scene from the story and the title of the story. The experimenter read the title of the story aloud and advanced the screen to initiate the video play. The picture prompt was replaced by the video, but the story title remained on the screen. Immediately after each video ended, the experimenter stopped the participants' screen sharing so that they viewed only the experimenter's video on Zoom, maximizing the view of their listener. Participants were instructed to retell the story in as much detail as they could remember.

After completing this process for the practice video and all four stories, participants engaged in a 20-minute filled delay in which they completed a standardized language assessment with the experimenter. After the filled delay, the participants were prompted to retell the stories again. The experimenter provided the title of each story and asked them to again retell the story in as much detail as they could remember. Participants retold the stories one more time on a Zoom call one-week later and again were prompted with the story titles. If participants did not recall anything about a story after hearing the title, they were briefly shown the picture prompt to facilitate their recall. If they still did not remember, they were asked to make up a story about the picture with a beginning, a middle, and an end. Participants rarely required picture prompts at the one-week delay (2 NCs and 4 TBIs) and when required, prompts were needed for only 1 or 2 stories. Thus, participants retold all four Carl stories three times: Immediately after (no delay), 20-minutes later (short delay), and one-week later (long delay).

2.2.4 Recall Coding

All retellings were transcribed using Rev audio transcription services. These transcripts were double checked by a research assistant who watched the participant videos and filled in utterances marked "unintelligible" by Rev whenever possible. Each story was divided into 10-12 story details. To calculate the number of story details recalled at each timepoint, coders read each story transcript and assigned the details a value of 1 if it was present and 0 if it was absent. All coding was completed by two coders (Authors SC and VGP; VGP was blind to study hypotheses). Prior to beginning recall coding, the coders completed a training set of a random selection of one timepoint for 12 participants for each of the 4 stories. Disagreements were discussed and a consensus was reached for the training set. The two coders then independently coded an overlapping set of

52 participants for all stories and delays (43% of the data). Agreement on whether a story detail was recalled was 92.2%.

2.2.5 Speech Coding

To examine whether complementary information in gesture was integrated into the participants' retelling of the narrative, we focused on the specific words participants produced when retelling the key details of the stories that had been paired with gestures. When participants recalled story details that were paired with redundant and complementary gestures, the coders categorized whether the participants' produced (1) a Speech Match – the participant said the same word the narrator said when she produced the gesture (e.g., "He searched for a recipe"), (2) a Gesture Match – the participant said a word that clearly reflected the gesture the narrator produced (e.g., "He searched for a recipe online"), or (3) Other – the participant said a word that neither directly matched the narrator's speech or gesture (e.g., "He looked for a recipe"). Gesture Matches provide an indication that participants integrated unique information from gesture into their narrative retellings. Details paired with redundant gestures could only be coded as a Speech Match or Other since there is no unique information conveyed by the gesture (see Appendix B for speech coding guide). The same two coders categorized Match type on the same set of 52 participants. One of the coders automated the process by using an Excel VBA Macro to identify keywords that corresponded to Match types. In some cases, participants said a word that matched a gesture that the narrator did not produce in that version (e.g., if they said, "He looked through a cookbook" but they saw the version with the typing movement). All Gesture Match codes were cross-checked with the version participants saw, and in cases where participants' speech matched the gesture from the wrong version, we changed the Gesture Match code to Other. Agreement on Match type for details paired with gestures was 93.7%.

2.2.6 Gesture Coding

Our primary measure of interest was the words participants used when they retold details paired with complementary gestures; However, we were also interested in whether the participants reproduced representative gestures when retelling story details in which the narrator gestured. Participants saw 16 gestures across the four stories. When participants recalled a story detail paired with gesture, we coded whether they also produced a gesture on the same key word as the narrator. When the participants gestured, we coded gesture type as either a representative gesture (i.e., a meaningful movement depicting size, shape, location, or movement), or a beat gesture (i.e., short, rhythmic movements that are temporally but not semantically linked to the speech signal). Gesture coding was completed by the same two coders above. The coders trained on a set of 5 participants, examining all timepoints and stories. Disagreements were discussed until a consensus was reached. We then coded a randomly selected overlapping set of 18 participants (15% of the data). Agreement on whether a gesture was produced was 97.1%. When a gesture was produced, agreement on gesture type (e.g., representative or non-representative) was 93.1%. Gesture coding was hindered by the inconsistent gesture space visibility due to the Zoom data collection format. Despite high inter-rater agreement, we used these data only in an exploratory analysis below.

2.2.7 Analysis

To examine whether our experimental manipulation was effective, we predicted the likelihood of participants saying a different word than what the narrator said (coded as a Gesture Match or Other) as a function of gesture type (redundant vs. complementary). We examined only the no delay timepoint as an indication of how gesture type affected the words participants produced immediately after hearing the stories. We used a generalized linear model and dummy coded the redundant gesture type as the reference level.

For all other analyses, we used binomial mixed effect regression models using the glmer function in lme4 (Bates et al., 2015) in R version 4.2.1 (R Core Team, 2022) to predict the likelihood of participants producing our dependent variables of interest as a function of participant group (TBI, NC), timepoint (No Delay, Short Delay, Long Delay) and their interactions. The data were dummy coded such that the NC group and the No Delay timepoint always served as the reference levels. The random effects structure, including whether the model includes random intercepts and slopes by person and item were determined using the Buildmer package in R (Voeten, 2020). Significant coefficients for logit-linked binomial regressions were interpreted with odds ratios. To examine story recall, we predicted the likelihood of recalling a story detail. The final model included random intercepts for participant and story. To examine whether participant integrated unique information from gesture in their narrative retellings, we analyzed the likelihood of participants producing a word that matched the narrator's gesture (coded as a Gesture Match) for the 8 story details presented with complementary gestures. The final model included random intercepts for participant and story. Finally, we conducted an exploratory analysis to investigate whether participants with and without TBI were more likely to produce a representative gesture at the key moments in which the narrator produced gestures across timepoints. The final model included random slope for the effect of delay by participant and a random intercept for story.

2.3 Results

2.3.1 Story Recall

We examined the likelihood that participants would recall a detail as a function of participant group, delay, and their interaction (Figure 2.2). Participants with TBI were significantly less likely to recall a story detail than their non-injured peers (β=-0.60, z=-3.89, p<.001), where the odds of a non-injured participant recalling a detail were 1.82 times greater than a participant with TBI. There was also a significant effect of delay; non-injured participants were less likely to recall a story detail after the long (one-week) delay compared to no delay (β=-0.43, z=-6.23, p<.001), where the odds of recalling a detail immediately after hearing the story were 1.54 times greater than after a one-week delay. There was no significant effect of the short delay relative to no delay on story recall (β=0.01, z=0.07, p=0.94). There was no significant interaction between participant group and recall at the short delay timepoint (β=-0.17, z=-1.79, p=0.07) or between participant group and recall at the long delay timepoint (β=-0.18, z=-1.90, p=0.06), indicating that the effect of time on story recall did not significantly differ by participant group.

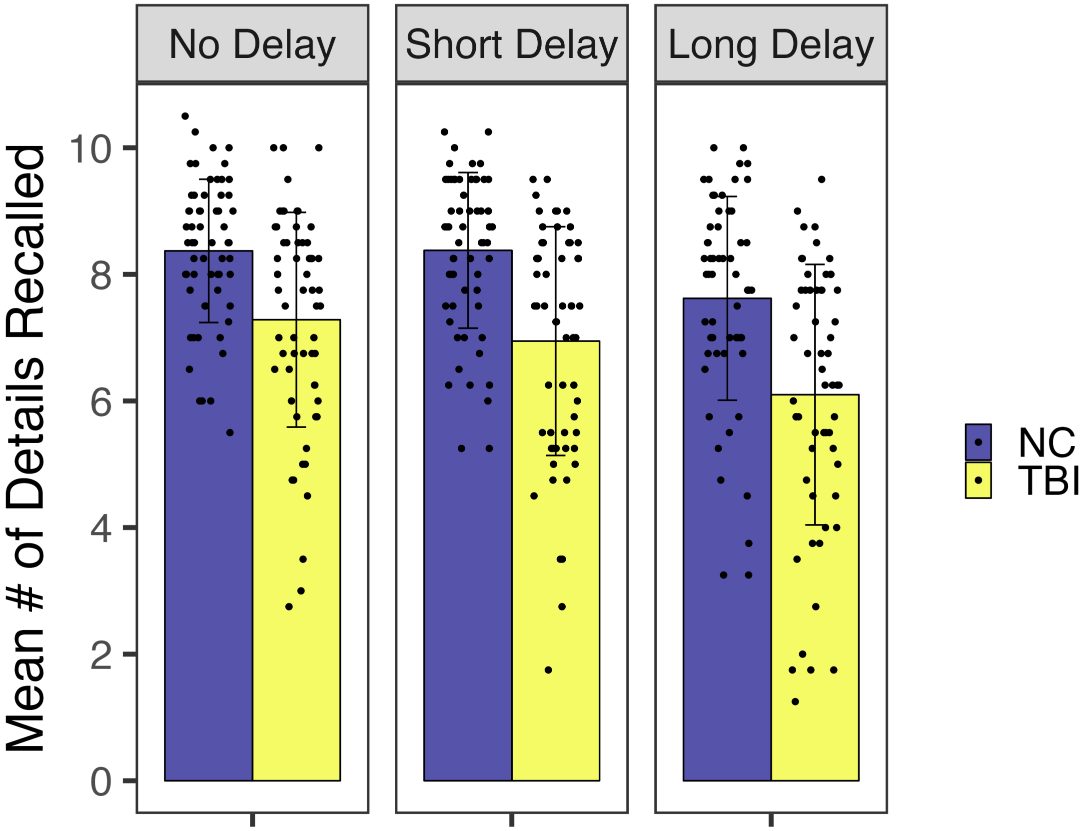

Figure 2.2: Mean number of story details recalled by NC and TBI participants at each of the three timepoints. Bars represent standard deviation of the mean.

2.3.2 Gesture Type Manipulation

We examined whether complementary gestures were more likely than redundant gestures to lead participants to use a different word than the narrator during retellings. The effect of participant group did not reach significance (β=0.45, z=1.87, p=.06), indicating that participants with and without TBI did not significantly differ in their likelihood of changing the narrator's target words in their retellings. There was a significant effect of gesture type (β=2.45, z=12.08, p<.001), where the odds of participants using a different word than the narrator were 11.59 times greater when retelling details paired with complementary gestures compared to those paired with redundant gestures. There was no significant interaction between participant group and gesture type (β=-0.51, z=-1.84, p=.07). These results suggest that our intended gesture type manipulation was effective; complementary gestures containing unique information beyond what was conveyed in speech were more likely to result in participants using different words than the narrator in their retellings. Lack of interaction between group and gesture type suggests that this was true for both participant groups.

2.3.3 Gesture Integration

We examined the likelihood of participants producing a Gesture Match during retellings of details paired with complementary gestures as a function of participant group, delay, and their interaction (Figure 2.3). There was no significant effect of group (β=-0.004, z=-0.02, p=.99), indicating that participants with TBI did not significantly differ from non-injured peers in their likelihood of integrating information from gesture into their retellings. There was no significant effect of short delay relative to no delay on gesture integration (β=0.20, z=1.29, p=.20); however, there was a significant effect of the long delay on gesture integration (β=0.38, z=2.42, p=.02), where non-injured participants were 1.47 times more likely to produce a gesture match at the long delay timepoint than no delay. There was no significant interaction between participant group and likelihood of producing a Gesture Match at the short delay (β=0.08, z=-0.33, p=.74) or long delay (β=-0.23, z=-0.98, p=.33), indicating that the effect of delay on likelihood of producing a Gesture Match did not significantly differ by participant group.

2.3.4 Exploratory Analysis: Gesture Production

In an exploratory analysis, we investigated whether participants with and without TBI were more likely to produce a representative gesture at the key moments in which the narrator produced gestures across Delay timepoints. Because the study was conducted on Zoom, there was variability in how much of the participants' body and gesture space was visible. Gesture space was coded as the height of the bottom video frame relative to the participant's body. At the no- and short-delay timepoints (session 1), gesture space corresponded to Chest (NC: n = 11; TBI: n = 15), Elbow (NC: n = 30; TBI: n = 25) and Hip height (NC: n = 19; TBI: n = 20). At the long-delay timepoint (session 2), gesture space corresponded to Chest (NC: n = 14; TBI: n = 15), Elbow (NC: n = 19; TBI: n = 18) and Hip height (NC: n = 27; TBI: n = 24). One participant with TBI was unable to connect their web camera and had no visible gesture space at the long delay. A generalized

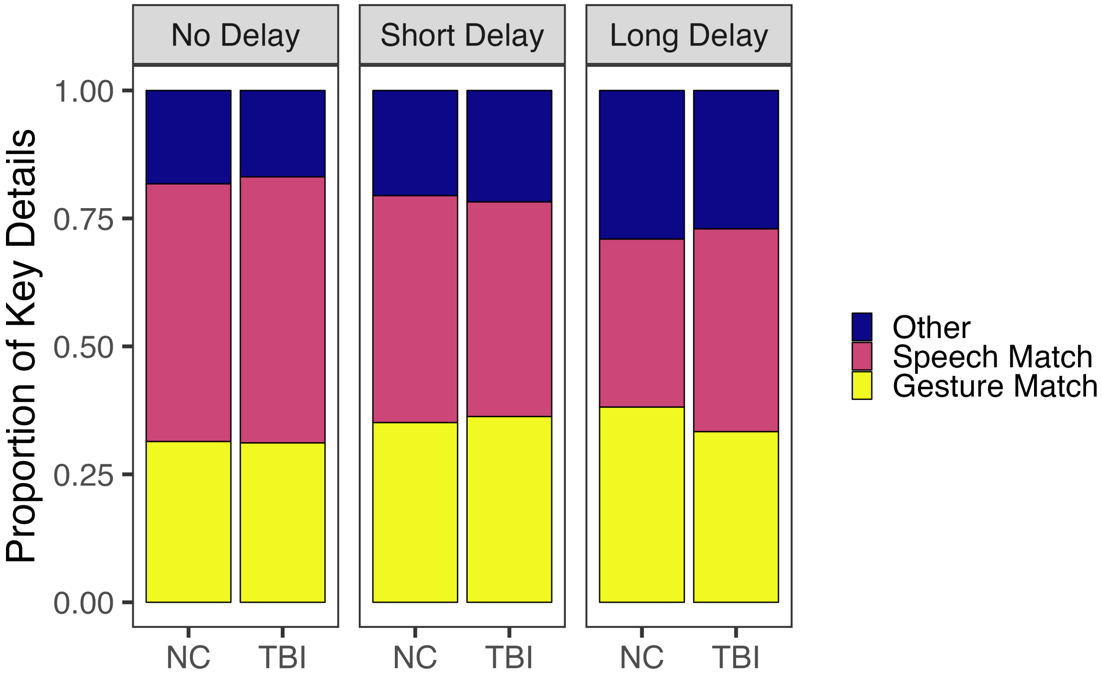

Figure 2.3: Of the story details presented with complementary gestures that were recalled at each time point (max = 8), the proportion of participants' retellings that matched the narrator's speech (speech match), matched the narrator's gesture (gesture match), or neither (other) for non-injured comparison participants (NC) and participants with traumatic brain injury (TBI).

linear model predicting the likelihood of producing a representative gesture as a function of visible gesture space indicated that participants were significantly less likely to produce a representative gesture when the bottom of the video frame was elbow relative to hip height (β=-0.05, z=-3.25, p=.001) and chest relative to hip height (β=-0.14, z=-8.01, p<.001), suggesting that data loss occurred when visible gesture space was restricted. However, a chi square test indicated that there was no difference in the distribution of gesture space categories by participant group at either the session 1 (X^2(1, N = 120) = .16, p = .92) or session 2 timepoints (X^2(1, N = 117) = 1.10, p = .58). Likewise, although there are numerically more participants with hip-height gesture space at session 2 compared to session 1, a chi square test did not reveal any significant differences in the distribution of gesture space categories for the session 1 and session 2 timepoints (X^2(1, N = 237) = 5.25, p = .07).

When participants recalled a detail that was paired with a gesture (redundant or complementary), we analyzed the likelihood that they produced a representative gesture when retelling that detail as a function of participant group and delay. Participants with TBI did not significantly differ from non-injured peers in their likelihood of producing representative gestures when retelling key details (β=-0.32, z=-0.78, p=.43). Non-injured participants did not differ in their likelihood of producing representational gestures at the short compared to the no delay timepoint (β=0.08, z=0.45, p=.66) and a lack of significant interaction between group and the short delay timepoint (β=0.16, z=0.68, p=.50) indicated that this pattern was similar for participants with TBI. Non-injured participants were significantly more likely to produce a representational gesture when retelling key details at the long delay compared to no delay timepoint (β=1.11, z=5.38, p<.001), where the odds of producing a representational gesture one week later was 3.04 times greater than immediately after hearing the story. A lack of significant interaction between participant group and the long delay timepoint (β=0.08, z=0.29, p=.77), indicated that this effect did not significantly differ for the TBI group.

2.4 Discussion

Despite recalling significantly fewer story details than non-injured peers, participants with TBI were as likely to integrate unique information from the narrator's gesture into their narrative retellings and produce representative gestures when retelling key details. In addition, all participants were more likely to report information from gesture in their speech retellings and produce representative gestures themselves one-week later compared to immediately after hearing the story. This suggests that although memory for stories is more verbatim in immediate retellings, over time, information from gesture is integrated and potentially strengthened in the mental representation, even for people with traumatic brain injury.

Although our finding of intact speech-gesture integration in TBI has exciting implications for the utility of gesture to support comprehension and memory in TBI, these findings are contrary to our prediction. We hypothesized that disruptions in multimodal integration may underlie the difficulties people with TBI encounter when communicating in rich, dynamic social settings that require processing and integration of multiple co-occurring cues (e.g., speech, gesture, facial expression, eye gaze, voice, body language, situational context, and communication partners' knowledge states). In the current study, we isolated speech and gesture cues to examine if brain injury disrupts speech-gesture integration. All gestures were highly salient iconic gestures that were large, produced clearly, and embedded in an entertaining narrative, thus offering the best shot at capturing participants' attention. It is possible that people with TBI would have more difficulty relative to non-injured peers when processing speech and gesture in more dynamic settings such as dyadic or multiparty conversation or with the layering of multiple social cues. Although we see accumulating evidence of intact processing of social cues in isolation, including eye gaze (Mutlu et al., 2019), interpersonal distance (Mutlu et al., 2019), disfluencies (Diachek et al., 2023), and now gesture, the combinatorial effect of these cues have not been investigated in TBI.

Self-report from participants in this study suggest that some individuals may have difficulty processing language in rich communicative contexts. For example, three participants with TBI initially closed their eyes when asked to listen to and retell the stories and when prompted to watch the video of the narrator said, "I was doing that to help my brain to focus on the story itself," and "I can't look at the screen. If I sit there and look at the person telling the story, I'll concentrate on what her mannerisms are and how she's saying it, and it will distract me from actually paying attention to what's being said." These direct quotes suggest that for some individuals, attending to, processing, and integrating both audio and visual information is difficult. More work is needed to understand when and how breakdowns in multimodal processing or integration occur and who is most at risk at the individual level.

Although often cited as a barrier, the inherent heterogeneity of cognitive and neural profiles in individuals with TBI affords the ability to unravel the mechanisms supporting cognitive functions and responsiveness to intervention (Covington & Duff, 2021). Future directions should leverage more naturalistic communication paradigms that reflect the language processing demands of everyday life to advance this study. Although gesture is an integral component of language, it is not routinely examined in studies of communication and language processing in individuals with neurogenic communication disorders. This omission gives us an incomplete understanding of their communicative abilities and hinders development of mechanistic accounts of cognitive-communication disorders. Consequently, gesture is also not routinely assessed in clinical practice when treating adults with neurogenic communication disorders. These results support the need for a multimodal approach to both assessment and treatment of language disorders. Ecologically valid assessments that reflect real-world complex communication demands in which listeners must integrate incoming information from multiple sources may be more sensitive to communication disruptions after brain injury. Further, we provide preliminary evidence that gesture may support comprehension and memory after brain injury, in which people with TBI showed intact integration and maintenance of gestured information over time. Expanding research paradigms to address maintenance and generalization of new learning is critical, as this is the goal of all speech-language rehabilitation.

Implementation of short and long delay timepoints was a critical feature of the current study's design. Although there is substantial evidence that gesture promotes learning and memory (Cook & Fenn, 2017; S. Cook, 2018), few studies have examined the enduring nature of this benefit. Two areas that have demonstrated a role of gesture in retention of learning are math learning and word learning. Children show improved learning of mathematical equivalence at a four-week post-test both when observing the teacher produce speech and gesture simultaneously (Congdon et al., 2017) and when producing gestures themselves during encoding (Cook et al., 2008). Benefits of gesture for retention of learning have also been shown in healthy young adults. Undergraduate students recalled more items at a three-week delay post-test when producing spontaneous or instructed gestures when previously describing animated vignettes of spatial movements and actions (Cook et al., 2010), and undergraduates who learned foreign words paired with gesture at encoding showed a memory boost as long as one-week (Macedonia et al., 2011; Sweller et al., 2020) and 14-months later

(Macedonia & Klimesch, 2014). Critically, Congdon and colleagues (2017) found that differences in gesture training conditions only emerged after a delay, suggesting that study paradigms which do not extend testing beyond immediate timepoints may miss condition or group effects entirely. Given the robust literature on the benefits of gesture for communication and memory, there is a need for more longitudinal studies to examine the durability of these benefits across all functions of gesture and in special populations. In the current study, participants were more likely to report information from gesture and produce gestures themselves one week later, suggesting that gesture may receive an additional boost during memory consolidation. The finding that the effect of the one-week delay on producing Gesture Matches did not differ by participant group suggests that the benefit of gesture is durable, even in individuals with TBI. This is particularly exciting as our group has recently shown that not only to people with TBI have difficulty with initial encoding of new information, but they also have increased difficulty holding onto it; in a word learning paradigm, people with TBI show immediate deficits in word learning relative to their non-injured peers, but this performance gap grew at the one-week post-test (Morrow et al., 2023). In addition to the inclusion of gesture, there are other factors that might have supported retention of learning in the current study. For example, learning was embedded in short entertaining narratives with built in rehearsal at the immediate and short-delay timepoints prior to the long-delay recall. Continued investigation into the factors that scaffold learning and memory and promote retention over time is needed. It is an open question whether gesture can boost learning, maintenance, and generalization of new learning in traumatic brain injury to narrow this gap.

Indeed, these results open the possibility that gesture could be leveraged to support communication and memory in populations with cognitive-communication disorders. There is a robust literature on the benefits of gesture for communication and cognition; however, these functions have been understudied in TBI (Clough & Duff, 2020). For example, gesture serves many self-oriented cognitive functions including facilitating the activation, manipulation, packaging, and exploration of spatio-motoric information (Kita et al., 2017), improving working memory by reducing the cognitive load (Cook et al., 2012; Goldin-Meadow et al., 2001; Ping & Goldin-Meadow, 2010), focusing attention and enhancing cognitive flexibility (Khatin-Zadeh et al., 2022), facilitating the retrieval of meanings from metaphors and abstract concepts (Argyriou et al., 2017), improving comprehension and memory (Dargue et al., 2019; Hostetter, 2011), and promoting transfer of new learning (Cook et al., 2013). Our finding that people with TBI as a group show intact speech-gesture integration suggests that people with TBI may still have access to the cognitive and communicative benefits that gesture affords. Even patients with hippocampal amnesia and severe memory impairment show benefits of gesture for comprehension and memory (Hilverman, Clough, et al., 2018; Hilverman, Cook, et al., 2018), suggesting that gesture may be weighted more heavily as a particularly salient resource when memory is severely disrupted. Indeed, despite recalling fewer details for stories overall, patients with amnesia were more likely to report information from gesture in their immediate retellings than non-injured and brain-damage comparison participants (Hilverman, Clough, et al., 2018). This is consistent with the finding in the current study that despite recalling fewer details at the long delay, participants were more likely to report information from gesture one-week later compared to immediately after hearing the story. Memory disruption is highly prevalent in TBI, yet successful rehabilitation and community reintegration depends on (re)learning. Identifying ways to support memory and learning in this population is paramount for improving treatment outcomes, and the utility of gesture to support learning and memory warrants further study.

One limitation of the current study is the use of Zoom for data collection, a necessary design decision due to the Covid-19 pandemic. This resulted in inconsistent capturing of the participants' gesture space and impeded our ability to do a full analysis of gesture production. Still, we provide a novel finding that people with TBI did not differ from non-injured peers in their likelihood of producing representative gestures during narrative recall. This suggests that people with TBI can effectively use gesture to communicate. Studies of gesture production in TBI are limited, with one examining gesture production during a naming test (Kim et al., 2015) and others using rating scales of nonverbal or pragmatic language skills (Aubert et al., 2004; Rousseaux et al., 2010; Sainson et al., 2014). Much work is needed to examine the frequency, type, and functions of gesture after TBI, particularly in social interaction. For example, the gestures of non-injured participants reflect their sensitivity to others' knowledge states (Campisi & Özyürek, 2013; Hilliard & Cook, 2016; Holler & Bavelas, 2017; Holler & Wilkin, 2009, 2011), and even patients with hippocampal amnesia who have severe declarative memory impairment modulate gesture height (Hilverman et al., 2019) and frequency (Clough et al., 2022) based on shared knowledge with their listener. Given that people with TBI can present with theory of mind and social cognition deficits (Lin et al., 2021; McDonald, 2013), future work should examine how people with TBI produce and adapt their gestures across communication contexts and partners.

These results expand our understanding of language comprehension of multimodal communication following traumatic brain injury. By studying speech and gesture together, this research more closely approximates the real-world communication contexts that characterize and enrich everyday life and yields more ecologically valid assessments. This approach may in turn inform mechanistic accounts of cognitive-communication disorders and new treatment targets to improve the communicative lives of people with TBI. This evidence of intact speech-gesture integration in TBI has exciting implications for future work exploring whether gesture may be leveraged in rehabilitation to improve learning and memory after TBI. Future work should build on this foundation to explore whether the cognitive and communicative benefits of gesture that are widely documented in non-injured individuals extend to patient populations with cognitive-communication disorders.

In the following chapter, we present findings from a follow-up study examining speech-gesture integration in real time using eye-tracking in a visual world paradigm. This gives us additional information about not only whether people with TBI can integrate co-ocurring speech and gesture, but also about the timecourse of that integration. Even though participants with TBI showed intact co-speech gesture integration in their narrative retellings, it is possible that eye-tracking could more sensitively reveal delays or reductions in speech-gesture processing. We investigate this possibility in Chapter 3.

CHAPTER 3

Reduced On-line Speech Gesture Integration during Multimodal Language Processing in Adults with Moderate-Severe Traumatic Brain Injury: Evidence from Eye-Tracking

3.1 Introduction

Language is multimodal, containing both speech and gesture. Gesture is a form of visual language that enriches everyday communication. Although gestures occur simultaneously with speech, they often communicate unique information, particularly about visuospatial descriptions and actions (Alibali, 2005; Feyereisen & Havard, 1999; Hostetter & Alibali, 2019; Melinger & Levelt, 2004). Gestures that meaningfully depict aspects of the visual world (e.g., size, shape, or movement of objects) are called iconic gestures (McNeill, 1992). Speech and gesture are both semantically and temporally related; however, the onset of iconic gestures often proceeds their lexical affiliates in speech (Fritz et al., 2021; Morrel-Samuels & Krauss, 1992; ter Bekke et al., 2020). The lexical affiliate is the word(s) most closely related to the gesture meaning. For example, in the sentence, ”He picked up the book,” paired with a lifting gesture, ”picked up” would be considered the lexical affiliate. In a corpus of conversational data, it was found that on average, the start of the gesture movement occurred 672 ms before the lexical affiliates, and the start of the meaningful stroke of the gesture movement occurred 215 ms before the lexical affiliates (ter Bekke et al., 2020). To comprehend the speech-gesture signal, listeners must integrate temporal and semantic features of speech and gesture during multimodal language processing. Many studies have used eye-tracking to examine spoken language processing as the speech signal unfolds in real time. However, the study of multimodal language processing has received much less attention. Using an adapted visual world paradigm, we examine how listeners use information from gesture to resolve temporary referential ambiguity in speech. Critically, we also examine whether this process is disrupted in individuals with moderate-severe traumatic brain injury (TBI), advancing our understanding of the effects of cognitive-communication impairment in rich multimodal communication contexts.

3.1.1 Language Processing in a Visual World

The visual world paradigm (Tanenhaus et al., 1995) has been used to identify how and when language processing interacts with visual context by measuring participants gaze to objects in a visual scene while they listen to auditory stimuli. At the single word level, eye fixations reveal partial activation of semantically and phonologically related competitors. For example, upon hearing the word “lock,” participants show increased fixations to pictures of key and log (Yee & Sedivy, 2006). Visual attention is also guided by our perceptual and conceptual knowledge about objects, including their shapes, colors, and functions (Huettig & Altmann, 2007, 2011; Yee et al., 2011). For example, hearing the word “snake” increases fixations to a visual competitor rope on the screen (Huettig & Altmann, 2007).

In addition to conceptual knowledge about words driving visual attention, words also occur within a larger linguistic context which can constrain or disambiguate meaning. For example, Altmann and Kamide (1999) measured visual attention to objects in a scene while listening to sentences in which the verb constrained the candidate meanings for the upcoming object referent (e.g., “The boy will eat the cake,” where the cake was the only edible object in the scene) and sentences in which the verb did not constrain the referent (e.g., “The boy will move the cake”). They found that participants made anticipatory eye movements toward cake after hearing the verb “eat” more so than after hearing the verb ”move.” During online sentence processing, listeners’ visual attention is influenced by both semantic and syntactic information conveyed by the words they hear, with fixations guided to candidate referents continuously and based on partial phonetic information (Dahan & Tanenhaus, 2004). Further, listeners use visual context to guide comprehension in the face of ambiguity in linguistic meaning (Ryskin et al., 2017; Snedeker & Trueswell, 2004; Spivey et al., 2002). For example, in sentences with a temporarily ambiguous prepositional phrase (e.g., “Put the apple on the towel in the box”), participants use the visual context to correctly disambiguate whether the phrase “on the towel” was intended to modify the noun apple (e.g., the apple that is on the towel) or to specify the goal of the verb ”put” (e.g., where to put the apple, as in ”Put the apple on the towel. Then move it to the box”; see Spivey et al., 2002). Thus, language understanding is contextual and requires the integration of both visual and linguistic input.

3.1.2 Contributions of Gesture to Language Processing

Collectively, studies using the visual world paradigm provide several insights into the phonological, syntactic, and semantic constraints that influence on-line language processing and the ways language interacts with the visual world. However, all these studies used auditory-only language stimuli. Of note, recently the visual world paradigm has been extending to manual languages as well in which the visual modality contains both linguistic and non-linguistic information. Both adult and child users of American Sign Language show evidence of semantic prediction, making anticipatory fixations to the target referent when the verb constrained the sentence-final noun (Lieberman et al., 2018) and adult users of German Sign Language show phonological priming effects for sign pairs sharing hand shape and movement (Wienholz, 2021). Thus, addressees integrate visual context with linguistic information during language processing, even within a single visual modality. The current study examines multimodal language processing in which the signal contains both verbal and visual language in speech and gesture. Gesture is an integral component of language, with existing theories of gesture positing that gesture and spoken language share one common conceptual origin (McNeill, 1992, 2005, 2013; McNeill & Duncan, 2000) or are two closely integrated systems that interact during production (de Ruiter, 2000; Kita & Özyürek, 2003). Gestures provide temporal (Fritz et al., 2021; Morrel-Samuels & Krauss, 1992; ter Bekke et al., 2020) and semantic (McNeill, 1992) overlap with speech and can also constrain sentence meaning. For example, gestures can be used to disambiguate homophones (Holle & Gunter, 2007; Obermeier et al., 2011, 2012) and pronoun referents (Goodrich Smith & Hudson Kam, 2012, 2015). However, little is known about how gesture interacts with spoken language and visual context during language processing.

There has been increasing interest in expanding the visual world paradigm to study the interaction of gesture with visual context. Most of this early work has focused on the influence of iconic gestures on language processing although there is evidence that beat gestures (i.e., rhythmic movements) may also direct attention by emphasizing or stressing contrastive information (Morett et al., 2021). Iconic gestures, in particular, play a role in predictive language processing due both to their semantic relatedness with the speech signal and tendency to occur before their semantic affiliates in speech (Hu, 2020). Saryazdi and Chambers (2022) examined how iconic features of grasping gestures reflecting the size and shape of object referents directed attention in a visual scene. For example, hearing the sentence “Pick up the candy” paired with a small pinching gesture on the word “Pick” diverts eye gaze to the target candy and away from the phonological competitor candle. This effect was moderated by object size, with a larger effect observed when the gesture differentiated a small target from a larger competitor in the visual scene.

Our group has extended this line of work, using an adapted visual world paradigm, to examine how listeners use meaningful information provided uniquely in the gesture modality to resolve temporary ambiguity in speech. Healthy young adults watched videos of a speaker producing subject-verb-object sentences in English (e.g., “The girl will eat the very good sandwich”) during which the speaker either produced a meaningful sandwich-holding gesture or a meaningless grooming movement on the verb phase “will eat.” Each trial contained pictures of the target item (sandwich), a semantic competitor related to the verb (apple), and two distractor items (e.g., piano, guitar) (see Figure 3.1 below). We found that participants were more likely to fixate the target item before hearing the referent in speech when the speaker produced a meaningful gesture on the verb. Gesture continued to have a facilitative effect on predictive target fixations in the presence of noise-degraded speech and when the speaker was wearing a surgical mask (Clough et al., in prep). Thus, the visual world paradigm has great utility for examining influences of multimodal language cues alongside speech in a visual context.

3.1.3 Disruptions to Language Processing in Clinical Populations

Another important application of the visual world paradigm is to study language processing in clinical and neurodiverse populations. This has the potential both to improve understanding about the communicative abilities of these populations and yield insights into the neural and cognitive resources that support language processing. For example, although they did not include gesture, Yee and colleagues (2008) leveraged the unique neural profile of individuals with Broca's and Wernicke's aphasia who have lesions to the anterior and posterior language regions, respectively, to examine the neural underpinnings of lexical processing. Participants listened to words spoken in isolation (e.g, ”hammer”) while viewing an array of four pictures, one of which depicted a semantic competitior (e.g., nail) or a phonological competitor (e.g., hammock). Although participants with both Broca's and Wernicke's aphasia showed increased fixations to a semantic competitor of the target (e.g., looking at nail when they hear “hammer”), demonstrating lexical co-activation in line with healthy young and age-matched adults, they showed aberrant patterns of lexical activation when the competitor shared phonological onsets with the target. Whereas participants with Broca's aphasia did not show significant increases in fixations to phonological competitors, participants with Wernicke's aphasia showed stronger phonological competitor effects than their healthy age-matched comparisons. Studying on-line language processing in individuals with bilateral hippocampal lesions and amnesia has also informed our understanding of the role of the hippocampus and memory in everyday language use. Although patients with amnesia show intact patterns of fixations to target items in a visual scene based on relatively preserved semantic and syntactic knowledge (Brown-Schmidt et al., 2020; Ryskin et al., 2018), they show impairments in their abilities to link information across short sentences and discourse history to resolve linguistic ambiguity (Covington et al., 2020; Kurczek et al., 2013; Rubin et al., 2011). Studies of on-line multimodal language processing in clinical populations are limited but ripe for investigation. It is possible that the relative weight of speech and gesture cues differs for individuals with cognitive or communication disorders. In face-to-face conversation, participants with aphasia were more likely to fixate on their communication partner's gestures than were healthy comparison participants, indicating that listeners may depend more heavily on gesture for comprehension in the face of language impairment (Eggenberger et al., 2016; Preisig et al., 2018). However, multimodal language processing may also tax cognitive resources. Using eye-tracking, Silverman and colleagues (2010) showed that although iconic gestures facilitated comprehension in neurotypical participants, it hindered comprehension in participants with high functioning autism, who showed patterns of impaired speech-gesture integration. In the current study, we examine whether on-line speech gesture integration is disrupted in adults with moderate-severe TBI.

3.1.4 Speech-Gesture Integration in Adults with Traumatic Brain Injury

TBI is a disorder of brain connectivity that results in widespread damage to white matter tracts throughout the brain (Hayes et al., 2016). The pattern of cognitive deficits is heterogeneous (Covington & Duff, 2021), and people with TBI can have disruptions to a variety of cognitive domains including memory (Bigler et al., 1996; Palacios et al., 2013; Rigon et al., 2019, 2020; Velikonja et al., 2023), attention and processing speed, (Dockree et al., 2004; Ponsford et al., 2023; VanSolkema et al., 2020), executive functioning (Jeffay et al., 2023; B. C. McDonald et al., 2002), social cognition (Bibby & McDonald, 2005; S. McDonald & Flanagan, 2004; Turkstra et al., 2018), and communication (Dahlberg et al., 2006; Togher et al., 2023). Individuals with TBI can present with deficits in multisensory processing and integration (Campbell et al., 2021; Kerley et al., 2020; S. McDonald et al., 2019). However, the effects of these deficits on language processing are understudied. Successful communication requires integration of perceptual, emotional, and situational cues with shared world knowledge (MacDonald, 2017). Disruptions in the ability to process and integrate multiple cues may adversely affect social participation and may underlie the well-documented communicative impairments in TBI, such as impaired perception of irony (Martin & McDonald, 2005) and sarcasm (Channon et al., 2005).

Few studies have examined whether TBI impairs speech-gesture integration. One study examined gesture comprehension in isolation by asking participants to watch silent movies with gestures and found that participants with TBI were successful at both interpreting simple and complex standard communication acts (e.g., gesturing for someone to take a seat) but were impaired at interpreting gestures communicating deceit and irony (Bara et al., 2001). Another study found that although gestures combined with speech improved comprehension of indirect requests, participants with TBI were still impaired at interpreting indirect requests relative to non-injured comparison participants (Evans & Hux, 2011). In a previous study by our group (Clough et al., Submitted), we tested for behavioral evidence that participants with TBI integrated unique information provided only in gesture (e.g., a speaker saying, “He searched for a new recipe,” while producing a typing gesture) in their narrative retellings of stories. We found that participants with TBI did not significantly differ from non-injured peers in their likelihood of reporting information from gesture in their retellings (e.g., saying, “He searched for a new recipe online”) despite having poorer recall for stories overall. Although the literature is limited, collectively these studies provide evidence that gesture does influence language comprehension in TBI. However, to date, no studies have examined the on-line processing of speech and gesture in real time in TBI. It is possible that eye-tracking may more sensitively reveal delays or reductions in speech-gesture integration that are not always apparent in the behavioral responses of adults with TBI. Using eye-tracking to examine multimodal processing in TBI not only has the potential to improve

Table 3.1: Descriptive statistics for TBI and NC groups

	Sex (n)		**Age (years)**			**Edu (years)**			**TSO (months)**		
	Male	Female	Mean (SD)	Min	Max	Mean (SD)	Min	Max	Mean (SD)	Min	Max
TBI	18	27	38.76 (9.99)	24	55	14.60 (2.65)	11	20	58.42 (56.22)	6	248
NC	19	25	37.93 (10.67)	20	55	14.73 (2.59)	12	20	NA	NA	NA

Note. TBI = traumatic brain injury. NC = non-injured comparison. Education (Edu) reflects years of highest degree obtained. Time since onset (TSO) is presented in months.

sensitivity of communication deficits in TBI but also could inform new treatment targets and improve our understanding of communicative abilities after brain injury.

3.1.5 Current Study

We examined on-line speech-gesture integration in adults with and without moderate-severe TBI, using the same adapted visual world paradigm described above (Clough et al., in prep). Hypotheses for the current study were preregistered (https://osf.io/uyqv6). As in healthy young adults, we predicted that participants would be more likely to look at the target picture (e.g., sandwich) during the critical analysis window (the period of ambiguity in the sentence when the speech stream did not uniquely identify the upcoming referent) when the speaker produces a meaningful gesture compared to a meaningless grooming movement. We expected a main effect of group, such that participants with TBI would be less likely to fixate on the target item during the critical analysis window than non-injured participants. We also predicted a group-by-movement type interaction such that the effect of gesture on fixations to the target would be smaller in the TBI group relative to the non-injured group.

3.2 Materials and Methods

3.2.1 Participants

Participants were 45 adults with moderate-severe TBI and 45 non-injured comparison (NC) participants. Due to an equipment failure that led to $>50\%$ data loss, 1 NC participant was excluded from analysis, as per our preregistration protocol. Thus, the final sample was 45 participants with TBI and 44 NC participants. The two groups were matched on sex, age, and education (Table 3.1).

Participants were recruited from the Vanderbilt Brain Injury Patient Registry (Duff et al., 2022). All participants with TBI sustained their injuries in adulthood and were in the chronic stage of recovery, at least 6 months post injury. Participants were classified as moderate-severe by the Mayo Classification System (Malec et al., 2007) and met at least one of the following criteria: (1) Glasgow Coma Scale (GCS) <13 within 24 hours of acute care admission, (2) positive neuroimaging findings (acute CT findings or lesions visible on a chronic MRI), (3) loss of consciousness (LOC) >30 minutes, or (4) post-traumatic amnesia PTA >24 hours. See Table 3.2 for a summary of individual injury demographics.

3.2.2 Stimuli

Participants watched videos of a speaker producing subject-verb-object sentences (e.g., "The girl will eat the sandwich."). During onset of the verb phrase (e.g., "will eat"), the speaker sometimes produced a meaningful iconic gesture that disambiguates the target referent object (e.g., a sandwich-holding gesture). On other trials, the speaker produced a meaningless grooming (self-touch) movement (e.g., an arm scratch movement). The movements were triphasic (McNeill, 1992), consisting of a preparation phase in which the speaker lifted their hands from resting position, the movement stroke (i.e., either the meaningful portion of the gesture or the act of performing the grooming movement), and a retraction phase in which the speaker returned their hands to a resting position. There were 80 unique stimulus sentences (See supplementary materials, Table SI 1). Two videos were recorded for each sentence, one version with a meaningful gesture and another version with meaningless grooming movement version, by each of four speakers (2 male, 2 female). Thus, in total, there were 640 unique stimulus videos. These 640 items were put into a single randomized order and then divided into 8 blocks of 80 trials each. From the 8 blocks, we used a Latin square sampling design to create 8 stimulus lists of all possible consecutive orders of 3 blocks (e.g., blocks 1:3, blocks 2:4, blocks 3:5, etc.). Participants were randomly assigned to one of these lists, so that all participants viewed a variety of target items and speakers. The stimulus videos were placed in a visual scene. On each trial, participants viewed the video in the middle of the screen and saw four picture objects, 1 in each of the four corners. These objects consisted of the target item (e.g., sandwich), a semantically related competitor item (e.g., apple), and two distractor items (e.g., piano and guitar). The location of the target and competitor items were randomized across trials. See Figure 3.1 for an example trial.

3.2.3 Procedure

Participants were seated at a computer with a desktop-mounted Eye-link 1000 eye-tracker with their head stabilized in a padded chin rest. Participants were fitted with Bluetooth cordless and noise-canceling headphones and listened to a sample audio file to ensure audibility. All participants self-reported the audio sample was sufficiently loud. Participants were given the following instructions: "On each trial, you will see one video and four pictures. In the video, a speaker will talk about a girl. The speaker will tell you what tasks the girl needs to do. Your job is to click the object the girl needs to perform the task." Participants then completed 2 practice trials to ensure they understood the directions. On a given trial, the objects appeared on the screen immediately. The video appeared after a one-second delay. The video disappeared after it finished playing,

Table 3.2: Demographic and injury information for participants with TBI

ID	Age	Edu	Etiology	TSO	LOC	Neuroimaging	GCS	PTA
5003	31-35	18	Ped vs. auto	69	N/A	SDH	11	>24 hours
5014	51-55	16	MVA	228	LOC >30 minutes	N/A	N/A	>24 hours
5016	21-25	16	MVA	61	LOC >30 minutes	SAH	13	>24 hours
5018	41-45	18	MVA	194	LOC >30 minutes	SAH	3	>24 hours
5019	46-50	16	Ped vs. auto	75	N/A	SAH; SDH	6	>24 hours
5021	41-45	18	MVA	74	LOC >30 minutes	EDH; SAH	3	>24 hours
5029	36-40	14	Non-motorized vehicle accident	55	LOC <30 minutes	SDH; IPH; SAH	14	<24 hours
5034	36-40	16	MVA	77	LOC >30 minutes	SAH	3	>24 hours
5040	41-45	12	MVA	117	LOC >30 minutes	SDH; SAH; uncal herniation	3	>24 hours
5041	31-35	16	MVA	98	No LOC	No acute intracranial findings	10	>24 hours
5046	46-50	18	Non-motorized vehicle accident	88	LOC <30 minutes	SAH	14	>24 hours
5050	31-35	18	Ground-level fall	57	LOC >30 minutes	SAH; IPH	15	<24 hours
5051	51-55	16	MVA	42	LOC <30 minutes	SAH; SDH	14	<24 hours
5052	31-35	14	MVA	44	LOC <30 minutes	SDH; SAH	9	>24 hours
5058	36-40	12	MCC	152	LOC <30 minutes	SAH; SDH; PCH	8	>24 hours
5086	36-40	16	Ped vs. auto	131	LOC >30 minutes	SAH	15	<24 hours
5095	41-45	12	Other	69	LOC >30 minutes	ICH; parenchymal contusions, SAH; SDH	3	>24 hours
5104	36-40	20	Struck by object	49	LOC <30 minutes	SDH; scattered SAH; right temporal hemorrhage	15	<24 hours
5108	41-45	12	MVA	44	LOC >30 minutes	Bilateral SAH	3	>24 hours
5111	26-30	16	MVA	84	LOC <30 minutes	Shear Injury; DAI		>24 hours
5118	26-30	18	MVA	63	LOC >30 minutes	SDH	10	>24 hours
5119	36-40	16	MVA	248	LOC >30 minutes	SAH; Possible right frontal contusion	N/A	>24 hours
5122	51-55	18	Non-motorized vehicle accident	41	LOC <30 minutes	SAH	15	>24 hours
5123	51-55	12	MCC	41	LOC <30 minutes	IPH; SDH; SAH	14	>24 hours
5125	51-55	12	Ground-level fall	29	No LOC	SDH; SAH	15	No
5126	46-50	12	MVA	44	LOC >30 minutes	SDH	3	>24 hours
5129	51-55	12	Other	27	LOC <30 minutes	SDH; SAH	12	<24 hours
5131	41-45	12	MVA	27	LOC >30 minutes	SDH	12	>24 hours
5137	26-30	16	Ped vs. auto	24	LOC >30 minutes	EDH; SDH: SAH	3	>24 hours
5141	26-30	12	MVA	21	LOC >30 minutes	SDH	13	<24 hours
5156	51-55	12	MVA	54	LOC >30 minutes	SDH	15	No
5158	31-35	16	MVA	18	LOC <30 minutes	SAH	15	N/A
5161	26-30	12	MVA	14	LOC >30 minutes	SDH; PCH; DAI	10	>24 hours
5164	46-50	16	Fall from height	16	LOC >30 minutes	SDH	3	>24 hours
5165	21-25	12	Other	19	LOC >30 minutes	SDH; SAH	8	>24 hours
5166	31-35	12	MVA	14	LOC >30 minutes	SAH	7	>24 hours
5168	21-35	12	MVA	13	N/A	SAH	14	>24 hours
5169	51-55	20	Non-motorized vehicle accident	18	LOC >30 minutes	SDH; SAH	N/A	<24 hours
5174	41-45	16	Ped vs. auto	19	LOC >30 minutes	DAI; SAH; IVH; cerebral hematoma	3	>24 hours
5175	31-35	16	Ground-level fall	11	N/A	SDH; SAH; bifrontal contusions	15	>24 hours
5176	26-30	12	MCC	6	LOC >30 minutes	Shear/DAI	7	>24 hours
5178	26-30	12	MVA	15	LOC >30 minutes	IPH; SAH; IVH; DAI	3	>24 hours
5179	26-30	12	Ped vs. auto	13	No LOC	IPH; SDH; SAH; hemorrhagic contusions	15	<24 hours
5182	36-40	12	Ground-level fall	16	LOC <30 minutes	SAH; SDH, hemorrhagic contusions, PCH	13	<24 hours
5183	31-35	11	MCC	10	LOC <30 minutes	Hemorrhagic contusions; extra-axial hemorrhage; SAH	14	>24 hours

Note. ID = participant ID number. Education (Edu) reflects years of highest degree obtained. MVA = motor vehicle accident. MCC includes both motorcycle and snowmobile accidents. Non-motor = non-motorized vehicle accident. Ped vs. auto = participant was hit by car while walking or running. Time since onset (TSO) is presented in months. Loss of consciousness (LOC) is presented in minutes. SDH = subdural hematoma. SAH = subarachnoid hemorrhage. IPH = intraparenchymal hemorrhage. IVH = intraventricular hemorrhage. ICH= intracranial hemorrhage. EDH = epidural hematoma. DAI = diffuse axonal injury. PCH = parenchymal hemorrhage. Glasgow Coma Scale (GCS) is total score at time of first post-injury measurement. PTA = post-traumatic amnesia. N/A = information was not available.

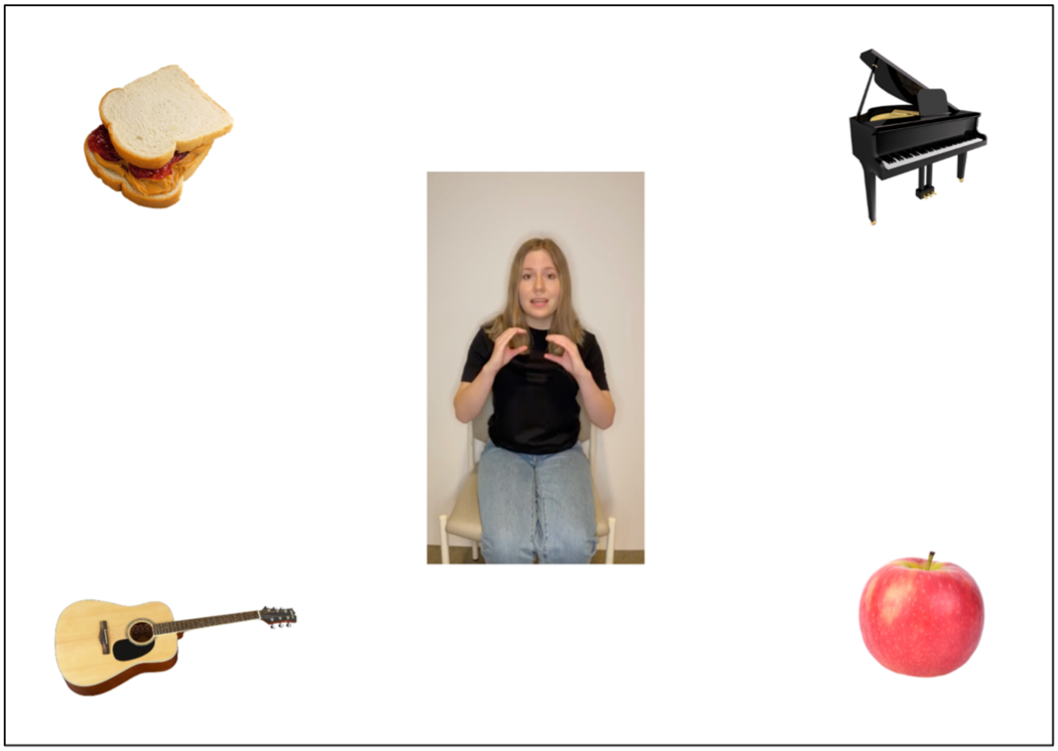

Figure 3.1: Example trial in the gesture movement condition. Participants viewed a video of a speaker saying, "The girl will eat the very good sandwich," while producing a sandwich-holding gesture on the verb, "will eat." In this example, the target is sandwich, the semantic competitor is apple, and the distractor items are piano and guitar.

and the pictures remained on the screen until the participant clicked one. A drift-check occurred every 5 trials. If the drift-check failed, the eye-tracker was re-calibrated. The experiment took approximately 45 minutes to complete. Participants were offered breaks every 80 trials (i.e., 2 breaks at 15-minute intervals).

3.2.4 Analysis

Accuracy in clicking the picture corresponding to the target word was >97.5% for all participants. All participants had minimal data loss, with fixations recorded to one of the five regions of interest (corresponding to the video or 4 object locations) at high proportions; across all 10ms bins of tracking data across all trials, the proportion of bins with fixations to one of the five regions of interest ranged from 0.87 to 1.0 in the NC group (M = 0.97, sd = 0.03) and 0.88 to 1.0 in the TBI group (M = 0.97, sd = 0.03).

The dependent measure was binary fixations to the target object in each of a series of 10ms bins across all trials within a participant. The analysis window began 180ms after the onset of the speakers' movement stroke for both the gesture and grooming movement conditions, coded uniquely for each stimulus video, and ended at the average onset of the target object word produced in speech, 2700 ms later. Thus, we examine fixations to the target object during the critical window between movement stroke and spoken referent, in which the target referent was ambiguous in speech. This analysis window was offset by 180ms due to the time needed to launch an eye-movement (Boff et al., 1986), minus a 20 ms baseline to calculate the first-order autocorrelation AR(1). We used dynamic generalized linear mixed models (GLMM), an extension of autoregressive mixed-effect models (Cho et al., 2018) to predict fixations to the target item (1) or not the target item (0). Fixed effects included participant group (NC vs. TBI, with NC dummy coded as reference level), movement type (effects coded; grooming movement = -0.5, gesture = 0.5), trial number (mean centered and scaled) and their interactions. We also included fixed effect covariates for AR(1) (effects coded), and time (mean-centered and scaled). Models were conducted using the glmer function in lme4 (Bates et al., 2015) in R version 4.2.1. (R Core Team, 2022), and the random effects structure was determined using the Buildmer package in R (Voeten, 2019). The maximal model included random slopes for movement type, trial number, time, and AR(1) by participant and a random slope for item. The selected model included a random slope for trial number by participant only.

3.3 Results

We present the overall timecourse of fixation proportions to the video, target item and competitor item locations averaged across all trials for the NC and TBI groups in Figure 3.2. Proportion of target fixations by group and movement type during the critical analysis window are presented in Figure 3.3, illustrating the effects reported below. Appendix C shows the individual effects of movement type by participant in the NC and TBI groups. We modeled binary fixations to the target item as a function of participant group, movement type, trial number, and their interaction with covariates for Time and AR1. Results of the dynamic GLMM model are presented in Table 3.3.

There was a significant effect of movement type ($\beta = 0.61$, z = 19.36, $p < .001$); NC participants were 1.84 times more likely to fixate the target item during the critical analysis window when the speaker produced a meaningful gesture compared to a meaningless grooming movement. There was no significant effect of group ($\beta = 0.16$, z = 0.87, p = 0.38), indicating that participants with TBI did not significantly differ from NC participants in their likelihood of fixating the target item. A significant group*movement type interaction ($\beta = -0.21$, z = -4.86, $p < .001$) indicated that the effect of movement type differed by group. To probe this interaction, we reverse-dummy coded the variables, setting the TBI group as the reference level. Although the effect of movement type was also significant for TBI participants ($\beta = 0.40$, z = 13.37, $p < .001$), it was attenuated in the TBI group. Whereas NC participants were 1.84 times more likely to fixate the target item when the speaker produced a gesture compared to grooming movement, participants with TBI were 1.49 times more likely to fixate the target item with gesture.

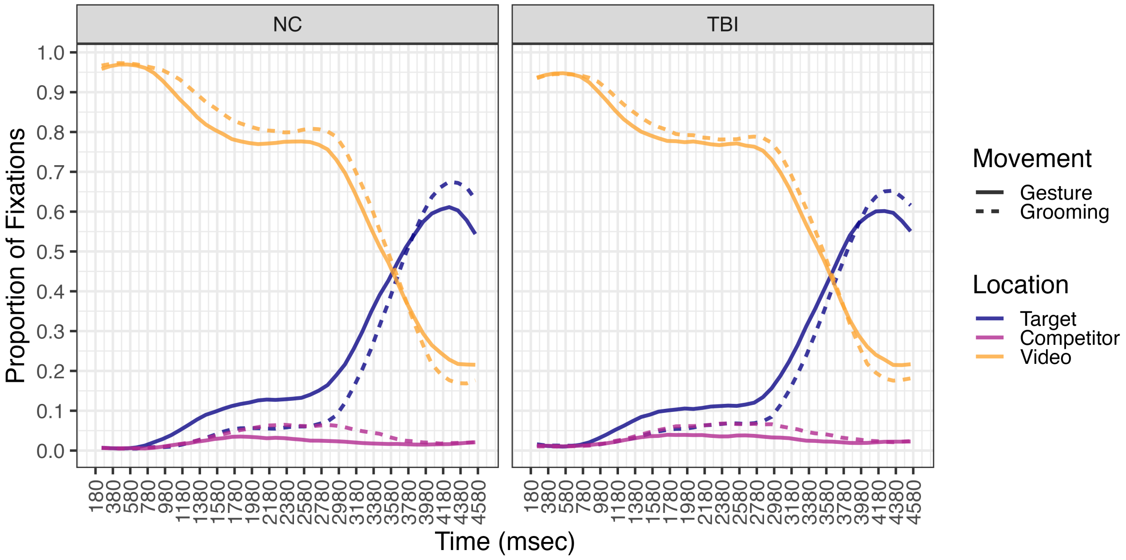

Figure 3.2: Average proportion of fixations to target, competitor, and video across a trial by group, starting at 180ms after movement stroke and ending at average response time of participants' picture click.

There was a significant effect of trial number on likelihood of fixations to the target (β = -0.09, z = -2.45, p = .01); across both grooming and gesture trials, the likelihood of fixating the target item during the critical window decreased over the course of the experiment for non-injured participants. A lack of significant interaction between group and trial number (β = -0.04, z = -0.71, p = .48) indicated that the magnitude of this effect was not significantly different for participants with TBI. There was a significant interaction between movement type and trial number (β = 0.10, z = 3.16, p = .002), where the positive effect of gesture on fixations to the target item increased across trials of the experiment. There was no three-way interaction between movement type, trial number, and group (β = -0.05, z = -1.26, p = .21). The significant effect of time (β = 0.48, z = 30.88, p <.001) reflects the tendency to increase target fixations over time within a trial, and the significant effect of AR1 (β = 10.63, z = 487.56, p <.001) reflects the serial dependency from time-point to time-point in whether or not participants fixated the target at a given time point.

3.4 Discussion

During language processing, listeners are exposed to communicative information from multiple modalities. In addition to the unfolding speech signal, language occurs in rich visual contexts, and speakers produce visible language in the form of gestures. Yet, few studies have examined the influence of gesture on language processing. We demonstrated that listeners use information from gesture to resolve temporary referential ambiguity in speech, making more anticipatory fixations to the target item when the speaker produces an iconic gesture on the verb. This replicates previous work by our group examining on-line speech gesture

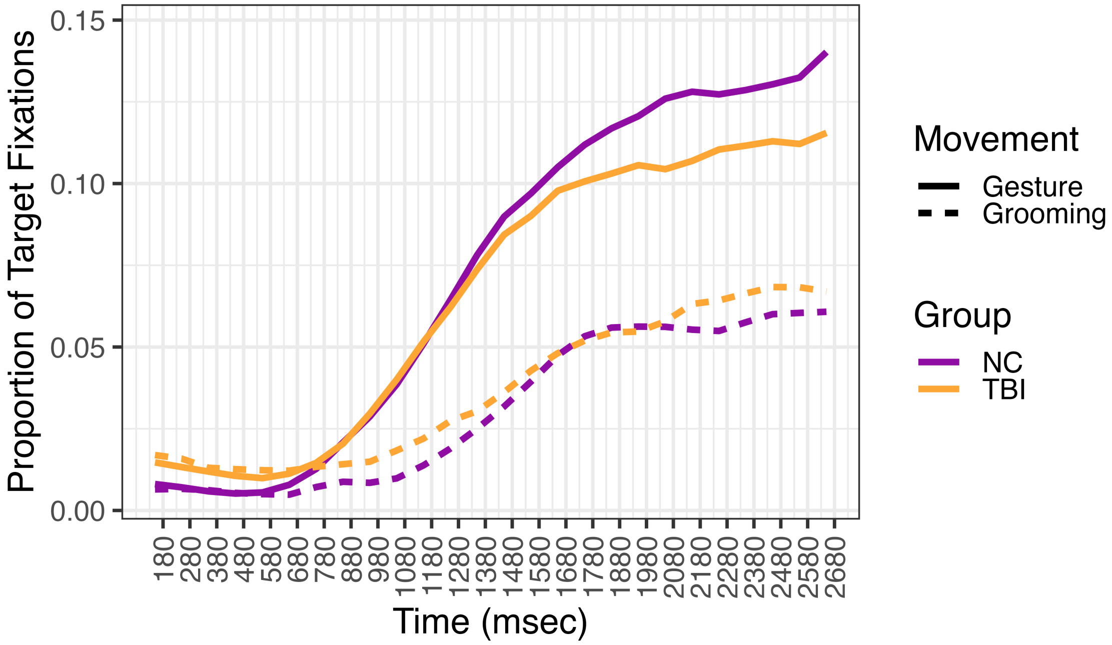

Figure 3.3: Proportion of fixations to target item by participant group and movement type during the critical analysis window, beginning 180 seconds after the onset of the movement stroke produced by the speaker in gesture to the average onset of the target referent produced by the speaker in speech.

integration in undergraduate students (cite undergrad preprint) and extends this finding to a larger and more age- and education-diverse sample of non-injured participants. The critical question addressed by the current study was whether traumatic brain injury disrupts on-line speech-gesture integration in an adapted visual world paradigm.

We found that although participants with TBI did show a significant effect of gesture on target fixations, this effect was attenuated relative to non-injured participants. This suggests that adults with TBI can integrate meaningful information from gesture during online language processing, but they may benefit less from gesture than non-injured peers. We demonstrate the utility of eye-tracking as a sensitive tool to detect disruptions in language processing in TBI. Although participants with TBI demonstrated high accuracy in their click responses to the target items, their fixations reveal evidence of reduced on-line speech-gesture integration. Studies of other clinical populations, including children with specific language impairment and hearing loss, have shown a similar pattern of results in which eye-tracking uniquely reveal language processing differences, despite accurate behavioral responses (Klein et al., 2023; McMurray et al., 2010). This has important clinical implications for identifying language deficits after TBI. Assessments that isolate spoken language and focus only on behavioral accuracy may miss disruptions to language processing in-the-moment and fail to characterize patients' abilities to use and process language in context. Indeed, current assessment

Table 3.3: Results of dynamic GLMM for participants with TBI (n=45) and non-injured participants (n=44), 240 trials and 5,361,360 observations.

Fixed Effects	*Estimate*	*SE*	*z-value*	*p-value*
(Intercept)	-7.274	0.135	-53.811	<0.001
Movement (grooming = -0.5, gesture = 0.5)	0.609	0.031	19.363	<0.001
Group (NC = 0, TBI = 1)	0.164	0.188	0.870	0.384
AR1	10.626	0.022	487.564	<0.001
Time	0.483	0.016	30.883	<0.001
Trial	-0.094	0.038	-2.454	0.014
Movement*Group	-0.210	0.043	-4.860	<0.001
Movement*Trial	0.098	0.031	3.160	0.002
Group*Trial	-0.037	0.052	-0.711	0.477
Movement*Group*Trial	-0.054	0.043	-1.262	0.207
Random Effects	*Variance*		*SD*	
Participant (intercept)	0.807		0.898	
Trial slope by participant	0.046		0.214	

practices lack sensitivity to detect communication deficits in TBI (Barwood & Murdoch, 2013; Blyth et al., 2012), necessitating a shift to more ecologically valid and multimodal language assessments. Critically, the attenuation in gesture benefit identified in the current study is likely to scale up in more complex communication contexts. In this case, gestures were embedded in a predictable carrier phrase, and the gestures were large, iconic, and highly salient. In everyday language use, sentences are not produced one at a time, but rather are delivered in a continuous incremental stream of linguistic input that builds on discourse history and accumulates across turns of an interaction. It is possible that the benefit of gesture might suffer additional reductions in more dynamic or interactive contexts such as dyadic or group conversation or with the layering of additional social and cognitive demands. We discuss further implications for this research below.

Despite the attenuated effect of gesture in the TBI group, gesture did facilitate their fixations to the target item, showing evidence of on-line speech-gesture integration in TBI. This complements a previous finding by our group (Clough et al., Submitted) that adults with TBI also successfully integrate unique information from gesture into their comprehension of and memory for stories. This converging evidence from behavioral and eye-tracking methods builds a foundation for understanding the communicative abilities of adults with TBI from a multimodal language perspective, taking into consideration the fact that real-world communication occurs in rich environments that contain a variety of social cues, including gesture and visual context. However, the current study represents a controlled experimental paradigm in which the role of gesture in language processing was isolated from other communicative cues. In addition to demonstrating evidence of successful gesture comprehension, adults with TBI also show intact perception of other social cues when studied in isolation, including eye-gaze (Mutlu et al., 2019), interpersonal distance (Mutlu et al., 2019), and disfluencies (Diachek et al., 2023). The finding that adults with TBI show successful social cue perception in isolation suggests that the fundamental building blocks of language processing and social communication are available to them. However, little is known about how both adults with and without TBI weight and integrate co-occurring information from multiple social cues during language processing. Studying the combinatorial effect of these cues in TBI may reveal unique insights into when and how communication breakdowns occur in the kinds of rich multimodal communication contexts that characterize everyday life. It is possible that social communication impairments in TBI might arise from disruptions to the rapid integration of multiple cues across speakers, modalities, and time. In particular, the hallmark diffuse axonal injury and overall reduced connectivity of neural pathways may disrupt multimodal processing and integration (Hayes et al., 2016; McDonald et al., 2019).

This is the first study of on-line speech-gesture integration in individuals with TBI and one of only a few studies to examine gesture comprehension in TBI (Bara et al., 2001; Clough et al., Submitted, Evans & Hux, 2011), addressing a clear gap in our understanding of language processing after TBI (Clough & Duff, 2020). The benefits of gesture for comprehension and memory are well documented in neurotypical individuals (Dargue et al., 2019; Hostetter, 2011), yet it is unclear whether these benefits extend to adults with TBI. Further, very little is known about how adults with TBI use gesture in spontaneous language production. There is a large literature supporting evidence for self-oriented cognitive functions of gesture for the speaker (Kita et al., 2017), providing additional motivation to increase the study of gesture in adults with TBI who can present with deficits across cognitive domains (e.g., memory, attention, executive function, working memory, perception, language). It remains an open empirical and clinically imperative question whether gesture can be leveraged to improve communication and cognition in individuals with TBI.

In the current study, we demonstrate feasibility and utility in using gaze as a window into the cognitive-linguistic processes of adults with TBI as they unfold in real time. Participants with TBI tracked accurately and were able to sustain position in the chin rest for the duration of the 45-minute eye-tracking experiment. The current study also revealed many insights into methodological considerations for future studies examining multimodal communication with eye-tracking. Although many participants in both groups shifted their gaze to objects during the critical analysis window, others remained fixated on the video until it disappeared from view (see supplementary materials for individual participant effects), potentially reducing our ability to detect measures of semantic integration of gesture in these individuals. The video stimuli were a crucial component of the current study's multimodal design, expanding on other implementations of the visual world scene which have largely examined gaze in response to auditory stimuli only. The use of video stimuli more accurately reflect the dynamic language processing demands that characterize face-to-face communication in which the listener must integrate multiple meaningful channels of information while also filtering out irrelevant stimuli. However, to reduce the impact of the strong attentional capture of the video, future studies might consider having the video disappear after critical information in gesture has been produced or creating stimuli that provide meaningful information in the gesture modality only without subsequent disambiguation in speech (e.g., "The girl will eat the very good food" with a sandwich-holding gesture). There are many other potential avenues for studying speech-gesture integration in rich visual contexts. For example, they current eye-tracking study included picture options in the four corners, but others might include more elaborate visual scenes in which the speaker is integrated into the visual context. Yet another possibility would be to use virtual reality and avatars to simulate real-world environments in a virtual world paradigm which can be combined with eye-tracking (Peeters, 2019). Future elaborations on these designs have the potential to provide unique insights into how people direct attention and integrate information across social cues in rich multimodal communication contexts.

Finally, although we show evidence that adults with TBI can integrate information from speech and gesture in real time, there are likely individual differences in cognitive or neuroanatomical profile that moderate speech-gesture integration abilities. For example, in neurotypical people, working memory is posited as a key cognitive resource in speech-gesture integration (Özer & Göksun, 2020a) with many studies reporting modest relationships between working memory and gesture comprehension (Aldugom et al., 2020; Özer & Göksun, 2020b; Wu & Coulson, 2014, 2015), and neural correlates of speech-gesture integration have been identified across the left frontal-posterior temporal network (for a review, see Kandana Arachchige et al., 2021; Özyürek, 2014). Given the diffuse nature of grey and white matter injury in TBI and the inherent heterogeneity in cognitive profiles (Covington & Duff, 2021), studying speech-gesture integration in TBI has the potential to yield additional insights into the mechanisms supporting multimodal communication. We do not expect that speech-gesture integration would be disrupted in all individuals with TBI. Examining the factors that predict successful speech-gesture integration is an important future direction for identifying people who are most at risk for multimodal language processing deficits and subsequently informing assessment and personalized treatment practices to improve the communicative lives of adults with TBI. This study advances our understanding of the communicative abilities of adults with TBI and could lead to a more mechanistic account of the communication difficulties adults with TBI experience in rich real-world communication contexts that require the processing and integration of multiple co-occurring cues. The findings highlight the importance of increasing the ecological validity of language assessment and continued efforts to identify the cognitive and neural mechanisms that support multimodal language processing.

GENERAL DISCUSSION

This thesis aimed to address a large gap in our understanding of multimodal communication in TBI. As a first exploration in this space, we focused on the abilities of adults with TBI to process and integrate co-occurring speech and gesture across two experiments. This research question was motivated by the literature review in Chapter 1 which demonstrated an almost complete lack of empirical studies characterizing the gesture production and comprehension abilities of people with TBI. Continuing this work is critical for advancing the assessment and rehabilitation of cognitive-communication disorders. In Chapter 3, I presented evidence that on-line speech-gesture integration is reduced in TBI. Expanding beyond speech-only assessments of language has the potential to more sensitively identify disruptions to real-world language use that requires the rapid processing and integration of multiple co-occurring cues across speakers, discourse history, and contexts. Assessments of multimodal language processing could be used to inform treatment targets and measure progress toward goals. Another clinical implication of this work is identifying the utility of gesture to support communication and memory in populations with cognitive-communication disorders. In Chapter 2, I demonstrated that despite having poorer recall for story details, participants with TBI were as likely as non-injured peers to report information from gesture in their narrative retellings, and this remained true one-week later. This provides preliminary evidence that gesture can be leveraged to support learning after TBI. Given the high incidence of memory impairment after TBI, identifying ways to support memory and learning in this population is paramount for supporting their rehabilitation and reintegration into communities.

On the surface, the results from Chapter 2 and Chapter 3 may seem in conflict. In Chapter 2, participants with TBI demonstrated successful speech-gesture integration in their narrative retellings, and in Chapter 3, participants with TBI demonstrated reduced speech-gesture integration during on-line multimodal language processing. This prompts a question about whether the attenuation observed in on-line speech-gesture integration is a functional and clinically significant difference given intact overt behavioral responses in click accuracy and narrative retellings. It is important to keep in mind that these disruptions in multimodal language processing occurred at the sentence level and although participants with TBI did successfully integrate gesture when listening to stories, these stories were also short, averaging about 30 seconds each, and the gestures produced by the narrator were highly iconic and visually salient. It is likely that disruptions in multimodal language processing would become even more apparent with additional communicative and cognitive demands. Through conversations with the participants, it is clear that some people with TBI experience difficulty navigating communication in a multisensory world. For example, in Chapter 2, three participants attempted to close their eyes while listening to the stories to reduce distraction from the visual modality. Although these two studies provide novel insights into the communicative abilities of adults with TBI, more work is needed to understand when communication breakdowns occur in rich multimodal communication contexts.

These studies examined how multimodal information from gesture interacts with co-occurring information in speech to inform language processing in the moment. In this case, receiving additional information in gesture (e.g., a typing movement on the word ”searched” or a sandwich-holding movement on the word ”eat”) affected the listeners' comprehension and interpretation of the message in real time. These findings align with a larger literature in the field of gesture studies that has examined speech-gesture integration using a variety of techniques (e.g., behavioral, EEG, fMRI) by manipulating the relationship between speech and gesture (e.g., redundant, complementary, incongruent) (Cassell et al., 1999; Kandana Arachchige et al., 2021; McNeill et al., 1994; Özyürek, 2014). However, multimodal integration is not unique to speech and gesture. At a perceptual level, audiovisual integration occurs during speech processing at even the phoneme level in which incongruent lip movements can change the perceived sound the listener hears (e.g., the McGurk effect; McGurk & MacDonald, 1976). The binding of two separate stimuli into a unitary audiovisual event is facilitated by the temporal proximity and semantic congruency of the cross-modal inputs (Spence, 2007). Multimodal inputs also form the basis of rich episodic memory representations in which the hippocampus plays a critical role in the relational binding of co-occurring people, places, and things and their spatiotemporal relationships (Eichenbaum & Cohen, 2001). While these perspectives take into account that integration occurs in the moment and is facilitated by temporal proximity, integration can also occur across time. For example, memories for related experiences form overlapping neural representations that allow us to flexibly retrieve and act on prior knowledge and generalize to new experiences (Schlichting & Preston, 2016). These different approaches to studying integration are not mutually exclusive and can be studied together (e.g., examining long-term recall of in-the-moment processing of speech and gesture). The studies presented here demonstrated that not only does gesture get rapidly integrated with sentence context during on-line language processing (Chapter 3), but information from gesture also influences long-term memory representations for what happened in a story and is potentially strengthened over time (Chapter 2). Although there is some evidence that multisensory integration can be impaired after TBI (Campbell et al., 2021; Kerley et al., 2020; S. McDonald et al., 2019), the effects of these deficits on communication and memory are understudied.

In Chapter 3, we present evidence that speech-gesture integration can be reduced after TBI. It is an open question what underlies this attenuation. The diffuse nature of axonal injury characteristic of TBI can produce disruptions across a variety of cognitive domains. It is possible that disruptions to a number of cognitive resources might impair multimodal langauge processing. One likely candidate is working memory which has been posited as a key cognitive resource involved in gesture production and comprehension in neurotypical populations. However, reduced processing speed and attentional processes may also contribute. A future goal of this research program is to design tasks that are sensitive to individual differences in multimodal language processing abilities in order to identify the cognitive and neural mechanisms that support the processing and integration of co-occurring cues in rich communication contexts. In addition to advancing basic science informing mechanistic accounts of the relationship between speech and gesture, this work has the potential to identify individuals most at risk for communication difficulties and poorer outcomes in social participation and quality of life.

It is essential that assessment practices for cognitive-communication disorders take a more ecologically valid approach that aligns with the rich real-world contexts in which adults with TBI often experience communication breakdowns. Currently, there is a lack of consensus amongst clinicians on which assessments to use to measure cognitive-communication disorders (Frith et al., 2014; Turkstra et al., 2005). A subset of standardized tests have demonstrated adequate reliability and content validity but give little consideration to functional context (Turkstra et al., 2005). Non-standardized assessment practices often involve eliciting monologic and conversational discourse samples; however, the implementation of these assessments in controlled clinical or laboratory settings may hinder generalizability to dynamic real-world contexts (Coelho et al., 2005). For example, these assessments are usually conducted one-on-one in a distraction-free environment with supports from a trained speech-language pathologist. Studies of discourse in TBI have largely focused on spoken communication (Coelho, 2007; Hough & Barrow, 2003), and when non-verbal communication is examined, it is most often studied in isolation (Mutlu et al., 2019; Radice-Neumann et al., 2007; Rigon et al., 2016; Turkstra, 2005). This thesis takes a critical step in addressing this problem by studying speech-gesture integration in TBI. Future studies can build on this work by systematically increasing the complexity by adding additional communication cues, speakers, and discourse history to capture the components that lead to communication breakdowns in TBI.

Gesture is integral part of language. Our hands shape the way we think, speak, and remember and enrich our daily interactions. Multimodality is an inherent feature of language that includes both visual and verbal channels of information. It is clear that some of the message comes in gesture, allowing speakers to both show and tell. The inclusion of gesture in theoretical accounts of speech and language is imperative for advancing the study of communication disorders across the scope of speech-language pathology clinical practice and improving the functional communication of the populations we serve. The research presented here represents a first step toward understanding the multimodal communication abilities of adults with moderate-severe TBI but is only a foundation for a much larger set of empirical questions that warrant future study. Studying multimodal communication may yield additional insights into when and how communication breaks down after brain injury. However, the benefits of gesture in TBI are also understudied. For example, it may be possible to harness the cognitive and communicative benefits of gesture to support rehabilitation of individuals with cognitive-communication disorders. It is our hope that new advances in the study of gesture continue to inform our understanding of the cogntive neuroscience of language and improve the communicative lives of adults with TBI.

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APPENDIX

Appendix A. Carl Stories

Carl Celebrates Halloween

For Halloween, Carl decided he wanted to be Frankenstein (**BOLTS**). He was going to a Halloween party, and he knew that the girl he liked would be there and he wanted to impress her. So, he went to the costume store and got bolts for his neck and one big google eye (**EYE**). Then on his way to the party, he stopped and got a flower (**PICKED/CUT**) to give to the girl. Before he even got to the party, he saw her outside and got excited and ran toward her, but she didn't recognize him and got scared so she hit him (**PUNCH/SLAP**).

Carl Chops Some Wood

Carl wanted to start a fire in his backyard, so he got an ax to split wood. All of his friends told him to get face protection (**GOGGLES/MASK**), but he didn't think he needed it. He took the ax outside and wildly chopped at the wood (**AX SWING**). His neighbor was watching and came over and asked if he'd chop some logs for her too. So, Carl got excited and chopped faster and faster and faster (**AX SWING**). And of course, when he least expected it, half of a log flew up and hit him in the face (**NOSE/FOREHEAD**)

Carl Cooks Dinner

Carl decided to try a new recipe for his friends when he had them over for dinner. He searched and searched (**BOOK/COMPUTER**) for a new recipe to try and finally found one for meatballs. He ground up the meet himself and then formed the meat into balls (**BALLS**). When his friends came over, he started cooking the meatballs (**OVEN/STOVE**). Then he went in the other room and talked and talked and talked (**TALK**) to his friends. But he forgot about the meatballs, and when he went back into the kitchen, they were burnt to a crisp.

Carl Goes to the Circus

One day, Carl decided to try his luck on the flying trapeze. He went to the store and bought a new outfit covered in stars (**STARS**) that he thought would make him look like a professional. Then he caught a ride (**HITCHHIKE/TAXI**) down to the nearby circus to talk to the ringmaster. The ringmaster was desperate for a trapeze artist and asked Carl to do his first show that very same night (**TONIGHT**). But Carl didn't mention that he had never actually been on a trapeze before, so as soon as Carl got up on the bar, he got scared and let go and flew off into the crowd (**FLIP/SOAR**).

Appendix B. Speech Coding Guide

In each story, the narrator produced four gestures. Two of these gestures were redundant gestures which depicted information overlapping with speech, and two of the gestures were complementary gestures which depicted new information that was not available in speech. The key words indicated in boldface represent the word the narrator said when she produced each gesture. When participants recall the details below, code their response as a Speech Match if they say the same word as the narrator, a Gesture Match if they say a word that reflects the narrator's gesture, and Other if their words do not directly match the narrator's speech or gesture. For complementary gestures, participants saw one of two versions listed in parentheses after the key word. Gesture matches depend on the version the participants saw. For example, a response of "She slapped him" would be coded as a Gesture Match if they saw the version where the narrator made a slapping movement on the phrase "She hit him" but would be coded as Other if they saw the version where the narrator made a punching movement. Details paired with redundant gestures can only be coded as Speech Match or Other since there is no unique information provided in gesture. See guide below for examples of responses corresponding to code categories.

CARL CELEBRATES HALLOWEEN			
Key Detail	**Speech Match**	**Gesture Match**	**Other**
Carl decided he wanted to be **Frankenstein**.	Frankenstein Frankenstein's monster	NA	zombie
He got bolts for his neck and one big googly **eye**.	Eye eyeball	NA	Stuff Things bolts
He stopped and **got** (PICKED/CUT) a flower to give to the girl.	Got Get	picked Picked up grabbed	Bought Brought took
		Cut Snipped trimmed	
She got scared and she **hit** him. (SLAPPED/PUNCHED)	Hit hitting	slapped Smacked whacked	Beat up
		Clocked socked popped decked walloped	

CARL CHOPS SOME WOOD			
Key Detail	**Speech Match**	**Gesture Match**	**Other**
All of his friends told him to get face **protection** (GOGGLES/MASK).	protection	goggles Eye protection Safety glasses	Safety gear Something for his face
		mask Face covering Face shield Head gear Head protection	
He wildly **chopped** at the wood.	chopped	NA	Split cut
Carl got excited and chopped **faster** and faster.	faster	NA	Wildly Frantically Quickly Sped up Excitedly vigorously crazy frenzied carried away Chopping and chopping harder
Half of a long flew up and hit him in the **face** (NOSE/FOREHEAD).	face	Nose	Eye mouth
		Forehead head	

CARL COOKS DINNER			
Key Detail	**Speech Match**	**Gesture Match**	**Other**
He **searched** and searched (BOOK/COMPUTER) for a new recipe to try.	searched	Cookbook Menu Recipe book	Looked Looked up
		Computer Online Internet Google	
He formed the meat into **balls**.	Balls meatballs	NA	Patty Shape Circle
He started **cooking** (OVEN/STOVE) the meatballs.	cooking	Oven Put them in to cook Baking (sheet)	Fixing dinner
		Stove Put them on to cook frying pan	
He went in the other room and **talked** to his friends.	talked	NA	(chit) chatted Conversations Speaking Entertaining Visited Hang out socializing

<table>
<tr><th colspan="4">CARL GOES TO THE CIRCUS</th></tr>
<tr><th>Key Detail</th><th>Speech Match</th><th>Gesture Match</th><th>Other</th></tr>
<tr><td>He bought a new outfit covered in **stars**.</td><td>stars
star spangled</td><td>NA</td><td>Sparkly
Flashy
Shiny
designs</td></tr>
<tr><td rowspan="2">He caught a **ride** (HITCHHIKE/TAXI) down to the nearby circus.</td><td rowspan="2">ride</td><td>hitched</td><td rowspan="2">Took a car
Took a bus
Went down
Headed down
Walked
drove
Hightailed
traveled</td></tr>
<tr><td>hailed
Waved down
Flagged down</td></tr>
<tr><td>The Ringmaster asked Carl to do his first show that very same **night**.</td><td>Night
tonight</td><td>NA</td><td>Day
evening</td></tr>
<tr><td rowspan="2">He let go and **flew** (FLIP/SOAR) off into the crowd.</td><td rowspan="2">flew</td><td>flipped
Whirled
Twirled
Spun
tumbled</td><td rowspan="2">Fell
Crashed
Swung
Let go
Drops
Slipped
Plummeted
sailed</td></tr>
<tr><td>soared
Flung
Shot
Flew straight</td></tr>
</table>

Appendix C. Target fixations by movement type for individual participants in NC and TBI groups

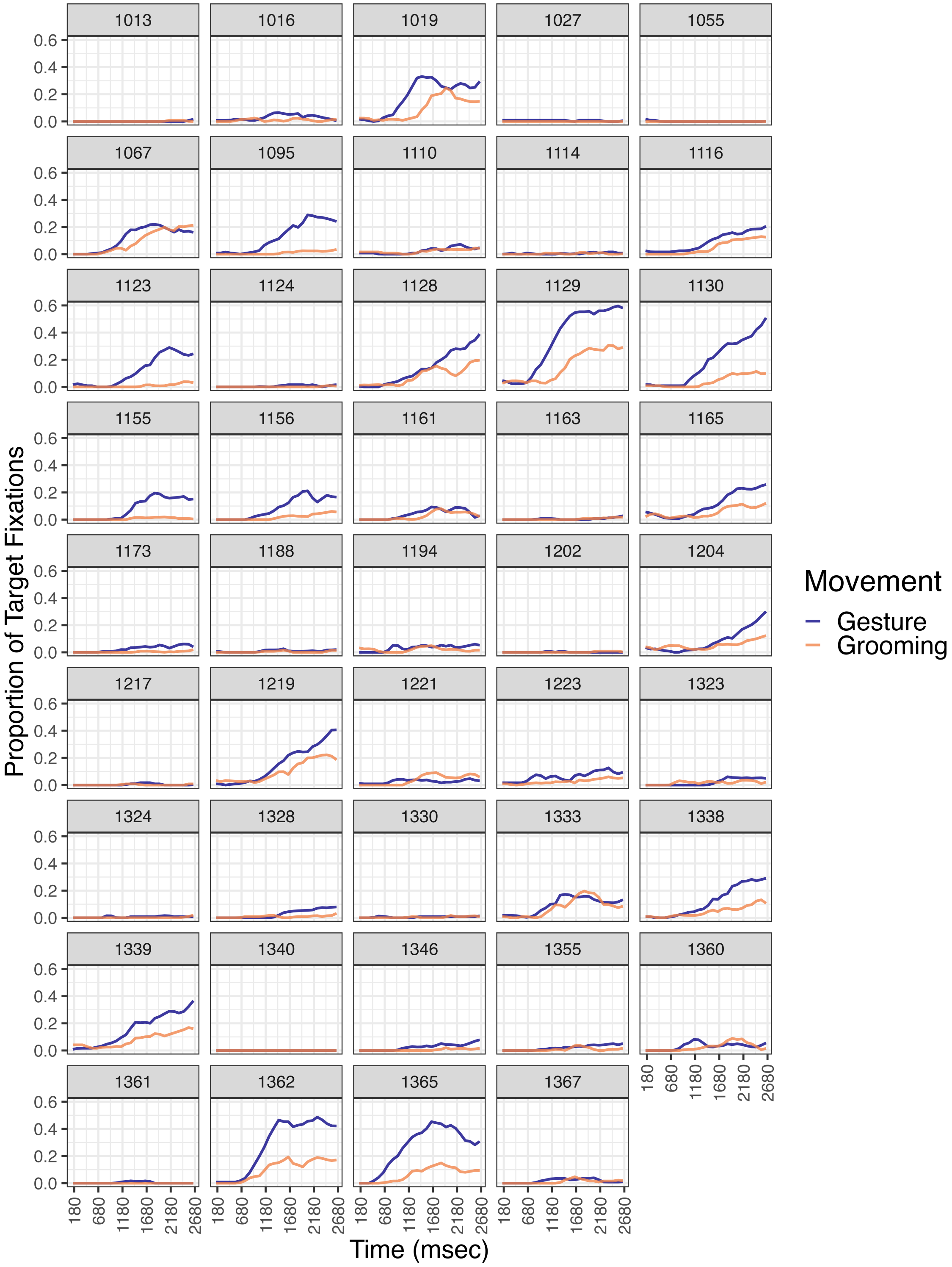

Figure C.1. Target fixations by movement type for individual participants in NC group.

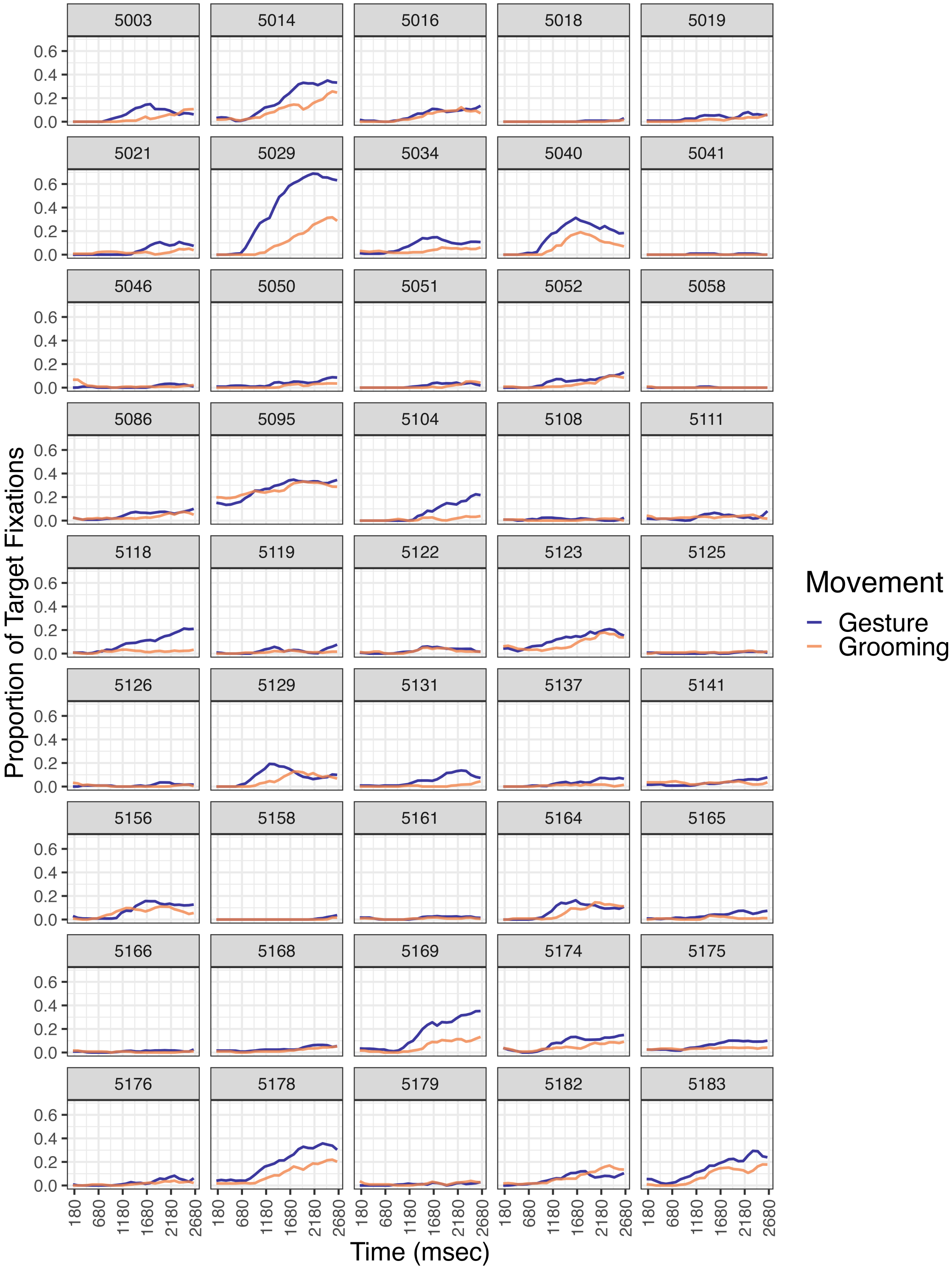

Figure C.2. Target fixations by movement type for individual participants in TBI group.