Playing with neurons: Identifying non-invasive tools for neural rehabilitation in aphasia

By

Juhi Kidwai
M.Sc., All India Institute of Speech and Hearing, India, 2014
B.Sc., All India Institute of Speech and Hearing, India, 2011

Submitted to the graduate degree program in the Dept. of Speech-Language-Hearing: Sciences and Disorders (Intercampus Program of Communicative Disorders) and the Graduate Faculty of the University of Kansas in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Chair: Jonathan Brumberg, Ph.D.

Susan T. Jackson, Ph.D.

Holly Storkel, Ph.D.

Steven Warren, Ph.D.

Robert Fiorentino, Ph.D.

Date Defended: 16 July 2021

The dissertation committee for Juhi Kidwai certifies that this is the
approved version of the following dissertation:

Playing with neurons: Identifying non-invasive tools for neural rehabilitation in aphasia

Chair: Jonathan S. Brumberg, Ph.D.

Date Approved: 16 July 2021

Abstract

Stroke rehabilitation necessitates assessment and intervention that addresses neural changes and language recovery after aphasia. Recently, there has been increased interest in direct neurological assessment through non-invasive electroencephalography, and intervention through non-invasive brain stimulation for post-stroke speech and language recovery. However, clinical practice is still far from widespread implementation of neuroimaging and neurostimulation in stroke intervention protocols. Further, there is lack of research exploring the perspectives of key stakeholders in managing language recovery through technological practices in non-fluent aphasia. The overarching aim of this dissertation was to describe ways of including technology for identifying neural changes and supporting neuroplasticity in post-stroke aphasia.

This dissertation has five chapters. Chapter one is the introduction that expresses the need of close examination of neural changes in stroke rehabilitation. Stroke is one of the leading causes of chronic disability worldwide resulting in serious economic and social consequences. Long-term effects of stroke include deficits in cognitive, linguistic, motor, and emotional domains. Rehabilitation of stroke has gradually progressed towards identifying disrupted neural patterns to eventually support neurorehabilitation that move a person close to pre-morbid levels of functioning. This chapter introduces the use of electroencephalography and non-invasive brain stimulation for a rehabilitation protocol that supports neuroplasticity through heavy involvement of technology in conventional speech and language treatment paradigms for linguistic recovery in post-stroke aphasia.

Chapter two is an electroencephalography study to identify whether changes in neural activity preceding spoken words can be used as objective markers of speech intention. This study specifically explored an event-related potential (ERP) in three speech production protocols in

healthy young adults with a future goal of identifying the nature of ERP in older adults and individuals with aphasia.

Chapter three is a scoping review to synthesize intervention research that uses high- tech augmentative and alternative communication (AAC) devices and non-invasive brain stimulation (NIBS) for aphasia rehabilitation. This study was aimed at identifying the clinical parameters for the implementation of AAC and NIBS. Specifically, the first evaluation was the current methods of access for high-tech AAC and methods of stimulation for NIBS. Secondly, this study recognizes the trend of incorporating technological intervention from acute to chronic stages of stroke recovery. Thirdly, it assesses the use of direct neurological assessment as an outcome measure for rehabilitation paradigms.

Chapter four is a survey study to investigate stakeholders' perspectives in using high-tech communication supports for aphasia rehabilitation. Specifically, it explores speech-language pathologists' preferences in using high-tech AAC devices for linguistic recovery in their clinical practice. In addition, the study also explores how AAC clinical practice differs in developed and developing countries to identify definite factors that can support clinicians in incorporating high-tech devices for post-stroke linguistic rehabilitation.

Chapter five concludes the dissertation by putting together the story of how electroencephalography can elicit event-related potentials (ERP) that can indicate speech intention in post-stroke aphasia. The specific ERP can be modulated through non-invasive brain stimulation and high-tech speech generating devices to stimulate appropriate feedback loops for errorless relearning of speech production.

Acknowledgments

Firstly, I’m deeply indebted to my brilliant advisor Dr. Jonathan Brumberg for patiently teaching me the difficult concepts of computational neuroscience and the ropes of academic writing. I would like to thank all my committee members, Dr. Holly Storkel, Dr. Steven Warren, Dr. Susan Jackson, and Dr. Robert Fiorentino for their unwavering encouragement and guidance in my path from an international speech-language pathology student to a research scholar. I wouldn’t have survived the last five years of a doctoral program in this country without my committee’s unrelenting support and belief in my work. I would like to thank Dr. Navin Viswanathan and Dr. Annie Olmstead for their continued support and kindness. Their insightful comments became my pointers for the cultural transition. I am grateful to my lab members Chavis Lickvar-Armstrong and Rebekah Manweiler who have helped at every step of research noted in this dissertation. In addition, I would like to thank all my friends who have walked alongside me and made this doctoral journey so much fun. Lastly, I want to acknowledge my parents and my sister who have been the wind under my wings and have ensured that I successfully complete every education endeavor I take on.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction to stroke-related speech and language deficits

‘Those who play rarely become brittle in the face of stress or lose the healing capacity.”

-Stuart Brown.

The quote from a famous medical researcher applies beautifully to neurons in the face of stroke. According to the World Health Organization and American Stroke Association, stroke can be described as a vascular etiology resulting in rapidly developing signs of cerebral dysfunction, spinal cord damage, and retinal cell death that can last a day or longer, leading to death (Sacco et al., 2013; Warlow, 1998). Stroke (also called cerebrovascular accident) can be broadly categorized into ischemic stroke and hemorrhagic stroke (Musuka, Wilton, Traboulsi, & Hill, 2015). Ischemic stroke occurs due to blood supply interruption and hemorrhagic stroke occurs due to blood vessel rupture, both leading to cell death in the affected brain area (Bamford, Sandercock, Dennis, Burn, & Warlow, 1991). Despite being the second leading cause of death globally, stroke has a high morbidity rate in chronic survivors making it a disease of immense public health importance (Donkor, 2018). Preventive measures and improved health care have considerably increased the number of stroke survivors leading to a rising global burden of disease and related disability (Avan et al., 2019; Platz, 2019).

Stroke-related disability often includes impairment of the language system leading to difficulty in expressing and comprehending language in verbal, written, or gestural mode. The acquired language impairment because of stroke in the dominant hemisphere is called aphasia, and it develops in about one-third of people who experience stroke (Benson & Ardila, 1996; Berthier, 2005; Engelter et al., 2006). The population with aphasia is heterogenous with individual profiles varying in the type and severity of language impairment. Since language is essential to human communication, aphasia as a disorder restricts participation in family, professional and community activities leading to a reduced quality of life (Ross & Wertz, 2003; Spaccavento et al., 2014). Aphasia severity especially for non-fluent types can range from occasional word-finding difficulty to having no effective word production. Along with language impairment, people with stroke-induced aphasia often have apraxia of speech, which is a motor speech deficit affecting their ability to plan and program speech motor movements (McNeil, 2009). The impact of aphasia and concomitant related disorders for individuals with aphasia and their family members highlights the importance of effective rehabilitation strategies to restore speech and language.

The time from the onset of stroke is divided into phases for recovery-related processes: a) hyperacute phase (first 24 hours), b) acute phase (first 7 days), c) early subacute phase (first 3 months), d) late subacute phase (4-6 months), e) chronic phase (>6 months) (Bernhardt et al., 2017). Neural reorganization begins within hours of stroke onset through neuroplastic mechanisms of axonal and dendritic sprouting for new synaptic formations (Carmichael, Wei, Rovainen, & Woolsey, 2001; Kitagawa, 2007). Spontaneous neural recovery is expected to occur in the first few weeks reaching a relative plateau around three months and ceasing at six months leading to a chronic deficit, especially for motor symptoms (Kwakkel, Kollen, van der Grond, & Prevo, 2003; Nishimura et al., 2007). However, there is considerable evidence for achieving improved speech and language outcomes through intervention much later in the chronic phase (Cramer, 2008; Johnson et al., 2019).

Even with growing treatment of acute stroke, a majority of individuals face long-term disability with a sizeable effect on their functional independence and quality of life (Grefkes & Fink, 2020). New strategies of improved neurorehabilitation are needed to alleviate the effects of stroke-related disability by focusing on post-stroke neural reorganization. It is important to further our understanding of neuroplasticity after stroke in order to develop novel strategies that promote functional neural recovery. Neuroimaging methods offer a unique opportunity for non-invasively revealing the spatiotemporal neural correlates of stroke recovery (Grefkes & Fink, 2011). Neural reorganization post-stroke can be achieved with training like any other learning task. Functional recovery through variable degrees of neural reorganization has been attained through conventional training-based intervention approaches like speech-language therapy or physical therapy and novel multimodal approaches like high-tech AAC and dance based therapy (Alankus, Lazar, May, & Kelleher, 2010; Demers & McKinley, 2015). A potential alternative for directly observing and possibly stimulating neural activity is through neuroimaging and non-invasive brain stimulation.

With the recent technological advances, electroencephalography (EEG) continues to be an excellent non-invasive method for assessing temporal neural corelates of speech and language processing. EEG uses scalp electrodes to measure electrical activity generated in large, synchronously-firing neuron populations through event-related potentials and sensorimotor rhythms (Light et al., 2010). Event-related potentials (ERPs) are neural electrical potentials generated in response to a specific event (e.g., speak a word, look at a picture of your dog) (Binnie & Prior, 1994; Luck, 2005). Sensorimotor rhythms are neurophysiological rhythmic activities generated in the sensorimotor cortex and can be modulated with respect to an internal or external event (e.g., sleep, motor imagery, articulatory movement) (Yuan & He, 2014). The EEG methodology involves averaging many time-locked experimental trials to probe linguistic processing with millisecond precision.

EEG offers a way to understand post-stroke cortical plasticity, which is the ability of the cerebral cortex to functionally reorganize as a consequence of learning and experience. Post-stroke cortical plasticity refers to mechanisms supporting neural reorganization to reinitiate functioning with the remaining undamaged brain. Non-invasive brain stimulation including transcranial magnetic stimulation and transcranial direct current stimulation are ways to modify post-stroke cortical plasticity by directly manipulating the excitability of the remaining neural networks. Transcranial magnetic stimulation generates a consistent series of magnetic pulses that stimulate the cortico-spinal neural mechanisms (Klomjai, Katz, & Lackmy-Vallée, 2015). Transcranial direct current stimulation induces subthreshold modulation of neuronal membrane potentials by passing low amplitude current through two scalp electrodes. The current dissertation explores electroencephalography for measuring speech processes likely affected by stroke, and the ways in which non-invasive brain stimulation and high-tech AAC are currently being used for enabling mechanisms of neuroplasticity and speech and language recovery in stroke-induced aphasia.

References

Alankus, G., Lazar, A., May, M., & Kelleher, C. (2010). *Towards customizable games for stroke rehabilitation*. Paper presented at the proceedings of the Special Interest Group for Computer-Human Interaction (SIGCHI) conference on human factors in computing systems, Atlanta, Georgia, USA.

Avan, A., Digaleh, H., Di Napoli, M., Stranges, S., Behrouz, R., Shojaeianbabaei, G., . . . Azarpazhooh, M. R. (2019). Socioeconomic status and stroke incidence, prevalence, mortality, and worldwide burden: an ecological analysis from the Global Burden of Disease study 2017. *BioMed Central Medicine, 17*(1), 191-202.

Bamford, J., Sandercock, P., Dennis, M., Burn, J., & Warlow, C. (1991). Classification and natural history of clinically identifiable subtypes of cerebral infarction. *Lancet, 337*(8756), 1521-1526.

Benson, D. F., & Ardila, A. (1996). *Aphasia: A clinical perspective*. New York, NY, US: Oxford University Press.

Bernhardt, J., Hayward, K. S., Kwakkel, G., Ward, N. S., Wolf, S. L., Borschmann, K., . . . Cramer, S. C. (2017). Agreed definitions and a shared vision for new standards in stroke recovery research: The stroke recovery and rehabilitation roundtable taskforce. *International Journal of Stroke, 12*(5), 444-450.

Berthier, M. L. (2005). Poststroke Aphasia. *Drugs & Aging, 22*(2), 163-182.

Binnie, C. D., & Prior, P. F. (1994). Electroencephalography. *Journal of Neurology, Neurosurgery, and Psychiatry, 57*(11), 1308-1319.

Carmichael, S. T., Wei, L., Rovainen, C. M., & Woolsey, T. A. (2001). New patterns of intracortical projections after focal cortical stroke. *Neurobiology of Disease*, *8*(5), 910-922.

Cramer, S. C. (2008). Repairing the human brain after stroke: I. Mechanisms of spontaneous recovery. *Annals of Neurology, 63*(3), 272-287.

Demers, M., & McKinley, P. (2015). Feasibility of delivering a dance intervention for subacute stroke in a rehabilitation hospital setting. *International Journal of Environmental Research and Public Health*, *12*(3), 3120-3132. Retrieved from https://www.mdpi.com/1660-4601/12/3/3120

Donkor, E. S. (2018). Stroke in the 21st century: A snapshot of the burden, epidemiology, and quality of life. *Stroke Research and Treatment*, *2018*, 235-245.

Engelter, S. T., Gostynski, M., Papa, S., Frei, M., Born, C., Ajdacic-Gross, V., . . . Lyrer, P. A. (2006). Epidemiology of aphasia attributable to first ischemic stroke: Incidence, severity, fluency, etiology, and thrombolysis. *Stroke, 37*(6), 1379-1384.

Grefkes, C., & Fink, G. R. (2011). Reorganization of cerebral networks after stroke: New insights from neuroimaging with connectivity approaches. *Brain*, *134*(5), 1264-1276.

Grefkes, C., & Fink, G. R. (2020). Recovery from stroke: current concepts and future perspectives. *Neurological Research and Practice*, *2*(1), 17-25.

Johnson, L., Basilakos, A., Yourganov, G., Cai, B., Bonilha, L., Rorden, C., & Fridriksson, J. (2019). Progression of aphasia severity in the chronic stages of stroke. *American Journal of Speech Language Pathology*, *28*(2), 639-649.

Kitagawa, K. (2007). CREB and cAMP response element-mediated gene expression in the ischemic brain. *The Federation of European Biomechanical Societies Journal, 274*(13), 3210-3217.

Klomjai, W., Katz, R., & Lackmy-Vallée, A. (2015). Basic principles of transcranial magnetic stimulation (TMS) and repetitive TMS (rTMS). *Annals of Physical and Rehabilitation Medicine, 58*(4), 208-213.

Kwakkel, G., Kollen, B. J., van der Grond, J., & Prevo, A. J. (2003). Probability of regaining dexterity in the flaccid upper limb: Impact of severity of paresis and time since onset in acute stroke. *Stroke, 34*(9), 2181-2186.

Light, G. A., Williams, L. E., Minow, F., Sprock, J., Rissling, A., Sharp, R., . . . Braff, D. L. (2010). Electroencephalography (EEG) and event-related potentials (ERPs) with human participants. *Current Protocols in Neuroscience,6,*1-24.

Luck, S. (2005). *An Introduction to The Event-Related Potential Technique*. Cambridge, MA: The MIT Press.

McNeil, M. R. (2009). *Clinical management of sensorimotor speech disorders*. New York, NY*:* Thieme.

Musuka, T. D., Wilton, S. B., Traboulsi, M., & Hill, M. D. (2015). Diagnosis and management of acute ischemic stroke: speed is critical. *Canadian Medical Association Journal, 187*(12), 887-893.

Nishimura, Y., Onoe, H., Morichika, Y., Perfiliev, S., Tsukada, H., & Isa, T. (2007). Time-dependent central compensatory mechanisms of finger dexterity after spinal cord injury. *Science, 318*(5853), 1150-1155.

Platz, T. (2019). Evidence-based guidelines and clinical pathways in stroke rehabilitation—An international perspective. *Frontiers in Neurology, 10*(200), 25-39.

Ross, K., & Wertz, R. (2003). Quality of life with and without aphasia. *Aphasiology, 17*(4), 355-364.

Sacco, R. L., Kasner, S. E., Broderick, J. P., Caplan, L. R., Connors, J., Culebras, A., . . . Higashida, R. T. (2013). An updated definition of stroke for the 21st century: A statement for healthcare professionals from the American Heart Association/American Stroke Association. *Stroke, 44*(7), 2064-2089.

Spaccavento, S., Craca, A., Del Prete, M., Falcone, R., Colucci, A., Di Palma, A., & Loverre, A. (2014). Quality of life measurement and outcome in aphasia. *Neuropsychiatric Disease and Treatment, 10*, 27-37.

Warlow, C. (1998). Epidemiology of stroke. *The Lancet, 352*, S1-S4.

Yuan, H., & He, B. (2014). Brain-computer interfaces using sensorimotor rhythms: Current state and future perspectives. *Institute of Electrical and Electronics Engineers (IEEE) Transactions on Biomedical Engineering, 61*(5), 1425-1435.

Chapter 2: Using electroencephalography to identify speech intention

Introduction

Speech production is a complex process driven by a speaker’s communicative intent to translate ideas and thoughts for a listener and respond to others (Bara, 2010; Grice, 1975; Sperber & Wilson, 1995). The process of speech production consists of many overlapping components and has been studied from a range of theoretical contexts that tend to focus on specific parts of the whole process (Hickok, 2014). For instance, prior models of speech production have focused on linguistic aspects (Dell, Burger, & Svec, 1997; Indefrey & Levelt, 2004; Levelt, Roelofs, & Meyer, 1999), whereas others have focused on sensorimotor control (Golfinopoulos, Tourville, & Guenther, 2010; Guenther, Ghosh, & Tourville, 2006). An integrated model of speech production often interfaces between its linguistic and sensorimotor control components (Civier, Bullock, Max & Guenther, 2013; Hickok, 2012).

The goal of this pilot study was to identify an electrophysiological neural marker that represents a connection between linguistic and motor processes during speech production for the eventual goal of assessing speech and language function in aphasia. Many integrated models of verbal communication use an intention signal to begin linguistic processing that converts communicative thoughts into linguistic units (Foygel & Dell, 2000; Hickok, 2012; Walker & Hickok 2016). As a word is selected during linguistic processing, lexical-auditory and lexical-motor targets are generated that work through feedforward and feedback loops in the dynamic articulatory motor system for word production (Walker & Hickok, 2016).

In a general model illustrating the components of speech production (Figure 1), speech intention forms a vital link between overlapping linguistic (Levelt, Roelofs, & Meyer, 1999) and motor speech processes (Guenther, 2016; van Der Merwe, 1997), and if severed can result in

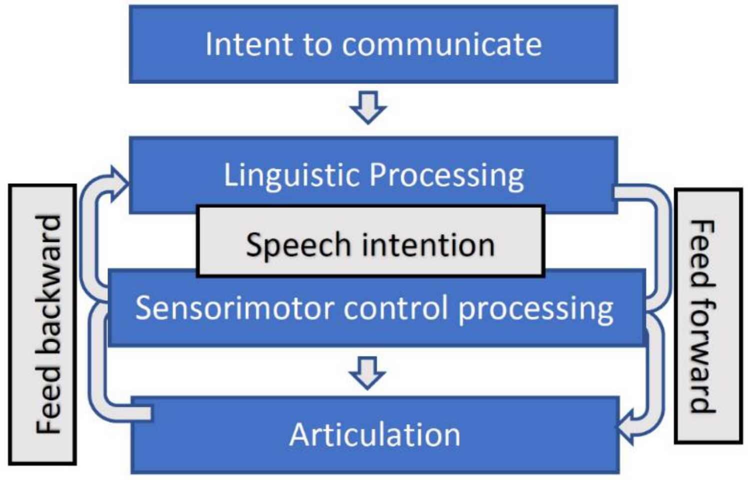

Figure 1: A general model of speech production highlighting speech intention

disrupted speech production. In this type of model, message compilation in linguistic processing involves morphosyntactic and phonological planning that is transmitted to the motor speech system for generating a motor program. This feedforward system is accompanied by a feedback system that integrates auditory and somatosensory information of the executed motor commands for comparison with intended speech and linguistic targets (e.g., Guenther, 2016). Key to this functionality is a simultaneous process of speech intention that facilitates feedforward communication between the linguistic and speech-motor subsystems.

An objective measure of speech intention may help improve our understanding of the relationships between neural processes involved in language and speech production and narrow the effects of neural dysfunction to linguistic-only (prior to speech intention), speech-only (following speech intention), or the transition between the two processes (the intention process itself). Speech intention is being proposed as the transitional stage in which linguistic commands are transferred to the motor speech system for planning and programming. A general consensus is that linguistic-only processes are affected in aphasia and speech-only processes are affected in apraxia of speech (Dronkers, Ivanova, & Baldo, 2017). If linguistic-only processes are treated through conventional speech-language therapy, then there is a possibility that difficulty in utterance of a trained word can be attributed to speech intention process. Electroencephalography (EEG) is one objective measure of brain function that can be used to examine the transition stage of speech intention in the midst of the rapidly and simultaneously occurring linguistic and speech motor processes (Beres, 2017). Specifically, the contingent negative variation (CNV), an event-related potential that reflects anticipation of a motor response, is particularly well-suited with prior known effects due to speech and language production (Ning, Peng, Liu, & Yang, 2017; Vanhoutte et al., 2016; Vanhoutte et al., 2015; Wu & Thierry, 2017).

The contingent negative variation (CNV) is an electroencephalographic slow cortical potential observed during a two-cue motor paradigm where the second (S2), imperative stimulus is contingent on a first (S1), warning stimulus (Walter, Cooper, Aldridge, McCallum, Winter, 1964). The first (warning) stimulus elicits an early orienting response with a late expectancy wave generated prior to the second, imperative stimulus (Loveless & Sanford, 1974; Rohrbaugh, Syndulko, & Lindsley, 1976). The slope or mean amplitude of the late CNV portion occurring just before S2 represents preparation for a motor act like moving your arm (Bareš, Nestrašil, & Rektor, 2007; Birbaumer, Elbert, Canavan, Rockstroh, 1990; Fan et al., 2007; McCallum, 1988). While the CNV was originally reported to indicate anticipation and preparation of a motor response (Walter et al., 1964), it has been recently observed during expectation and anticipation of a linguistic stimulus (Mnatsakanian & Tarkka, 2002; Tarkka & Basille, 1998) and behavioral performance and perceptual timing (e.g., decision-making between auditory signals as ‘short’ or ‘long’, He & Zempel, 2013). The CNV is also sensitive to anticipation of complex speech movements compared to simple lip stretching and rounding, which further supports its use in measuring speech intention (Wohlert, 1993). The late CNV component was chosen in this pilot study to investigate speech intention as the transitional link between linguistic and sensorimotor control as suggested in Figure 1, since speech intention may be represented as an anticipation or expectancy of speech-motor control (e.g., imperative stimulus) contingent on some speech production task (e.g., warning stimulus). In the current study, the slope of the late CNV component was the primary dependent measure of speech intention in order to capture overall trends in greater negativity associated with prominent late CNV components, rather than average amplitude that may be affected by earlier components of the CNV.

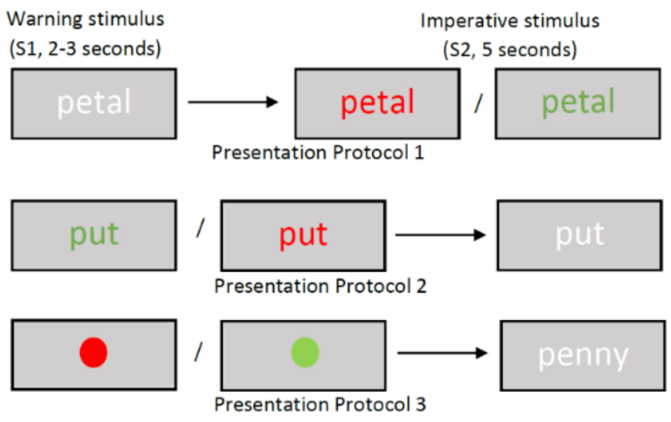

Figure 2: Presentation protocols to elicit the CNV and a flow of stimulus presentation as seen by the participants

For the current investigation, three different visual presentation protocols were used to elicit the CNV in response to speech intention that varied the amount and type of information available to participants at the warning and imperative stimuli of the classical CNV paradigm. By varying the amount, type, and timing of information in our three different stimulus presentations, the goal was to determine the combination that invoked the greatest CNV negativity (i.e., steepest slope reflecting speech intention) for a spoken word production task. In each of the protocols, the warning stimulus (S1) was used to indicate the decision to speak, the word to speak, or both, once the imperative stimulus (S2) appeared. As the CNV is maximally negative prior to the imperative stimulus (S2), it was hypothesized that the presence of a CNV prior to speaking (S2), and differences between the Go/NoGo trials, are an indication of speech intention and transmission of linguistic commands to the motor speech system. In particular, greater differences in CNV slope between speaking trials versus not speaking was predicted for Protocols 2 and 3 in which the decision to speak is made during the warning stimulus (S1) representing speech and language planning and anticipation of word production, respectively, compared to Protocol 1 where participants did not know if they would have to speak the word or withhold response until the imperative stimulus (S2) appeared. Further, Protocol 2 provided both the instruction to speak and the word to speak at the warning stimulus (S1), which was designed to represent rehearsal and speech intention processing (Ludyga et al., 2018; Vanhouttte et al., 2014) whereas Protocol 3 presented the instruction to speak (S1) before the word presentation (S2) and was designed to prime the speech intention system only. Protocol 1 was designed similar to previous CNV experiments in which the word was provided before the instruction to speak; this protocol reflects a general motor gating (Wohlert, 1993). A summary of the paradigm differences is shown in Table 1.

Table 1: Hypothesized linguistic and speech-motor processing at the warning (S1) and imperative (S2) stimuli as well as the S1-S2 interval for each protocol in the present study

Protocol	**S1 processing**	**S2 processing**	**S1-S2 interval processing**
Protocol 1	Linguistic	Speech-motor + gating	General motor preparation
Protocol 2	Linguistic and speech-motor	Gating only	Rehearsal, speech preparation
Protocol 3	Speech-motor	Linguistic + gating	Speech preparation / initiation

Materials and method

Participants. Eighteen healthy young adults in the age range of 18-36 years (M= 24.6; SD= 4.27) were recruited into three groups of six participants each for the three presentation protocols (9 females, 9 males, all right-handed). All participants were fluent speakers of American English with self-reported normal or corrected vision, speech, language, and hearing and no reported neurological or neuromotor complaints. All participants provided their written informed consent to participate in our study that was approved by the Institutional Review Board of the University of Kansas. Data from one participant was not included in this analysis due to technical recording errors during data collection, leaving data from 17 participants for further analysis.

Presentation Protocols. The three presentation protocols investigated in this study (shown in Figure 2) varied the information presented to participants at each of the two stimulus cues - warning and imperative. In the first presentation protocol, the warning stimulus (S1) included only word information (colored white) for participants who then received an imperative stimulus (S2) to either speak (change to green) or withhold response (change to red) and should elicit responses for motor preparation and gating. The CNV is most commonly elicited in paradigms such as this, where the participant receives an S1 stimulus to orient to the task and then performs the task at S2 (Kowalski et al., 2018; Lasaponara, Glicksohn, Mauro, Ben-Soussan, 2019; Neuhaus, 2019; Ning, Peng, Liu, & Yang, 2017). In the second presentation protocol, the warning stimulus (S1) provided both the word and the task instruction to speak (green-colored) or to withhold response (red-colored) at the imperative stimulus (S2) at which time the word color changed to white. We hypothesized participants would practice the target word through mental rehearsal processes as well as engaging speech intention. Protocol 2 is very similar to other CNV paradigms focused on speech and language production where the participant is aware of the exact word (S1) to be produced at a later time (S2) (Ludyga et al., 2018; Vanhouttte et al., 2014; Vanhoutte et al., 2016; Vanhoutte et al., 2015). In the third presentation protocol, we combined the motor initiation and speech-focused qualities of the first two protocols to focus in on speech-specific initiation processing without confounding mental rehearsal. This protocol is a novel protocol prepared for this study. For the third protocol, participants viewed a green or red colored circle warning stimulus (S1) that instructed participants to either speak or withhold response for a target word provided at the imperative stimulus (S2) through a change in color to white. By providing only the instruction to speak without content, participants can only prime the speech production and initiation systems without rehearsal. The third presentation protocol follows a novel paradigm to elicit CNV associated with speech motor preparation by defining the task at S1 and then providing the word at S2 (cf. Maxfield, Morris, Frisch, Morphew, & Constantine, 2015; Wu & Thierry, 2017), eliminating linguistic rehearsal focusing on speech-motor anticipation and intention. All three protocols recorded the CNV before speech production to eliminate contamination of the recorded EEG due to electromyographical artifacts associated with orofacial muscle contractions during speech production.

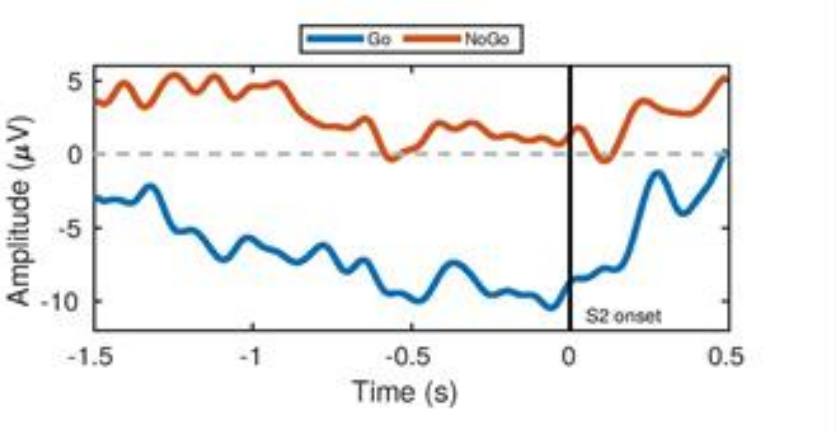

Figure 3: Example of the contingent negative variation for Go (blue) and NoGo (red) trials.

Stimuli. A total of 90 different words were included in this study each beginning with an initial /p/ to help minimize orofacial artifacts. The words were grouped according to three syllable structures (CVC, CVCV, CVCVC) and three levels (low, medium, high) of word frequency of occurrence in the English language as determined by SUBTLEX$_{US}$ (Brysbert & New, 2009) and randomly presented through PsychoPy (Peirce et al., 2019). All words were repeated twice, once each for Go and NoGo conditions for a total of 180 trials.

Procedure. EEG recordings took place in a sound-treated booth using 62 active electrodes (g.HIamp, Guger Technologies) arranged uniformly according to the 10-10 standard (Oostenveld and Praamstra, 2001). In the first presentation protocol, the participants were presented with a white-colored word warning stimulus (S1) on the screen, then instructed to speak immediately at the imperative stimulus (S2) if the color of the word changed to green, or withhold their response if the color of the word changed to red. For the second presentation protocol, participants were presented with a green- or red-colored word on the screen at the warning stimulus (S1). If the word color was green, participants were instructed to immediately speak the word aloud when it turned white at the imperative stimulus (S2), and to withhold their response at the imperative stimulus if the initial word color was red. For the third presentation protocol, participants were presented with a green- or red-colored circle in the center of the screen at the warning stimulus (S1). If the circle was green, then participants were to speak the upcoming white-colored word presented at the imperative stimulus (S2) displayed on the screen, and to remain silent if the circle was red. In all protocols, the warning stimulus was presented for a random duration between 2 to 3 seconds followed by the imperative stimulus (S2), which stayed on the screen for 5 seconds. Each trial was separated by a 4-second blank-screen interval (Figure 2).

EEG analysis. EEG analysis was performed in MATLAB and statistical analyses in R. EEG data were recorded at a sampling rate of 512 Hz referenced to the left earlobe with a ground electrode placed on the forehead just below location AFz. A visual synchronization marker was additionally presented in PsychoPy and recorded simultaneously with the EEG signals by a photodiode to ensure precise alignment of each trial and stimulus (imperative and warning). The resultant signals were band-pass filtered from 0.1 to 30 Hz and downsampled to 128 Hz after which ocular artifacts were removed using Independent Component Analysis (Bell & Sejnowski, 1995) where independent components were removed by visual inspection for wave morphology, power spectral density, and spatial concentration around electrodes over the eyes and forehead. The continuous signal was separated into epoch windows of 1.5 seconds that included the time range from 1.5 seconds before the imperative stimulus, with baseline correction using the mean amplitude in the 0.5 seconds prior to the warning stimulus of each trial. Since the trials were separated by a 4-second blank interval, we were able to use a relatively long baseline period (0.5 s) to improve stability of the baseline while avoiding possible influences from the previous trial.

Statistical Analysis. Preprocessed EEG data from sixteen participants (N = 6, Protocol 1; N = 6, Protocol 2; N = 5, Protocol 3) was analyzed to first derive a subject average CNV separately for Go/NoGo trials for 15 EEG channels with hemisphere location Left (electrode ID 3), Right (electrode ID 4), Midline (electrode ID z), and scalp locations FC, F, C, CP and P according to the 10-10 standard. Slopes were computed from the linear regression of participant average CNV responses in Go and NoGo trials separately in the interval -1.5 to 0 s relative to S2 and their difference computed as the dependent measure for statistical analysis. The slope was taken as a measure of increasing CNV negativity with differences in slope indicating differences in processing between Go and NoGo trials. Statistical analysis was performed for the 15 EEG channels per participant grouped according to laterality, left, center (midline), and right. A mixed effects model was used to evaluate the main effects of protocol type and hemispheric laterality and their interaction, with participant ID as a random factor. Statistically significant results at $p < .05$ were separately examined in post-hoc comparisons using Tukey's adjustment method.

Results

An example of a CNV response for Go and NoGo conditions is shown in Figure 3 where the average of all Go trials is shown in blue and NoGo in red that demonstrates amplitude decreasing toward the S2 alignment point (e.g., negative slope). A summary of average CNV slope differences is represented through box plots with mean values (black dots) for each electrode for each subject in Figure 4. Although our protocol included target words of a variety of frequencies and complexities, an initial analysis revealed no statistically significant effects of syllable structure and word frequency on the CNV and are not discussed in the remainder of these results. There was a main effect of hemispheric laterality (F (2,232) = 7.30, *p* = .03) and an interaction effect of protocol and hemispheric laterality (F (4, 232) = 2.98, *p* = .01) for CNV slope differences. Though a main effect of protocol was not significant (F(2,14) = 2.25, p = 0.38), post-hoc comparisons of slope differences revealed the statistically significant main effect of hemisphere and the interaction effect was driven by statistically significant differences between right and left hemisphere electrodes (left: 0.139 µV/s, right: -0.632 µV/s: t (232) = 2.59, *p* = .028) and between right hemisphere and center electrodes (right: -0.632 µV/s, center: 0.175 µV/s : t (232) = 2.71, *p = .020*) in Protocol 3. These values suggest a main result that the CNV differences for Go and NoGo conditions occur most reliably in Protocol 3. Additionally, these results show that right hemisphere electrodes appear to be consistently more negative-going (due to negative slope) than midline and left electrodes, which is corroborated by visual inspection of grand average CNV responses by protocol and laterality (Figures 5a-d).

Discussion

This study evaluated speech motor preparatory activity as reflected by the CNV preceding spoken words. Specifically, speech intention was examined by the slope of the late CNV response elicited in a word production task. The analysis focused on determining the factors in each of three presentation protocols that differed in the amount and type of information provided to participants at the warning and imperative stimuli of a classical CNV paradigm for maximizing differences in the late CNV component between Go and NoGo trial conditions. Our main hypothesis was that Protocol 1 would reflect general motor preparation and gating, Protocol

2 would reflect mental rehearsal, and Protocol 3 would reflect priming for intention to speak in healthy individuals.

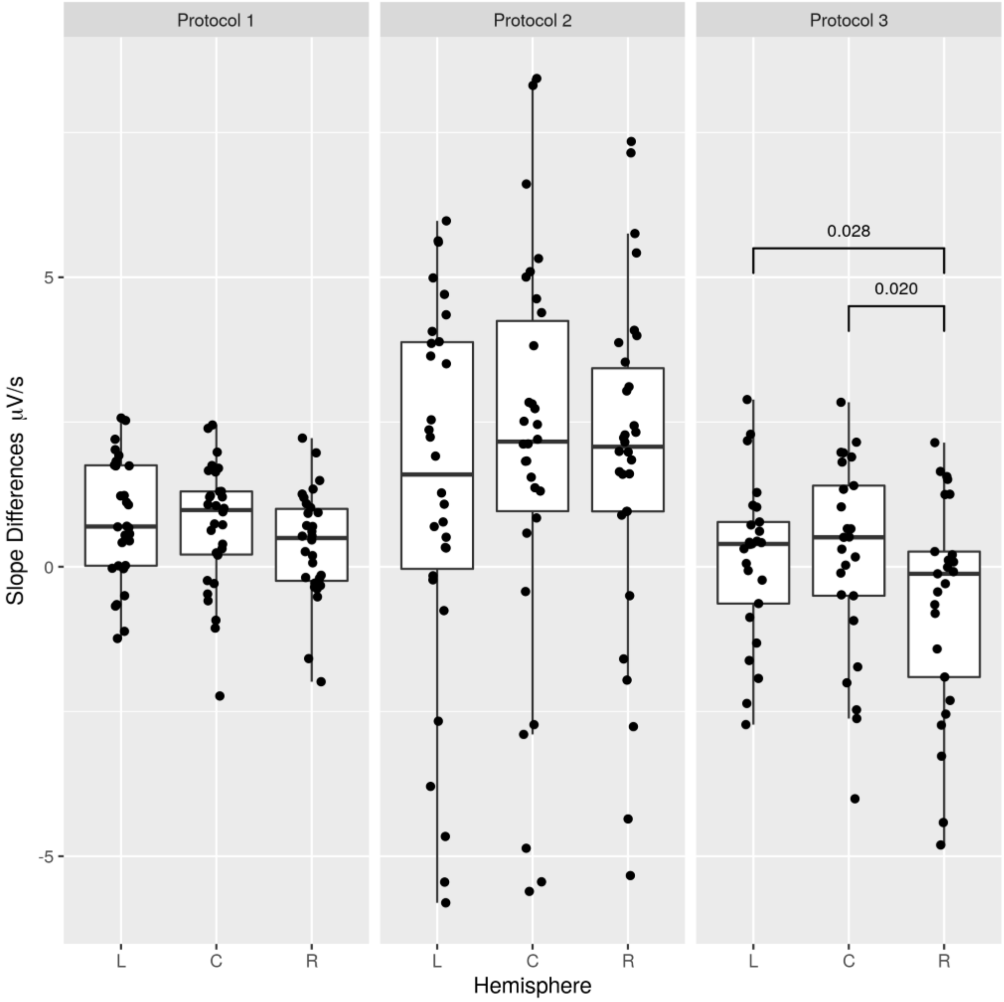

Figure 4: Summary of average CNV slope difference for each protocol (1-3) and electrode location by hemisphere (L: left, R: right, C: center/midline) with p-values provided for multiple comparisons testing. The data points represent the electrode channels for each subject.

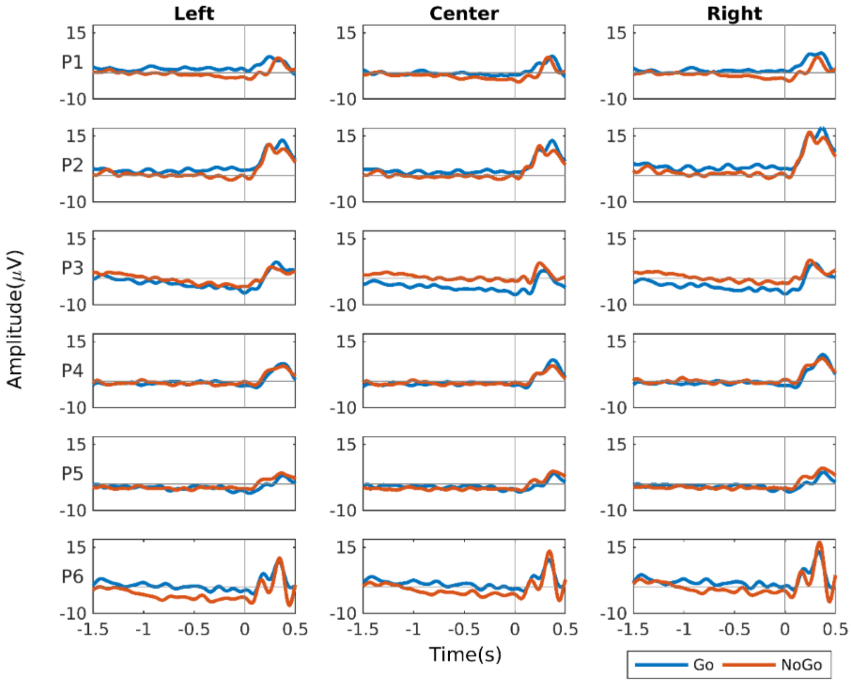

Figure 5a: Participant average CNV waveforms for Go and NoGo trials for individual participants from Protocol 1. The waveforms are aligned to S2 onset (0 seconds on x-axis).

This research note is narrowly focused on investigating the CNV response as a possible objective measure for quantifying speech intention. The larger goal is to validate this measure with future study of Protocol 3 for use in tracking speech intention through the complex and overlapping processes involved in fluent speech production as well as speech production in adverse conditions, such as mismatches between feedback and expectations and in populations with difficulty initiating and producing expressive speech and language. The CNV has been used previously to assess motor intention and speech preparation; therefore, it is ideally suited to quantitatively measure intentional processes in speech (Ning et al., 2017; Vanhoutte et al., 2016; Vanhoutte et al., 2015; Wu & Thierry, 2017). Thus, the goal of the current pilot study was to identify a CNV paradigm that maximized CNV differences between spoken utterances (Go) and silence (NoGo), and reflects speech intentional processes between the warning and imperative stimulus as a reflection of the link between linguistic and motor speech processes during speech production.

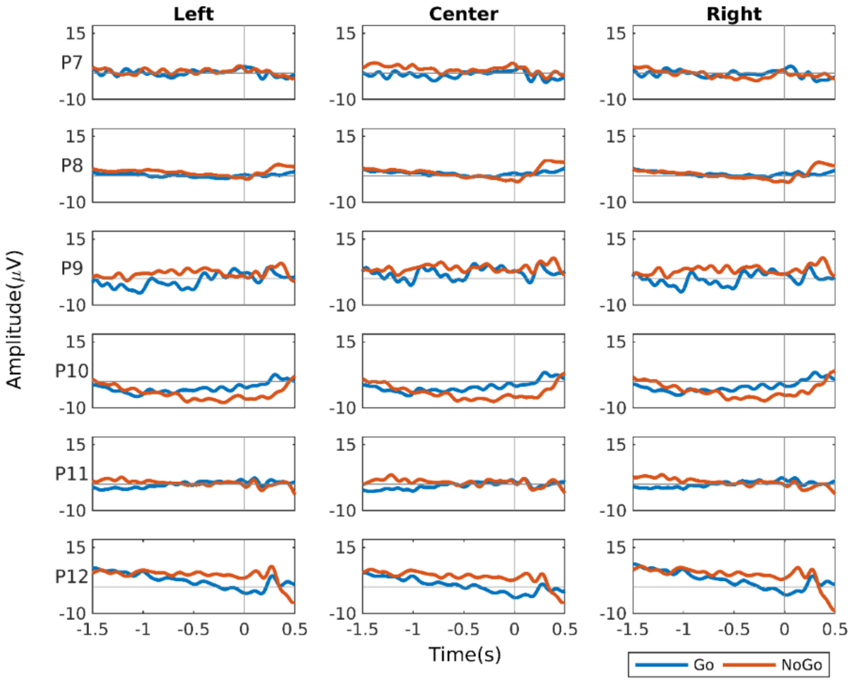

Figure 5b: Participant average CNV waveforms for Go and NoGo trials for individual participants from Protocol 2. The waveforms are aligned to S2 onset (0 seconds on x-axis).

For this pilot study, only Protocol 3 resulted in statistically significant differences between Go and NoGo trials in terms of the average differences between Go / NoGo CNV waveform slopes for hemispheric laterality comparisons between left and right, and center and right electrodes. Protocol 2 provided participants with both the task goal and the target word content at S1, where participants likely used the warning-imperative stimulus interval to rehearse the target word as well as prime for production at the imperative stimulus possibly confounding observation of the intention signal alone. Since all three protocols involved a speaking task, it may be assumed that speech preparation is a default process during the S1-S2 interval but Protocols 1 and 2 are burdened with additional linguistic processing of the word stimulus. The combination of default speech preparation and linguistic processing in Protocol 2 may be why we did not see reliable effects of Go/NoGo slope differences as were observed in Protocol 3, which were counter to our initial hypotheses.

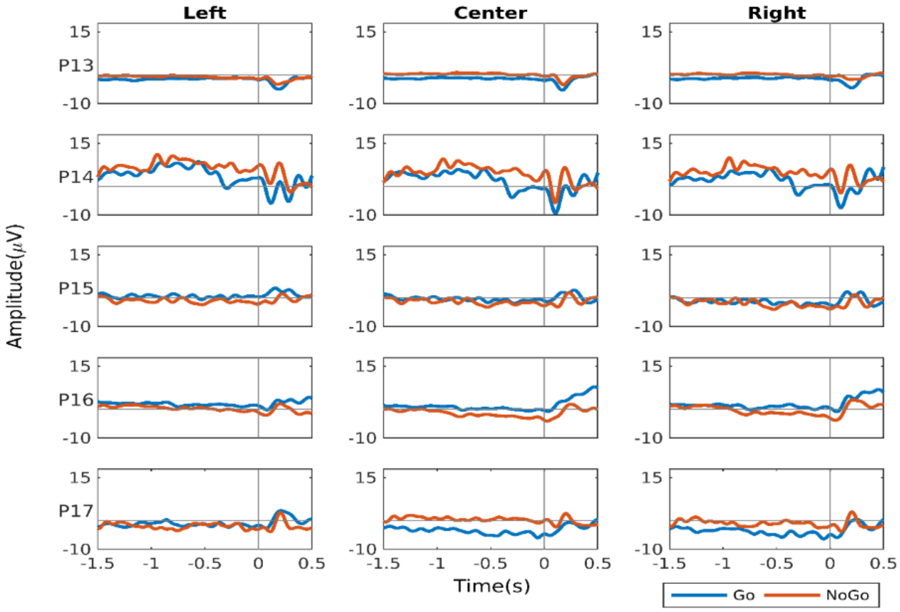

Figure 5c: Participant average CNV waveforms for Go and NoGo trials for individual participants from Protocol 3. The waveforms are aligned to S2 onset (0 seconds on x-axis).

On the other hand, Protocol 3 provided information about task goals (to speak or to remain silent) at the warning stimulus but withheld the content of the word to be spoken until the imperative stimulus. As a result, participants engaged in both linguistic and speech motor processing at S2 and were limited to priming their production systems to process the upcoming stimulus during the warning-imperative stimulus interval. The hemispheric laterality effects seen in Protocol 3 may be attributed to anticipation of the word on the screen or execution of the decision-making process or a general intent to communicate, which are all related to the speech intention process. Finally, Protocol 1 provided the target word without the task goal at the warning stimulus, so participants may have rehearsed the target word without priming/initiating the production system.

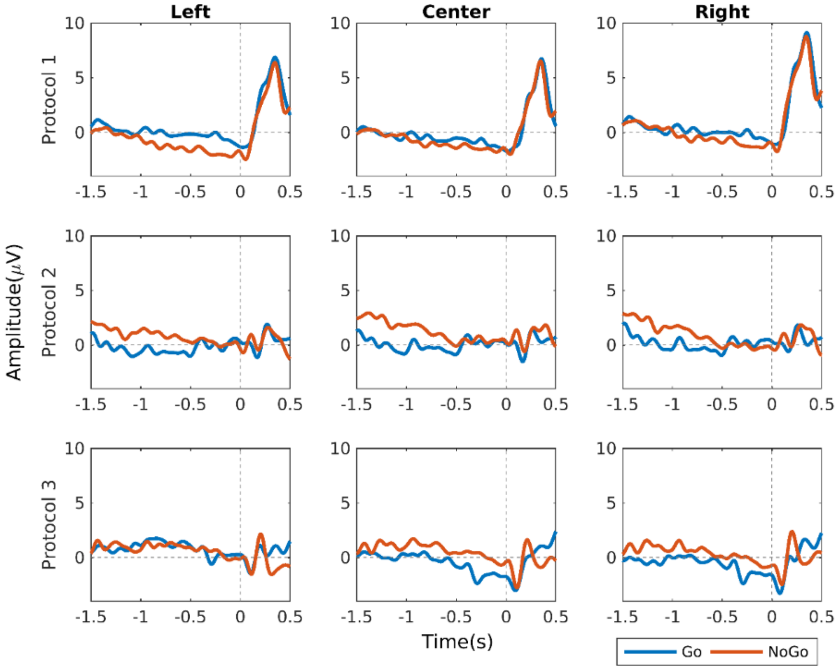

Figure 5d: Grand average CNV for Go and NoGo trials each protocol by hemisphere laterality. The waveforms are aligned to S2 onset (0 seconds on x-axis).

Based on our criteria, the results of this pilot work suggest using Protocol 3 to isolate neural processes of speech intention for further investigation in healthy young participants, and others including those with difficulty initiating expressive productions as opposed to Protocol 2, which is unable to separate the overlapping functions of linguistic processing and speech intention. Finding an objective neural marker of speech intention will provide a way to quantify speech intention in current models of speech production and track intentional mechanisms through the complex overlapping processes involved in speech production.

Successful identification of the CNV as an objective marker of speech intention may help describe the speech and language deficits associated with stroke-induced aphasia, particularly non-fluent aphasia. The deficit in non-fluent aphasia is thought to be in linguistic processing with a relatively intact motor speech system (Bareš, Nestrašil, & Rektor, 2007; Gainotti, Miceli, Silveri & Villa, 1982). Through speech-language therapy, individuals with non-fluent aphasia improve their linguistic processing but continue to have difficulty verbalizing practiced words. So, a question arises of the specific process underlying persistent speech production deficits in non-fluent aphasia associated with stroke. The identification of speech intention through CNV in non-fluent aphasia can be assessed for the transmission of linguistic commands to the motor system to explain whether the deficit in non-fluent aphasia is only in linguistic processing or in both linguistic processing and transmission of linguistic commands to the motor system. Also, if CNV reflects speech intention just prior to the motor speech processing, then it can also be used as an objective marker for rehabilitation in apraxia of speech. Additionally, CNV can also be used as an objective neural marker for speech intention and a way to measure progress even if both aphasia and apraxia of speech co-exist post-stroke. The current study is however, conducted to determine feasibility and an optimal protocol to establish CNV as a neural marker for speech intention in a healthy population.

Conclusion

The current study examines speech intention as a transition process between lexical processing and speech motor production with distinct neural components that can be quantified using an electrophysiological marker. The findings of our pilot study provide evidence for speech intentional processes through EEG evaluation of three speech production paradigms eliciting a CNV response. Using the CNV paradigm, we were able to manipulate the type and amount of information provided to participants as they prepared to speak and then executed speech motor production. The paradigm that maximized differences in CNV slopes between Go and NoGo trials targeted speech intention processes by providing participants only with information about the task goal and withheld the production stimulus until a later time. This paradigm configuration forced participants to limit their preparatory activities to priming and initiating speech production. These findings for Protocol 3 not only provide a way to quantify and track intentional mechanisms as the link between linguistic and speech processes using EEG in healthy individuals, but also may provide an important measure for assessment in individuals with difficulty producing / initiating speech, such as those with non-fluent aphasia who know the word they wish to speak but are unable to produce it. The identification of speech intention in individuals who have had a stroke with resultant speech disruption may be used to investigate whether the disruption is primarily in linguistic processing, speech motor processes, or their link.

References

Bara, B. G. (2010). *Cognitive pragmatics-The mental process of communication*. Cambridge, MA: The MIT Press.

Bareš, M., Nestrašil, I., & Rektor, I. (2007). The effect of response type (motor output versus mental counting) on the intracerebral distribution of the slow cortical potentials in an externally cued (CNV) paradigm. *Brain Research Bulletin, 71*(4), 428-435.

Bell, A. J., & Sejnowski, T. J. (1995). An information-maximization approach to blind separation and blind deconvolution. *Neural Computation*, *7*(6), 1129–1159.

Beres, A. M. (2017). Time is of the essence: A review of electroencephalography (EEG) and event-related brain potentials (ERPs) in language research. *Applied Psychophysiology and biofeedback*, *42*(4), 247-255.

Birbaumer, N., Elbert, T., Canavan, A. G., & Rockstroh, B. (1990). Slow potentials of the cerebral cortex and behavior. *Physiological Reviews, 70*(1), 1-41.

Brysbert, M., & New, B. (2009). Moving beyond Kucera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods, 41*, 977-990.

Civier, O., Bullock, D., Max, L., & Guenther, F. H. (2013). Computational modeling of stuttering caused by impairments in a basal ganglia thalamo-cortical circuit involved in syllable selection and initiation. *Brain and language*, *126*(3), 263-278.

Dell, G. S., Burger, L. K., & Svec, W. R. (1997). Language production and serial order: a functional analysis and a model. *Psychological review, 104*(1), 123–147.

Dronkers, N. F., Ivanova, M. V., & Baldo, J. V. (2017). What do language disorders reveal about brain-language relationships? From classic models to network approaches. *Journal of the International Neuropsychological Society : JINS, 23*(9-10), 741-754

Fan, J., Kolster, R., Ghajar, J., Suh, M., Knight, R. T., Sarkar, R., & McCandliss, B. D. (2007). Response anticipation and response conflict: An event-related potential and functional magnetic resonance imaging study. *The Journal of Neuroscience, 27*(9), 2272-2282.

Foygel, D., & Dell, G. S. (2000). Models of impaired lexical access in speech production. *Journal of Memory and Language, 43*(2), 182-216.

Gainotti, G., Miceli, G., Silveri, M. C., & Villa, G. (1982). Some anatomo-clinical aspects of phonemic and semantic comprehension disorders in aphasia. *Acta Neurologica Scandinavica, 66*(6), 652-665.

Golfinopoulos, E., Tourville, J. A., & Guenther, F. H. (2010). The integration of large-scale neural network modeling and functional brain imaging in speech motor control. *Neuroimage*, *52*(3), 862–874.

Grice, H. P. (1975). Logic and conversation. In P. Cole & J. L. Morgan (Eds.), *Syntax and semantics: Speech acts* (Vol. 3, pp. 41–58). New York, NY: Academic Press.

Guenther, F.H. (2016). *Neural control of speech.* Cambridge, MA: MIT Press.

Guenther, F. H., Ghosh, S. S., & Tourville, J. A. (2006). Neural modeling and imaging of the cortical interactions underlying syllable production. *Brain and Language*, *96*(3), 280–301.

He, B. J., & Zempel, J. M. (2013). Average is optimal: an inverted-U relationship between trial-to-trial brain activity and behavioral performance. *PLoS Computational Biology*, *9*(11), e1003348.

Hickok, G. (2012). Computational neuroanatomy of speech production. *Nature Reviews Neuroscience*, *13*(2), 135-145.

Hickok, G. (2014). The architecture of speech production and the role of the phoneme in speech processing. *Language, Cognition, and Neuroscience*, *29*(1), 2-20.

Indefrey, P. & Levelt, WJM (2004). The spatial and temporal signatures of word production components. *Cognition*, *92*(1), 101-144.

Kowalski, J. T., Falkenhagen, F., Radtke, Y., Niederberger, U., Petermann, F., Darabaneanu, S., Steinmann, E.,Gerber, W., & Siniatchkin, M. (2018) Contingent negative variation in acute trauma patients: A prospective exploratory study. *Biological Psychology*, *138*, 126-132.

Lasaponara, S., Glicksohn, J., Mauro, F., Ben-Soussan, T.D. (2019). Contingent negative variation and P3 modulations following mindful movement training. *Progress in Brain Research, 244*, 101-114.

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences, 22*(1), 1-75.

Loveless, N. E., & Sanford, A. J. (1974). Effects of age on the contingent negative variation and preparatory set in a reaction-time task. *Journal of Gerontology, 29*(1), 52-63.

Ludyga, S., Herrmann, C., Mücke, M., Andrä, C., Brand, S., Pühse, U., & Gerber, M. (2018). Contingent negative variation and working memory maintenance in adolescents with low and high motor competencies. *Neural Plasticity, April.*

Maxfield, N. Morris, K., Frisch, S. A. Morphew, K., Constantine, J.L. (2015). Real-time processing in picture naming in adults who stutter ERP evidence. *Clinical Neurophysiology, 126*(2), 284 -296.

McCallum, W. (1988). Potentials related to expectancy, preparation, and motor activity. In Picton, T. (Ed.), *Handbook of electroencephalography and clinical neurophysiology: Revised series* (Vol.3, pp.427–534). New York, NY: Elsevier.

Mnatsakanian, E., & Tarkka, I. (2002). Task-specific expectation is revealed in scalp-recorded slow potentials. *Brain Topography, 15*, 87-94.

Neuhaus, C. (2019). “You should praise” – “You should kill”: The contingent negative variation indicates moral goodness and badness. *Frontiers in Human Neuroscience*, *13*, 1-15.

Ning, N., Peng, D., Liu, X., & Yang, S. (2017). Speech timing deficit of stuttering: Evidence from contingent negative variations. *PLOS ONE, 12*(1), e0168836.

Oostenveld, R., & Praamstra, P. (2001). The five percent electrode system for high-resolution EEG and ERP measurements. *Clinical Neurophysiology, 112*(4), 713–719.

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., . . . Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods, 51*(1), 195-203.

Rohrbaugh, J. W., Syndulko, K., & Lindsley, D.B. (1976). Brain wave components of the contingent negative variation in humans. *Science*, *191(4231)*, 1055-1057.

Sperber, D., & Wilson, D. (1995). *Relevance: Communication & Cognition (2nd ed.)*. Oxford, UK: Blackwell.

Tarkka, I. M., & Basile, L. F. H. (1998). Electric source localization adds evidence for task specific CNVs. *Behavioural Neurology, 11*, 634-728.

van Der Merwe, A. (1997). A theoretical framework for the characterization of pathological speech sensorimotor control. In Malcolm R McNeil (Ed.), *Clinical management of sensorimotor speech disorders*. (pp 1-26). New York: Thieme.

Vanhoutte, S., Van Borsel, J., Cosyns, M., Batens, K., van Mierlo, P., Hemelsoet, D., Van Roost, D., Corthals, P., De Letter, M., & Santens, P. (2014). CNV amplitude as a neural correlate for stuttering frequency: A case report of acquired stuttering. *Neuropsychologia, 64,* 349–359.

Vanhoutte, S., Cosyns, M., van Mierlo, P., Batens, K., Corthals, P., De Letter, M., . . . Santens, P. (2016). When will a stuttering moment occur? The determining role of speech motor preparation. *Neuropsychologia, 86,* 93-102.

Vanhoutte, S., Santens, P., Cosyns, M., van Mierlo, P., Batens, K., Corthals, P., . . . Van Borsel, J. (2015). Increased motor preparation activity during fluent single word production in developmental stuttering: A correlate for stuttering frequency and severity. *Neuropsychologia, 75*, 1-10.

Walker, G. M., & Hickok, G. (2016). Bridging computational approaches to speech production: The semantic-lexical-auditory-motor model (SLAM). *Psychonomic Bulletin & Review, 23*(2), 339–352.

Walter, W.G., Cooper, R., Aldridge, V.J., McCallum, W.C., & Winter, A.L., (1964). Contingent negative variation: an electric sign of sensorimotor association and expectancy in the human brain. *Nature, 203,* 380–384.

Wohlert, A. B. (1993). Event-related brain potentials preceding speech and nonspeech oral movements of varying complexity. *Journal of Speech, Language, and Hearing Research, 36*(5), 897-905.

Wu, Y.J., & Thierry, G. (2017). Brain potentials predict language selection before speech onset in bilinguals. *Brain and Language, 171,* 23 - 30.

Chapter 3: Review of technological intervention for aphasia rehabilitation

Introduction

Aphasia is an acquired language disorder caused by neurological damage following stroke. The language difficulties of aphasia limit the individual's participation in socio-professional domains increasing the probability of emotional distress and depression (Spaccavento et al., 2014). Therefore, a persistent need remains to improve the linguistic abilities and quality of life of people with aphasia (Ross & Wertz, 2003). Behavioral speech-language therapy is the primary solution to aid language recovery in aphasia, but the extent of recovery to premorbid levels of functioning is relatively low (Brady, Kelly, Godwin, Enderby, & Campbell, 2016). To this end, a fundamental goal of aphasia research is to find therapeutic solutions that improve the extent of post-stroke language recovery.

In recent years, novel technological interventions are being increasingly researched and used adjuvant to speech-language therapy for enhancing communicative outcomes in aphasia (Simmons-Mackie, King, & Beukelman, 2013). The current study aims to explore the area of technological interventions for improving linguistic outcomes in aphasia. Scoping reviews can examine the extent of research activity while identifying gaps in research literature and can summarize research findings to determine the future prospect of a systematic review (Arksey & O'Malley, 2005). A scoping review design was used to narrowly assess specific technology and summarize research findings for investigating the emerging role of technological intervention as a therapeutic tool. The main goal was to identify and summarize clinical parameters of technological interventions like non-invasive brain stimulation (NIBS) approaches and high-tech augmentative and alternative communication (AAC) that support neuroplasticity in the post-stroke brain.

Neurorehabilitation is based on an understanding of healthy brain function and post-stroke dysfunction (Kiran & Thompson, 2019). Language recovery in aphasia is based on underlying neural reorganization that can be enhanced through technological supports. Neural reorganization in post-stroke aphasia constitutes changes in the underlying neural areas representing language functions (Hamilton, Chrysikou, & Coslett, 2011). Three models of neuroplasticity that form the basis of neurorehabilitation in aphasia recovery are: (1) inclusion of residual perilesional language areas in the left hemisphere, (2) compensatory inclusion of homotopic language areas in the right hemisphere, and (3) or both recruitment of perilesional left hemisphere language areas and homotopic right hemisphere language areas. In addition, there is sometimes inefficient recruitment of right hemisphere areas that inhibits language recovery in Models 2 and 3. The field of neurorehabilitation mainly aims to develop therapeutic solutions that stimulate appropriate neural systems through one of the models of neuroplasticity, for language recovery translating into improved quality of life for people with aphasia (Szaflarski et al., 2011). Non-invasive brain stimulation (NIBS) is one route for promoting post-stroke neuroplasticity.

Non-invasive brain stimulation is comprised of transcranial magnetic stimulation (TMS) and transcranial direct stimulation (tDCS). TMS refers to the application of magnetic pulses to a specific scalp (Rossi, Hallett, Rossini, & Pascual-Leone, 2009). TMS works on principle of electromagnetic induction consisting of a stimulator device, which has capacitors that can hold large currents connected to a coil of copper wires. The simulator is used to generate a time-varying magnetic field that penetrates the skull and induces an electric current in the neuronal cells perpendicular to the coil. The induced electric current can depolarize the neuronal membrane and modulate the action potentials of nearby neurons. TMS can be delivered in a single pulse or as a set of repetitive pulses per second (rTMS). When rTMS is delivered at a low frequency (<5Hz), it decreases cortical excitability and when delivered at high frequency (>5Hz), it increases cortical excitability (Fitzgerald, Fountain, & Daskalakis, 2006). Theta burst stimulation (TBS) is a newer protocol that modifies the standard rTMS by producing longer lasting and stable changes in cortical excitability (Huang, Edwards, Rounis, Bhatia, & Rothwell, 2005). TBS consists of three pulses at 50 Hz delivered rapidly every 200ms. These pulses can be continuous (cTBS) or interrupted (iTBS) every few seconds. TMS and its variations have been used to support neurorehabilitation by following any one of the models of neuroplasticity (Hamilton et al., 2011). Also, TMS studies have been used to inhibit and stimulate neural networks in people with mostly chronic aphasia and are evaluated through functional neuroimaging and changes in speech and language therapeutic outcomes.

Another approach in NIBS is transcranial direct current stimulation (tDCS), a neuromodulatory technique that works by passing electric currents of small amplitude (1-2ma) directly through the brain via two large saline-soaked sponge electrodes (often 5X7 cm2 or 5X5 cm2, Nitsche & Paulus, 2000). The active electrode that stimulates the brain regions is placed on the target site on the scalp, and the reference electrode that receives the current is placed on the forehead. The current passing through the electrodes in tDCS is sufficient to modulate the resting membrane potentials of the neuronal cells without generating an action potential. Like rTMS, tDCS can be excitatory and inhibitory. Anodal tDCS (a-tDCS) stimulates cortical excitability and cathodal tDCS (c-tDCS) inhibits cortical excitability (Nitsche & Paulus, 2000; Nitsche & Paulus, 2001). Application of tDCS for aphasia recovery has followed the first two models of neuroplasticity to increase excitability in perilesional and residual left hemisphere areas (Baker, Rorden, & Fridriksson, 2010; Fridriksson, Richardson, Baker, & Rorden, 2011; Marangolo, 2013) and inhibit the overactivation of right hemisphere areas (Monti et al., 2008; You, Kim, Chun, Jung, & Park, 2011).

Along with NIBS, an indirect path for promoting neuroplasticity in stroke-induced aphasia is through augmentative and alternative communication (AAC). High-tech augmentative and alternative communication (AAC) devices refocus therapy on the individual holistically rather than solely improving core skills like comprehension, speech, and swallowing (Garrett & Lasker, 2007). Clinical application of AAC strategies can be categorized into no-tech, low-tech, and high-tech solutions (Cook & Polgar, 2015). The no-tech category relies on interpretation of facial expressions and voluntary motor movements, and low-tech utilizes technology like cards, picture books, alphabet boards, choice from written words/messages, and display boards with extended lexicons. Interpretation of eye-gaze, gestures, mimicking, pointing, writing, drawing, are a few ways of accessing low-tech AAC (Smith & Connolly, 2008; van de Sandt-Koenderman, 2004). High-tech AAC are electronic devices that can be accessed through direct touch, eye-tracking, switches, head and body movement, neural and muscular potential estimation, and brain computer interfaces to achieve a communicative outcome (Elsahar, Hu, Bouazza-Marouf, Kerr, & Mansor, 2019). Dedicated AAC devices/smart devices can be accessed through simple to complex methods of access by integrating a hardware and software to support a user’s communication needs and to optionally translate message text into speech via a speech generating device (SGD).

The theory of intersystemic reorganization postulates a weak neural system can be strengthened by being paired with a stronger intact intervention system (Luria, 1972). The theory emphasizes that a person merges two functionally different systems into a new related system. By extrapolating from this theory, stimulatory NIBS and restorative high-tech AAC can be used to augment spoken language recovery from the subacute rehabilitation stage (Dietz, Vannest, Maloney, Altaye, Holland, & Szaflarski, 2018). NIBS approaches provide an opportunity to directly alter neuronal plasticity, whereas high-tech AAC can indirectly alter neural plasticity like conventional speech-language therapy. High-tech AAC includes systems with fully developed text messages and visual scene displays that can stimulate the post-stroke language system and can enable the user to self-cue their residual language networks by drawing from the high-tech AAC system via intact visual input modalities in the event of word-finding difficulty. Neural reorganization of language systems in post-stroke aphasia can be enhanced with accurate articulatory output and corrective feedback of the intended message from the high-tech AAC system in place of an incorrect utterance or no utterance; as such the rewiring of the language systems can be aided with high-tech AAC systems (Fillingham, Sage, & Ralph, 2006).

Language recovery in aphasia is a non-linear process with different patterns of neuroplastic recovery over a series of stages classified as acute, subacute and chronic stage of recovery (Bernhardt et al., 2017; Kiran & Thompson, 2019). Technological intervention such as high-tech AAC can support the neural recovery process from the subacute stage (7 days to 6 months post stroke) where the brain undergoes neurophysiological changes enabling spontaneous recovery to the chronic phase (>6 months) of neurophysiological stability (Cramer, 2008; Teasell et al., 2012). However, technological interventions are generally incorporated only during the chronic stage following the long-standing notion that technological intervention meddles with the neurophysiological changes leading to spontaneous recovery in the early stages impeding language recovery (Dietz et al., 2014; Jacobs, Drew, Ogletree, & Pierce, 2004). As a result, NIBS and AAC approaches are considered only after a speech-language recovery plateau is reached. There is emerging evidence, however, that neurorehabilitation through NIBS and AAC can enhance the process of spontaneous recovery and salvage language rehabilitation from the subacute stage leading to a more functional neural reorganization in the chronic stages of recovery (Spielmann, Sandt-Koenderman, Heijenbrok-Kal, & Ribbers, 2018; van de Sandt-Koenderman, Wiegers, & Hardy, 2005). The treatment task used during neurorehabilitation therapy and the outcome measures used for evaluating treatment effectiveness vary based on the clinical researcher, aphasia symptoms and severity, and the neurorehabilitation therapy used. Electroencephalography and functional magnetic resonance imaging can provide evidence of treatment-induced neuroplasticity for both direct NIBS approaches and indirect high-tech AAC approaches (Barwood et al., 2011; Dietz et al., 2018; Szaflarski, Eaton, et al., 2011).

The primary research question driving this scoping review was to evaluate evidence for the utility of NIBS and high-tech AAC devices as therapeutic tools to improve linguistic communication skills in individuals with aphasia. The overarching question was subdivided into three smaller questions identifying: (1) the methods of access for high-tech AAC and methods of stimulation for NIBS used in stroke-induced aphasia, (2) the use of technology from acute to chronic stages of stroke-induced aphasia, and (3) the relation of the technological intervention measure with outcome assessment measure.

Method

Search of studies. The researcher consulted with a research librarian with experience in evidence synthesis studies to develop the search strategy for this study. The search terms related to the research question were organized using the *Population*, *Intervention* and *Outcome* from the PICO framework (Schardt, Adams, Owens, Keitz, & Fontelo, 2007). *Comparison* from the PICO strategic search framework was not included to organize the search strategy as ‘comparison’ among research studies was not required since each technology and its parameters were different and the comparison did not improve the quality of this scoping review. The concepts from the PICO framework from this study include: (1) *Population*-people with aphasia, (2) *Intervention*- high-tech AAC, TMS, and tDCS and (3) *Outcome*-naming, reading, conversation, linguistic abilities. These concepts were combined to identify relevant literature through a search of PsycInfo (Proquest), Proquest Dissertations and Theses Global, PubMed, Web of Science, IEEE, ACM, and Cochrane electronic databases. A comprehensive search, customized for each database, was conducted in March 2020 using a set of search terms combined with the Boolean term 'OR' for finding literature that used the three interventions (high-tech AAC, TMS, & tDCS) for communication difficulties in aphasia. The complete search strategy for this study is available in Table 1 of Supplemental Data at the end of this chapter. The keywords were applied to titles and abstracts to ascertain the eligibility of the study for review.

Inclusion/Exclusion Criteria. The review included case reports and observational studies related to individuals with aphasia undergoing technological interventions like NIBS: TMS, tDCS, and high-tech AAC with the following access methods: physical contact, eye-tracking, electromyography, and electroencephalography brain-computer interface that were published in English-language peer-reviewed journals. Initially, this search included publications from 1995 to 2020. Seminal systematic reviews on the use of NIBS (Shah-Basak, Wurzman, Purcell, Gervits, & Hamilton, 2016) and high-tech AAC (Russo et al., 2017) for aphasia rehabilitation included studies through 2015. So, for the current study, the inclusion criteria were curtailed to studies published from 2015 to 2020.

Research articles were excluded if: (1) not published in English; (2) not peer-reviewed original research (e.g., systematic reviews, meta-analysis, proposals for randomized controlled trial, editorials); (3) population was not individuals with aphasia (e.g., Alzheimer's disease, traumatic brain injury, amyotrophic lateral sclerosis, neurodegenerative diseases, stroke without aphasia etc.); (4) targeted intervention was not focused on linguistic communication abilities (e.g., focus on motor rehabilitation); (5) targeted technology was used only for assessment (e.g., eye tracking measures for syntactic assessment, computational modeling was done to inform tDCS montage) and not for rehabilitation or tele-rehabilitation.

Selection of publications for review. Studies meeting the search criteria from each database were uploaded into CADIMA software (https://www.cadima.info/index.php) where two Ph.D. students independently screened titles and abstracts against inclusion and exclusion criteria (Figure 1). The conflicts arising from the students' selection were resolved by a faculty member. The database search identified 5042 studies and were reduced to 3611 after removal of duplicates. A total of 228 articles met the study criteria after title/abstract review. The full text of these articles was obtained and reviewed to determine eligibility and to sort the studies in a customized data extraction table for answering the research questions. Following the review of 228 full-text articles, 126 articles were active research studies using novel technology for aphasia intervention from 1995 to 2020. On application of the publication year filter (2015-2020), there were a total of 45 included studies with six studies that used high-tech AAC, 11 studies used TMS, and 28 studies used tDCS to improve linguistic measures in individuals with aphasia. tDCS is a more recent technology, easily available, cost-effective and can be simultaneously used with speech-language therapy without any additional learning from the person with aphasia.

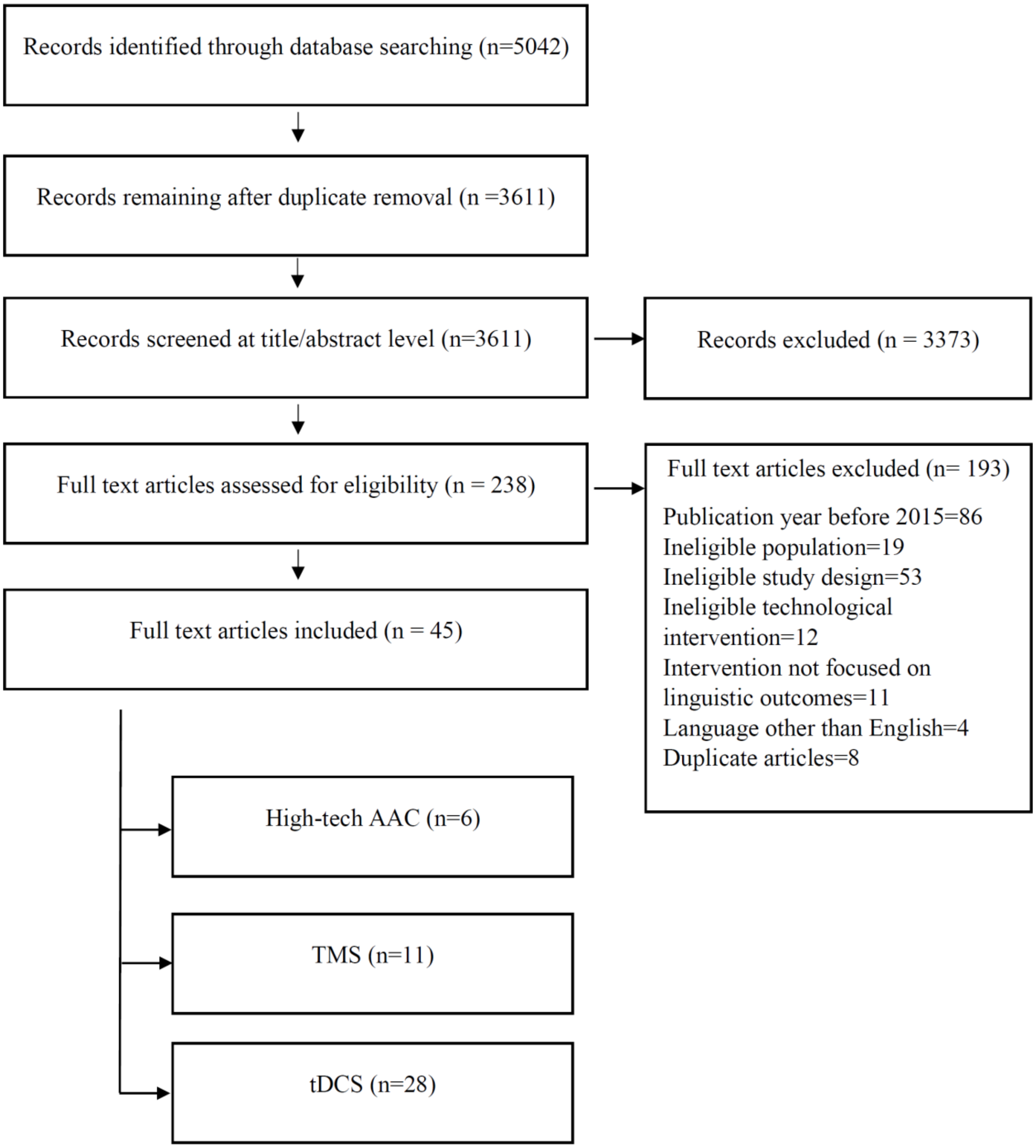

Figure 1: PRISMA flow diagram depicting the study selection process

Approach to analysis and synthesis. The current scoping review included study designs such as observational and experimental studies with varying risks of bias in the absence of multiple randomized controlled trials in this area of study (Chidambaram & Josephson, 2019; El-Gilany, 2018). Information extracted from the eligible studies by two researchers on separate spreadsheets pertained to the target population, study design, severity and type of aphasia, description of the technology and its application, period of intervention, outcome measures, and the main findings. Information from the two spreadsheets was compared and filtered into three tables, one for high-tech AAC, one for TMS, and one for tDCS. If information was not identified in the study, then it was reported as missing in the final tables. The columns in the final tables (Table 2 and Table 3 in Supplemental data) were edited to ensure that the extracted relevant data directly answered the research questions according to the following criteria:

a) Study characteristics: The study design (e.g., observational case study), and the sample size for each study was recorded.

b) Participant characteristics: The following was recorded for each study meeting participant criteria for this review; the mean and standard deviation for age, whether the sample included fluent or non-fluent types of aphasia, severity of aphasia, phase of recovery, the domain of language, and the particular activity being worked upon in the study.

c) Intervention details: Specific details for the three targeted interventions high-tech AAC, TMS, and tDCS were noted separately. For high-tech AAC, the type of AAC, the duration of the technological application, and the method of access for the device were recorded. For TMS, the specific type of TMS (e.g., theta burst stimulation), duration of application, model of stimulation, and the site of stimulation were recorded. For tDCS, the specific type of tDCS (e.g., anodal), daily and weekly duration of the application, the intensity of current, and the site of the anode and cathode electrodes were recorded.

d) Outcome measures: For each study, the outcome measure that was used to measure the effectiveness of the treatment was recorded for inclusion of standardized test materials related to the task used in the study and neuroimaging measures to check for neural changes as a result of the treatment.

Results

Among the 45 included studies, 647 persons with aphasia participated whose age range was 18-83 years. Participants in the studies that mentioned the type (83.4%) and severity (73.4%) of aphasia ranged from mild to severe non-fluent aphasia (77.8%). Treatment effectiveness in studies was evaluated using single-subject designs and individual analyses (35.5%), and the remaining studies used experimental group designs.

What are the methods of access for high-tech AAC used in aphasia rehabilitation?

High-tech AAC involves smart devices that have two broad categories of access methods- direct selection and indirect selection (Dowden & Cook, 2002). In the six studies that were included in this review, five of them (83.3%) used high-tech AAC through direct selection by touch access. Residual motor and visual abilities of individuals with aphasia aid in direct selection access of high-tech AAC devices. Direct selection refers to the individual with aphasia specifically indicating the desired icon on the displayed selection set without selecting any other icon in the process. High-tech AAC devices have three types of direct selection: a) pointing with physical contact and force, b) pointing with physical contact but no force, and c) pointing without physical contact (e.g., eye tracking).

The one remaining study used scanning and electroencephalography to detect an event-related potential P300 brain computer interface for accessing AAC to select letters on the screen. Access method via indirect selection involves a series of steps before the final desired icon is selected. Indirect selection is considered for individuals whose residual linguistic, motor, and visual abilities do not support direct selection (Elsahar et al., 2019; Pitt & Brumberg, 2018). Scanning is a primary method for indirect selection where the selection set is sequentially presented either visually or auditorily. The individual with aphasia can scan the selection set automatically by moving the cursor in the desired direction and then select the desired icon using single- to multi-switch arrays, eyetracking, or event-related potentials via a brain-computer interface.

What are the types of stimulation for tDCS used in aphasia rehabilitation? tDCS can be unilateral anodal (Wu, Wang, & Yuan, 2015), unilateral cathodal (Silva, Mac-Kay, Chao, Santos, & Gagliadi, 2018), bilateral (Manenti et al., 2015), high definition (HD) (Richardson, Datta, Dmochowski, Parra, & Fridriksson, 2015), and cerebellar (Sebastian et al., 2017). In the current review, anodal stimulation (excitatory) emerged as the most commonly used stimulation pattern because neural reorganization of the left hemispheric perilesional areas as in the first model of neuroplasticity has support in the literature as the optimal mechanism of neuroplastic changes for language recovery (Shah, Szaflarski, Allendorfer, & Hamilton, 2013). The excitatory anodal stimulation is implemented by placing the active electrode on the left hemisphere language areas. The optimal electrode montage is identified through initial placement of electrodes in frontal areas (e.g., F3 and F4 according to the international 10-20 EEG measurement system) in early training sessions for a task (e.g., picture naming) by evaluating which particular montage results in greatest post-stimulation accuracy in task measures and neuroimaging measures (Lifshitz Ben Basat, Gvion, Vatine, & Mashal, 2016; Norise, Sacchetti, & Hamilton, 2017; Shah-Basak et al., 2015). Electrode placement in bilateral tDCS stimulation refers to when the excitatory anode is placed on left Broca’s area and the inhibitory cathode is placed on the contralesional right homologue of Broca’s area (Costa, Giglia, Brighina, Indovino, & Fierro, 2015; Feil et al., 2019; Manenti et al., 2015; P. Marangolo et al., 2016).

Bilateral tDCS can be applied either 20 minutes before or simultaneously for the first 20 minutes in a 45minute to 1-hour speech-language therapy session (Costa et al., 2015; Feil et al., 2019; Marangolo et al., 2016). Most of these studies (N=14) applied 2mA current for a period of 20 minutes in conventional tDCS. The stimulation from the same amplitude of current can be increased using HD-tDCS, which is a variant of conventional tDCS that uses a ring of small electrodes in place of large pads (Villamar et al., 2013). A 4 X 1 HD-tDCS montage involves four small return electrodes arranged in a circle around a central electrode placed on the target area. The strength of the generated electric field is maximum under the central electrode as the current is constrained by the outer ring of electrodes, thus reducing the extent of the electric field in comparison to conventional electrodes places across the head. Another way of electrode placement is cerebellar tDCS, where anodal and cathodal stimulation of the right cerebellum has been found to modulate language fluency in healthy individuals (Pope & Miall, 2012; Turkeltaub, Swears, D’Mello, & Stoodley, 2016) and individuals with aphasia (Sebastian et al., 2020; Sebastian et al., 2017). Stimulation of the right cerebellum produces an electric field that can transmit to the left cerebrum through intact neural pathways (Wessel & Hummel, 2018).

What are the methods of stimulation for TMS used in aphasia rehabilitation? TMS can be implemented as low frequency rTMS (Yoon, Han, Yoon, Kim, & Yi, 2015), high frequency rTMS (Zhang et al., 2017), both low and high frequency rTMS (Hu et al., 2018), iTBS (Szaflarski et al., 2018), cTBS (Georgiou, Konstantinou, Phinikettos, & Kambanaros, 2019), and both iTBS and cTBS (Vuksanović et al., 2015). Most studies in this scoping review used inhibitory low frequency rTMS delivered at 1 Hz for 20 minutes citing the ‘interhemispheric inhibition hypothesis’ (Harvey et al., 2017; Ren et al., 2019; Zhang et al., 2017). The interhemispheric inhibition model of recovery assumes that stroke-induced damage to the left hemisphere releases the right hemisphere from transcallosal inhibition. This results in increased right hemisphere activation that also increases deleterious transcallosal inhibition of the residual left hemisphere language area responses (Fregni & Pascual-Leone, 2007). Inhibitory low frequency rTMS to the right Broca’s area is consistent with suppressing the inefficient compensatory recruitment of the right hemisphere.

Alternately, activation of the left perilesional areas has been shown to improve reorganized language networks (Kiran & Thompson, 2019). Zhang et al. (2017) used high frequency rTMS (≥5Hz) for 20min/day for 10 days during a 2-week period followed by speech-language therapy for an individual with Conduction aphasia four months after her stroke and reported improvement in language outcomes and significant activation in left hemisphere perilesional areas. rTMS operates by modulating the cerebral excitability underlying the functional recovery seen at the behavioral level (Cirillo et al., 2017; Hoffman & Cavus, 2002). In this application, low- frequency rTMS reduces the cortical activity of the right hemisphere and high frequency rTMS enhances the cortical neural activity of the left hemisphere. In a study by Hu et al. (2018), high frequency rTMS showed long term rehabilitative effects of TMS intervention while low frequency rTMS showed immediate and marked benefits in language recovery.

Unlike tDCS, TMS is applied separately followed by speech-language therapy (Yoon et al., 2015). Most of rTMS studies in the current review applied 1200 pulses in 20 minutes (Harvey et al., 2017; Hu et al., 2018; Yoon et al., 2015) sometimes followed by speech-language therapy. On the other hand, bilateral theta burst stimulation (TBS) can be applied with 600 intermittent TBS (iTBS) pulses in 200 seconds and 600 continuous TBS (cTBS) pulses in 40 seconds (Vuksanović et al., 2015). iTBS, facilitatory in nature, applied to the left hemisphere in individuals with mild to severe types of aphasia has shown potential in improving linguistic outcomes (Szaflarski et al., 2018). cTBS, inhibitory in nature, has been applied to the right hemisphere in a format of 50 Hz triplets of TMS pulses at 5 Hz for a total of 600 pulses in 40 seconds on four different days (Harvey et al., 2019) or 10 consecutive days (Georgiou et al., 2019).

How does application of technology change from subacute to chronic stage of recovery? Among the final selected 45 research studies, there were 10 studies that had participants during the subacute phase of recovery, and the remaining 35 studies included participants during the chronic phase of recovery. Overall, technological intervention was seen to be prevalent during the chronic stage of recovery. Specifically, for high-tech AAC, one study (Kleih, Gottschalt, Teichlein, & Weilbach, 2016) included two participants with subacute stroke and the remaining five studies had participants with chronic stroke. There was a total of 28 tDCS studies with three studies including participants (n=76) with subacute stroke (Feil et al., 2019; Guillouët et al., 2020; Spielmann et al., 2018). As for the 11 TMS studies, four studies had participants (n=87) with subacute stroke and seven with chronic stroke (Haghighi, Mazdeh, Ranjbar , & Seifrabie, 2017; Rubi-Fessen et al., 2015; Yoon et al., 2015; Zhang et al., 2017).

What is the relation between technological intervention and outcome assessment measure? High-tech AAC and non-invasive brain stimulation are technological approaches that offer a possible means to influence neuroplasticity during aphasia recovery. An excellent way to evaluate effectiveness of technological interventions is through neuroimaging measures as neurological change can be objectively assessed. Specifically, half (3/6) of the AAC studies, almost half (5/11) of the TMS studies, and one fourth (8/28) of the tDCS studies used a neuroimaging measure for evaluating pre-post treatment neural recovery. Structural and functional MRIs were the most used neuroimaging measure, though one TMS study used computed tomography (Vuksanović et al., 2015) and one tDCS study used EEG approximate entropy (Wu et al., 2015).

Discussion

The purpose of the current scoping review was to evaluate the use of technological approaches like high-tech AAC and NIBS as therapy aids for improving linguistic outcomes by targeting neural recovery in individuals with aphasia. Three main points of investigation were a) the methods of access and stimulation for high-tech AAC and NIBS respectively, b) the transitional use of technological approaches through different stages of aphasia recovery, and c) use of objective markers of neural recovery for measuring technological effectiveness. The results in this scoping review indicate that technological approaches show potential for neural reorganization and enhance communicative outcomes for individuals with stroke-induced aphasia. The studies included in the review incorporate several AAC devices and different combinations for stimulation through transcranial magnetic stimulation and transcranial direct stimulation as the primary intervention tool adjuvant to conventional speech-language therapy for participants with different types and severity of aphasia.

The study designs for high-tech AAC studies were mainly observational- case reports and case series that evaluated linguistic outcomes and technological effectiveness through pre-post treatment design. Studies with transcranial magnetic stimulation mainly used randomized controlled trials where participants were randomly categorized into two groups and the experimental group received TMS with speech-language therapy and control group received only speech-language therapy. Studies with transcranial direct current stimulation largely used cross over clinical trials where the two groups of participants underwent the same intervention at different time points in the study. Studies involving TMS and tDCS also did follow-up evaluations after a washout period ranging from one week to months. The lack of consistency in research design of the different technological approaches can be attributed to the duration and manner of application of each technology. Using AAC device as a therapeutic tool essentially implies that each individual with aphasia must learn a new skill of using a device to create and transmit a message that is influenced by a multitude of factors to facilitate neural recovery. Alternatively, non-invasive brain stimulation including TMS and tDCS are direct applications of magnetic fields and electric currents that can influence neural reorganization and can be carried out in small amounts of time for a larger group of people. The study design for each of these studies was noted to answer the overarching question of how these technologies are utilized for improving communicative outcomes for people with aphasia in research settings for their eventual transition to regular clinical practice.

Studies with high-tech AAC mainly used a direct method of access as individuals with aphasia have substantial motor skills post stroke. However, for people with severe aphasia, novel methods of access are being developed like the brain computer interface. Brain computer interfaces are devices that can detect a neural signal, process it as a response for a particular task and convert it into a command for a speech-generating device (Shih, Krusienski, & Wolpaw, 2012). The duration of sessions in studies using AAC followed a similar timeline to conventional speech-language therapy, with 30- to 45-minute sessions twice in a week spread over months. Studies with TMS largely included 10-20 sessions of 20-minute stimulation each followed by 30- to 45-minute speech language therapy. Studies with tDCS had a variable range of sessions from 5 to 25 but largely, studies included 10 sessions of 20 minutes each either prior to or in conjunction with 45-minute speech-language therapy sessions.

Participants included in studies with high-tech AAC ranged from mild to severe aphasia. Some studies mentioned the severity rating scores from standardized tests for each of the participants or did not mention severity of their included participants. The type of aphasia was clearly stated in all studies with AAC except one. Broca's aphasia was the most common type of aphasia to be included for remediation in AAC studies. All individuals included in this study had a mean age range of 56-66 years. Studies with TMS also included participants with mild to severe range of aphasia with more participants in the severe range. Most of the TMS studies (N= 7/11) stated a clear classification of aphasia types for their participants and the mean age range of 49 to 67.9 years. Most studies with tDCS (N=16/28) included in the review did not state aphasia severity of their participants, and type of aphasia was largely non-fluent with some studies specifically stating the type as Broca's or Anomic and the mean age range of participants range from 53.15 to 70 years. Most participants in the studies using technological approaches were older adults (49- 70years) with non-fluent types of aphasia with variable severity (mild to severe).

In terms of stages of stroke induced aphasia recovery, studies with AAC included participants during the chronic phase of recovery only. This could possibly be attributed to AAC being considered as a last option for linguistic recovery in individuals with aphasia after a relatively low plateau of speech-language recovery has reached (Dietz, Wallace, & Weissling, 2020). In studies with TMS, participants included were in both subacute and chronic stages of recovery possibly because TMS is a widely available tool in clinical neurology and has been used for treatment of neuropsychological disorders (Basil, Mahmud, Mathews, Rodriguez, &

Adetunji, 2005; Galletta, Rao, & Barrett, 2011; Rossi, Hallett, Rossini, & Pascual-Leone, 2009). In studies with tDCS, only 4 studies included participants during subacute recovery and remaining 24 studies had participants in chronic stages of recovery, which may reflect the immaturity of this novel technological approach and limited success in improving linguistic outcomes in subacute cases (Shah-Basak et al., 2015; Shah-Basak et al., 2016).

The outcome measures for evaluating effectiveness of these technological approaches as a therapeutic tool ranged from task-related behavioral outcomes to standardized test scores to neuroimaging corelates. Studies with AAC mainly assessed effectiveness through behavioral outcomes often paired with structural and functional magnetic resonance imaging corelates by measuring identification of untrained items from a practiced semantic category. Studies with TMS largely used standardized test material to measure the effectiveness of TMS along with functional magnetic resonance imaging and diffusion tensor imaging. Studies with tDCS used both scores from standardized tests and task-related behavioral outcome measures combined with electroencephalography, structural magnetic resonance imaging, and functional magnetic resonance imaging. Studies with NIBS tend to use more neuroimaging measures to first evaluate the site of stimulation and secondly to objectively measure neural reorganization with some behavioral outcomes (Arthurs & Boniface, 2002; Sejnowski, Churchland, & Movshon, 2014).

Limitations. There was lack of consistency between the research design and methodology of the included studies for a comparative discussion of technological effectiveness. Based on the technology, there were differences in the design and the duration and manner of application of each technology as well. These differences, however, do not take away from the global relevance of these novel technologies influencing neural reorganization in post-stroke aphasia recovery. In addition, most of the studies included in this review lacked specific mention of the type and severity of aphasia, which will be needed in the future to develop individualized tailor-made programs based on the site of lesion and symptoms of the participant.

Conclusion

Stroke-induced aphasia leads to long-term difficulties in communication and active participation in social and professional domains. The evidence from this scoping review suggests novel technological approaches like high-tech AAC, TMS, and tDCS may be a useful tool to support individuals in having a better quality of life. The practical application of these technologies still remains in the developmental stage and speaks to a need for developing standardized models of intervention for each technology to guide clinicians, patients, caregivers, and bioengineers in the clinical decision-making process.

Novel technological approaches in heterogenous studies like those mentioned in this scoping review present potential therapeutic tools to improve communicative outcomes in individuals with stroke-induced aphasia from the early (subacute) through late (chronic) stages of recovery. Improvement in reporting of the study design and participant characteristics may lead to better interpretation of the scientific results of neurorehabilitation. Additionally, these technologies would ideally improve functional communication in individuals with aphasia, and developing a standardized model of delivery has potential relevance for other clinical researchers and clinicians supporting individuals with post-troke aphasia.

Supplemental Data

Table 1: Complete search strategy

PSYCINFO (PROQUEST)	
Search	Search Terms
#1	MAINSUBJECT.EXACT(“Aphasia”) OR MAINSUBJECT.EXACT(“Cerebrovascular Accidents”) OR noft(aphasiacs) OR noft(aphasia) OR noft (anomia) OR noft(paraphasia) OR noft(stroke near/3 effect) OR noft(“cerebrovascular accident”) OR (contre coup) OR noft(contrecoup)
#2	MAINSUBJECT.EXACT("Transcranial Direct Current Stimulation") OR MAINSUBJECT.EXACT("Transcranial Magnetic Stimulation") OR MAINSUBJECT.EXACT("Functional Magnetic Resonance Imaging") OR MAINSUBJECT.EXACT("Augmentative Communication") OR MAINSUBJECT.EXACT("Eye Movements") OR MAINSUBJECT.EXACT("Electromyography") OR MAINSUBJECT.EXACT("Electroencephalography") OR MAINSUBJECT.EXACT("P300") OR noft("transcranial magnetic stimulation") OR noft(rtms) OR noft("transcranial direct current stimulation") OR noft(tdcs) OR noft("functional magnetic resonance imaging") OR noft("fmri") OR noft("non invasive brain stimulation") OR noft(nibs) OR noft("augmentative and alternative communication") OR noft(aac) OR noft("eye tracking") OR noft("eye movement") OR noft("visual response") OR noft(electromyography) OR noft(emg) OR noft(electroencephalography) OR noft(eeg) OR noft("brain computer interfaces") OR noft("brain computer interface") OR noft(p300) OR noft("Steady state visually evoked potential") OR noft("motor imagery")
#3	MAINSUBJECT.EXACT("Quality of Life Measures") OR noft(language) near/3 noft(recovery) OR noft(standardized aphasia test) OR noft("western aphasia battery") OR noft(wab) OR noft(Boston Diagnostic Aphasia Examination) OR noft(bdae) OR noft("Porch Index of Communicative Ability") OR noft(verb naming test) OR noft("boston naming test") OR noft("philadelphia naming test") OR noft("pyramids and palm trees test") OR noft("quality of life measure") OR noft("quality of life measures") OR noft("quality of life scale") OR noft("quality of life scales") OR noft("International Classification of Functioning Disability and Health") OR noft("icf framework") OR noft("Life Participation Approach to Aphasia") OR noft(lpaa)
#4	#1 AND #2 AND #3

PUBMED	
Search	Search Terms
#1	Aphasia[Mesh] OR Anomia[Mesh] OR Stroke[Mesh] OR aphasia[Title/Abstract] OR aphasics[Title/Abstract] OR

	anomia[Title/Abstract] OR paraphasia[Title/Abstract] OR stroke effects[Title/Abstract] OR cerebrovascular accident[Title/Abstract] OR contre coup[Title/Abstract] OR contrecoup[Title/Abstract]
#2	Transcranial Magnetic Stimulation[Mesh] OR Transcranial Direct Current Stimulation[Mesh] OR Magnetic Resonance Imaging[Mesh] OR Communication Aids for Disabled[Mesh] OR Eye Movements[Mesh] OR Eye Movement Measurements[Mesh] OR Electromyography[Mesh] OR Electroencephalography[Mesh] OR Brain-Computer Interfaces[Mesh] OR Event-Related Potentials, P300[Mesh] OR "Transcranial magnetic stimulation"[Title/Abstract] OR rtms[Title/Abstract] OR Transcranial direct current stimulation[Title/Abstract] OR functional magnetic resonance imaging[Title/Abstract] OR fmri[Title/Abstract] OR "non invasive brain stimulation"[Title/Abstract] OR nibs[Title/Abstract] OR "augmentative and alternative communication"[Title/Abstract] OR "eye tracking"[Title/Abstract] OR "eye movement"[Title/Abstract] OR "visual response"[Title/Abstract] OR electromyography[Title/Abstract] OR electromyographic[Title/Abstract] OR emg[Title/Abstract] OR electroencephalography[Title/Abstract] OR electroencephalographic[Title/Abstract] OR eeg[Title/Abstract] OR "brain computer interface"[Title/Abstract] OR "brain computer interfaces"[Title/Abstract] OR "Steady state visually evoked potential"[Title/Abstract] OR p300[Title/Abstract] OR "motor imagery"[Title/Abstract]
#3	Quality of Life[Mesh] OR Language Tests[Mesh] OR International Classification of Functioning, Disability and Health[Mesh] OR "western aphasia battery" [Title/Abstract] OR wab [Title/Abstract] OR Boston Diagnostic Aphasia Examination [Title/Abstract] OR bdae [Title/Abstract] OR Porch Index of Communicative Ability [Title/Abstract] OR verb naming test [Title/Abstract] OR "boston naming test" [Title/Abstract] OR "philadelphia naming test" [Title/Abstract] OR "pyramids and palm trees test" [Title/Abstract] OR "quality of life measure" [Title/Abstract] OR "quality of life measures" [Title/Abstract] OR "quality of life scale" [Title/Abstract] OR "quality of life scales" [Title/Abstract] OR "International Classification of Functioning Disability and Health" [Title/Abstract] OR icf framework [Title/Abstract] OR Life Participation Approach to Aphasia [Title/Abstract] OR lpaa [Title/Abstract]
#4	#1 AND #2 AND #3

WEB OF SCIENCE	
Search	Search Terms
#1	aphasia OR aphasics OR paraphasia* OR anomia OR stroke NEAR/3 effect OR "cerebrovascular accident" OR contre coup OR contrecoup
#2	"transcranial magnetic stimulation" OR "transcranial direct current stimulation" OR rtms OR "functional magnetic resonance imaging" OR "functional mri" OR fmri OR "non invasive brain stimulation" OR nibs OR

	"augmentative and alternative communication" OR "eye tracking" OR "eye sensor" OR "optical sensor" OR "eye movement*" OR electromyography OR electroencephalography OR emg OR eeg OR "visual response" OR "brain computer interface*" OR p300 OR "steady state visually evoked potential" OR "motor imagery"
#3	standardized aphasia test OR language NEAR/3 recovery OR "western aphasia battery" OR wab OR "boston diagnostic aphasia examination" OR bdae OR "porch index of communicative ability" OR verb naming test OR "boston naming test" OR "philadelphia naming test" OR "pyramids and palm trees test" OR "quality of life" OR "international classification of functioning disability and health" OR "icf framework" OR "life participation approach to aphasia" OR lpaa
#4	#1 AND #2 AND #3

IEEE	
Search	Search Terms
#1	aphasi* OR anomia OR stroke OR "cerebrovascular accident" OR paraphasia
#2	Brain-computer interfaces [IEEE Terms] OR Magnetic resonance imaging [IEEE Terms] OR Electroencephalography [IEEE Terms] OR Electromyography [IEEE Terms] OR "transcranial magnetic stimulation" OR "transcranial direct current stimulation" OR fmri OR "functional magnetic resonance imaging" OR nibs OR "non invasive brain stimulation" OR "augmentative and alternative communication" OR "eye tracking" OR "eye sensor*" OR "optical sensor*" OR "tracking bar*" OR "eye movement*" OR "visual response" OR electromyography OR Electroencephalography OR "brain computer interface*" OR "steady state visually evoked potential" OR p300 OR "motor imagery"
#3	standardized aphasia test OR western aphasia battery OR boston diagnostic aphasia examination OR bdae OR porch index of communicative ability OR "verb naming test" OR "boston naming test" OR "philadelphia naming test" OR "pyramids and palm trees test" OR "quality of life" OR "quality of life measure*" OR "quality of life scale*" OR "international classificaction of functioning disability and health" OR icfdh OR "icf framework" OR "life participation approach to aphasia" OR lpaa
#4	#1 AND #2 AND #3

ACM	
Search	Search Terms
#1	aphasi* OR anomia OR stroke OR "cerebrovascular accident" OR paraphasia
#2	"transcranial magnetic stimulation" OR "transcranial direct current stimulation" OR fmri OR "functional magnetic resonance imaging" OR nibs OR "non invasive brain stimulation" OR "augmentative and alternative communication" OR "eye tracking" OR "eye sensor*" OR "optical sensor*"

	OR "tracking bar*" OR "eye movement*" OR "visual response" OR electromyography OR Electroencephalography OR "brain computer interface*" OR "steady state visually evoked potential" OR p300 OR "motor imagery"
#3	standardized aphasia test OR western aphasia battery OR boston diagnostic aphasia examination OR bdae OR porch index of communicative ability OR "verb naming test" OR "boston naming test" OR "philadelphia naming test" OR "pyramids and palm trees test" OR "quality of life" OR "quality of life measure*" OR "quality of life scale*" OR "international classificaction of functioning disability and health" OR icfdh OR "icf framework" OR "life participation approach to aphasia" OR lpaa
#4	#1 AND #2 AND #3

PROQUEST DISSERTATIONS & THESES	
Search	Search Terms
#1	aphasi* OR anomia OR stroke OR "cerebrovascular accident" OR paraphasia
#2	"transcranial magnetic stimulation" OR "transcranial direct current stimulation" OR fmri OR "functional magnetic resonance imaging" OR nibs OR "non invasive brain stimulation" OR "augmentative and alternative communication" OR "eye tracking" OR "eye sensor*" OR "optical sensor*" OR "tracking bar*" OR "eye movement*" OR "visual response" OR electromyography OR Electroencephalography OR "brain computer interface*" OR "steady state visually evoked potential" OR p300 OR "motor imagery"
#3	standardized aphasia test OR western aphasia battery OR boston diagnostic aphasia examination OR bdae OR porch index of communicative ability OR "verb naming test" OR "boston naming test" OR "philadelphia naming test" OR "pyramids and palm trees test" OR "quality of life" OR "quality of life measure*" OR "quality of life scale*" OR "international classificaction of functioning disability and health" OR icfdh OR "icf framework" OR "life participation approach to aphasia" OR lpaa
#4	#1 AND #2 AND #3

COCHRANE LIBRARY	
Search	Search Terms
#1	aphasi* OR anomia OR stroke OR "cerebrovascular accident" OR paraphasia
#2	"transcranial magnetic stimulation" OR "transcranial direct current stimulation" OR fmri OR "functional magnetic resonance imaging" OR nibs OR "non invasive brain stimulation" OR "augmentative and alternative communication" OR "eye tracking" OR "eye sensor*" OR "optical sensor*" OR "tracking bar*" OR "eye movement*" OR "visual response" OR electromyography OR Electroencephalography OR "brain computer interface*" OR "steady state visually evoked potential" OR p300 OR "motor imagery"

#3	standardized aphasia test OR western aphasia battery OR boston diagnostic aphasia examination OR bdae OR porch index of communicative ability OR "verb naming test" OR "boston naming test" OR "philadelphia naming test" OR "pyramids and palm trees test" OR "quality of life" OR "quality of life measure*" OR "quality of life scale*" OR "international classificaction of functioning disability and health" OR icfdh OR "icf framework" OR "life participation approach to aphasia" OR lpaa
#4	#1 AND #2 AND #3

Table 2: Summary of the characteristics of study and participants

Citation	**Study Design**	**N**	**Mean Age (years)**	**Gender (M/F)**	**Stage of recovery (Subacute/ chronic)**	**Type of aphasia**	**Severity of aphasia**
High-tech Augmentative and Alternative Communication							
Kleih et al., 2016	Case series	5	58.6	2M/3F	Subacute (1) Chronic (4)	NE	Mild to Severe
Brock et al., 2017	Case series	2	61	1M/1F	Chronic	Broca's aphasia	Moderate to severe
Kurland et al., 2018	Case Series	21	66.4		Chronic	Anomic (6) Optic (2) Conduction (1) TCS (2) TCM (2) Broca's (3) Wernicke's (3) Global (1) Mixed TC (1)	Mild to Severe
Haldin et al., 2018	Case report	1	64	1F	Chronic	Broca's aphasia	NE
Conroy et al., 2018	Case series	20	65.2	11M/9F	Chronic	TCS (1) Broca's (7) Anomia (9) MN (1) TCM (2)	Based on BNT scores
Dietz et al., 2018	Randomized controlled trial	12	57.08	5M/7F	Chronic	Global (1) Broca's (4) Conduction (2) Wernicke's (2) Anomic (3)	Based on WAB-R scores
Transcranial Magnetic Stimulation							
Vuksanovic et al., 2015	Case report	1	63	1M	Chronic	Non-fluent	Severe
Yoon et al., 2015	Randomized controlled trial	20	60.46	15M/5F	Subacute (NE) Chronic (NE)	NE	Moderate
Rubi-Fessen et al., 2015	Randomized controlled trial	30	67.9	14M/16F	Subacute (30)	Wernicke's (13) Anomic (7) Global (4) Broca's (6)	Mild to Severe

Zhang et al., 2017	Case report	1	39	1F	Subacute	Conduction	Based on WAB-R scores
Harvey et al., 2017	Case series	9	61	7M/2F	Chronic	Non-fluent	Mild to moderate
Haghighi et al., 2017	Randomized controlled trial	12	55	5M/7F	Subacute	Broca's aphasia (12)	Severe
Szaflarski et al., 2018	Single subject experimental design	12	49	9M/3F	Chronic	Anomic (8) Broca's (2) Global (1) Conduction (1)	Mild to severe
Hu et al., 2018	Randomized controlled trial	40	46.5	24M/16F	Chronic	Non fluent	Mild to severe
Georgiou et al., 2019	Case series	2	61, 39	1M/1F	Chronic	Anomic (1) Global (1)	Moderate Severe
Harvey et al., 2019	Single subject experimental design	11	55.5	9M/2F	Chronic	Broca's (4) Anomic (6) Conduction (1)	Mild to severe
Ren et al., 2019	Randomized controlled trial	45	65.95	28M/18F	Subacute	Global (45)	Severe
Transcranial direct current stimulation							
Wu et al., 2015	Non-randomized controlled trial	12	43.2	10M/2F	Subacute	Broca's (8) Mixed (2) Conductive (1) Anomic (1)	Severe
Manenti et al., 2015	Case report	1	49	1F	Chronic	Non - fluent	NE
Richardson et al., 2015	Randomized crossover clinical trial	8	60.63	4M/4F	Chronic	Anomic (3) Broca's (5)	Mild to moderate
Shah-Basak et al., 2015	Randomized cross over clinical trial	12	63.6	10M/2F	Chronic	Non-fluent	Moderate
Campana et al., 2015	Randomized cross over clinical trial	20	57.1	11M/9F	Chronic	Non-fluent	NE
Costa et al., 2015	Case Report	1	57	1F	Chronic	Non-fluent	Severe
Galletta et al., 2015	Case Report	1	43	1M	Chronic	Anomic	Mild
Meinzer et al., 2016	Randomized controlled trial	26	59.9	18M/8F	Chronic	Broca's (9) Wernicke's (9)	NE

						Global (6) Amnestic (2)	
Basat et al., 2016	Single subject experimental design	7	70	5M/2F	Chronic	Anomic (4) Broca’s (2)	NE
Marangolo et al., 2016	Randomized crossover clinical trial	9	58.2	5M/4F	Chronic	Non-fluent	NE
Santos et al., 2018	Randomized placebo controlled clinical trial	13	56	7M/6F	Chronic	Anomic (7) Brocas’ (6)	NE
Keser et al., 2017	Randomized crossover clinical trial	10	56.4	4M/6F	Chronic	Broca’s (9) TCM (1)	NE
Branscheidt et al., 2017	Randomized crossover clinical trial	16	61.1	12M/4F	Chronic	Broca’s (5) Amnestic (6) Global (1)	NE
Darkow et al., 2017	Randomized crossover clinical trial	16	56.7	10M/6F	Chronic	NE	Mild
De Tomasso et al., 2017	Case report	1	58	1M	Chronic	Non fluent	NE
Norise et al., 2017	Sham-controlled partial cross over design	9	62	7M/2F	Chronic	Non fluent	Mild to severe
Sebastian et al., 2017	Randomized crossover clinical trial	1	57	1M	Chronic	Non fluent	Severe
Fridriksson et al., 2018	Randomized clinical trial	74	60	52M/22F	Chronic	Broca’s (39) TCM (1) Global (3) Wernicke’s (5) Conduction (15) Anomic (11)	Based on WAB-R scores
Sandars et al., 2018	Case series	1	81	1M	Chronic	Broca’s (1)	NE
Marangolo et al., 2018	Randomized crossover clinical trial	12	57.75	6M/6F	Chronic	Non-fluent	Mild
Spielmann et al., 2018	Randomized crossover clinical trial	58	57.9	40M/18F	Subacute	Fluent (30) Non-fluent (20) Mixed (8)	Based on test scores

Spielman et al., 2018	Randomized crossover study	13	53.15	10M/3F	Chronic	Non-fluent (6) Fluent (7)	Mild to severe
Silva et al., 2018	Randomized controlled trial	14	52.38	8M/6F	Chronic	Broca’s (6) Anomic (8)	Mild to moderate
Pestalozzi et al., 2018	Single subject experimental design	14	57.4	7M/7F	Chronic	Anomic (6) Conduction (4) Broca’s (3) Global (1)	NE
VilaNova et al., 2019	Crossover clinical trial	12	57.6	6M/6F	Chronic	Transcortical (2) Broca’s (5) Anomic (4) Conduction (1)	NE
Feil et al., 2019	Randomized controlled trial	12	NE	10M/2F	Subacute	Non-fluent	Moderate
Fiori et al., 2019	Crossover clinical trial	20	63	12M/8F	Chronic	Non-fluent	Based on Token Test scores
Guillouet et al., 2020	Randomized crossover clinical trial	14	53.8	10M/4F	Subacute (6) Chronic (4)	Mixed (3) Broca (4) Wernicke (1) Anomic (1) TCM (3) Conduction (2)	NE

N= Number of participants with aphasia, M= Male, F= Female, NE= not specified, TCS= Transcortical Sensory, TCM=Transcortical Motor, MN= Mixed Non-Fluent, BNT= Boston Naming Test, WAB-R=Western Aphasia Battery Revised

Table 3: Intervention and outcome details

Citation	**Specific subtype of intervention**	**Duration of technological application**	**Method of access/stimulation**	**Outcome Measures**
High Tech Augmentative and Alternative Communication				
Kleih et al., 2016	BCI2000-P300 Speller	A week of training followed by 12 copy spelling sessions	EEG-BCI	Task related behavioral measures
Brock et al., 2017	Dynavox Vmax with scene displays and grid displays	9-20 sessions of 1.5 hour each	Direct access through finger touch	Task related behavioral measures
Kurland et al., 2018	iPad-iBooks Author GoToMeeting video conferencing software	24 sessions of 30 minutes each and 1 probe session	Direct access through finger touch	Task related behavioral measures
Haldin et al., 2018	UltraSpeech Player	17 sessions of 45minutes each	Direct access	Task related behavioral measures + fMRI
Conroy et al., 2018	Repeated Increasingly Speeded Production (RISP) Computer based program	12 sessions (NE)	Direct access through finger touch	Task related behavioral measures +sMRI
Dietz et al., 2018	Dynavox Vmax ™	12 sessions of 1 hour each	Direct access through finger touch	Task related behavioral measures +fMRI
Transcranial Magnetic Stimulation (TMS)				
Vuksanovic et al., 2015	Bilateral Theta Burst Stimulation	15 sessions	iTBS on Left hemisphere and cTBS on Right hemisphere	Task related behavioral measures + CT scan
Yoon et al., 2015	Repetitive TMS	20 sessions of 20 minutes each	Inhibitory low frequency on Right hemisphere	Task related behavioral measures
Rubi-Fessen et al., 2015	Repetitive TMS	10 sessions of 20 minutes each	Inhibitory low frequency on Right hemisphere	Task related behavioral measures
Zhang et al., 2017	Repetitive TMS	10 sessions of 20 minutes each	Facilitatory high frequency on Left hemisphere	Standardized test material + fMRI + DTI

Harvey et al., 2017	Repetitive TMS	10 sessions of 20 minutes each	Inhibitory low frequency on Right hemisphere	Standardized test material + fMRI
Haghighi et al., 2017	Repetitive TMS	10 sessions of 20 minutes each	Inhibitory low frequency on Right hemisphere	Standardized test material
Szaflarski et al., 2018	Theta Burst Stimulation	10 sessions of 200 seconds each	iTBS on Right hemisphere	Standardized test material + fMRI
Hu et al., 2018	Low Frequency rTMS High frequency rTMS	10 sessions of 10 minutes each	Right hemisphere	Standardized test material
Georgiou et al., 2019	Theta Burst Stimulation	10 sessions of 40 seconds each	cTBS of right hemisphere	Standardized test material
Harvey et al., 2019	Theta Burst Stimulation	4 sessions of 40 seconds each	cTBS of right hemisphere	Standardized test material + fMRI
Ren et al., 2019	Repetitive TMS	15 sessions of 20 minutes each	Right hemisphere	Standardized test material
Transcranial direct current stimulation (tDCS)				
Wu et al., 2015	Anodal	20 sessions of 20 minutes each	Left Wernicke’s point	Standardized test material + EEG
Manenti et al., 2015	Bilateral	20 sessions of 25 minutes each	Dorsolateral prefrontal cortex	Standardized test material
Richardson et al., 2015	HD-tDCS + CS tDCS	10 sessions of 20 minutes each	Individual optimal montage	Standardized test material + fMRI
Shah-Basak et al., 2015	Bilateral	10 sessions of 20 minutes each	Individual optimal montage	Standardized test material + sMRI
Campana et al., 2015	Anodal	10 sessions of 20 minutes each	Left frontal gyrus	Standardized test material + fMRI
Costa et al., 2015	Bilateral	13 sessions of 20 minutes each	Left Broca’s area and Right Broca’s area	Standardized test material
Galletta et al., 2015	Anodal	10 sessions of 20 minutes each	Left Broca’s area	Standardized test material
Meinzer et al., 2016	Anodal	10 sessions of 20 minutes each	Left primary motor cortex	Standardized test material
Basat et al., 2016	Bilateral	10 sessions of 10 minutes each	Left IFG, Right IFG, Left STG, Right STG	Standardized test material
Marangolo et al., 2016	Bilateral	15 sessions of 20 minutes each	Left Broca’s area and Right Broca’s area	Standardized test material + fMRI

Santos et al., 2018	Anodal	5 sessions of 20 minutes each	Left Broca's area	Standardized test material
Keser et al., 2017	Anodal	1 session of 20 minutes	Right IFG	Standardized test material
Branscheidt et al., 2017	Anodal	1 session of 20 minutes	Motor cortex	Task related behavioral measure
Darkow et al., 2017	Anodal	1 session of 20 minutes	Left motor cortex	Standardized test material + fMRI
De Tomasso et al., 2017	Dual tDCS	12 sessions of 20 minutes	Anode over the left parietal area and Cathode over the right homologue area	Standardized test material
Norise et al., 2017	Bilateral	10 sessions of 20 minutes each	Individual optimal montage	Standardized test material
Sebastian et al., 2017	Cerebellar tDCS	15 sessions of 20 minutes each	Anode on the right cerebellum	Standardized test material + fMRI
Fridriksson et al., 2018	Anodal	15 sessions of 20 minutes each	Left hemisphere	Standardized test material
Sandars et al., 2018	Bilateral	24 sessions of 20 minutes each	Left and Right hemisphere motor cortices	Standardized test material
Marangolo et al., 2018	Cerebellar tDCS	20 sessions of 20 minutes each	Cathode on the right cerebellar cortex	Task-related behavioral measures
Spielman et al., 2018a	Anodal	5 sessions of 20 minutes each	Anode on Left IFG	Task-related behavioral measures
Spielmann et al., 2018b	Anodal	3 sessions of 20 minutes each	Anode on Left IFG and Left STG	Task-related behavioral measures
Silva et al., 2018	Cathodal	5 sessions of 20 minutes each	Cathode on Right Broca's homologous area	Standardized test material
Pestalozzi et al., 2018	Anodal	2 sessions of 20 minutes	Anode on Left dorsolateral prefrontal cortex	Standardized test material + fMRI
VilaNova et al., 2019	Anodal	10 sessions of 20 minutes	Anode on Left Broca's area	Task-related behavioral measures
Feil et al., 2019	Bilateral	10 sessions of 20 minutes each	Anode on left hemisphere Cathode on right hemisphere	Standardized test material
Fiori et al., 2019	Cathodal HD tDCS	10 sessions of 20 minutes each	Cathode on Right homologue of Broca's area	Standardized test material

Guillouet et al., 2020	Bilateral tDCS	10 sessions of 20 minutes each	Anode on left IFG and cathode on right IFG	Standardized test material

EEG-BCI = Electroencephalography-Brain Computer Interface, fMRI= functional Magnetic Resonance Imaging, sMRI= structural Magnetic Resonance Imaging, CT= Computed Tomography, DTI= Diffusion Tensor Imaging, rTMS= repetitive Transcranial Magnetic Stimulation, iTBS= intermittent Theta Burst Stimulation, cTBS= continuous Theta Burst Stimulation, HD-tDCS= High- definition Transcranial Direct Current Stimulation, CS-tDCS= Conventional Sponge Transcranial Direct Current Stimulation, IFG= Inferior Frontal Gyrus, STG= Superior Temporal Gyrus.

References

Arksey, H., & O'Malley, L. (2005). Scoping studies: towards a methodological framework. *International Journal of Social Research Methodology, 8*(1), 19-32.

Arthurs, O. J., & Boniface, S. (2002). How well do we understand the neural origins of the fMRI BOLD signal? *Trends in Neurosciences, 25*(1), 27-31.

Baker, J. M., Rorden, C., & Fridriksson, J. (2010). Using transcranial direct-current stimulation to treat stroke patients with aphasia. *Stroke, 41*(6), 1229-1236.

Barwood, C. H., Murdoch, B. E., Whelan, B. M., Lloyd, D., Riek, S., JD, O. S., . . . Wong, A. (2011). Improved language performance subsequent to low-frequency rTMS in patients with chronic non-fluent aphasia post-stroke. *European Journal of Neurology, 18*(7), 935-943.

Basat, A.L., Gvion, A., Vatine, J., & Mashal, N. (2016). Transcranial direct current stimulation to improve naming abilities of persons with chronic aphasia: A preliminary study using individualized based protocol. *Journal of Neurolinguistics, 38*, 1-13.

Basil, B., Mahmud, J., Mathews, M., Rodriguez, C., & Adetunji, B. (2005). Is there evidence for effectiveness of transcranial magnetic stimulation in the treatment of psychiatric disorders? *Psychiatry, 2*(11), 64-69. Retrieved from https://pubmed.ncbi.nlm.nih.gov/21120098

Bernhardt, J., Hayward, K. S., Kwakkel, G., Ward, N. S., Wolf, S. L., Borschmann, K., . . . Cramer, S. C. (2017). Agreed definitions and a shared vision for new standards in stroke recovery research: The stroke recovery and rehabilitation roundtable taskforce. *International Journal of Stroke, 12*(5), 444-450.

Brady, M. C., Kelly, H., Godwin, J., Enderby, P., & Campbell, P. (2016). Speech and language therapy for aphasia following stroke. *Cochrane Database of Systematic Reviews 2016*(6).

Branscheidt, M., Hoppe, J., Zwitserlood, P., & Liuzzi, G. (2018). tDCS over the motor cortex improves lexical retrieval of action words in poststroke aphasia. *Journal of Neurophysiology, 119*(2), 621–630.

Brock, K., Koul, R., Corwin, M., & Schlosser, R. (2017). A comparison of visual scene and grid displays for people with chronic aphasia: a pilot study to improve communication using AAC. *Aphasiology, 31*, 1-25.

Campana, S., Caltagirone, C., & Marangolo, P. (2015). Combining Voxel-based Lesion-symptom Mapping (VLSM) With A-tDCS Language Treatment: Predicting Outcome of Recovery in Nonfluent Chronic Aphasia. *Brain Stimulation, 8*(4), 769–776.

Chidambaram, A. G., & Josephson, M. (2019). Clinical research study designs: The essentials. *Pediatric Investigation, 3*(4), 245-252.

Cirillo, G., Di Pino, G., Capone, F., Ranieri, F., Florio, L., Todisco, V., . . . Di Lazzaro, V. (2017). Neurobiological after-effects of non-invasive brain stimulation. *Brain Stimulation, 10*(1), 1-18.

Cook, A., & Polgar, J. (2015). *Assistive technologies principles and practice* (Vol. Fourth Edition). St. Louis, MO: Mosby, Elseiver Inc.

Costa, V., Giglia, G., Brighina, F., Indovino, S., & Fierro, B. (2015). Ipsilesional and contralesional regions participate in the improvement of poststroke aphasia: A transcranial direct current stimulation study. *Neurocase, 21*(4), 479-488.

Cramer, S. C. (2008). Repairing the human brain after stroke: I. Mechanisms of spontaneous recovery. *Annals of Neurology, 63*(3), 272-287.

Darkow, R., Martin, A., Würtz, A., Flöel, A. and Meinzer, M. (2017), Transcranial direct current stimulation effects on neural processing in post-stroke aphasia. Human Brain Mapping, 38, 1518-1531.

De Tommaso, B., Piedimonte, A., Caglio, M. M., D'Agata, F., Campagnoli, M., Orsi, L., . . . Pinessi, L. (2017). The rehabilitative effects on written language of a combined language and parietal dual-tDCS treatment in a stroke case. *Neuropsychological Rehabilitation, 27*(6), 904-918.

Dietz, A., Vannest, J., Collier, J., Maloney, T., Altaye, M., Szaflarski, J. P.,, & Holland, S. P. (2014). *AAC revolutionizes aphasia therapy: Changes in cortical plasticity and spoken language.* Paper presented at the American Speech-Language-Hearing Association Annual Convention, Orlando, FL.

Dietz, A., Vannest, J., Maloney, T., Altaye, M., Holland, S., & Szaflarski, J. P. (2018). The feasibility of improving discourse in people with aphasia through AAC: Clinical and functional MRI correlates. *Aphasiology, 32*(6), 693-719.

Dietz, A., Wallace, S. E., & Weissling, K. (2020). Revisiting the role of augmentative and alternative communication in aphasia rehabilitation. *American Journal of Speech-Language Pathology, 29*(2), 909-913.

Dowden, P., & Cook, A. (2002). Choosing effective selection techniques for beginning communicators. In *In J. Reichle, Beukelman, D., Light, J., Implementing an augmentative communication system: exemplary strategies for beginning communicators.* Baltimore: Paul H. Brookes Publishing Co.

El-Gilany, A. H. (2018). What is case series? *Asploro Journal of Biomedical and Clinical Case Reports, 1*(1), 10-15.

Elsahar, Y., Hu, S., Bouazza-Marouf, K., Kerr, D., & Mansor, A. (2019). Augmentative and alternative communication (AAC) advances: A review of configurations for individuals with a speech disability. *Sensors, 19*(8), 1911-1935.

Feil, S., Eisenhut, P., Strakeljahn, F., Müller, S., Nauer, C., Bansi, J., . . . Mylius, V. (2019). Left shifting of language related activity induced by bihemispheric tDCS in postacute aphasia following stroke. *Frontiers in Neuroscience, 13*(295), 1-7.

Fillingham, J. K., Sage, K., & Lambon Ralph, M. A. (2006). The treatment of anomia using errorless learning. *Neuropsychological Rehabilitation, 16*(2), 129-154.

Fiori, V., Nitsche, M. A., Cucuzza, G., Caltagirone, C., & Marangolo, P. (2019). High-Definition Transcranial Direct Current Stimulation Improves Verb Recovery in Aphasic Patients Depending on Current Intensity. *Neuroscience, 406*, 159-166.

Fitzgerald, P. B., Fountain, S., & Daskalakis, Z. J. (2006). A comprehensive review of the effects of rTMS on motor cortical excitability and inhibition. *Clinical Neurophysiology, 117*(12), 2584-2596.

Fregni, F., & Pascual-Leone, A. (2007). Technology insight: noninvasive brain stimulation in neurology-perspectives on the therapeutic potential of rTMS and tDCS. *Nature Clinical Practical Neurology, 3*(7), 383-393.

Fridriksson, J., Richardson, J. D., Baker, J. M., & Rorden, C. (2011). Transcranial direct current stimulation improves naming reaction time in fluent aphasia. *Stroke, 42*(3), 819-821.

Galletta, E. E., Rao, P. R., & Barrett, A. M. (2011). Transcranial magnetic stimulation (TMS): potential progress for language improvement in aphasia. *Topics in Stroke Rehabilitation, 18*(2), 87-91.

Garrett, K. L., & Lasker, J. P. (2007). AAC and severe aphasia: Enhancing communication across the continuum of recovery. *Perspectives on Neurophysiology and Neurogenic Speech and Language Disorders, 17*(3), 6-15.

Georgiou, A., Konstantinou, N., Phinikettos, I., & Kambanaros, M. (2019). Neuronavigated theta burst stimulation for chronic aphasia: two exploratory case studies. *Clinical Linguistics & Phonetics, 33*(6), 532-546.

Guillouët, E., Cogné, M., Saverot, E., Roche, N., Pradat-Diehl, P., Weill-Chounlamountry, A., . . . Charveriat, S. (2020). Impact of combined transcranial direct current stimulation and speech-language therapy on spontaneous speech in aphasia: A randomized controlled double-blind study. *Journal of the International Neuropsychological Society, 26*(1), 7-18.

Haghighi, M., Mazdeh, M., Ranjbar , N., & Seifrabie, M. A. (2017). Further evidence of the positive influence of repetitive transcranial magnetic stimulation on speech and language in patients with aphasia after stroke: Results from a double-blind intervention with sham condition. *Neuropsychobiology, 75*(4), 185-192.

Haldin, C., Acher, A., Kauffmann, L., Hueber, T., Cousin, E., Badin, P., Perrier, P., Fabre, D., Perennou, D., Detante, O., Jaillard, A., Lœvenbruck, H., & Baciu, M. (2018). Speech recovery and language plasticity can be facilitated by Sensori-Motor Fusion training in chronic non-fluent aphasia. A case report study. *Clinical linguistics & phonetics*, *32*(7), 595–621.

Hamilton, R. H., Chrysikou, E. G., & Coslett, B. (2011). Mechanisms of aphasia recovery after stroke and the role of noninvasive brain stimulation. *Brain and Language, 118*(1-2), 40-50.

Harvey, D. Y., Mass, J. A., Shah-Basak, P. P., Wurzman, R., Faseyitan, O., Sacchetti, D. L., . . . Hamilton, R. H. (2019). Continuous theta burst stimulation over right pars triangularis facilitates naming abilities in chronic post-stroke aphasia by enhancing phonological access. *Brain and Language, 192*, 25-34.

Harvey, D. Y., Podell, J., Turkeltaub, P. E., Faseyitan, O., Coslett, H. B., & Hamilton, R. H. (2017). Functional reorganization of right prefrontal cortex underlies sustained naming improvements in chronic aphasia via repetitive transcranial magnetic stimulation. *Cognitive and Behavioral Neurology, 30*(4), 133-144.

Hoffman, R. E., & Cavus, I. (2002). Slow transcranial magnetic stimulation, long-term depotentiation, and brain hyperexcitability disorders. *American Journal of Psychiatry, 159*(7), 1093-1102.

Hu, X.-y., Zhang, T., Rajah, G. B., Stone, C., Liu, L.-x., He, J.-j., . . . Chen, Y.-d. (2018). Effects of different frequencies of repetitive transcranial magnetic stimulation in stroke patients with non-fluent aphasia: a randomized, sham-controlled study. *Neurological Research, 40*(6), 459-465.

Huang, Y.-Z., Edwards, M. J., Rounis, E., Bhatia, K. P., & Rothwell, J. C. (2005). Theta burst stimulation of the human motor cortex. *Neuron, 45*(2), 201-206.

Humphreys, G. F., Halai, A. D., & Lambon Ralph, M. A. (2018). Time for a quick word? The striking benefits of training speed and accuracy of word retrieval in post-stroke aphasia. *Brain*, *141*(6), 1815–1827.

Jacobs, B., Drew, R., Ogletree, B. T., & Pierce, K. (2004). Augmentative and alternative communication (AAC) for adults with severe aphasia: Where we stand and how we can go further. *Disability and Rehabilitation, 26*(21-22), 1231-1240.

Keser, Z., Dehgan, M. W., Shadravan, S., Yozbatiran, N., Maher, L. M., & Francisco, G. E. (2017). Combined Dextroamphetamine and Transcranial Direct Current Stimulation in Poststroke Aphasia. *American Journal of Physical Medicine & Rehabilitation*, *96* (10 Suppl 1), S141–S145.

Kiran, S., & Thompson, C. K. (2019). Neuroplasticity of language networks in aphasia: advances, updates, and future challenges. *Frontiers in Neurology, 10,* 1-15.

Kleih, S. C., Gottschalt, L., Teichlein, E., & Weilbach, F. X. (2016). Toward a P300 based brain-computer interface for aphasia rehabilitation after stroke: Presentation of theoretical considerations and a pilot feasibility study. *Frontiers in Human Neuroscience, 10,* 1-13.

Kurland, J., Liu, A., & Stokes, P. (2018). Effects of a Tablet-Based Home Practice Program With Telepractice on Treatment Outcomes in Chronic Aphasia. *Journal of Speech, Language, and Hearing Research, 61*(5), 1140-1156.

Lifshitz Ben Basat, A., Gvion, A., Vatine, J.-J., & Mashal, N. (2016). Transcranial direct current stimulation to improve naming abilities of persons with chronic aphasia: A preliminary study using individualized based protocol. *Journal of Neurolinguistics, 38,* 1-13.

Luria, A. (1972). *Traumatic aphasia*. The Hague: Mouton.

Manenti, R., Petesi, M., Brambilla, M., Rosini, S., Miozzo, A., Padovani, A., . . . Cotelli, M. (2015). Efficacy of semantic–phonological treatment combined with tDCS for verb retrieval in a patient with aphasia. *Neurocase, 21*(1), 109-119.

Marangolo, P. (2013). tDCS over the left inferior frontal cortex improves speech production in aphasia. *Frontiers in Human Neuroscience, 7,* 1-10 .

Marangolo, P., Fiori, V., Sabatini, U., De Pasquale, G., Razzano, C., Caltagirone, C., & Gili, T. (2016). Bilateral transcranial direct current stimulation language treatment enhances functional connectivity in the left hemisphere: preliminary data from aphasia. *Journal of Cognitive Neuroscience*, *28*(5), 724-738.

Meinzer, M., Darkow, R., Lindenberg, R., & Flöel, A. (2016). Electrical stimulation of the motor cortex enhances treatment outcome in post-stroke aphasia. *Brain*, *139*(4), 1152–1163.

Monti, A., Cogiamanian, F., Marceglia, S., Ferrucci, R., Mameli, F., Mrakic-Sposta, S., . . . Priori, A. (2008). Improved naming after transcranial direct current stimulation in aphasia. *Journal of Neurology, Neurosurgery, and Psychiatry*, *79*(4), 451-453.

Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *The Journal of Physiology*, *527*(3), 633-639.

Nitsche, M. A., & Paulus, W. (2001). Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. *Neurology*, *57*(10), 1899-1901.

Norise, C., Sacchetti, D., & Hamilton, R. (2017). Transcranial direct current stimulation in post-stroke chronic aphasia: the impact of baseline severity and task specificity in a pilot sample. *Frontiers in Human Neuroscience*, *11*, 1-12 .

Pestalozzi, M. I., Di Pietro, M., Martins Gaytanidis, C., Spierer, L., Schnider, A., Chouiter, L., Colombo, F., Annoni, J. M., & Jost, L. B. (2018). Effects of Prefrontal Transcranial Direct Current Stimulation on Lexical Access in Chronic Poststroke Aphasia. *Neurorehabilitation and neural repair*, *32*(10), 913–923.

Pitt, K. M., & Brumberg, J. S. (2018). Guidelines for feature matching assessment of brain-computer interfaces for augmentative and alternative communication. *American Journal of Speech-Language Pathology*, *27*(3), 950-964.

Pope, P. A., & Miall, R. C. (2012). Task-specific facilitation of cognition by cathodal transcranial direct current stimulation of the cerebellum. *Brain Stimulation*, *5*(2), 84-94.

Ren, C., Zhang, G., Xu, X., Hao, J., Fang, H., Chen, P., . . . Gao, F. (2019). The effect of rTMS over the different targets on language recovery in stroke patients with global aphasia: a randomized sham-controlled study. *BioMed Research International, eCollection 4589056.*

Richardson, J., Datta, A., Dmochowski, J., Parra, L. C., & Fridriksson, J. (2015). Feasibility of using high-definition transcranial direct current stimulation (HD-tDCS) to enhance treatment outcomes in persons with aphasia. *Neurorehabilitation, 36*(1), 115-126.

Ross, K., & Wertz, R. (2003). Quality of life with and without aphasia. *Aphasiology, 17*(4), 355-364.

Rossi, S., Hallett, M., Rossini, P. M., & Pascual-Leone, A. (2009). Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. *Clinical Neurophysiology, 120*(12), 2008-2039.

Rubi-Fessen, I., Hartmann, A., Huber, W., Fimm, B., Rommel, T., Thiel, A., & Heiss, W.-D. (2015). Add-on effects of repetitive transcranial magnetic stimulation on subacute aphasia therapy: Enhanced improvement of functional communication and basic linguistic skills. a randomized controlled study. *Archives of Physical Medicine and Rehabilitation, 96*(11), 1935-1944.e1932.

Russo, M. J., Prodan, V., Meda, N. N., Carcavallo, L., Muracioli, A., Sabe, L., . . . Olmos, L. (2017). High-technology augmentative communication for adults with post-stroke aphasia: a systematic review. *Expert Review of Medical Devices, 14*(5), 355-370.

Sandars, M., Cloutman, L., & Woollams, A. M. (2018). Manipulating laterality and polarity of transcranial direct current stimulation to optimise outcomes for anomia therapy in an individual with chronic Broca's aphasia. *Aphasiology, 32*(7), 814-838.

Santos, M., Cavenaghi, V., mac kay, a. p., Serafim, V., Venturi, A., Truong, D., . . . Gagliardi, R. (2017). Non-invasive brain stimulation and computational models in post-stroke aphasic patients: Single session of transcranial magnetic stimulation and transcranial direct current stimulation. A randomized clinical trial. *Sao Paulo Medical Journal, 135(5),* 475-480.

Schardt, C., Adams, M. B., Owens, T., Keitz, S., & Fontelo, P. (2007). Utilization of the PICO framework to improve searching PubMed for clinical questions. *BMC Medical Informatics and Decision Making, 7*, 16-30.

Sebastian, R., Kim, J. H., Brenowitz, R., Tippett, D. C., Desmond, J. E., Celnik, P. A., & Hillis, A. E. (2020). Cerebellar neuromodulation improves naming in post-stroke aphasia. *Brain Communications*, *2*(2), 23-45.

Sebastian, R., Saxena, S., Tsapkini, K., Faria, A. V., Long, C., Wright, A., . . . Hillis, A. E. (2017). Cerebellar tDCS: A novel approach to augment language treatment post-stroke. *Frontiers in Human Neuroscience, 10*(695), 456-509 .

Sejnowski, T. J., Churchland, P. S., & Movshon, J. A. (2014). Putting big data to good use in neuroscience. *Nature Neuroscience, 17*(11), 1440-1441.

Shah-Basak, P. P., Norise, C., Garcia, G., Torres, J., Faseyitan, O., & Hamilton, R. H. (2015). Individualized treatment with transcranial direct current stimulation in patients with chronic non-fluent aphasia due to stroke. *Frontiers in Human Neuroscience, 9*(201), 453-501.

Shah-Basak, P. P., Wurzman, R., Purcell, J. B., Gervits, F., & Hamilton, R. (2016). Fields or flows? A comparative metaanalysis of transcranial magnetic and direct current stimulation to treat post-stroke aphasia. *Restorative Neurology and Neuroscience, 34,* 537-558.

Shah, P., Szaflarski, J., Allendorfer, J., & Hamilton, R. (2013). Induction of neuroplasticity and recovery in post-stroke aphasia by non-invasive brain stimulation. *Frontiers in Human Neuroscience, 7*(888), 149-195.

Shih, J. J., Krusienski, D. J., & Wolpaw, J. R. (2012). Brain-computer interfaces in medicine. *Mayo Clinic Proceedings, 87*(3), 268-279.

Silva, F. R. D., Mac-Kay, A., Chao, J. C., Santos, M. D. D., & Gagliadi, R. J. (2018). Transcranial direct current stimulation: A study on naming performance in aphasic individuals. *Communication Diosrders Audiology Swallowing, 30*(5), e20170242.

Simmons-Mackie, N., King, J., & Beukelman, D. (2013). *Supporting communication for adults with acute and chronic aphasia*. Baltimore: Brooks Publishing.

Smith, M. M., & Connolly, I. (2008). Roles of aided communication: perspectives of adults who use AAC. *Disability and Rehabilitation: Assistive Technology, 3*(5), 260-273.

Spaccavento, S., Craca, A., Del Prete, M., Falcone, R., Colucci, A., Di Palma, A., & Loverre, A. (2014). Quality of life measurement and outcome in aphasia. *Neuropsychiatric Disease and Treatment, 10*, 27-37.

Spielmann, K., Van de Sandt-Koenderman, W. M. E., Heijenbrok-Kal, M. H., & Ribbers, G. M. (2018)a. Comparison of two configurations of transcranial direct current stimulation for treatment of aphasia. *Journal of Rehabilitation Medicine*, *50*(6), 527-533.

Spielmann, K., Van de Sandt-Koenderman, W. M. E., Heijenbrok-Kal, M. H., & Ribbers, G. M. (2018)b. Transcranial direct current stimulation does not improve language outcome in subacute poststroke aphasia. *Stroke, 49*(4), 1018-1020.

Szaflarski, J. P., Eaton, K., Ball, A. L., Banks, C., Vannest, J., Allendorfer, J. B., . . . Holland, S. K. (2011). Poststroke aphasia recovery assessed with functional magnetic resonance imaging and a picture identification task. *Journal of Stroke and Cerebrovascular Diseases, 20*(4), 336-345.

Szaflarski, J. P., Griffis, J., Vannest, J., Allendorfer, J. B., Nenert, R., Amara, A. W., . . . Zhou, X. (2018). A feasibility study of combined intermittent theta burst stimulation and modified constraint-induced aphasia therapy in chronic post-stroke aphasia. *Restorative Neurology and Neuroscience, 36*(4), 503-518.

Szaflarski, J. P., Vannest, J., Wu, S. W., DiFrancesco, M. W., Banks, C., & Gilbert, D. L. (2011). Excitatory repetitive transcranial magnetic stimulation induces improvements in chronic post-stroke aphasia. *Medical Science Monitor, 17*(3), 132-139.

Teasell, R., Mehta, S., Pereira, S., McIntyre, A., Janzen, S., Allen, L., . . . Viana, R. (2012). Time to rethink long-term rehabilitation management of stroke patients. *Topics in Stroke Rehabilitation, 19*(6), 457-462.

Turkeltaub, P. E., Swears, M. K., D'Mello, A. M., & Stoodley, C. J. (2016). Cerebellar tDCS as a novel treatment for aphasia? Evidence from behavioral and resting-state functional connectivity data in healthy adults. *Restorative Neurology and Neuroscience, 34,* 491-505.

van de Sandt-Koenderman, M., Wiegers, J., & Hardy, P. (2005). A computerised communication aid for people with aphasia. *Disability and Rehabilitation, 27*(9), 529-533.

van de Sandt-Koenderman, M. (2004). High-tech AAC and aphasia: Widening horizons? *Aphasiology, 18*(3), 245-263.

Vila-Nova, C., Lucena, P. H., Lucena, R., Armani-Franceschi, G., & Campbell, F. Q. (2019). Effect of Anodal tDCS on Articulatory Accuracy, Word Production, and Syllable Repetition in Subjects with Aphasia: A Crossover, Double-Blinded, Sham-Controlled Trial. *Neurology and Therapy, 8*(2), 411-424.

Villamar, M. F., Volz, M. S., Bikson, M., Datta, A., Dasilva, A. F., & Fregni, F. (2013). Technique and considerations in the use of 4x1 ring high-definition transcranial direct current stimulation (HD-tDCS). *Journal of Visualized Experiments* (77), e50309.

Vuksanović, J., Jelić, M. B., Milanović, S. D., Kačar, K., Konstantinović, L., & Filipović, S. R. (2015). Improvement of language functions in a chronic non-fluent post-stroke aphasic patient following bilateral sequential theta burst magnetic stimulation. *Neurocase, 21*(2), 244-250.

Wessel, M. J., & Hummel, F. C. (2018). Non-invasive cerebellar stimulation: a promising approach for stroke recovery? *Cerebellum, 17*(3), 359-371.

Wu, D., Wang, J., & Yuan, Y. (2015). Effects of transcranial direct current stimulation on naming and cortical excitability in stroke patients with aphasia. *Neuroscience Letters, 589*, 115-120.

Yoon, T. H., Han, S. J., Yoon, T. S., Kim, J. S., & Yi, T. I. (2015). Therapeutic effect of repetitive magnetic stimulation combined with speech and language therapy in post-stroke non-fluent aphasia. *Neurorehabilitation, 36*(1), 107-114.

You, D. S., Kim, D.-Y., Chun, M. H., Jung, S. E., & Park, S. J. (2011). Cathodal transcranial direct current stimulation of the right Wernicke’s area improves comprehension in subacute stroke patients. *Brain and Language, 119*(1), 1-5.

Zhang, H., Chen, Y., Hu, R., Yang, L., Wang, M., Zhang, J., . . . Du, X. (2017). rTMS treatments combined with speech training for a conduction aphasia patient: A case report with MRI study. *Medicine, 96*(32), e7399.

Chapter 4: Incorporation of high-tech AAC in clinical practice

Introduction

Stroke is the leading cause of long-term disability in the US and in India (Benjamin et al., 2017; Pandian & Sudhan, 2013) with stroke-induced aphasia seen in roughly 1 in 250 people in the US and 1 in 240 people in India (NIDCD, 2015; omicsonline.org). Individuals with aphasia experience difficulties in communication resulting from damage to brain areas that are responsible for language comprehension and expression (Basso, 2003; Davis, 2007). The deficits in functional communication can lead to limited participation in the socioprofessional domain affecting their quality of life (Ross & Wertz, 2003; Spaccavento et al., 2014). A combination of conventional speech-language therapy and high-tech communication supports can improve language outcomes for individuals who continue to encounter long-term communication challenges (Dietz, Wallace, & Weissling, 2020).

High-tech communication supports (HTCS) are comprised of augmentative and alternative communication (AAC) approaches that can refocus therapy on the individual holistically rather than solely improving core skills like comprehension, speech, and swallowing (Garrett & Lasker, 2007). Clinical application of AAC strategies can be categorized into no-tech, low-tech, and high-tech solutions (Cook & Polgar, 2015). The no-tech category is the oldest form of AAC and relies on interpretation of facial expressions and voluntary motor movements, such as gestures to deliver non-verbal messages (Smith, 2006). Low-tech utilizes supports like cards, picture books, alphabet boards, choice from written words/messages, and display boards with extended lexicons. Interpretation of eye-gaze, gestures, mimicking, pointing, writing, and drawing are a few ways of accessing low-tech AAC (Van de Sandt-Koenderman, 2004). HTCS are smart devices that can be operated through simple to complex methods of access by integrating a hardware and software to support a user's communication needs and to optionally translate a message text into speech. Specifically, high-tech AAC includes electronic devices, mobile phones, and speech-generating computerized systems that can be operated through direct finger touch, eye-tracking, switches, head and body movement, neural and muscular potential estimation, and brain-computer interfaces to achieve a communicative outcome (Elsahar et al., 2019).

The Human Activity Assistive Technology (HAAT) model provides an interactive framework, for supporting the selection of appropriate assistive technology to perform an activity in a specific context by prioritizing the needs and abilities of the individual with aphasia while optimizing the use of technology (Figure 1, Cook & Polgar, 2015; Giesbrecht, 2013; Iacono, Lyon, Johnson & West, 2013). The framework of the HAAT model is similar to the International Classification of Functioning, Disability, and Health (ICF) model by the World Health Organization (WHO) that addresses the impact of a health condition (e.g., aphasia) on body structures and functions for execution of activities and participation within the context of an individual's environment. HTCS adds to the conventional speech-language therapy program as it can improve participation in activities of daily living while influencing and supporting the anatomical, physiological, and environmental needs of an individual with aphasia. In the HAAT model, the interaction between the individual and assistive technology is emphasized to support the communication process, in a way that technology prioritizes the activities and abilities of the individual with aphasia.

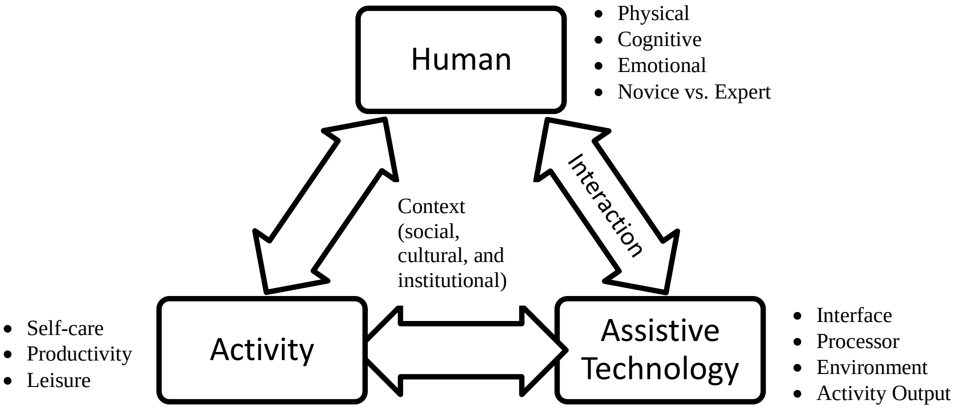

Figure 1: The Human Activity Assistive Technology model

Individuals with aphasia can be classified into different stages on a continuum from partner dependent communicators to independent communicators (Lasker, Garrett & Fox, 2007). An aim of AAC-based intervention is to help individuals with aphasia to progress on the continuum of independence (Garrett & Lasker, 2005). For instance, an individual with severe aphasia can first use HTCS as an emerging AAC communicator during subacute rehabilitation. As recovery progresses, the HTCS can be adapted and cues can be faded to shift away from stored message communication to specific-needs communication. HTCS can further support rehabilitation by including fully developed text messages in visual scene displays that are designed to stimulate the existing language system and by drawing from the intact visual input modalities to self-cue residual language networks (Dietz et al., 2018). The use of HTCS from the initial stages of recovery can help strengthen communication and support their residual language networks through alternative communicative output and accurate feedback. As residual language networks strengthen, communication can become more independent and the use of HTCS can be gradually reduced.

HTCS are rapidly evolving to provide more tailored communication solutions for people with aphasia at their specific stage of recovery, and several factors lead to their successful use in clinical practice, including extent of stroke-induced cognitive and physical deficits, complex training required for using a HTCS, methods of access, cost of device, etc. (Cook & Polgar, 2015; Elsahar et al., 2019; Hodge, 2007). Speech-language pathologists (SLPs)/clinicians play an active part in the inclusion and future use of HTCS for aphasia rehabilitation especially given their vital role in procurement, assessment, selection, prescription, and continuing intervention with HTCS for aphasia. As SLPs are an integral part of the multidisciplinary team of professionals involved in the recovery of an individual with aphasia, they form a central link between device manufacturers, clinic/hospital, client, insurance policy, and other professionals. The current study surveys viewpoints in two countries where SLPs are becoming central to long-term care for people with stroke-induced aphasia.

Pioneers of the interdisciplinary field of AAC have been predominant in North America, leading to a more Anglo-European perspective on inclusion of HTCS for aphasia (Bridges, 2004; Huer & Soto, 1996). The leading organizations for inclusion of AAC for communication disorders like the American Speech-Language-Hearing Association (ASHA) and the International Society for Augmentative ad Alternative Communication (ISAAC) are based out of the US and Canada. ASHA was established in 1925, and ISAAC was formed in 1983, with the US gaining membership in 1991. As the field of AAC progressed, ASHA in 2005 included AAC as a subsection in one of the content standards in the ASHA Certification Standards of Practice, and in 2014, changed wording from “communication modalities” to “augmentative and alternative communication modalities” for accurate reflection of the standard’s intention. Further, there has been a steady increase in the number of graduate programs offering dedicated

AAC coursework in pre-service training in the US (Johnson & Prebor, 2019). Support for HTCS in the US was formalized in the Individuals with Disabilities Act (1988) followed by Assistive Technology Act (2004) that ensured that individuals with disabilities had easy access to assistive technology. Additionally, government healthcare in the US (Medicaid) has had provisions for healthcare equipment since the late 1970s, and in April 2015 Medicare began covering AAC devices specifically the speech-generating devices for people with communication impairments (Centers for Medicare & Medicaid Services, 2015). Over the past 20 years, the model of using HTCS for improving communicative outcomes has been broadly adopted by SLPs in western Anglo-European nations.

In developing countries where the field of AAC has emerged later, AAC-related service and device dissemination are gradually picking up. One such developing country is India where the field of speech-language pathology started with the establishment of the All India Institute of Speech and Hearing (AIISH) in 1965. The Indian Speech and Hearing Association (ISHA) as a professional organization began working in 1967 and the Rehabilitation Council of India started certifying SLPs as health professionals in 1992. Another organization, The Indian Institute of Cerebral Palsy (1974), started the National Resource Center for Augmentative and Alternative Communication in 2005. A specialized AAC unit started at AIISH in 2003, and dedicated AAC coursework began in 2005. India became a member of ISAAC in 2008. Even though Indian government policies like the Assistance to Disabled Persons for Purchase and Fitting of Aids and Appliances (ADIP scheme, 1981), the Persons with Disability Act (1995), the National Trust for the Welfare of Persons with Autism, Cerebral Palsy, Mental Retardation and Multiple Disabilities Act (1999) provide equal opportunities, protection of rights and full participation to individuals with disabilities including communication disorders, these policies rarely provide for acquisition and intervention with HTCS for individuals with communication impairments. In light of the policy differences in both countries, the current study aims to survey the factors affecting use of HTCS in aphasia rehabilitation by SLPs in the US who have a relatively established structure of AAC practice and explore those factors for using HTCS for aphasia recovery in India with a less developed AAC infrastructure. The identification of these factors can help us understand the evolution of AAC device inclusion in clinical practice in both countries, particularly for factors involved in clinical training, aphasia assessment, and intervention focused towards HTCS for aphasia.

Despite the differences in the development of the field and AAC resources, the burgeoning population of India does lead to a comparable number of individuals with aphasia to the US (NIDCD, 2015, omicsonline.org). According to the NIDCD (2015), there are 180,000 new cases of aphasia per year in the US, with 1 in 250 people currently living with aphasia. In India, the incidence of stroke ranges from 105 to 152/100,000 per year and the prevalence of stroke ranges from 44.29 to 559/100,000 (Kamalakannan, Gudlavalleti, Gudlavalleti, Goenka, Kuper, 2017). Approximately, 43% of Indian individuals experiencing aphasia are 85 years and older, and 15% of the population with aphasia is under 65 years (omicsonline.org).

Improved medical services and preventive measures have considerably increased the number of stroke survivors with aphasia (Avan et al., 2019). Since aphasia is a communication disorder that presents in different ways based on the size and location of lesion, different individuals require different communication modalities and intervention tools (Marshall, 2010). To contribute to the international AAC literature, the current study aims to elucidate American and Indian SLPs' viewpoints about clinician- and client-driven factors for inclusion of HTCS in aphasia care. The major research questions were: a) What are the education practices, and AAC-specific training in a developed country like the US and a developing country like India? As SLPs play a pivotal role in therapeutic intervention, clinical training and practice can identify gaps in resources available for SLPs to incorporate HTCS in therapy programs. Secondly, b) What are the similarities in the SLP practices in both countries and their impacts on HTCS provision? Thirdly, c) What is different in AAC service provision and how does it influence HTCS availability for aphasia assessment and intervention in each country?

Method

Participants. Speech-language pathologists (SLPs) working in the US and India were recruited and provided with a survey on their education and clinical practice with regard to AAC and aphasia. SLPs in the USA were identified and recruited through the ASHA via the Special Interest Group (SIG) 2 (Neurogenic Communication Disorders), and state speech and hearing organizations. In India, SLPs were recruited through the Indian Speech and Hearing Association (ISHA), and the All India Institute of Speech and Hearing (AIISH). The current study was approved by the Institutional Review Board of the University of Kansas.

Instrumentation. A questionnaire was developed to explore the current trends in professional practice of using high-tech communication supports (HTCS) for people with aphasia. The broad areas were the coursework and training for AAC, awareness and availability of tools for assessment, procurement, and success with device usage. The questionnaire was then checked and edited for relevance by a SLP specializing in AAC practice for individuals with aphasia in the US. The online survey was designed utilizing Qualtrics survey software. Before beginning the survey, participants first read and completed an informed consent form, which was followed by the questionnaire of 41 content-related items that included polar (yes/no), multiple-choice, and multiple-answer questions as well as an option for subjective detailed answers.

The questions in the survey were categorized into three main sections- professional demographics, assessment, and management procedures. The first block of survey questions on professional demographics requested information about the SLP's education, AAC training, work setting, and current caseload. The second block of survey questions was intended to elicit details about AAC assessment, device availability for assessment and rehabilitation, practices surrounding trial devices, and recommendation of HTCS for intervention. The third block of survey questions focused on HTCS-aided aphasia rehabilitation. Survey items were designed to solicit professionals' viewpoints on current AAC practice trends with respect to their own training and preparedness to include novel technological options in their therapy programs.

As the survey was prepared electronically, conditions were placed on questions; for example, if a participant responded affirmatively to past involvement with assessment using AAC, then survey questions on the topic of AAC assessment were presented to respondents; a negative response triggered skip-logic that advanced the survey to the next major subsection of questionnaire items. This skip logic was applied to all sub blocks of questions in the three major sections until the completion of the questionnaire.

Procedure. In the US, ASHA SIG 2 and all the 50 state speech and hearing organizations were contacted, and permission was requested to post advertisements for the survey on their web portal. The Qualtrics survey link was then posted on the ASHA SIG 2 and 15 state speech and hearing organizations' web portal without a fee. The survey link also was posted on social media through private Facebook groups – the University of Kansas Speech-Language-Hearing and Child Language Doctoral Program Graduate Student Organization and Clinical Research for SLPs. In India, the survey link was posted on the web portal of the Indian Speech and Hearing Association (ISHA). Email contacts of SLP alumni were requested from AIISH and individual e-mail invitations with the survey link were sent to SLPs practicing in India. Respondents who received an e-mail link to access the survey received two reminder e-mails- one after two weeks of the original e-mail and the second after 6 weeks from the original e-mail. The survey link was also posted on the Indian Facebook groups - Audiology and Speech jobs and other related professionals, and the Aphasia and Stroke Association of India. The Qualtrics survey link was active for four months from its launch.

Data Analysis. The Qualtrics survey software platform tracked responses based on country and manner of response (e-mail, social media, organization/group webpage). Responses to each question were segregated based on completion of the entire survey and country of work. Raw numbers of responses have been converted to percentages for figures and tables.

Results

Through a period of ffour months, 175 SLPs responded to the survey. In the 175 responses, 100 SLPs responded to all the questions on the survey (skip logic was not activated), and these complete survey responses were considered for further analysis. The survey respondents were 57 SLPs from the US and 43 from India, who were certified by ASHA or the Rehabilitation Council of India (RCI), respectively, to professionally provide services in each country. The survey solicited information from the SLPs in three broad blocks of questions: demographics, aphasia assessment using high-tech devices, and the use of devices for aphasia intervention. The survey is available as supplemental materials and responses are grouped according to survey questions.

What are the AAC education and training practices of SLPs?

Education and training (Q5, Q9, Q10, Q11). SLPs in the US (48) and in India (32) reported to have a Master’s degree as their highest level of education. The remaining US SLPs

(9) and Indian SLPs (5) who responded to the survey completed a higher doctoral degree. SLPs in India can be certified and work professionally without supervision after graduating with a Bachelor's degree in Speech and Hearing (6). Fifty-one of the 57 American SLPs had completed AAC coursework and/or clinical training for device usage with clients. Out of 43 Indian SLP responses, 37 had received AAC education either during the graduate coursework or during service hours for AAC provision at work. American SLPs (51) had more hours of dedicated AAC clinical training than Indian SLPs (37, Table 1). The holistic combination of education avenues and clinical AAC training was proportioned differently in the US and India (Table 1).

Table 1: AAC education and training of the survey respondents

Education Avenues	**USA (57)**	**India (43)**
Graduate coursework	78 %	78%
Clinical Practicum	41%	57%
Conference	49%	27%
In-service at workplace	55%	16%
Hours of Training		
0-5 hours	12%	24%
6-10 hours	22%	32%
11-15 hours	12%	8%
16-20 hours	35%	27%
Others*	20%	8%

Others*= Respondents gave subjective answers ranging from 1 day of observation to a semester worth of hours.

Work experience and settings (Q8). The survey respondents had the options of selecting all their current work settings. American SLPs worked in hospitals (25), schools (21), followed closely by skilled nursing facilities (16), university clinics (14), and private clinics (11). Indian SLPs worked mainly in private clinics (23) and hospitals (19) followed by university clinics (12) and schools (9) (Table 2).

Table 2: Survey respondent’s work settings

Work settings	**American SLPs (57)**	**Indian SLPs (43)**
School	39%	21%
Private Clinic	21%	56%
Hospital	46%	44%
Skilled Nursing Facility	30%	No Response
Residential Facility	5%	7%
Long-Term Care Facility	18%	No Response
University Clinic	26%	26%

Caseload (Q12, Q13). The survey respondents in both countries reported fewer adults with acquired neurological disorders on their current caseload in comparison to children with communication disorders (Figure 2a). Both American and Indian SLP respondents reported having a similar current caseload of adults with aphasia (Figure 2b).

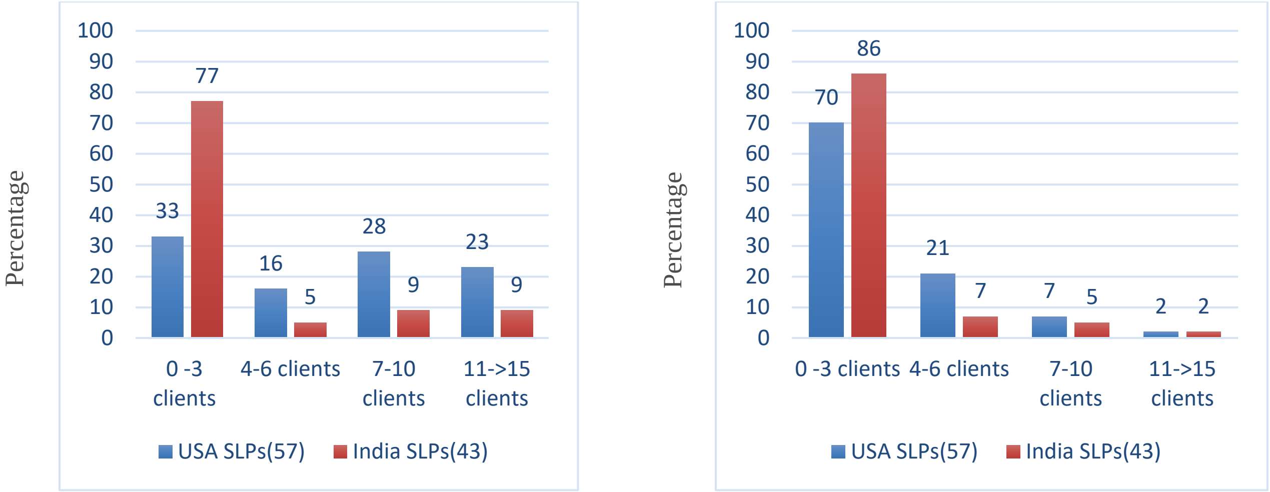

Figure 2 (a, left): Adult caseload of the survey respondents, 2 (b, right): Aphasia caseload of the survey respondents

What are the AAC assessment considerations?

Timeline for consideration of an AAC device (Q14, Q15). American SLPs (31) and Indian SLPs (18) reported an AAC assessment as part of their speech-language assessment protocol. American SLPs (57) reported they consider using a high-tech device for intervention within a month (24) or within first six months post-CVA (20). Similarly, Indian SLPs (43) also decide about a HTCS within a month (15) or within the first six months of CVA (14).

AAC assessment tools (Q18, Q19). Responses to the open-ended question revealed that American SLPs (6) and Indian SLPs (4) used dedicated assessment tests such as The Multimodal Communication Screening Test for Persons with Aphasia (MCST-A, Lasker & Garrett, 2006). SLPs from both countries reported using several other tools to assess AAC candidacy, speech, language, cognitive, and motor abilities during an assessment session. These tools included informal observation, checklists, protocols from AAC device companies, assessment with computer applications (e.g., Lingagraphica Device Assessment Tool, AAC Evaluation Genie) and standardized tools like the Aphasia Needs Assessment (Garrett & Beukelman, 2006), Cognitive Linguistic Quick Test (CLQT; Helm-Estabrooks, 2001), Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975), Western Aphasia Battery-Revised (Kertesz, 2006), Language Acquisition through Motor Planning (LAMP, Halloran & Halloran, 2009), and The Makaton Vocabulary-Indian Version (Walker, Ghate, & Lal, 2002).

Trial devices for assessment (Q20, Q21, Q22, Q23). The ownership of the trial devices used during an assessment session was different between the two countries as American SLPs used devices loaned from the manufacturing company whereas Indian SLPs mostly used a trial device owned by the clinic (Figure 3). Despite ownership differences, American SLPs (57) reported use of one (12) to two trial devices (16) during assessment. Indian SLPs (43) used one (8) to two trial devices (16) during assessment as well. SLPs in the US (47) and India (33) noted including mobile devices and iPads with AAC applications for assessment.

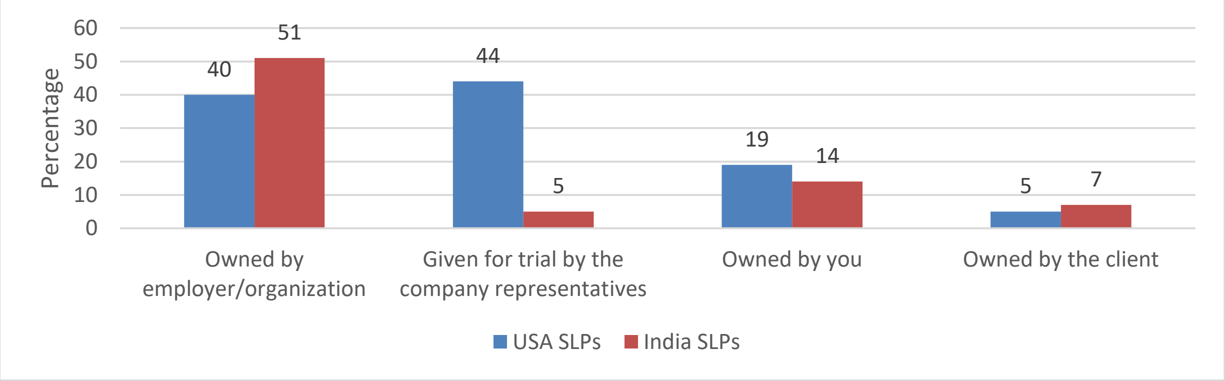

Figure 3: Trial device ownership

AAC assessment session (Q 25, Q26, Q27). Areas assessed for device use were language comprehension and expression, motor skills, symbol identification, literacy, and candidacy for both US SLPs (57) and Indian SLPs (43). A typical single device assessment session ranged for about one hour (18 US SLPs and 12 Indian SLPs), and at least two sessions (17 US SLPs and 14 Indian SLPs) were used for a detailed assessment in each country. American (11) and Indian SLPs (3) also reported continuous assessment during ongoing therapy sessions to come to a decision for updating a high-tech communication device.

What are the AAC intervention patterns for aphasia rehabilitation?

Multidisciplinary professional teams (Q16, Q17, Q28). There were 14 American SLPs and 7 Indian SLPs who reported being part of a team that focused on using multimodal assessment and intervention inclusive of high-tech communication supports. For assessment, American (26) and Indian (20) SLPs reported that the team comprised of a general physician, neurologist, physical therapist, occupational therapist, and nurse. In the US (30), the primary decision-makers for device purchase to be used for intervention included the SLP, the client, and the primary caregiver. In India (22), the team members included the SLP, physical therapist, occupational therapist, client, and caregiver for purchase of the device for intervention.

Client-driven factors (Q29). Success with a trial device (39) and family support to use a communication device during rehabilitation (39) were the highest rated client-driven factors in the US whereas financial factors (29) and comfort with technology (28) were the most common client-driven factors in India (Figure 4).The respondents could choose multiple answers for this question and also mention factors not on the list, but no personalized response was obtained.

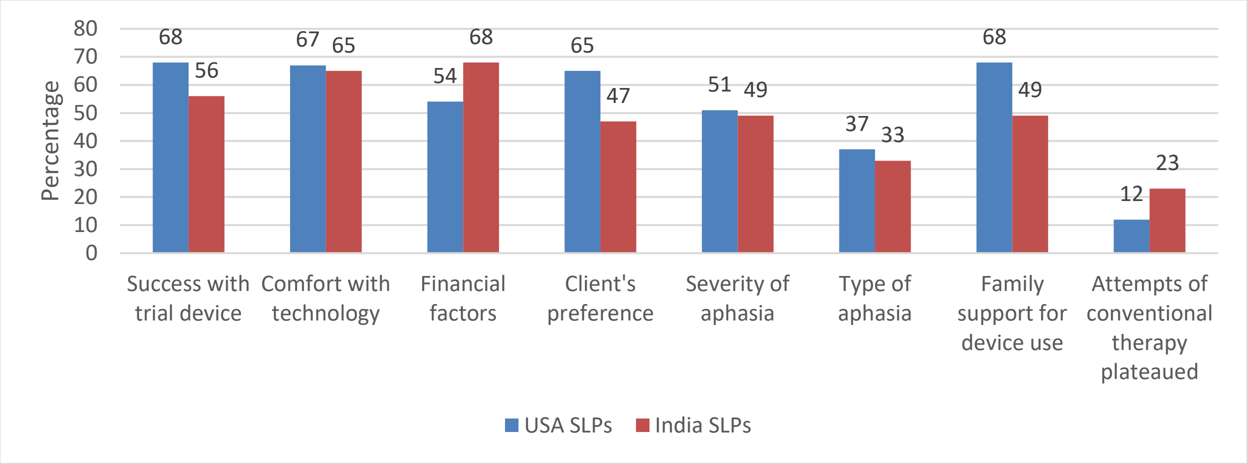

Figure 4: Client-driven factors for use of high-tech communication supports

Clinician-driven factors (Q30). Availability of a device for trial (36) was the most important factor influencing the SLPs’ recommendation in the US, whereas in India, availability of a trial device (25) and experience with high-tech communication devices (25) were important factors (Figure 5). For this question, survey respondents could choose all the factors listed and submit their own responses as well. Some of responses generated were post-purchase customer service, troubleshooting assistance, and their prior experience with the device for aphasia intervention.

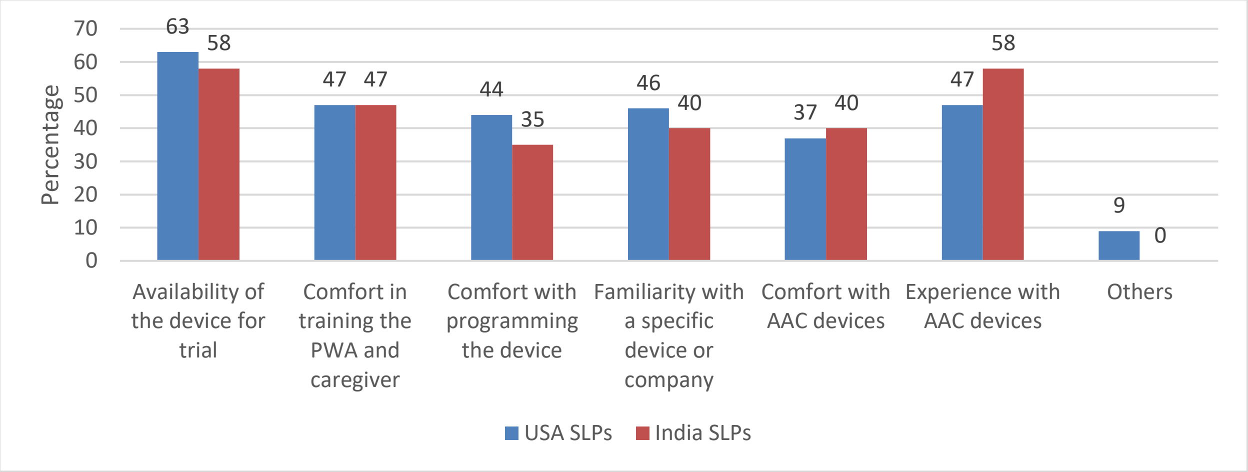

Figure 5: Clinician-driven factors for use of high-tech communication supports

Prescription of a high-tech communication support (Q31, Q32, Q33). American SLPs (29) and Indian SLPs (21) reported recommending a high-tech communication support for at least one individual with aphasia to half their caseload of people with aphasia (Table 3). In addition, US SLPs (17) and Indian SLPs (8) chose level of comfort in securing funding for a prescription of HTCS. Also, 26 US SLPs and 5 Indian SLPs felt comfortable with programming a high-tech device by themselves.

Table 3: Recommendation to use high-tech communication supports during intervention

Number of IWAs recommended with an AAC device on your caseload	**USA SLPSs (57)**	**India SLPs (43)**
1	25%	30%
2	20%	9%
Half of the caseload	7%	9%
All the persons on your caseload	5%	2%
Specific number	14%	7%

Caregiver training (Q34, Q35, Q36, Q37). A large portion of the survey respondents (51 US SLPs and 40 Indian SLPs) considered caregiver training an essential part of the intervention program. The number of hours of family and caregiver training was dependent on the client and the caregivers, and often education and training was provided in each session in both countries (34 US SLPs and 22 Indian SLPs). For the purposes of this survey, questions on family/caregiver training were divided into three broad categories: (a) device operations, (b) techniques or teaching strategies, and (c) resource access. Survey respondents indicated that in device operations, 46 American and 24 Indian SLPs initially focus on basic operations like switching the device on/off, charging, volume settings, and customization of vocabulary and pages. In teaching strategies, aided language stimulation and creating opportunities for using the high-tech communication support was commonly seen in both countries (44 US SLPs and 30 Indian SLPs). In resource access, opening online technical support and backing up the device was emphasized in the US and India (42 US SLPs and 24 Indian SLPs). A surprising finding was that only six US SLPs and one India SLP reported that caregivers followed up on training about 60-100% of the time to support the use of a HTCS outside of a clinic.

Places of device use (Q38). The places of device use other than clinic (42 US SLPs and 34 Indian SLPs) and home (38 US SLPs and 31 Indian SLPs) such as community spaces (20 US SLPs and 14 Indian SLPs) was low in both countries.

Commonly used high-tech communication support (Q39, Q40). Both in the US (42 SLPs) and India (18 SLPs), SLPs reported an iPad with applications was the most used HTCS for aphasia rehabilitation. Other devices in the US included Tobii Dynavox, Prentke-Romich Company, other Windows-based tablets and Saltillo products. In India, Windows-based tablets and devices like AVAZ were the commonly used devices after iPad. Survey responses indicated that 25 American SLPs and 14 Indian SLPs carried out individualized programming of high-tech devices for their aphasia caseload.

Abandonment of device (Q41, Q42). Abandonment of high-tech devices by individuals with aphasia is a serious issue after the entire process of obtaining a device, programming, and training the individual and family members. Increased time for message creation from a device (37 US SLPs) and caregiver's ability in support and maintenance of the device were considered the reasons for abandonment in the US, whereas difficulty in using the device outside of clinical settings (27 Indian SLPs) without continuous clinician help was most responsible for device abandonment in India (Figure 6).

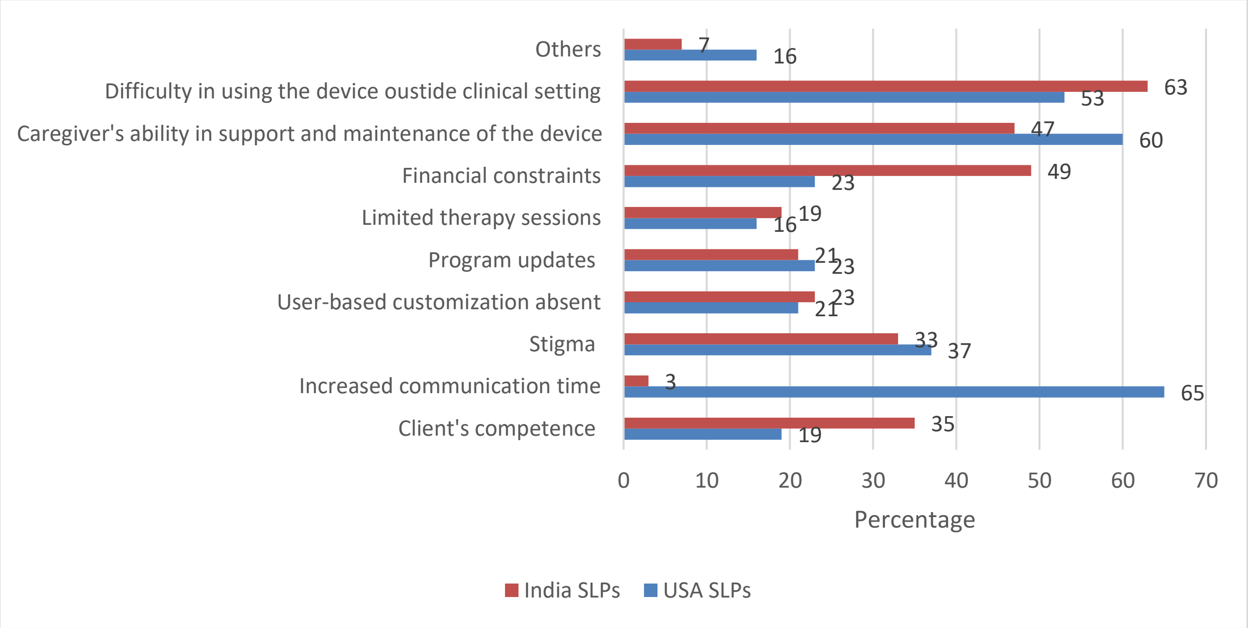

Figure 6: Factors influencing abandonment of high-tech communication supports

Discussion

The purpose of this survey was to identify factors perceived as important by SLPs for recommending high-tech communication supports for individuals with aphasia in the US and India by analyzing standard clinical AAC practices. Individuals with aphasia present with a diverse pattern of communication deficits, thus requiring new communication environments and methods that capitalize on the post stroke operational and linguistic competencies. The three broad areas for analysis in this study were: (1) AAC coursework and clinical training, (2) device-based speech-language pathology assessment, and (3) intervention using high-tech communication supports for aphasia recovery. The similarities and differences noted in the practice patterns indicate country-specific factors that influence prescription of HTCS for aphasia care. The specific clinical implications are presented in Table 4.

Similarities in device-based practice in the US and India. Survey respondents from the US and India indicated graduate and doctoral degrees as their highest level of education. This result is unsurprising given the Master's degree completion is a requirement for certification in the US through ASHA and state professional licensing organizations. Master's degree is encouraged and preferred in India, even though SLPs can obtain certification by the Rehabilitation Council of India after completing an undergraduate degree in speech and hearing. Augmentative and alternative communication is required graduate coursework by ASHA as stated in Standard IV-C Knowledge Outcomes, and for graduate certification by Rehabilitation Council of India, though not for the undergraduate degree. These requirements ensure all certified SLPs with graduate education in either country have the relevant knowledge to incorporate AAC for assessment and intervention. However, SLPs in India with clinical certification following completion of an undergraduate degree only don't always have AAC coursework, potentially limiting their knowledge and comfort with AAC practices that may require future in-service training.

The consideration of high-tech devices for aphasia rehabilitation largely occurs within the first six months following a stroke in both countries to support communication recovery. The results from this study reflects emerging practices for recommending high-tech communication supports for aphasia (Mofatt, Pourashahid, & Baecker, 2017) as opposed to previous beliefs that HTCS are the last resort after failure at other strategies and treatments (Fried-Oken, Beukelman, & Hux, 2012; Tiwari & Krishnan, 2011). Early introduction of AAC devices can help an individual with aphasia in expressing basic needs, participate in the decision-making process about healthcare, actively take part in therapy and regain social roles (Light & McNaughton, 2014).

The survey participants reported using informal evaluation checklists as the primary method to determine candidacy for a device in the US and in India. Once candidacy was determined, then assessment methods included dynamic and application-based assessment combined with consultations with team members and interviews with family members for further evaluation of the needs of the individual (McBride, 2011). The areas assessed during device-based assessment in both the US and India primarily include taking a case history, evaluating language and communication, and symbol assessment. Specifically, AAC specialists in both countries also use trial devices, assess for access methods, check for comfort with low to high-tech devices and provide personalized AAC instruction (Dietz, Quach, Lund & McKelvey, 2012).

Survey respondents in both US and in India reported using one or two trial devices during assessment. This finding adds to the mounting evidence that SLPs specializing in AAC in the US tend to schedule multiple sessions with a minimum of two trial devices (Dietz et al., 2012). Both American and Indian SLPs reported continuous assessment during ongoing therapy sessions to come to a decision for selecting and updating a high-tech communication device as opposed to one initial assessment. An evaluation for a HTCS must consider an individual's needs (Beukelman & Mirenda, 2013) and abilities with an understanding that both will change gradually during recovery (Quist & Llyod, 1997) and the individual with aphasia will require follow-up support as appropriate (Lloyd, 2011).

The final prescription of HTCS for individuals with aphasia was relatively low in both countries despite survey responses indicating a consideration of early AAC intervention for aphasia rehabilitation. Findings from the ASHA National Outcomes Measurement Systems revealed that only a small percentage of individuals with chronic aphasia received AAC intervention (Rogers, Roye, & Mullen, 2014). In contrast to past case reports and survey responses in the current study, Dietz et al. (2020) concluded AAC intervention is generally recommended as a last resort when severity of aphasia prevents successful verbal communication.

iPads emerged as a common HTCS in both US and India as they are easily obtained and affordable creating a more direct path for SLPs to procure the device and initiate rehabilitation and caregiver training (Dolic, Pibernik & Bota, 2012; Ogletree, McMurry, Schmidt, Evans, 2018). Caregiver training was identified as an integral part of HTCS intervention in both countries as communication partner instruction positively supports functional communication and encourages expressive language of individuals with aphasia (Kent-Walsh, Murza, Malani, Binger, 2015). Relearning to communicate with a HTCS can often be taxing for an individual with aphasia leading to device abandonment at rates similar in both countries. In cases of abandonment, support from the clinician, team members, family, and communication partners is weak for device-based communication (Johnson, Inglebret, Jones & Ray, 2006).

Differences in device-based practice in the US and India. Although AAC coursework during graduate programs is similar for SLPs in the US and in India, the overall AAC education avenues differ for SLPs in the two countries. Beyond the coursework at school, conference-based education and workplace-based in-service training is widely different for SLPs in the two countries. The survey responses indicated that American SLPs continued with additional AAC education and training after their formal academic training through conference workshops and work settings. Indian survey respondents indicated they had fewer opportunities for continued post-graduate education and fewer hours of post-graduate AAC training. Additional opportunities for continuing education in AAC could support greater involvement of HTCSs in Indian clinical practice.

The number of work years for American and Indian survey respondents also was different, though this may be attributed to the way the survey was distributed in the US and in India. In the US, SLPs from ASHA SIG 2 and 15 state speech and hearing organizations received and completed the survey. In India, alumni from AIISH and my professional contacts received and completed the survey. So, Indian survey respondents may have had lesser years of work experience after graduate school when they completed the survey. Generally, the work settings for SLPs in the US are different from the work settings of SLPs in India. In the US, SLPs can work at schools, university clinics, private clinics, hospitals, skilled nursing facilities, assisted living facilities, and long-term care facilities. However, in India, SLPs work at schools, university clinics, private clinics, and hospitals. There are sparingly few establishments like long-term care facilities, skilled nursing facilities, or assisted living primarily concentrated in urban areas with exorbitant costs (Gangadharan, 2003, Tripathy, 2014). Even when considering non-educational work settings that focus on aphasia intervention, SLPs in the US appear to have a greater variety of opportunities to encounter people with aphasia (Grabowski, 2021).

Based on the current survey, the ownership of the trial device used during assessment and the initial weeks of intervention was different in the US and India. In the US, SLPs were able to borrow a trial AAC device from the manufacturers or from their workplace. A small number of American SLPs also owned the iPad/Windows-based tablet that worked as a trial device. From this survey specifically, Indian SLPs when using a trial device borrowed it from their clinic or used their personal device. The survey responses revealed that the team members involved in the decision-making process for purchase of HTCS for an individual with aphasia in the US were primarily the SLP, individual with aphasia, and the caregiver. However, in India the team members involved in decision making for communication support purchase was larger, including the SLP, physical therapist, occupational therapist, caregiver and the individual with aphasia.

Client-driven factors are major determiners for using a HTCS during aphasia recovery. In this survey, American and Indian SLPs rated a prepared list of factors that they considered were important for the individuals with aphasia with whom they worked, including a) success with trial device, b) comfort with technology, c) financial factors, d) client's preferences, e) aphasia severity, f) aphasia type, g) family support for device use, and h) attempts at conventional therapy had plateaued. The survey respondents from the US noted that success with the trial device and family support for the device were the most important client-rated factors that influenced the individual with aphasia to successfully use the device. Caregivers or family members often take on the role of AAC facilitators and communication partners who assist in AAC service coordination and provide information about the individual's daily communication needs and personal preferences (Binger et al., 2012). Thus, they influence the successful use of the communication support for language-based communication. Survey respondents from India noted that financial factors and comfort with technology were factors that were most relevant to individuals with aphasia for successful use of the communication supports. The affordability and accessibility of the communication support were important to individuals with aphasia in India as dedicated communication supports are expensive and not as widely available when compared to the US.

American and Indian SLPs rated a list of clinician-driven factors for successful use of high-tech communication support. The factors included a) availability of device for trial, b) comfort in training the individual with aphasia and caregiver, c) comfort with programming the device, d) familiarity with a specific device or company, e) comfort with AAC devices, f) experience with AAC devices, and g) any other relevant factor. American survey respondents noted that availability of trial devices was the most relevant followed closely by experience in AAC devices and being comfortable in training the IWA and caregiver. SLPs lead programming and personalization of high-tech devices to enable the IWA for maintaining a sense of control while conducting meaningful conversation through a system (Dietz, et al., 2012). American survey respondents noted that availability of trial device for assessment supported their assessment. Indian survey respondents noted that experience with AAC devices and availability of trial devices were the salient factors influencing their successful use of HTCS for aphasia care.

Table 4: Clinical implications for HTCS based intervention

Clinical implications in the US	**Clinical implications in India**
Increase exposure to programming AAC devices	Increase coursework, clinical training, and exposure to programming AAC device
Increase awareness about integrating AAC devices in intervention programs	Increase awareness about integrating AAC devices in intervention programs
Reduce the time in message creation and communication	Develop AAC applications in regional languages.

Limitations. This survey was posted online on dedicated SLP forums in both countries and survey respondents were SLPs. So, the sampling error in relation to survey methodology was relatively reduced (Dillman, 2000) as the survey respondents in both countries were certified practicing members in the field of speech-language pathology. This survey had options for individualized answers in almost all questions but lacked singular open-ended questions to look for missed topics considered important for high-tech device use in each country. Additionally, nonresponse error and measurement error (Dillman, 2000) may have occurred in this survey. Nonresponse error occurred when the survey respondents who did not respond had different answers than those who did respond. There were 75 partially filled responses that were not included in the final data analysis, and responses from the SLPs who refrained from responding altogether contributed towards nonresponse errors. Measurement error may have occurred in responses to misunderstood questions, as the selected responses to misunderstood questions can become irrelevant to the questions on the survey. Despite these methodological limitations, this survey study is a unique report to identify factors for high-tech device inclusion for aphasia care in a developed and a developing country.

Conclusion

Exposure to AAC training during formal educational coursework and in programming AAC devices was important for American survey respondents to effectively incorporate high-tech devices and applications in aphasia rehabilitation. In the US, awareness of high-tech devices for aphasia rehabilitation needed to be increased among clinicians and adults with aphasia to improve an individual's communicative outcomes and quality of life. An iPad with AAC applications was common for aphasia rehabilitation as it's an easily available device that can circumvent the entire process of scheduling an appointment from the company representative, loaning trial devices, selecting one high-tech device, and working through health insurance to procure it. Caregiver training and increasing opportunities for communication using the device were considered as important clinician-driven factors for successful use of the device for communication. Also, consistent practice using the device outside clinical settings could reduce the time of creating a message thus improving communication through HTCS.

In India, AAC coursework and training during formal education for modern device-based technology could support SLPs in becoming aware of the novel rehabilitative technology and become comfortable with including it in clinical practice. Clinician exposure in acquiring and programming HTCS for individual needs was identified as an important area as SLPs are the primary resource personnel dispensing information about high tech devices to individuals with aphasia and their family members. Awareness about aphasia, availability of speech-language therapy, high-tech device availability throughout the country, and reducing stigma to communicate using a device was paramount for high-tech device inclusion in aphasia rehabilitation. Respondents in India reported using applications available on iPad and Android PlayStore and speech-generating devices developed in India for individuals with aphasia.

Responsibility and training of family members was emphasized for efficient use of the device outside of the clinical settings. Lastly, availability of high-tech devices with vocabulary and page setup in regional languages would increase the comfort of individuals with aphasia and their caregivers.

Application of high-tech devices for aphasia rehabilitation is based on many different factors in a developed country like the US and a developing country like India. Success with high-tech devices for improving communication can be enhanced by focusing on the interaction of resources available to the SLP and the individual needs of a person with aphasia. A need exists for additional research on the factors that enable the individual to succeed in communicating in each recovery setting whether it be acute medical, inpatient rehabilitation, outpatient rehabilitation, or long-term care in developed and developing countries.

Supplemental Data

Qualtrics Survey

Use of AAC in aphasia rehabilitation: A survey

The Department of Speech-Language-hearing at the University of Kansas supports the practice of protection for human subjects participating in research. The following information is provided for you to decide whether you wish to participate in the present study. You should be aware that even if you agree to participate, you are free to withdrawat any time without penalty.

We are conducting this study to better understand assessment for Augmentative and Alternative Communication in the population with aphasia. This will entail your completion of the survey. Your participation is expected to take approximately 10 minutesto complete this survey. There is no anticipated risk in filling this survey.

Although participation may not benefit you directly, you will become aware of information about some aspects of AAC assessments and usage for individuals with aphasia. This survey will help us gain a better understanding of the clinician dependent factors potentially influencing AAC success with aphasia in the US and India. Your participation is solicited, although strictly voluntary. Your name will not be associated in any way with research findings. No identifiable information will be provided in this study. It is possible, however, with internet communications, that through intent or accident someone may seeyour response.

If you would like additional information concerning this study before or after it is completed, please feel free to contact us by email at juhi_kidwai9@ku.edu. Completion of this survey indicates your willingness to take part in this study. If you have any additional questions about your rights as a research participant, may call (785) 864-7429 or (785) 864-7385, write the Human Research Protection Program (HRPP), University of Kansas, 2385 Irving Hill Road, Lawrence, Kansas 66045-7568, or email irb@ku.edu.

Sincerely,
Juhi Kidwai, Ph.D. student
Principal Investigator
Dept. of Speech-Language-Hearing
3001 Dole Human Development Center
University of Kansas
Lawrence, KS 66045
juhi_kidwai9@ku.edu

I consent to participate in this survey.

○ Yes
○ No

Q2. In which country, do you practice as a speech language pathologist?

○ India
○ United States of America

Q3. Are you RCI certified speech language pathologist?

○ Yes
○ No

Q4. Are you an ASHA certified Speech language pathologist?

○ Yes
○ No

Q5. What is the highest level of education you have received?

○ Undergraduate degree
○ Graduate degree
○ Doctoral degree
○ Clinical Doctorate degree
○ Post-doctoral degree
○ ☐ Others, please specify:

Q6. What is your gender?

○ Male
○ Female
○ Transgender
○ Don't wish to specify

Q7. How many years have you worked as a speech language pathologist?

○ 0-3 years
○ 3-6years
○ 6-10 years
○ 10-15years
○ 15-30 years
○ > 30 years

Q8. In what settings do you practice as a speech language pathologist?Select all that apply

☐ School
☐ Private clinic
☐ Hospital
☐ Skilled nursing facility
☐ Residential facility

Q9.

Have you received training in AAC during your schooling or when providing services in AAC?

☐ Yes
☐ No

Q10.

Where did you receive training in AAC? Select all that apply

☐ Graduate coursework
☐ Clinical practicum
☐ Conference
☐ In-service at workplace

Q11. How many hours of training/education did you receive in AAC?

○ 0-5 hours
○ 6-10 hours
○ 11-15 hours
○ 16-20 hours
○ ____________ other

Q12. How many adults are on your current caseload?

○ 0
○ 1-3
○ 4-6
○ 7-10

Q13. How many adults on your current caseload are diagnosed with aphasia?

○ 0
○ 1-3
○ 4-6
○ 7-10
○ 11-15
○ > 15

Q14. At what point post-cerebrovascular accident(CVA), do you begin considering fitting with an AAC device?

○ < 1 month
○ 1-6 month
○ 6- 12 months
○ 12-18 months
○ > 18 months

Q15. Do you conduct AAC assessment for persons with aphasia?

○ Yes
○ No

Q16. Are you member of team conducting AAC assessment for persons with aphasia?

○ Yes
○ No

Q17. Who are members of your team for AAC assessment for a person with aphasia? Select all that apply

☐ General Physician
☐ Neurologist
☐ Occupational Therapist
☐ Physiotherapist
☐ Nurse
☐ ________ Others

Q18.
Are systematic evaluation procedures or evaluation tools (eg. MCST-A, AAC-ABA) used for AAC assessment for persons with aphasia?

○ Yes
○ Maybe
○ No

Q19. What AAC assessment tools do you use for persons with aphasia? Mention all that you use

Q20. Are devices available for trial during AAC assessment for persons with aphasia?

○ Yes
○ Maybe
○ No

Q21. Do you use devices for trial during AAC assessment?

☐ Definitely yes
☐ Probably yes
☐ Might or might not
☐ Probably not
☐ Definitely not

Q22. What AAC options or devices are available during trial? Mention all that apply

Q23. Where do you receive these devices?Select all that apply

☐ Owned by your employer/organization
☐ Given for trial by the company representatives
☐ Owned by you
☐ Owned by the client

Q24. Typically, how many devices are trialed during assessment?

○ 0
○ 1
○ 2
○ 3
○ 4 or more

Q25.
What areas of communication are formally assessed during the AAC assessment for persons with aphasia by you or any other professional on the team? Select all that apply

☐ Language comprehension and expression
☐ Motor Skills
☐ Symbol identfication
☐ Reading and writing skills
☐ AAC candidacy
☐ ______ Others

Q26.
How long is your typical AAC assessment session for a person with aphasia?

☐ 15 min-45 min
☐ 1 hour- 1.5 hours
☐ 2 hours-2.5 hours
☐ 3 hours- 3.5 hours
☐ ______ Other

Q27. How many sessions are typically utilized for AAC assessment for a person with aphasia?

☐ 1
☐ 2
☐ 3
☐ 4
☐ > 4
☐ ______ Other

Q28.
Who is involved in making the decision regarding what device can be purchased for the person with aphasia?

☐ Speech Language Pathologist and the client
☐ Team of professionals and the client
☐ Client and the caregiver
☐ ______ Others

Q29. What client-driven factors influence the decision of purchasing an AAC device for rehabilitation? Select all that apply

☐ Success with using the device during trial
☐ Comfort with technology
☐ Financial factors
☐ Client's preference
☐ Severity of aphasia
☐ Type of aphasia
☐ Family support in using the device
☐ Attempts of conventional therapy have plateaued
☐ ______ Others

Q30. What clinician-driven factors influence the decision of purchasing an AAC device for aphasia rehabilitation? Select all that apply

☐ Availability of the device for trial
☐ Experience with AAC device
☐ Comfort with AAC devices
☐ Familiarity with a specific device or company
☐ Comfort with programming the device
☐ Comfort in training person with aphasia and caregiver
☐ Others

Q31. Of the individuals with aphasia on your current caseload, how many have had the recommendation to use AAC devices?

☐ 0
☐ 1
☐ 2
☐ Half the persons with aphasia on your caseload
☐ All the persons with aphasia on your caseload
☐ Specific number

Q32.
How comfortable are you getting funding for an AAC device for person with aphasia?

○ Extremely comfortable
○ Moderately comfortable
○ Slightly comfortable
○ Neither comfortable nor uncomfortable
○ Slightly uncomfortable
○ Moderately uncomfortable
○ Extremely uncomfortable
○ I have never completed the process

Q33.
How comfortable are you programming an AAC device?

○ Extremely comfortable
○ Moderately comfortable
○ Slightly comfortable
○ Neither comfortable nor uncomfortable
○ Slightly uncomfortable
○ Moderately uncomfortable
○ Extremely uncomfortable
○ I have never programmed an AAC system

Q34.
If you provide therapy/intervention for an individual with aphasia who is using AAC do you recommend family/care provider training as part of your intervention?

○ Yes
○ No

Q35. How much family/care provider training do you typically recommend?

☐ A single 1-3 hour session
☐ Multiple sessions totaling up to 5 hours
☐ Dependent on the individual and the family/care providers
☐ Education and training provided at every therapy session
☐ ________ Other

Q36. Family/care provider education and training involves the following: (choose all that apply)

☐ ________ Device Operations (which operations do you teach)
☐ How to help the individual use the device (techniques or teaching strategies) ________
☐ ________ How to access resources (tech support, online video's, troubleshooting)

Q37. What percentage of family members/care providers follow up with training to support use of the device outside of therapy/clinic?

○ 0-20%
○ 21-40%
○ 41-60%
○ 61-80%
○ 81-100%

Q38.
In what settings does the PWA use the device? Select all the places

☐ At the clinic during session
☐ At home
☐ In the community
☐ ________ Specific places

Q39.
Which AAC devices or apps have you used with individuals with aphasia?
For eg: Tobii Dynavox-I15-Compass

☐ ________ Tobii Dynavox (which device and software)
☐ PRC-Prentke Romich Company (which device and user setup) ________
☐ ________ Saltillo (which device and user setup)
☐ ________ Apple ipad with app (indicate which app)
☐ Window's based tablet (indicate which app)
☐ ________ Other

Q40.
Do you carryout individualized programming for AAC devices of all the persons with aphasia on your caseload?

○ Yes
○ Maybe
○ No

Q41.

How often does a person with aphasia abandon the AAC device?

○ Sometimes
○ Half the time
○ Most of the time

Q42.

Why do you think the individuals you have seen do not use their AAC devices? Select all that apply

☐ Client's competence with device
☐ Client finds it difficult to use the device outside clinical settings
☐ Caregiver's difficulty in support and maintenance of the device
☐ Financial constraints
☐ Limited therapy sessions
☐ Program updates and customization
☐ Device does not have individualized user-based content
☐ Stigma or perception of others
☐ Increased time required for communication
☐ ________________ Others

References

Avan, A., Digaleh, H., Di Napoli, M., Stranges, S., Behrouz, R., Shojaeianbabaei, G., . . . Azarpazhooh, M. R. (2019). Socioeconomic status and stroke incidence, prevalence, mortality, and worldwide burden: an ecological analysis from the Global Burden of Disease Study 2017. *BMC Medicine, 17*(1), 191.

Basso, A. (2003). *Aphasia and its therapy*. Oxford, NY: Oxford University Press, Inc.

Benjamin, E. J., Blaha, M. J., Chiuve, S. E., Cushman, M., Das, S. R., Deo, R., Rajat Deo, R., de Ferranti, S. D., Floyd, J., Fornage, M., Gillespie, C., Isasi, C. R., Jiménez, M. C., Jordan, L. C., Judd, S. E., Lackland, D., Lichtman, J. H., Lisabeth, L., Liu, S., . . . American Heart Association Statistics Committee and Stroke Statistics Subcommittee. (2017). Heart disease and stroke statistics-2017 update: A report from the American Heart Association Circulation, *135(10),* e146–e603.

Beukelman, D.R., & Mirenda, P. (2013). *Augmentative & alternative communication: Supporting children & adults with complex communication needs.* Baltimore, MD: Brookes Publishing.

Binger, C., Ball, L., Dietz, A., Kent-Walsh, J., Lasker, J., Lund, S., . . . Quach, W. (2012). Personnel roles in the AAC assessment process. *Augmentative and Alternative Communication. 28*, 278-288.

Bridges, S. J. (2004). Multicultural issues in augmentative and alternative communication and language: Research to practice. *Topics in Language Disorders*, *24*, 62–75.

Centers for Medicare & Medicaid Services (2015). *Final decision memorandum on speech generating devices.* Retrieved from https://www.cms.gov/medicare-coverage-database/details/medicare-coverage-documentdetails.aspx?MCDId=26&mcdtypename=National+Benefit+Category+Analyses&MCDIndexType=3&bc=AgAEAAAAAAAAAA%3d%3d&#final

Cook, A.M.; Polgar, J.M. *Assistive technologies principles and practices*, 4th ed.; Elsevier: New York, NY.

Davis, G. A. (2007). *Aphasiology: Disorders and clinical practice* (2nd ed.). Needham Heights, MA: Allyn & Bacon.

Dietz, A., Quach, W., Lund, S. K., & McKelvey, M. (2012). AAC Assessment and clinical decision making: the impact of experience. *Augmentative and Alternative Communication, 28*(3), 148-159.

Dietz, A., Vannest, J., Maloney, T., Altaye, M., Holland, S., & Szaflarski, J. P. (2018) The feasibility of improving discourse in people with aphasia through AAC: clinical and functional MRI correlates, *Aphasiology, 32*(6), 693-719.

Dietz, A., Wallace, S. E., & Weissling, K. (2020). Revisiting the role of augmentative and alternative communication in aphasia rehabilitation. *American Journal of Speech-Language Pathology*, *29*(2), 909–913.

Dillman, D. A. (2000). *Mail and internet surveys: The tailored design method*. New York: John Wiley & Sons, Inc.

Dolic J., Pibernik J., Bota J. (2012) Evaluation of mainstream tablet devices for symbol based AAC communication. In: Jezic G., Kusek M., Nguyen NT., Howlett R.J., Jain L.C. (eds) *Agent and multi-agent systems. Technologies and Applications*. KES-AMSTA 2012. Lecture notes in computer science, vol 7327. Springer, Berlin, Heidelberg.

Elsahar, Y., Hu, S., Bouazza-Marouf, K., Kerr, D., & Mansor, A. (2019). Augmentative and alternative communication (AAC) advances: A review of configurations for individuals with a speech disability. *Sensors*, *19*(8), 1911-1935.

Fried-Oken, M., Beukelman, D. R., & Hux, K. (2012). Current and future AAC research considerations for adults with acquired cognitive and communication impairments. *Assistive Technology, 24*(1), 56-66.

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

Gangadharan K. R. (2003). Geriatric hospitals in India, today and in the future. *Journal of Aging & Social Policy*, *15*(2-3), 143–158.

Garrett, K. L. & Beukelman, D. R. (2006). *Aphasia needs assessment revised*. Retrieved from http://aac.unl.edu/screen/screen.html.

Garrett, K. L., & Lasker, J. P. (2007). AAC and severe aphasia: Enhancing communication across the continuum of recovery. *Perspectives on Neurophysiology and Neurogenic Speech and Language Disorders, 17*, 6–15.

Garrett, K., L., & Lasker, J., P. (2005). Adults with severe aphasia. In: *Augmentative and alternative communication: Supporting children and adults with complex communication needs*, Paul H. Brooks Publishing Company, Baltimore, Maryland, 467-516.

Giesbrecht E. (2013). Application of the human activity assistive technology model for occupational therapy research. *Australian Occupational Therapy Journal*, *60*(4), 230–240.

Grabowski, D. C. (2021). The future of long-term care requires investment in both facility- and home-based services. *Nature Aging*, *1*(1), 10-11.

Halloran, J., & Halloran, C. (2009). *LAMP: Language acquisition through motor planning*. Retrieved from http://www.aacandautism.com/lamp/why

Helm-Estabrooks, N. (2001). *Cognitive Linguistic Quick Test* (CLQT), Bloomington, Minnesota: Pearson Education, Inc.

Hodge, S. (2007). Why is the potential of augmentative and alternative communication not being realized? Exploring the experiences of people who use communication aids. *Disability & Society*, *22*(5), 457-471.

Huer, M. B., & Soto, G. (1996, August). *Critical emerging issues in AAC across cultures*. Paper presented at the 7th biennial conference of the International Society for Augmentative and Alternative Communication, Vancouver, Canada.

Iacono, T., Lyon, K., Johnson, H., & West, D. (2013). Experiences of adults with complex communication needs receiving and using low tech AAC: an Australian context. *Disability and Rehabilitation: Assistive Technology*, *8*(5), 392-401.

Johnson, J., Inglebret, E., Jones, C., & Ray, J. (2009). Perspectives of speech language pathologists regarding success versus abandonment of AAC. *Augmentative and Alternative Communication*, *22*, 85-99.

Johnson, R. K., & Prebor, J. (2019). Update on preservice training in augmentative and alternative communication for speech-language pathologists. *American Journal of Speech-Language Pathology*, *28*(2), 536-549.

Kamalakannan, S., Gudlavalleti, A., Gudlavalleti, V., Goenka, S., & Kuper, H. (2017). Incidence & prevalence of stroke in India: A systematic review. *The Indian Journal of Medical Research*, *146*(2), 175–185.

Kent-Walsh, J., Murza, K. A., Malani, M. D., & Binger, C. (2015). Effects of communication partner instruction on the communication of individuals using AAC: A meta-analysis. *Augmentative and Alternative Communication, 31*(4), 271–284.

Kertesz, A. (2006). *Western Aphasia Battery-Revised*, San Antonio, Texas: Pearson Education Inc.

Lasker, P.J. & Garrett, K.J. (2006). Using the Multimodal Communication Screening Test for persons with aphasia (MCST-A) to guide the selection of alternative communication strategies for people with aphasia, *Aphasiology, 20*(2-4), 217-232.

Lasker, J., P., Garrett, K., L, and Fox, L., E. (2007). Severe aphasia: In *Alternative communication strategies for adults with acute or chronic medical conditions.* Paul H. Brooks Publishing Company, Baltimore, Maryland, 2007, 163-206.

Light, J.; McNaughton, D. (2012). The changing face of augmentative and alternative communication: Past, present, and future challenges. *Augmentative and Alternative Communication, 28,* 197–204.

Light, J. C., &, McNaughton, D. (2014). Communicative competence for individuals who require augmentative and alternative communication: A new definition for a new era of communication? *Augmentative and Alternative Communication, 30,* 1–18.

Lloyd, L. (2011, January). *Training speech-language pathologists as AAC practitioners: Insuring AAC prerequisites for pre-service and in-service*. Session presented at the Eleventh Annual Conference on Augmentative and Alternative Communication Conference, Orlando, FL.

Marshall, J. (2010). Classification of aphasia: Are there benefits for practice? *Aphasiology, 24*(3), 408-412.

McBride, D. (2011). AAC evaluations and new mobile technologies: Asking and answering the right questions. *Perspectives on Augmentative and Alternative Communication*, *20*(1), 9-16.

McNaughton, D., & Light, J. (2013). The iPad and mobile technology revolution: Benefits and challenges for individuals who require augmentative and alternative communication. *Augmentative and Alternative Communication, 29,* 107–116.

Moffatt, K., Pourshahid, G., & Baecker, R. M. (2017). Augmentative and alternative communication devices for aphasia: the emerging role of "smart" mobile devices. *Universal Access in the Information Society*, *16*(1), 115-128.

National Institute on Deafness and Other Communication Disorders. (2015). NIDCD *f*act *s*heet: Aphasia [PDF] [NIH Pub. No. 97-4257]. Retrieved from https://www.nidcd.nih.gov/sites/default/files/Documents/health/voice/Aphasia6-1-16.pdf

Ogletree, B. T., McMurry, S., Schmidt, M., & Evans, K. (2018). The changing world of augmentative and alternative communication (AAC): Examining three realities faced by today's AAC provider. *Perspectives of the ASHA Special Interest Groups, 3*(12), 113-122.

OMICS International, Retrieved at https://www.omicsonline.org/india/aphasia-peer-reviewed-pdf-ppt-articles/

Pandian, J. D., & Sudhan, P. (2013). Stroke epidemiology and stroke care services in India. *Journal of Stroke, 15*(3), 128–134.

Porter, G., & Kirkland, J. (1995). *Integrating augmentative and alternative communication into group programs: Utilizing the principles of conductive education*. Toorak, Vic.: Spastic Society of Victoria.

Quist, R., & Lloyd, L. (1997). Principles and uses of technology. In L. Lloyd, D. Fuller, & H. Arvidson (Eds.), *Augmentative and alternative communication*. Boston, MA: Allyn & Bacon

Rogers, M. A., Roye, F., & Mullen, R. (2014). Measuring outcomes in aphasia and apraxia of speech in the context of a learning health care system. Paper presented at the 44th Clinical Aphasiology Conference, St. Simons Island, GA, United States.

Ross, K., & Wertz, R. (2003). Quality of life with and without aphasia. *Aphasiology, 17*(4), 355-364.

Smith, A. (2006) Speech motor development: Integrating muscles, movements, and linguistic units. *Journal of Communication Disorders, 39,* 331–349.

Spaccavento, S., Craca, A., Del Prete, M., Falcone, R., Colucci, A., Di Palma, A., & Loverre, A. (2014). Quality of life measurement and outcome in aphasia. *Neuropsychiatric Disease and Treatment, 10*, 27-37.

Tiwari, S., & Krishnan, G. (2011). Aphasia rehabilitation in India: A preliminary survey of speech-language pathologists. *Journal of the All India Institute of Speech & Hearing, 30*.

Tripathy J. P. (2014). Geriatric care in India: A long way to go. *Journal of Mid-life Health, 5*(4), 205–206.

van de Sandt-Koenderman, M.W.M.E. (2004) High-tech AAC and aphasia: Widening horizons? *Aphasiology 18*, 245–263.

Walker, M., Ghate, R., & Lal, R. (1992). *The Makaton Vocabulary-Indian Version*. Makaton India, Mumbai.

World Health Organization (WHO) (2003). International classification of functioning, disability, and health. Retrieved from http://www.who.int/classifications/icf/en/

Chapter 5: Neurorehabilitation in aphasia

Discussion and future directions

Aphasia. Aphasia is a debilitating consequence of stroke affecting many facets of linguistic comprehension and expression, whether gestural, written, or verbal (Lam & Wodchis, 2010; Wortman-Jutt & Edwards, 2019). Aphasia can be classified into several types and levels of severity depending on the site, and extent of stroke lesion, and white matter integrity (Basilakos et al., 2014; Patterson, 2018). Non-fluent aphasia types broadly refer to difficulties in expression emerging from deficits in anterior cortical areas of the dominant hemisphere that simultaneously support motor activity like in upper limb movements (Dronkers, Ivanova, & Baldo, 2017). Conventional speech-language therapy has shown great potential for improving communicative outcomes for individuals with aphasia; however, no single intervention protocol has proven most beneficial in regaining pre-stroke language skills (Brady, Kelly, Godwin, & Enderby, 2012). Non-invasive brain stimulation and high-tech augmentative and alternative communication strategies in combination with speech-language therapy add to the treatment repertoire to alleviate deficits associated with aphasia (Dietz, Wallace, & Weissling, 2020; Shah-Basak, Wurzman, Purcell, Gervits, & Hamilton, 2016).

Analysis of stroke-related deficits by divergent fields such as neuroscience (e.g., evoked potentials, blood oxygen levels), neurology (e.g., lesion size, white matter connectivity), psychology (e.g., intelligence quotient), linguistics (e.g., symbolic iconicity, gestures, linguistic features), speech science (e.g., formant frequency), evolutionary biology (e.g., animal communication), and speech-language pathology (e.g., functional communication, aphasia quotient) results in varied clinical perspectives (Wortman-Jutt & Edwards, 2019). For example, an exciting viewpoint that emerges from multidisciplinary studies is that there is possible interaction between speech and motor recovery in stroke-induced aphasia (Buchwald et al., 2018; Levy, Nichols, Schmalbrock, Keller, & Chakeres, 2001). Given that there is possible closeness and even some overlap in the neural structures of speech-language and hand-arm movement, collateral improvements in speech production have been seen with observation of movement, supporting a likely analogous correlation (Marangolo, Cipollari, Fiori, Razzano, & Caltagirone, 2012) speaking to the importance of neuroscience in multidisciplinary studies.

Electroencephalographic analysis of speech deficits in aphasia. Speech production is a complex process consisting of rapidly occurring and overlapping linguistic and sensorimotor processes (Civier, Bullock, Max, & Guenther, 2013; Hickok, 2012). This dissertation focusses on speech intention that forms an intermediary link between the overlying linguistic (Indefrey & Levelt, 2004) and sensorimotor aspects (vanDer Merwe, 1997), and when severed can disrupt speech production. Neural analysis of the fleeting link of speech intention requires a technique that can elicit time precise activity. Owing to good temporal resolution, electroencephalography can be used to evaluate speech intention. Electroencephalography is a measure that can record summed electrical activity generated by a large group of neuronal cells over a period of time as event-related potentials (Beres, 2017; Jeunet, Glize, McGonigal, Batail, & Micoulaud-Franchi, 2019; Sur & Sinha, 2009).

This dissertation found speech intention or anticipation of articulatory movement for speech can be identified using an event-related potential generally detected for anticipation of motor response, specifically the contingent negative variation (Kidwai, Brumberg, & Marsh, 2021; Vanhoutte et al., 2015). The contingent negative variation is divided into an early and late wave where the late wave generated prior to the second stimulus has been used for indicating anticipation of a linguistic stimulus (Bareš, Nestrašil, & Rektor, 2007; Mnatsakanian & Tarkka, 2002). In Chapter 2 of this dissertation, the contingent negative variation (CNV) has been proposed as an objective neural marker of speech intention by its elicitation in three different speech production protocols.

Speech intention in the aging and aphasia. Currently, speech intention, a nebulous term referring to the transitional stage of linguistic command transmission to the motor speech system, can be recognized with a CNV in healthy young adults (Kidwai et al., 2021). A future direction is to analyze the effects of aging on speech intention as denoted by the CNV to highlight age-related speech processing. The event-related potential, CNV also has been used as a measure of executive functioning as it originates from the anterior motor cortices (in the basal ganglia-thalamo-cortical loop) responsible for executive control (Vanhoutte et al., 2016). In older adults, cortical decline as a primary age effect is often seen as a reduction in the speed of executive functions like responding with speech (Lustig & Jantz, 2015). A selective reduction in the amplitude of the early and late CNV wave is suggestive of decline in executive control in higher age (Dirnberger et al., 2000). The latency of the late CNV is increased by 20 ms per decade indicating that older individuals perform a motor function with gradual reduction in speed as they age (Kropotov, Ponomarev, Tereshchenko, Müller, & Jäncke, 2016). Age-related changes in speech intention can be analyzed by eliciting CNV in one of the word production presentation protocols from Chapter 2. This information will be relevant as stroke-induced aphasia is seen more in the aging population.

Stroke-related speech and language deficits can be categorized under the headings of acquired apraxia of speech and aphasia, respectively, amongst other diagnoses (Bislick, McNeil, Spencer, Yorkston, & Kendall, 2017). Acquired apraxia of speech is a motor speech disorder often co-occurring with aphasia, a language disorder resulting from stroke in the dominant hemisphere (Duffy, 2013; McNeil, Robin, & Schmidt, 2009). Speech and language errors characterizing aphasia arise from deficits in the linguistic processes as opposed to speech production errors in acquired apraxia of speech emerging from deficits in motor planning/programming. The nature of these errors and the co-occurrence of these disorders leads to a difficulty in differential diagnosis (Duffy, 2013).

For the plain purpose of simplifying the underlying neural deficits in these disorders, the process of speech production can be viewed through a simple model that begins with a speaker's communicative intent, which leads to retrieval of semantic and phonological concepts from the mental lexicon (Levelt, Roelofs, & Meyer, 1999). These linguistic commands are then transferred to the motor speech system for planning and programming, also called speech intention. As speech intention reaches the sensorimotor system, a motor plan and program are made and sent to the articulators through feedforward systems, that is accompanied by a feedback system carrying the auditory and somatosensory information of the articulated speech (Golfinopoulos, Tourville, & Guenther, 2010; Tourville & Guenther, 2011). Based on this simplistic model, aphasia is a language disorder that occurs in the higher-level linguistic processes and apraxia of speech occurs during the following motor planning/programming processes. Speech intention, the transitional stage, can be analyzed in individuals with stroke related speech and language deficits to add to our understanding of speech and language processes and for differential diagnosis and treatment of aphasic and apraxic speech deficits.

Another future direction arising from this dissertation is the analysis of the CNV representing speech intention in individuals with only one diagnosis, either aphasia or apraxia of speech. The presence or absence of the CNV can be used to further our understanding of the underlying deficit in between the two disorders. If the CNV is present in individuals with aphasia, firstly, it can be analyzed and compared to the CNV elicited from healthy younger and older adults to confirm any differences arising due to stroke. Secondly, speech intention as denoted by the CNV can possibly vary when the individuals with aphasia accurately achieve the intended utterance in comparison to when they don't. This information can be relevant for designing specific treatment protocols. If the CNV is altogether absent in individuals with aphasia, it can be possibly deduced that aphasia as a diagnosis is comprised of a combination of linguistic and speech intention deficits rather than purely linguistic deficits.

Promoting neural recovery in aphasia. Since the CNV is an objective neural marker of speech intention, neuroimaging combined with electroencephalography can provide spatiotemporal neural correlates, that can be used as a stimulation site for neurostimulation treatment protocols (Lifshitz Ben Basat, Gvion, Vatine, & Mashal, 2016; Norise, Sacchetti, & Hamilton, 2017). For aphasia treatment, current speech-language therapy programs target linguistic processes before speech intention. A new combination of conventional speech language therapy (SLT) with neurostimulation can potentially be used with individuals with aphasia to focus on both linguistic processes and speech intention by additionally examining pre-post treatment CNV morphology along with functional outcome measures. Non-invasive brain stimulation, as mentioned in Chapter 3, includes transcranial magnetic stimulation and transcranial direct current stimulation. Transcranial direct current stimulation (tDCS) is a modern technique to stimulate brain areas for modulating cortical excitability by transmitting low amplitudes of current through electrodes placed on the scalp (Thair, Holloway, Newport, & Smith, 2017). In using speech-language therapy combined with tDCS, both linguistic and speech intention deficits can be addressed at a neural level to promote communicative outcomes in individuals with stroke-induced aphasia.

High-tech augmentative and alternative communication (AAC) strategies as mentioned in chapter 3 and 4, can be incorporated into speech-language therapy protocols to empower individuals with stroke-related speech and language deficits to actively and fully participate in their life activities (Dietz et al., 2020). High-tech AAC as an intervention strategy can serve two goals simultaneously: drive the theory of intersystemic reorganization to restore language performance and offer a quick communication alternative during anomic events (Dietz et al., 2018; Luria, 1972). The method of access for high-tech speech generating devices ranges from direct selection to scanning using different modalities. The modalities of access include head and body switches, eye-tracking, and neural and muscular potential estimation for brain computer interfaces (Elsahar, Hu, Bouazza-Marouf, Kerr, & Mansor, 2019).

In individuals with post-stroke aphasia, the contralesional hand and arm are often simultaneously impaired when stroke affects the anterior motor cortices of a hemisphere (Dobkin, 2005). Robotic arm treatment using electroencephalography-based brain-computer interface (EEG-BCI) can help stroke survivors to regain mobility in the affected arm and hand (Baniqued et al., 2021). Robotic exoskeleton arms are strapped on the individual’s affected arm (Molteni, Gasperini, Cannaviello, & Guanziroli, 2018). EEG-BCI assisted robotic arms can detect when a person is trying to generate a movement and move the robotic arm while assisting an individual move their stroke-affected arm (Molteni et al., 2018).

Like a robotic exoskeleton control, an EEG-BCI can control a high-tech AAC speech-generating device (Kleih, Gottschalt, Teichlein, & Weilbach, 2016). Stroke rehabilitation studies specially for non-fluent aphasia have highlighted the underlying proximate cortical areas that support both motor speech movements and upper limb and hand movements (Wortman-Jutt & Edwards, 2019). Similar to detecting a motor neural potential for robotic arm movement, an

EEG-BCI may detect speech intention through the CNV as the neural substrates for motor evoked potentials are close. An EEG-BCI on detecting an individual’s intent to speak through the CNV can convert it into a command for icon selection on a speech-generating device especially during inevitable anomic events.

Conclusion. Individuals with aphasia whose linguistic processes are affected and regain some level of pre-morbid functioning with speech-language therapy, continue to exhibit word-finding difficulties. In such cases, there is a possibility that an individual with aphasia can retrieve the word from the lexicon but is unable to transmit the linguistic command for that word to the motor speech system. This transmission or speech intention as denoted by the CNV can be detected by electroencephalography and supported though noninvasive brain stimulation and high-tech AAC. The accurate utterance through a high-tech AAC (speech-generating device) can stimulate the appropriate feedback loops to support errorless learning and improve utterance formulation in future speech opportunities, while serving as a compensatory tool during the anomic event (Fillingham, Sage, & Lambon Ralph, 2006). Similarly, in individuals with acquired apraxia of speech with motor speech difficulties, speech intention occurring prior to motor planning and programming can be identified with a CNV, supported through NIBS and high-tech AAC for saying the accurate word out loud. In this manner, successive errorless productions can be made by bypassing the affected motor speech system, that could stimulate the appropriate feedback systems and enable relearning of fluent productions.

The transition of these technological applications for neurorehabilitation from research into clinical practice largely depends on clinicians’ comfort and willingness to incorporate evidence-based new treatment techniques in their therapy programs (Johnson, Inglebret, Jones, & Ray, 2006). Chapter 4 alludes to some factors that speech-language pathologists (SLPs) consider while incorporating high-tech AAC devices into their aphasia therapies in the US and in India. The training and resources available to SLPs in developed and developing countries tend to play a significant role in the involvement of novel techniques in regular clinical practice. Finally, the treatment techniques targeting neuroplasticity could be a potential breakthrough for achieving approximate pre-morbid level of functioning in individuals with stroke-related speech and language deficits (Mang, Campbell, Ross & Boyd, 2013). The current dissertation demonstrates one narrow direction towards neurological assessment and rehabilitation for aphasia from a speech-language pathologist’s perspective.

References

Baniqued, P. D. E., Stanyer, E. C., Awais, M., Alazmani, A., Jackson, A. E., Mon-Williams, M. A., . . . Holt, R. J. (2021). Brain–computer interface robotics for hand rehabilitation after stroke: a systematic review. *Journal of Neuroengineering and Rehabilitation, 18*(1), 15-40.

Bareš, M., Nestrašil, I., & Rektor, I. (2007). The effect of response type (motor output versus mental counting) on the intracerebral distribution of the slow cortical potentials in an externally cued (CNV) paradigm. *Brain Research Bulletin, 71*(4), 428-435.

Basilakos, A., Fillmore, P. T., Rorden, C., Guo, D., Bonilha, L., & Fridriksson, J. (2014). Regional white matter damage predicts speech fluency in chronic post-stroke aphasia. *Frontiers in Human Neuroscience, 8*, 845-845.

Beres, A. M. (2017). Time is of the essence: A review of electroencephalography (eeg) and event-related brain potentials (ERPs) in language research. *Applied Psychophysiology and Biofeedback, 42*(4), 247-255.

Bislick, L., McNeil, M., Spencer, K. A., Yorkston, K., & Kendall, D. L. (2017). The nature of error consistency in individuals with acquired apraxia of speech and aphasia. *American Journal of Speech-Language Pathology, 26*(2s), 611-630.

Brady, M. C., Kelly, H., Godwin, J., & Enderby, P. (2012). Speech and language therapy for aphasia following stroke. *Cochrane Database Systematic Reviews*(5), CD000425.

Buchwald, A., Falconer, C., Rykman-Peltz, A., Cortes, M., Pascual-Leone, A., Thickbroom, G. W., . . . Edwards, D. J. (2018). Robotic arm rehabilitation in chronic stroke patients with aphasia may promote speech and language recovery (but effect is not enhanced by supplementary tDCS). *Frontiers in Neurology, 9*, 853-853.

Civier, O., Bullock, D., Max, L., & Guenther, F. H. (2013). Computational modeling of stuttering caused by impairments in a basal ganglia thalamo-cortical circuit involved in syllable selection and initiation. *Brain and Language, 126*(3), 263-278.

Dietz, A., Vannest, J., Maloney, T., Altaye, M., Holland, S., & Szaflarski, J. P. (2018). The feasibility of improving discourse in people with aphasia through AAC: Clinical and functional MRI correlates. *Aphasiology, 32*(6), 693-719.

Dietz, A., Wallace, S. E., & Weissling, K. (2020). Revisiting the role of augmentative and alternative communication in aphasia rehabilitation. *American Journal of Speech-Language Pathology, 29*(2), 909-913.

Dirnberger, G., Lalouschek, W., Lindinger, G., Egkher, A., Deecke, L., & Lang, W. (2000). Reduced activation of midline frontal areas in human elderly subjects: a contingent negative variation study. *Neuroscience Letters, 280*(1), 61-64.

Dobkin, B. H. (2005). Clinical practice. Rehabilitation after stroke. *The New England Journal of Medicine, 352*(16), 1677-1684.

Dronkers, N. F., Ivanova, M. V., & Baldo, J. V. (2017). What do language disorders reveal about brain-language relationships? From classic models to network approaches. *Journal of the International Neuropsychological Society, 23*(9-10), 741-754.

Duffy, J. R. (2013). *Motor Speech disorders-E-Book: Substrates, differential diagnosis, and management*: Elsevier Health Sciences, New York, NY.

Elsahar, Y., Hu, S., Bouazza-Marouf, K., Kerr, D., & Mansor, A. (2019). Augmentative and alternative communication (AAC) advances: A review of configurations for individuals with a speech disability. *Sensors, 19*(8), 1911-1935.

Fillingham, J. K., Sage, K., & Lambon Ralph, M. A. (2006). The treatment of anomia using errorless learning. *Neuropsychological Rehabilitation*, *16*(2), 129-154.

Golfinopoulos, E., Tourville, J. A. , Guenther, F.H. (2010). The integration of large-scale neural network modeling and functional brain imaging in speech motor control. *NeuroImage, 52*(3), 862 - 874.

Hickok, G. (2012). Computational neuroanatomy of speech production. *Nature Reviews Neuroscience, 13*(2), 135-145.

Indefrey, P., & Levelt, W. J. M. (2004). The spatial and temporal signatures of word production components. *Cognition*, *92*(1), 101-144.

Jeunet, C., Glize, B., McGonigal, A., Batail, J.-M., & Micoulaud-Franchi, J.-A. (2019). Using EEG-based brain computer interface and neurofeedback targeting sensorimotor rhythms to improve motor skills: Theoretical background, applications and prospects. *Neurophysiologie Clinique*, *49*(2), 125-136.

Johnson, J. M., Inglebret, E., Jones, C., & Ray, J. (2006). Perspectives of speech language pathologists regarding success versus abandonment of AAC. *Augmentative and Alternative Communication*, *22*(2), 85-99.

Kidwai, J., Brumberg, J. S., & Marsh, B. M. (2021). A neural marker of speech intention: Evidence from contingent negative variation. *Journal of Speech, Language, and Hearing Research*, 64(6S), 2392-2399.

Kleih, S. C., Gottschalt, L., Teichlein, E., & Weilbach, F. X. (2016). Toward a P300 based Brain-Computer Interface for aphasia rehabilitation after stroke: Presentation of theoretical considerations and a pilot feasibility study. *Frontiers in human neuroscience, 10*(547), 1-13.

Kropotov, J., Ponomarev, V., Tereshchenko, E. P., Müller, A., & Jäncke, L. (2016). Effect of aging on ERP components of cognitive control. *Frontiers in Aging Neuroscience*, *8*, 69-84.

Lam, J. M., & Wodchis, W. P. (2010). The relationship of 60 disease diagnoses and 15 conditions to preference-based health-related quality of life in Ontario hospital-based long-term care residents. *Medical Care*, *48(4),* 380-387.

Levelt, W. J., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioural and Brain Sciences, 22*(1), 1-75.

Levy, C. E., Nichols, D. S., Schmalbrock, P. M., Keller, P., & Chakeres, D. W. (2001). Functional MRI evidence of cortical reorganization in upper-limb stroke hemiplegia treated with constraint-induced movement therapy. *American Journal of Physical Medicine & Rehabilitation, 80*(1), 4-12.

Lifshitz Ben Basat, A., Gvion, A., Vatine, J.-J., & Mashal, N. (2016). Transcranial direct current stimulation to improve naming abilities of persons with chronic aphasia: A preliminary study using individualized based protocol. *Journal of Neurolinguistics, 38*, 1-13.

Luria, A. (1972). *Traumatic aphasia*. The Hague: Mouton.

Lustig, C., & Jantz, T. (2015). Questions of age differences in interference control: When and how, not if? *Brain Research, 1612*, 59-69.

Mang, C. S., Campbell, K. L., Ross, C. J. D., & Boyd, L. A. (2013). Promoting neuroplasticity for motor rehabilitation after stroke: considering the effects of aerobic exercise and genetic variation on brain-derived neurotrophic factor. *Physical Therapy, 93*(12), 1707-1716.

Marangolo, P., Cipollari, S., Fiori, V., Razzano, C., & Caltagirone, C. (2012). Walking but not barking improves verb recovery: Implications for action observation treatment in aphasia rehabilitation. *PLOS ONE, 7*(6), e38610-e38617.

McNeil M. R., Robin D. A., & Schmidt R. A. (2009). Apraxia of speech: Definition and differential diagnosis. In M.R. McNeil (Ed.), *Clinical Management of Sensorimotor Speech Disorders* (pp. 249–268). New York, NY: Thieme.

Mnatsakanian, E., & Tarkka, I. (2002). Task-specific expectation is revealed in scalp-recorded slow potentials. *Brain Topography, 15*, 87-94.

Molteni, F., Gasperini, G., Cannaviello, G., & Guanziroli, E. (2018). Exoskeleton and end-effector robots for upper and lower limbs rehabilitation: Narrative review. *PM&R: The Journal of Injury, Function and Rehabilitation,10*(9S2), 174-188.

Nicolas-Alonso, L. F., & Gomez-Gil, J. (2012). Brain computer interfaces, a review. S*ensors, 12*(2), 1211-1279.

Norise, C., Sacchetti, D., & Hamilton, R. (2017). Transcranial direct current stimulation in post-stroke chronic aphasia: The impact of baseline severity and task specificity in a pilot sample. *Frontiers in Human Neuroscience, 11*.

Patterson, J. (2018). Aphasia. In J. Kreutzer, J. DeLuca, & B. Caplan (Eds.), *Encyclopedia of Clinical Neuropsychology* (pp. 1-9). California: Springer International Publishing.

Shah-Basak, P. P., Wurzman, R., Purcell, J. B., Gervits, F., & Hamilton, R. (2016). Fields or flows? A comparative metaanalysis of transcranial magnetic and direct current stimulation to treat post-stroke aphasia. *Restorative Neurology & Neuroscience, 34*(4), 537-558.

Sur, S., & Sinha, V. K. (2009). Event-related potential: An overview. *Industrial Psychiatry Journal, 18*(1), 70-73.

Thair, H., Holloway, A. L., Newport, R., & Smith, A. D. (2017). Transcranial Direct Current Stimulation (tDCS): A beginner's guide for design and implementation. *Frontiers in Neuroscience, 11*(641), 1-13.

Tourville, J. A., & Guenther, F. H. (2011). The DIVA model: A neural theory of speech acquisition and production. *Language and Cognitive Processes, 26*(7), 952-981.

van Der Merwe, A. (1997). A theoretical framework for the characterization of pathological speech sensorimotor control. In Malcolm R McNeil (Eds.), *Clinical Management of Sensorimotor Speech Disorders*. (pp 1-26). New York: Thieme.

Vanhoutte, S., Cosyns, M., van Mierlo, P., Batens, K., Corthals, P., De Letter, M., . . . Santens, P. (2016). When will a stuttering moment occur? The determining role of speech motor preparation. *Neuropsychologia, 86*, 93-102.

Vanhoutte, S., Santens, P., Cosyns, M., van Mierlo, P., Batens, K., Corthals, P., . . . Van Borsel, J. (2015). Increased motor preparation activity during fluent single word production in Developmental Stuttering: A correlate for stuttering frequency and severity. *Neuropsychologia, 75*, 1-10.

Wortman-Jutt, S., & Edwards, D. (2019). Poststroke aphasia rehabilitation: Why all talk and no action? *Neurorehabilitation and Neural Repair*, *33*(4), 235-244.