Elevating Childhood Apraxia of Speech: Integrating Theory, Research and Practice

by

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Abstract

Background

Childhood apraxia of speech (CAS) has attracted controversy in the field of speech-language pathology for decades. There is some agreement that CAS is a neurological speech sound disorder that impairs a child's ability to plan and/or program the precise and sequential movements required for speech. However, despite the proliferation of CAS research over the last several decades, the accumulating body of evidence offers limited information regarding the cause and underlying mechanism of CAS and inconclusive evidence and inconsistent guidance to support and guide SLPs' clinical decision-making and management of CAS. A step toward advancing our current understanding of CAS and elevating SLP services requires the explicit integration of theory, research, and practice.

Objective

This doctoral dissertation had three specific objectives: (a) to describe and examine current SLP services and practices in Canada for CAS, (b) to provide an orientation to the use of theory in clinical practice, and (c) to offer a theory-based rationale and protocol for a clinical trial of somatosensory and auditory disruptions in children with and without CAS.

Methods

For the first objective, fifty-six (N=56) Canadian SLPs' were surveyed on their diagnostic, assessment, and treatment practices with children with CAS. For the second objective, I provided a clinically focused overview of theory and highlighted how theory can be applied to all aspects of clinical practice, using CAS as an example. For the third objective, a detailed clinical trial protocol was developed that will be the first to examine predictions regarding the cause of CAS within the context of the Directions Into Velocities of Articulators (DIVA) model, and related

print-to-speech model, by systematically comparing the independent and combined contributions of the auditory and somatosensory feedback systems during speech production and reading.

Results

Together, these interconnected studies advance our understanding of current practices for CAS. The findings indicated that despite growth and advances in CAS, there is still an immense gap between research and practice, with insufficient attention paid to theory. Moreover, the accumulating body of evidence offers limited information regarding the cause and underlying mechanism of CAS. These knowledge gaps restrict efforts to improve the quality, efficacy, and effectiveness of CAS services. The clinical trial proposed may help move us closer to an understanding of the core deficit in CAS, and help to inform the development of high-quality assessment, diagnostic and treatment procedures that directly target the underlying impairment.

Conclusion

This doctoral dissertation advances our understanding of the current practices in Canada for CAS and highlights the gaps/challenges in the clinical management of CAS. These studies highlight a number of needs in our approach to CAS and offer an immediate solution (i.e., employing theory more explicitly) as well as avenues in need of further exploration, such as focusing attention on closing the research-practice gap and expanding our examination of possible causal mechanisms underlying CAS. The systematic integration of theory, research and practice are necessary to reduce the controversy around CAS and improve our efficacy and efficiency in the diagnosis and management of this complex disorder.

Preface

This thesis is an original work by Cassidy L. Fleming. The research project referred to in chapter 3 received ethics approval from the University of Alberta Research Ethics Board, Project Name "Survey of Speech-Language Pathologists' Practices in Working with Children and Adolescents with Childhood Apraxia of Speech", No. 00085046, December 11, 2018.

Chapter 3 of this thesis has been submitted as "Survey of speech language pathology services for childhood apraxia of speech in Canada raises more questions than answers" to the *Canadian Journal of Speech-Language Pathology and Audiology*. I was responsible for study design, survey development, data collection and analysis, as well as composition of the manuscript. T. Paslawski and J. Cummine were the supervisory authors and were involved with concept formation of the study and contributed to manuscript edits.

Chapter 4 of this thesis is original work and at the time of defense has not been published. I was responsible for study design, literature review, and composition of the manuscript. T. Paslawski and J. Cummine were the supervisory authors and were involved with concept formation of the study and contributed to manuscript edits.

Chapter 5 of this thesis is a clinical trial study protocol. I was responsible for developing a study protocol for future use based on the current knowledge base. T. Paslawski and J. Cummine were the supervisory authors and were involved with concept formation of the study protocol and contributed to protocol edits. K. Ballard and T. Loucks were supervisory committee members who contributed to protocol edits. A version of this paper was submitted as a Clinical Trial Application (CTA) to the Health Canada Office of Clinical Trials, Therapeutic Products Directorate, Protocol Name "Towards a Better Understanding of Childhood Apraxia of Speech:

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Dedicated to the loving memory of my grandfather

Ray Ernest Yuskiw

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CHAPTER 1

Introduction

Childhood apraxia of speech (CAS) has attracted controversy in the field of speech-language pathology for decades. The literature contains various arguments concerning the definition of CAS, the characteristics of CAS, and the nature of the underlying impairment (ASHA, 2007; Maassen et al., 2010). Some individuals even questioned its existence, calling it "a label in search of a population" (Guyette & Diedrich, 1981). According to Shriberg, Aram, and Kwiatkowski (1997), "the validity of developmental verbal dyspraxia [CAS] as a childhood speech disorder is one of the most controversial nosological issues in speech pathology" (p. 273). Notwithstanding the foregoing, CAS provided speech-language pathologists (SLPs) with a label for children who exhibited "severe, irregular, and persistent speech disorders" in contrast to other more common speech sound disorders (SSDs; Shriberg et al., 1997).

The earliest historical descriptions of people showing characteristics consistent with apraxia, albeit of the limb, are relevant to our modern understanding of the disorder. In his seminal work, Liepmann (1908) first described apraxia as an inability to carry out voluntary motor acts despite preserved muscle strength. However, Jackson (1866, as cited in Wilson, 1908) has been credited for early descriptions of apraxia:

> *"In some cases of defect of speech the patient seems to have lost much of his power to do anything he is told to do, even with those muscles that are not paralysed. Thus, a patient will be unable to put out his tongue when we ask him, although he will use it well in semi-involuntary actions – for example, eating and swallowing. He will not make the particular grimace he is told to do, even when we make one for him to imitate. There is power in his muscles and in the centres for coordination of muscular groups, but he – the whole man, or the 'will' – cannot set them agoing. Such a patient will do a thing well one time and not at another. In a few cases patients do not do things so simple as moving the*

hand (i.e., the non-paralysed hand) when they are told.…A speechless patient who cannot put out his tongue when told will sometimes actually put his fingers in his mouth as if to help get it out; and yet, not infrequently, when we are tired of urging him, he will lick his lips with it" (p. 167-168).

In more recent years, the term *praxis* has been characterized by difficulty conceptualizing, planning, and programming a motor act (Stedman, 2005; Strand, 2020).

Almost 100 years later, Morley (1957) observed a group of children whose speech resembled that of CAS. Since then, numerous attempts have been made to define the disorder. In response to the lack of consensus in the literature, the American Speech-Language-Hearing Association (ASHA) Ad Hoc Committee on Apraxia of Speech in Children undertook a narrative review of research on CAS between 1995 and 2007. The subsequent ASHA technical report and position paper on CAS published in 2007 defined CAS as a "neurological childhood [SSD] in which the precision and consistency of movements underlying speech are impaired in the absence of neuromuscular deficits (e.g., abnormal reflexes, abnormal tone)" (ASHA, 2007). The primary underlying deficit proposed to be impaired in CAS is motor planning and/or programming (e.g., Grigos et al., 2015; Shriberg, 2010; Terband & Maassen, 2010), which can lead to the core characteristics of CAS reported in the literature: (a) inconsistent speech sound production, (b) disrupted prosody, and (c) disrupted movement transitions (e.g., ASHA, 2007; Iuzzini-Seigel, 2017; Murray et al., 2021; Strand, 2017).

To complicate things further, in many cases, children with CAS do not just display difficulties with speech. They often exhibit one or more comorbid disorders that continue into adolescence (Miller et al., 2019; Turner et al., 2019), such as language and learning disorders, literacy impairments, non-verbal oral apraxia (NVOA), and gross and fine motor difficulties (e.g., ASHA, 2007; Iuzzini-Seigel, 2019; Lewis et al., 2004; McNeill et al., 2009; Snowling &

Stackhouse, 1983; Shriberg et al., 1997; Teverovsky et al., 2009). While this is a recent and growing area of interest, few studies have explicitly examined the links between CAS and its comorbidities. Understanding the links is important not just for intervention, but also for assessment, diagnosis and to help to elucidate the possible underlying mechanism(s) that may explain a range of clinical features in CAS.

Of particular interest to this dissertation is the connections to literacy. According to Stackhouse and Wells (1997), the motor planning and/or programming deficits seen in CAS may have “flow-on effects” for language and literacy development. Gillon & Moriarty (2007) add that this may be due to the impact of the deficit on subsequent development of the linguistic and literacy systems. For example, inconsistent and inaccurate speech may provide inadequate input to the child’s developing linguistic system and thus may affect subsequent vocabulary and literacy development (Gillon & Moriarty, 2007; Stackhouse and Wells, 1997). Given the intense text-reliant society in which we currently live, literacy impairments secondary to CAS can have dire and far-reaching consequences for children diagnosed with CAS. This highlights the importance of taking a comprehensive approach to the study of CAS across the developmental domains of speech-motor, linguistic, and literacy development.

Despite the proliferation of CAS research over the last several decades, the accumulating body of evidence offers limited information regarding the cause and underlying mechanism of CAS and inconclusive evidence and inconsistent guidance to support and guide SLPs’ clinical decision-making and management of CAS. Moreover, few studies have critically examined the interrelationships between impaired developmental domains. These knowledge gaps restrict efforts to improve the quality, efficacy, and effectiveness of CAS services. In the pages that follow, I will highlight that a step toward advancing our current understanding of CAS and elevating SLP services requires the explicit integration of theory, research, and practice.

Theory, Research, and Practice

It is helpful to begin thinking about what theory, research, and practice are. A *theory* is a coherent set of statements that, when taken together, attempt to explain, describe, and make predictions regarding a phenomenon (Kerlinger and Lee, 2000). *Research* is the "systematic, controlled, empirical, amoral, public, and critical investigation of natural phenomena" (Kerlinger and Lee, 2000, p. 14). In this paper, *practice* within SLP is defined as the application or use of knowledge or skills.

There is a reciprocal and dynamic relationship between theory, research, and practice. Theory and research provide an essential foundation for clinical practice. Theory guides the development of many research questions and research helps generate new theories and determine whether support for theories exists. At the same time, practice informs and is informed by research and theory. It is the source of questions to be addressed by research and helps to advance and/or develop theories. Academic literature today brims with contributions elaborating on the complexities and long-standing barriers of using research in practice (e.g., Douglas & Burshnic, 2019; O'Connor & Pettigrew, 2009; Zipoli & Kennedy, 2005). Yet, theory and research are constantly changing, and the way that SLPs practice needs to reflect those changes. SLPs will continue to face challenges that will require the generation of new ideas and unique ways of solving problems. The studies contained in this doctoral dissertation aim to highlight the need for an approach to research and practice that involves systematic inquiry in which all relevant stakeholders (e.g., SLPs, educators, researchers, organizations) engage as equal partners with the goal of bridging and integrating theory, research and practice.

Dissertation Objectives

Toward this end, the specific goals of this dissertation were to: (a) describe and examine current SLP services and practices in Canada for CAS, (b) provide an orientation to the use of theory of clinical practice, and (c) offer a theory-based rationale and protocol for a clinical trial of somatosensory and auditory disruptions in children with and without CAS.

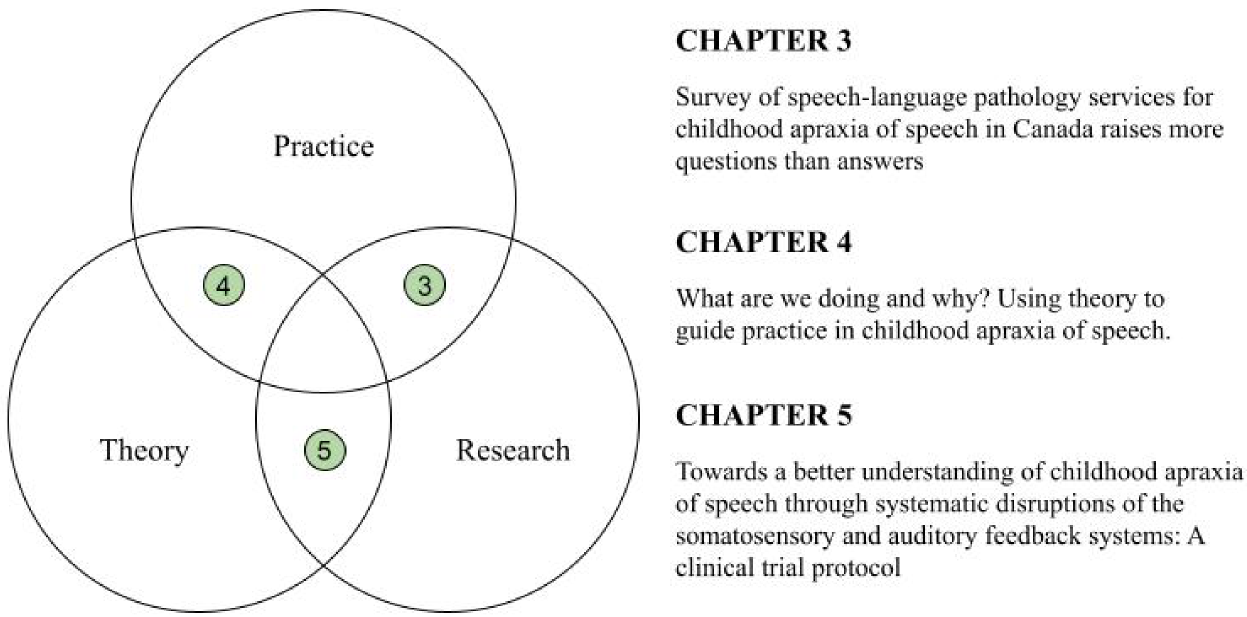


Figure 1. 1. The relationship between theory, research and practice.

To address the research objectives, I conducted an exploratory survey of SLP practices in Canada, examined the research for theory-guided practice in SLP with the intent of providing a broad overview, and carefully designed a clinical trial protocol. The thesis has been organized into six chapters. Following the introduction (Chapter 1), the second chapter is a literature review that situates this study within the area of CAS. The studies are then detailed in the following three chapters of this dissertation. The third chapter has been submitted for publication to the *Canadian Journal of Speech-Language Pathology and Audiology*. A version of the fifth chapter has been submitted as a Clinical Trial Application (CTA) to the Health Canada Office of Clinical

Trials, Therapeutic Products Directorate, and was sponsored by The Governors of the University of Alberta.

Chapter 1 presents the rationale for the dissertation. It provides a brief overview of CAS, focusing on the relationship between theory, research, and practice. It articulates the gaps in our knowledge, the need for targeted inquiries into each of the aforementioned domains, and the specific problems that will be addressed.

Chapter 2 reviews the literature I used as part of my research. It presents the major theoretical foundations and highlights the research findings and methodological contributions of key studies. Areas of focus for the chapter include theory, research, and practice in the area of CAS.

Chapter 3 reports an exploratory survey study that was conducted to (a) describe the characteristics of children and young people on SLP caseloads in Canada, (b) describe the diagnostic, assessment, and treatment practices of SLPs in Canada for CAS, and (c) where possible, determine whether or not practices were consistent with the best research recommendations. The results of this study were the impetus for the subsequent paper (Chapter 4) in which I discuss the use of theory to guide practice.

Chapter 4 highlights how systematic use of theory in clinical practice would support SLPs in the identification, description, understanding and integration of all of the variables that are applicable to a clinical case. This paper supports the final study (Chapter 5) which explicitly proposes to use theoretical models of speech and reading to understand the cause and underlying mechanism of CAS and the integration of systems in CAS (e.g., sensory, motor, and print).

Chapter 5 contains a clinical trial study protocol that will be the first to examine predictions within the Directions Into Velocities of Articulators (DIVA) model regarding the cause of CAS by systematically comparing the independent and combined contributions of the auditory and somatosensory feedback systems during speech production and reading.

Chapter 6 concludes with an overview of the previous chapters, a discussion and conclusion of this doctoral dissertation. It also includes a discussion of the opportunities, challenges, and implications of this work.

CHAPTER 2

Literature Review

2.1. Theory and Research

Theory and research have a close and reciprocating relationship. A theory is considered more or less valid based on the evidence provided through research, and research is strongest when guided by theory. Thus, they will be discussed together for ease of discussion. Drawing on literature from brain imaging, behaviour and computational modeling, the first subsection (*2.1.1.)* is dedicated to the etiological and core speech processes of CAS. The second and third subsections discuss the key characteristics (*2.1.2.*) and diagnostic and assessment of CAS (*2.1.3.*), with additional references to theories of speech motor control (*2.1.4.*) to follow. The research and behaviors of children with CAS that have been interpreted in the context of such theories are also discussed. Finally, reading impairments in the context of CAS are provided in later subsections (*2.1.5. and 2.1.6.).*

2.1.1. Etiological and Core Speech Processes of CAS

Until recently, the neural substrates that underlay CAS were largely unknown. In a number of imaging studies, no differences between typically developing (TD) children and children with idiopathic CAS have been reported in terms of brain structure (see for a review Liégeois & Morgan, 2012). Recent work using more advanced measures have found microscopic abnormalities including a thicker supramarginal gyrus, and morphological abnormalities in the left supramarginal gyrus, bilateral planum temporale (posterior to Heschl's gyrus) and bilateral Heschl's gyrus (Liegeois et al., 2014; Preston et al., 2014). Within the context of well-known speech production models (e.g., Directions Into Velocities of Articulators; Guenther & Vladusich, 2012), these regions are associated with somatosensory target/error maps and auditory target/error maps, respectively. Moreover, fractional anisotropy along white matter tracts of children with CAS is reduced between: (a) the left temporal gyrus (superior and middle) and left inferior frontal gyrus, (b) the left precuneus, right supplementary motor area, left cuneus, and right cerebellum, and lastly (c) the right angular gyrus, superior temporal gyrus, and inferior occipital gyrus (Fiori et al., 2016). These tracts connect speech-language regions involved in auditory feedback, speech motor control, and language comprehension. In general, it is clear that children with CAS may have deficits in multiple brain regions and white matter pathways. However, it is not known whether the white matter abnormalities are the primary cause of CAS or a secondary consequence of CAS due to altered grey matter function (Fiori et al., 2016).

The way in which these deficits are expressed at the level of speech production is heavily debated. For many decades, controversy and debate have surrounded whether the core impairment in CAS is in the speech-motor domain or phonological-linguistic domain (Guyette & Diedrich, 1981; Shriberg et al., 1997). This distinction is based on psycholinguistic models of speech production which are typically divided into four main stages: representational processes, motor planning, motor programming, and motor execution (Levelt, 2002; Nijland et al, 2003; Terband & Maassen, 2010; van der Merwe, 2009). Representational processes include encoding, storage, and retrieval of representations (i.e., phonological encoding and memory; Shriberg et al., 2017c), and are used to produce a phonetic plan (Maassen et al., 2010). The abstract phonetic plan is then transformed into a motor plan during the motor planning stage which includes identifying movement goals and the structures needed to achieve those goals. Next, the specific muscle requirements necessary to achieve the motor goal are selected (e.g., tone, movement velocity, force, and range) during motor programming (Maassen et al., 2010). Finally, motor execution refers to the resulting overt and volitional movement.

Those who view CAS as a speech-motor disorder propose that CAS results from a deficit in motor planning and/or programming (ASHA, 2007; Maassen, 2002; Terband et al., 2009). A deficit in motor planning and/or programming is supported by evidence that children with CAS exhibit: more variable and deviant coarticulation patterns than TD children (Maassen et al., 2001; Maas & Mailend, 2017; Nijland et al., 2002; 2003;), imprecise errors in real and non-words (Blech et al., 2007 cf. Shriberg et al., 2017c), greater movement variability and duration in the tongue, lips, and jaw than TD children and children with SSDs (Grigos et al., 2015), more addition/complication errors than children with SSDs (Shriberg, Lohmeier, et al., 2012), and deterioration of speech in the presence of noise masking (Iuzzini-Seigel et al., 2015). Conversely, those who view CAS as a phonological-linguistic disorder propose that CAS results from deficient phonological representations (Marion et al., 1993; Marquardt et al., 2002). Support for the phonological-linguistic perspective comes from studies that report that children with CAS exhibit: poorer auditory-perceptual identification and discrimination of words than TD children (Groenen et al., 1996), lower phonological awareness skills than TD children and children with SSDs (McNeill et al., 2009; Moriarty & Gillon, 2006), deficits in rhyming compared to TD children (Marion et al., 1993), and poorer ability to identify and construct syllables (Marquardt et al., 2002).

More recent descriptions suggest CAS is a multi-domain disorder with deficits in both phonological representations and motor planning and/or programming (Shriberg et al., 2012). The primary support for a deficit in phonological representations and motor planning and/or programming processes comes from Shriberg and colleagues (2017a-d) recent systematic study of 83 children, adolescents and young adults (ages 3 to 23) with idiopathic, neurogenetic, and congenital CAS, 22 adults (ages 45 to 84) with acquired apraxia of speech (AAS), and 205 children (ages 3 to 9) with SSDs. The authors evaluated participants' performance on the Syllable Repetition Task (SRT), an 18-item non-word imitation task designed to assess the integrity of speech production processes. Both children with CAS and adults with AAS had significantly lower phonological memory and motor planning and/or programming scores than children with SSDs. Children with CAS had significantly lower phonological encoding scores than children with SSDs, whereas adults with AAS performed similarly to children with SSDs. The authors interpreted these findings as support for a core deficit in both phonological memory and motor planning and/or programming processes. Moreover, they concluded that deficits in phonological encoding are the consequence of developmental or other moderating or mediating factors in children with CAS, as they are not present in adults with AAS. Although a similar pattern of findings was found in a separate group of children with CAS (Shriberg, Lohmeier, et al., 2012), a wide range of scores is reported in both studies and some children with CAS have been reported to obtain age-appropriate phonological memory scores (Rvachew & Matthews, 2017). Ultimately, how the constellation of deficits arises and how they are tied to the neural substrates of CAS is unknown.

From a development perspective, it has been argued that the "distinction between speech motor and phonological symptoms is based on the modular view of the speech production process" (Maassen et al., 2010, p. 244) in which phonological encoding, and motor planning, programming, and execution occur in a serial fashion. The "adult-like" modular speech production system emerges over the course of development in a dynamic interaction with perceptual, cognitive, language, and motor systems (Bishop, 1997; Goffman, 2010; Kent, 2000; Namasivayam et al., 2020; Nip et al., 2011; Shriberg, 2009; Smith, 2006; Strand & McCauley, 2019). Although exactly how these systems interact is not fully understood, many argue that early deficits in speech motor control can have multiple down-stream (i.e., motor processes) and up-stream effects (i.e., phonological-linguistic; Bishop, 1997; Green & Nip, 2010; Maassen et al., 2010; Terband et al., 2009). As an example of how speech motor control and phonological systems might interact, Green et al. (2000) demonstrated that the sequence of oral-motor development in children (i.e., control of jaw, followed by lips, then jaw and lip coupling, and finally independent jaw and lip movements) may place constraints on the sequence of phoneme acquisition and phonological development, providing evidence for why bilabials might emerge before fricatives. In the absence of a diagnostic marker for CAS, it is not possible to study how early deficits in oral motor control might contribute to later deficits in speech production.

In summary, due to the interactive nature of development, it is difficult to tease apart at what level the core deficit resides. Deficits in all stages of the speech production process have been reported in children with CAS, with deficits as early as age 3 in both representational and motor planning and/or programming processes. Moreover, it is apparent that children with CAS may vary in the extent to which deficits in representational or motor planning and/or programming processes contribute to the speech disorder at different stages in the developmental trajectory. Overall, evidence from kinematic and auditory masking studies comparing children with CAS to children with SSDs provide strong evidence that deficits in planning and/or programming the movements for speech contribute significantly to the overall presentation of CAS.

2.1.2. Characteristics of CAS

Given the variability in speech processes affected across children with CAS, it is understandable that children with CAS exhibit a wide range of behavioural characteristics that may change with age, severity of involvement, and task (ASHA, 2007). There is a general consensus among clinicians and researchers that the speech of children with CAS is characterized by inconsistent speech sound errors on consonants and vowels, disrupted movement transitions and prosodic errors (ASHA, 2007; Meredith & Potter, 2011; Murray et al., 2015; 2021; Rosenbek & Wertz, 1972; Shriberg, Lohmeier, et al., 2012; Strand et al., 2013). However, these features are not necessary or sufficient for a diagnosis of CAS (ASHA, 2007).

2.1.2.1. Inconsistent Errors

Inconsistent errors are often reported in children with CAS (ASHA, 2007; Betz & Stoel-Gammon, 2005; Grigos et al., 2015; Iuzzini-Seigel et al., 2017; Lewis, Freebairn, & Taylor, 2000; Meredith & Potter, 2011; Murray et al., 2015; Strand et al., 2013; Tubul-Lavy, 2012), and are most commonly indexed by phonemic inconsistency or token-to-token inconsistency. Phonemic inconsistency refers to the inconsistency of a single phoneme within and across words and word positions (e.g., /t/ is produced as /d, z, s, p/), whereas token-to-token inconsistency refers to inconsistency in repeated productions of the same word (e.g., "cat" is produced as "tat", "cat" and "dat"; Iuzzini-Seigel et al., 2017). The variable results on measures of speech inconsistency reported in the literature for children with CAS have been attributed to differences in metrics and stimuli (Iuzzini-Seigel et al., 2017). Iuzzini-Seigel et al. (2017) measured phonemic and token-to-token consistency in monosyllabic words, multisyllabic words, and sentences in TD children, and children with CAS, CAS plus language impairment (LI), LI, and SSDs. Token-to-token inconsistency across two trials of monosyllabic real words and across five trials of the phrase "buy Bobby a puppy" were moderately sensitive and specific for differential diagnosis of CAS from SSDs (monosyllabic: 75% sensitivity and 70% specificity; phrase: 70% sensitivity and 80% specificity). Moreover, both children with CAS and CAS plus LI exhibited inconsistency on all measures, whereas children with LI only exhibited inconsistency in the phrase “buy Bobby a puppy” (Iuzzini-Seigel et al., 2017). This suggests that speech inconsistency is a core feature of CAS that is not attributable to co-morbid LI. Strand et al. (2013) measured token-to-token inconsistency in children with CAS and other SSDs using the Dynamic Evaluation of Motor Speech Skill (DEMSS). The consistency subscore was moderately sensitive and highly specific for differential diagnosis of CAS from other SSDs (70% sensitivity; 93% specificity). Finally, Grigos et al. (2015) measured token-to-token inconsistency in TD children, children with CAS, and children with SSDs in one-, two-, and three-syllable words. Children with CAS were more inconsistent than both TD children and children with SSDs across all word types. The results of these studies provide compelling evidence that inconsistent errors on consonants are a core feature of CAS and can be used to support differential diagnosis of CAS from SSD and LI using specific stimuli.

Finally, although inconsistent vowel errors are often discussed, there is little description of the pattern of vowel errors in children with CAS in the literature (ASHA, 2007; Davis et al., 2005; Grigos et al., 2015; Rosenbek & Wertz, 1972; Shriberg et al., 1997). In an early description of 50 children with CAS, Rosenbek & Wertz (1972) reported that children with CAS often made vowel substitutions or distortions that were not present in children with articulation disorders. Davis, Jacks, & Marquardt (2005) evaluated vowel inventories and error patterns in three children with CAS. The authors reported that although children with CAS had complete vowel inventories, they often produced inaccurate vowels with no consistent pattern. More recently, Grigos et al. (2015) reported significantly lower percent vowels correct for children with CAS compared to children with SSDs. In addition, the vowel accuracy subscore of the DEMSS is able to correctly identify children without CAS (i.e., other SSDs) with 97%

specificity, despite low sensitivity for CAS (65%). Together, these studies suggest possible differences in vowel errors in children with CAS.

2.1.2.2. Disrupted Movement Transitions

Acoustic and kinematic studies have provided evidence that children with CAS exhibit atypical articulatory control (Case & Grigos, 2016; 2020; Grigos et al., 2015; Grigos & Case, 2018; Maas & Mailend, 2017; Maassen et al., 2001; Moss & Grigos, 2012; Moss & Lu, 2015; Nijland et al., 2002; 2003). Generally, articulatory control is measured using kinematic analysis tools (e.g., facial tracking, electromyography), or using indirect acoustic indicators such as formant frequencies or coarticulation.

Acoustic analysis of movement transitions is often indexed by coarticulation, which refers to "the influence of adjacent units of speech on one another" (Smith, 2006). Coarticulation can be anticipatory, which occurs when a particular sound influences an earlier-occurring sound, or carry-over, which occurs when a particular sound influences a later-occurring sound. Coarticulation is often measured in the acoustic signal by evaluating formant trajectories, which reflect the change in the shape of the vocal tract during speech production (Smith, 2006). Few studies have examined coarticulation in children with CAS (Maassen et al., 2001; Nijland et al., 2002; 2003; Maas & Mailend, 2017). Across these studies, children with CAS were reported to exhibit atypical coarticulation patterns including less anticipatory coarticulation and greater variability in coarticulation patterns than TD children and possibly children with other SSDs. Together, they suggest that children with CAS have more difficulty transitioning between sounds.

In a facial tracking study, Grigos et al. (2015) tracked movement of the articulators during production of the words "pop", "puppet" and "puppypop" in TD children, children with

CAS and children with SSDs. Children with CAS exhibited greater movement duration and variability than TD children and children with SSDs across all stimuli. Also, as the linguistic demands increased, children with CAS exhibited greater movement duration and variability than children with SSDs. The results of this study indicate that children with CAS have difficulty transitioning between movements. In addition, the difficulty increased as words became more complex, distinguishing them from children with SSDs. In three follow up studies using multidimensional analyses (i.e., perceptual transcription acoustic, and kinematic measures) , children with CAS exhibited increased movement variability when producing novel consonant-vowel (CV) combinations (Case & Grigos, 2016), vowels (Grigos & Case, 2018) and CV-CV-CV stimuli that closely approximated natural speech (Case & Grigos, 2020) in comparison to TD children and children with SSDs. Notably, the phonetic context (e.g., the specific vowel and consonant-vowel combinations) significantly impacted speech production. These findings add to our understanding of speech complexity, suggesting that motoric complexity (i.e., types of movement trajectories) must be considered in addition to linguistic complexity (i.e., syllable shapes).

Taken together, these findings suggest that children with CAS have difficulty moving from one articulatory configuration to another and that this is dependent on both the linguistic and motoric complexity of the task and stimuli. Moreover, despite consonants and vowels being accurate, children with CAS exhibit atypical coarticulation and movement patterns compared to children with SSDs. One implication of this is that children with CAS may require continued practice even after speech sound accuracy has improved.

2.1.2.3. Prosodic Errors

Children with CAS are often reported to have prosodic deficits including syllable segregation, inappropriate pauses, equal stress, or incorrect lexical and phrasal stress (ASHA, 2007; Grigos et al., 2015; Shriberg, Lohmeier, et al., 2012; Shriberg et al., 2017a). Shriberg et al. (2012) evaluated speech, prosody and voice measures in children with CAS (n=127) and SSDs (n=98). The features that best differentiated children with CAS from children with SSDs included poor planning and/or programming scores, low appropriate pauses, and low appropriate rate (80% sensitivity; 99% specificity). Murray et al. (2015) also attempted to identify a set of quantitative measures of speech for differential diagnosis of CAS. Using discriminant function analysis, the authors reported that syllable segregation (i.e., noticeable gaps between syllables), percentage of lexical stress matches, percent phonemes correct, and accuracy on repetition of "puhtuhkuh" in a diadochokinetic task had 91% predictive accuracy of CAS diagnosis. The results of this study suggest that prosodic errors (i.e., syllable segregation and percentage of lexical stress matches) are a core feature of CAS. Overall, there is compelling evidence that children with CAS have difficulties with prosody.

2.1.3. Diagnosis and Assessment of CAS

A lack of understanding of the core etiological and speech processes of CAS, as well as the characteristics, has made attempts to develop and validate diagnostic markers and assessment tools challenging. A number of diagnostic markers have been reported including inconsistent errors, coarticulation errors, prosodic errors, transcoding errors, movement variability, and lexical stress errors (ASHA, 2007; Murray et al., 2015; Shriberg et al., 2017). However, none of these diagnostic markers are sensitive or specific enough for differential diagnosis of CAS from other SSDs. Consequently, clinicians and researchers use a wide range of features when diagnosing CAS (ASHA, 2007; Meredith & Potter, 2011; Millspaugh & Weiss, 2006; Shriberg et al., 2011). Although some commercially available assessments may be helpful for differentiating CAS (Murray et al., 2015; Strand et al., 2019), there is currently no consensus on which tests or tasks should be used for identifying characteristics of CAS (Shriberg et al., 2017a). Operationally defined characteristics in future clinical and research studies is fundamental for ensuring greater precision and objectivity in describing and distinguishing CAS from other disorders. In addition, this will ensure reproducibility of results and provide a greater opportunity to develop a reliable and valid assessment protocol.

2.1.4. Models of Speech Motor Control

To this point, research in CAS has been restricted by the lack of a diagnostic marker and difficulty in teasing apart at what level the core deficit in speech production processes resides. To gain a better understanding of how the constellation of deficits in representational processes and motor planning and/or programming may arise in CAS, researchers have turned to computational models of speech motor control. Computational modeling refers to “the use of computers to simulate and study the behaviour of complex systems using mathematics, physics, and computer science” (NIBIB, 2016, p. 1). According to Mailend and Maas (2021), computational modelling constrains the “search space” and is crucial for developing hypotheses and generating and testing specific predictions regarding components of speech motor control and comparing it to human behaviour (p. 604). Moreover, using a computational model of speech motor control allows researchers to quickly simulate how changes or deficits in one part of the system might affect behaviour. In many cases, behavioural and neurological experimental data have been used to support the plausibility of each model.

Several models of speech motor control have been proposed in the literature including the Directions Into Velocities of Articulators (DIVA) model (Guenther, 1994; 2016), Task Dynamics (TD; Saltzman and Kelso, 1987; Saltzman and Munhall, 1989; see also Namasivayam et al., for the related Articulatory Phonology model), State Feedback Control (SFC; Houde and Nagarajan, 2011), ACTion-based model of speech production, speech perception, and speech acquisition (ACT; Kröger et al., 2009), Gestures Shaped by the Physics and by a Perceptually Oriented Targets Optimization (GEPPETO; Perrier et al., 2006), and Feedback Aware Control of Tasks in Speech (FACTS) model (Parrell, Ramanarayanan, et al., 2019). Parrel, Lammert, et al., (2019) provided a detailed discussion of each of these models with a focus on the similarities and differences between models. The existing models of speech motor control are constructed out of the same basic ideas (e.g., the ability to generate motor commands based on a motor plan) and components: feedforward control, feedback control, and predictive/internal model-based control (see Parrell, Lammert, et al., 2019 for a review). These ideas and components will be discussed within the context of one of the most complete computational models of speech motor control developed in the literature (Parrel, Lammert, et al., 2019), the DIVA model. The DIVA model was selected for this study because: a) it includes both auditory and somatosensory feedback systems, b) simulations have been able to match behavioural and neurological responses to perturbations, c) it is able to model coarticulation, a key characteristic in children with CAS, and d) the model has been extended to literacy, a common area of difficulty for children with CAS.

2.1.4.1. Directions Into Velocities of Articulators (DIVA) Model

The DIVA model (Bohland et al., 2010; Guenther, 1994; 2016; Guenther & Vladusich, 2012) was developed over the last 20 years at Boston University and the Massachusetts Institute of Technology and provides an integrated account of the neurobiological and behavioural perspectives of speech (Guenther & Vladusich, 2012). The DIVA model contains three subsystems: (a) a feedforward (motor) subsystem, (b) an auditory feedback subsystem, and (c) a somatosensory feedback subsystem. Briefly, the feedforward (motor) system utilizes stored speech-sound representations to produce speech, and the feedback system utilizes auditory and somatosensory feedback information to produce speech. Speech is acquired gradually by storing information related to individual speech sounds (i.e., how the child has heard and seen the sound produced), and comparing their own subsequent attempts at production with the expected production. Eventually, these attempts are refined into accurate representations of the speech sound inventory.

More specifically, the relationship between articulatory movements and their auditory and somatosensory consequences (i.e., *systemic mappings*) are acquired during the babbling stage. During the imitation stage, speech sounds are stored in the *speech sound map,* and the model learns the *auditory target* (e.g., formant frequencies) and the *somatosensory target* (e.g., tactile and proprioceptive information) for that sound. Next, the model attempts to produce the sound by predicting *feedforward commands* using stored information in the auditory and somatosensory targets. The actual production (i.e., the *auditory and somatosensory state)* is compared to the expected production (i.e., the *auditory and somatosensory targets)*. On the initial attempt, a mismatch between the actual production and the expected production will generate an error signal that is then sent to the *feedback control map.* The *feedback control map* transforms sensory information into corrective motor commands that are incorporated into subsequent attempts. Over time, the *feedforward commands* are produced with little error and thus with reduced reliance on the feedback system. This phase is referred to as building *phonemic mappings*. The *feedback system* will only contribute if there are changes in the auditory or somatosensory states (e.g., change in size/shape with growth) or if speech is perturbed (Bohland et al., 2010; Guenther & Vladusich, 2012; Terband et al., 2009).

2.1.4.2. DIVA Model and CAS

As discussed above, CAS is generally thought to reflect a primary deficit in transforming an abstract phonological plan into a motor plan and/or program (Terband et al., 2009), which corresponds to poor feedforward (motor) control. During the learning stages in DIVA, poor feedforward control is predicted to increase reliance on the feedback system (Terband et al., 2009). In a series of simulations, Terband and colleagues (2009; 2010) tested the predictions that children with CAS have poor feedforward control and subsequent reliance on feedback control (simulation 1), and if this could arise due to either reduced or degraded somatosensory information (simulation 2) or increased neural noise (simulation 3). The results of the first simulation showed that as the ratio between feedforward and feedback control was shifted from 90:10 (typical) to 55:45, the speech output showed an increase in four characteristics of CAS (e.g., deviant coarticulation, speech sound distortions, searching articulation and increased variability). The results of simulation 1 suggested that characteristics commonly associated with CAS could result from poor feedforward control and subsequent overreliance on feedback. In simulation 2 and 3, deficits posited to underlay poor feedforward control and reliance on feedback in CAS were simulated by adding noise to the somatosensory state and motor regions (simulation 2) or adding noise to the auditory state, somatosensory state and motor regions (simulation 3). In both simulations, there was an increase in characteristics of CAS. More importantly, reduced or degraded somatosensory information resulted in unstable/deviant feedforward commands in simulation 2, whereas feedforward commands were intact in simulation 3. Thus, experimental manipulations are required to dissociate the mechanisms (Terband, 2011).

2.1.4.3. Feedback Manipulations during Speech Production

Manipulations of the feedback system are often used to evaluate the contribution of auditory and somatosensory feedback, as well as the integrity of feedforward commands. Only two known behavioural studies have investigated the role of auditory feedback in children with CAS. To my knowledge, these are the only studies of children with any type of SSD. Iuzzini-Seigel et al. (2015) masked auditory feedback white noise in TD children, children with CAS and children with SSDs while they produced consonant-vowel-consonant (CVC) words. Children with CAS produced fewer optimal voice onset times for /p/ (i.e., produced distorted /p/ or sound perceived as /b/) and reduced vowel space area in the presence of white noise, whereas TD children and children with SSDs did not. The authors suggested that the children with CAS could not compensate for a lack of auditory feedback as they lack precise feedforward commands and rely on auditory feedback to accurately produce speech. Moreover, these results suggest that children with CAS and children with SSDs have different core deficits, as a lack of feedback only affected the CAS group. Terband et al. (2014) investigated the ability of TD children, children with CAS and children with SSDs to compensate and adapt for a real-time formant perturbation. In this paradigm, the first and second formants of the vowel /e/ were shifted during the production of CVC words. Compensation was measured as the difference between formant frequencies produced at the start and hold phase, whereas adaptation was measured as the difference between formant frequencies between the start and end phases. As a group, TD children were able to compensate for the perturbation and adapt their formants in the direction opposite of the perturbation. Conversely, children with CAS and SSDs were not able to compensate as they followed the perturbation direction, amplifying the shift. Although there were individual differences within each group, the proportion of TD children who compensated and adapted was higher than in the CAS and SSDs group. The authors interpreted these results as evidence that children with CAS and SSDs can perceive the change in auditory feedback and adjust but cannot compensate due to impaired internal models. Together, these results suggest children with CAS may rely on auditory feedback to a greater degree than children with SSDs and TD children (Iuzzini-Seigel et al., 2015), and that they may be unable to adapt their auditory-motor representations (Terband et al., 2014).

The contribution of the somatosensory system to speech production in children with CAS is not known. Despite atypical somatosensory function commonly being reported in CAS (ASHA, 2007; McCabe et al., 1998), the current evidence is limited and inconsistent (Newmeyer et al., 2009; Nijland et al., 2015; Terband et al., 2009). Newmeyer and colleagues (2009) evaluated the performance of 38 children with suspected CAS on the Sensory Profile (a standardized assessment of sensory processing in children). The children with CAS had atypical sensory processing in five sensory factors, including increased oral sensory sensitivity. Increased oral sensory sensitivity in comparison to TD children has also been reported in children with specific language impairment (van der Linde et al., 2013), autism spectrum disorder (ASD; Kientz & Dunn, 1997) and attention deficit hyperactivity disorder (ADHD; Dunn & Bennett, 2002). Conversely, in computational modeling, Terband and colleagues (2009; 2010) reported that the core impairment in CAS may be impaired feedforward commands secondary to reduced or degraded oral sensitivity. Nijland et al. (2015) investigated oral form discrimination performance in children with CAS (i.e., identification of geometric shapes in the mouth) and reported that children with CAS scored significantly lower than TD children - a potential indicator of poor somatosensory discrimination.

Only one known study has evaluated the effects of altered somatosensory feedback in children with CAS (Nijland et al., 2003). Nijland et al. (2003) evaluated vowel-consonant-vowel (VCV) utterances in TD children, children with CAS and adult women under normal feedback (i.e., no bite block) and under altered somatosensory feedback (i.e., bite block). In the presence of a bite block, children with CAS exhibited greater token-to-token variability in the second formant and less anticipatory coarticulation than TD children and adult women. The authors suggested that this reflected a poor ability to transition between movements and poor programming. It is possible that poor feedforward commands were preventing children with CAS from compensating for the change in somatosensory feedback.

In sum, children with CAS appear to be unable to compensate for a lack of auditory feedback (Iuzzini-Seigel et al., 2015), altered auditory feedback (Terband et al., 2014), and altered somatosensory feedback (Nijland et al., 2003). Given the variability in responses to manipulations of these systems in children with CAS, it is crucial to evaluate the integrity of each system within a single individual (i.e., via a repeated measures design) to determine how each system contributes to speech production.

2.1.5. CAS and Reading Impairments

Children with a history of oral language difficulties, and CAS, are at a high risk for reading impairments (e.g., Kamhi & Catts, 2005; Miller et al., 2019). Clinicians working with children with CAS, as well as parents of children with CAS, often report co-morbid reading impairments (Lewis et al., 2004; McNeill et al., 2009; Miller et al., 2019; Moriarty & Gillon, 2006; Teverovsky et al., 2009). For instance, Teverovsky et al. (2009) surveyed 201 parents on the functional characteristics of CAS, and 39% of parents reported that their children with CAS had difficulties learning to read (or in reading skills). Children with CAS have also been reported to exhibit poor real and non-word decoding (Lewis et al., 2004; Moriarty & Gillon, 2006; Stackhouse & Snowling, 1992), poor phonological awareness skills (McNeill et al., 2009; Moriarty & Gillon, 2006) and poor letter knowledge (McNeill et al., 2009; Moriarty & Gillon, 2006). Lewis et al. (2004) examined the speech, language and academic outcomes of children with CAS and compared them to children with isolated SSDs and children with combined speech and language disorders. Children were followed from preschool (ages 4-6) to school age (ages 8-10) and compared on measures of articulation, phonology, oral motor skills, language and conversational speech. During preschool, children with CAS performed similarly to children with combined speech and language disorders on all measures but performed worse than children with isolated SSDs. At school-age, children were again compared on the original measures, as well as spelling, decoding, reading comprehension, and cognition. Although children with CAS had improved articulation at school-age, they continued to have difficulties in syllable sequencing, non-word repetition, and language abilities. In addition, children with CAS exhibited difficulties with reading and spelling at school-age, including poor decoding of real words and non-words and poor reading comprehension. Finally, Miller and colleagues (2019) compared school-age children (ages 7-18) with CAS and SSDs on measures of reading. Results indicated that children with CAS were more likely to be classified as low-proficiency readers than children with SSDs based on non-word reading and single word decoding (65% compared to 24%; Miller et al., 2019).

Ultimately, children with CAS are at high risk of persistent reading difficulties (Lewis et al., 2004; Miller et al., 2019; Moriarty & Gillon, 2006; Stackhouse & Snowling, 1992). Given that speech production and reading rely on the same neural substrates and processes (Cummine et al., 2016; Graves et al., 2010; Price, 2012), it is important to understand the relationship between these two abilities.

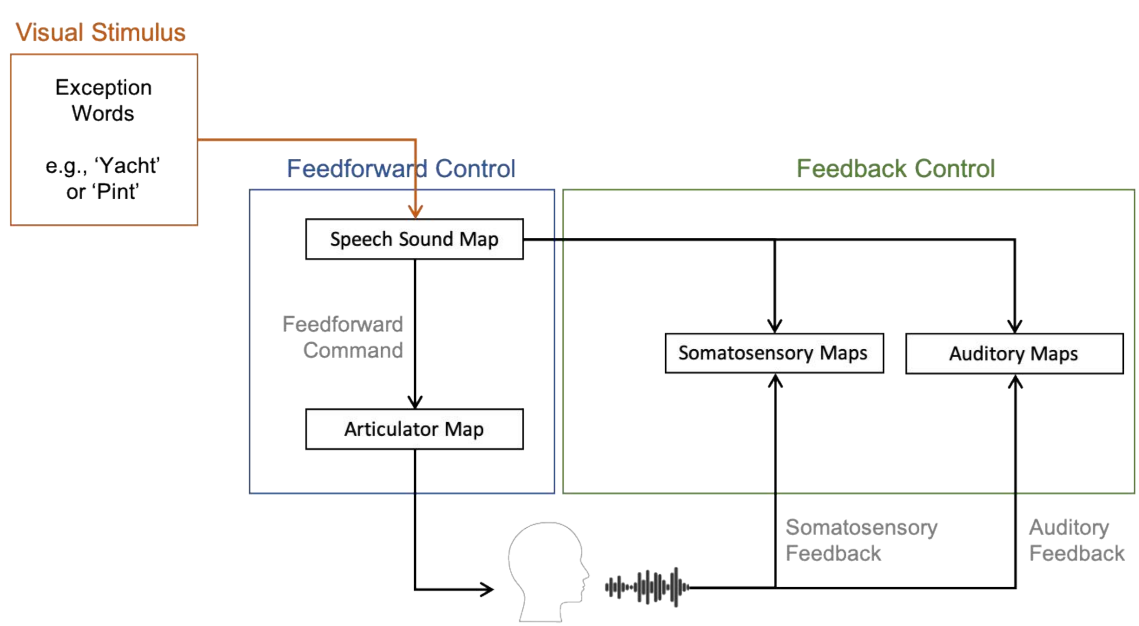
2.1.6. The Print-to-Speech Model

A recently adapted version of the DIVA model, the print-to-speech model (Cummine et al., 2016), provides a starting point for this inquiry. Each word in a child's mental lexicon (i.e., where basic knowledge about words is stored) will activate the sensory and motor systems (Cholin, 2008; Kroger and Cao, 2015; Kroger et al., 2019), as well as pragmatic/semantic, syntactic, phonological and visual representations (see for a review, Indefrey & Levelt, 2000; 2004; Indefrey, 2011). The print-to-speech model predicts how the recognition of visual word forms (i.e., reading) is built upon the acquisition and production of speech as predicted in the DIVA model (see also Rueckl et al., 2015, Stackhouse, 1989 and Stackhouse et al., 2002). Knowledge of how a word sounds and feels when produced (i.e., auditory and somatosensory feedback, respectively) scaffolds the development of knowledge about what a word looks like (Hulme & Snowling, 2014). This notion that reading development and skilled reading are heavily dependent on speech acquisition follows from many studies providing evidence that speech and reading have tightly coupled networks and that the speech production system remains engaged when reading simple words (Carreiras et al., 2007; Cummine et al., 2016; Fiez & Peterson, 1998; Guenther and Vladusich, 2012; Guenther, 1995; Kell et al., 2016; Price, 2012; Turkeltaub et al., 2002). What has yet to be tested is the inherent connections between peripheral auditory and somatosensory information and visual word recognition in both TD children, as well as children with CAS (see van den Bunt, 2017 for a discussion of the potential role of sensorimotor feedback in individuals with reading impairments).

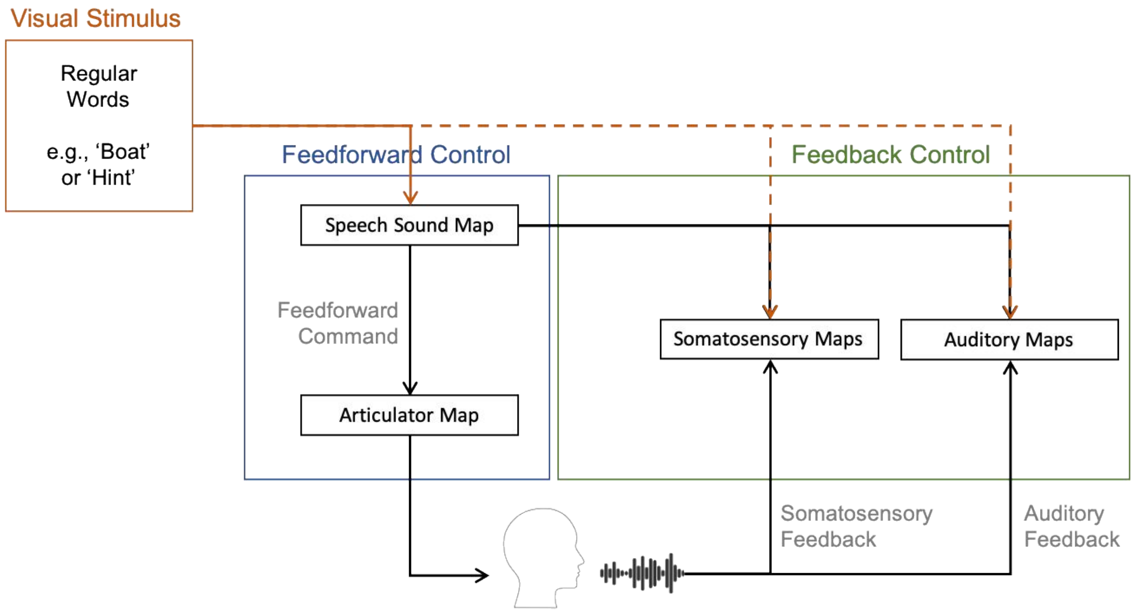
The print-to-speech model serves as a framework to explore predictions regarding the contribution of impairments in the feedforward and/or feedback system that could lead to CAS. First, the model has been tested by showing that the feedforward and feedback systems are differentially involved in reading specific word types (see Cummine et al., 2016; 2017; 2021a; 2021b for a more thorough description of the relationship between the speech production system and these reading tasks and word stimuli). Specifically, the feedback system is invoked to read novel words or non-words using auditory and somatosensory information (i.e., how it sounds and feels). For example, to generate the motor representation (overt or covert) for a non-word (e.g., “bint”), in combination with their knowledge of sound-letter relationships, a child utilizes their knowledge of how it sounds and feels to say sounds. Similarly, to generate the motor representation for a pseudohomophone (e.g., “bote”), a child utilizes the same auditory and somatosensory information. However, in this case, a familiar motor representation is already stored in the feedforward system (“boat”) and can be utilized. Finally, the feedforward system is used to generate representations for highly learned words such as those with predictable letter-to-sound relationships or high frequency words (i.e., regular words; e.g., boat). Exception words, on the other hand, that have an irregular letter-to-sound relationship depend on feedforward information for accurate identification. If feedback information is used, the word would be sounded out incorrectly (e.g., “yacht” might sound like “jaked”). The fact that regular words, with predictable letter-to-sound correspondences, continue to be read faster than exception words that have unpredictable letter-to-sound correspondences, provides evidence for the parallel operation of these two systems (Hino & Lupker, 1996; 2000). A schematic of feedforward and feedback contributions to reading is presented in Figure 1.1. Using this approach, we can test where breakdowns arise in the speech production system of CAS.

Second, the print-to-speech model extends the DIVA model to literacy skills, which is important for the reading impairments in CAS that include difficulties with spelling and decoding (Lewis, 2004; Moriarty & Gillon, 2006; Stackhouse & Snowling, 1992). Third, the print-to-speech model provides a unique opportunity to investigate the role of feedforward and feedback control in children with CAS, without the potential confound of inaccurate articulations. That is, it can be hard to test reading skills by reading aloud since it involves both speech (possibility of missing reading difficulties as they are attributed to speech difficulties) and reading (possibility of underestimating reading ability because of speech difficulties). Using this approach, children can silently read and respond to letter strings (i.e., a button press when the word is a real word) and the feedforward and feedback processes can still be measured. In summary, given the relationships between (a) the speech production system and reading and, (b) feedforward and feedback commands and specific word types (i.e., print-to-speech), one way of examining the feedforward and feedback systems in children with and without CAS is by utilizing silent reading tasks that vary in reliance on these systems.

A)

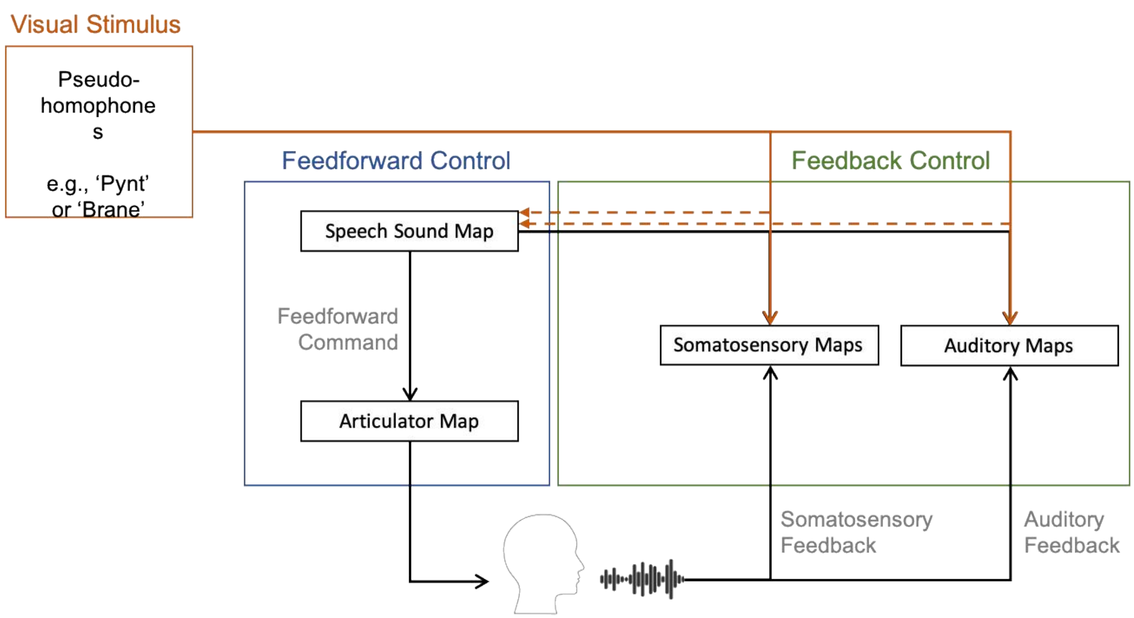


B)



Visual Stimulus
Regular Words
e.g., 'Boat' or 'Hint'
Feedforward Control
Feedback Control
Speech Sound Map
Feedforward Command
Articulator Map
Somatosensory Maps
Auditory Maps
Somatosensory Feedback
Auditory Feedback

C)



Visual Stimulus
Pseudo-homophone s
e.g., 'Pynt' or 'Brane'
Feedforward Control
Feedback Control
Speech Sound Map
Feedforward Command
Articulator Map
Somatosensory Maps
Auditory Maps
Somatosensory Feedback
Auditory Feedback

D)

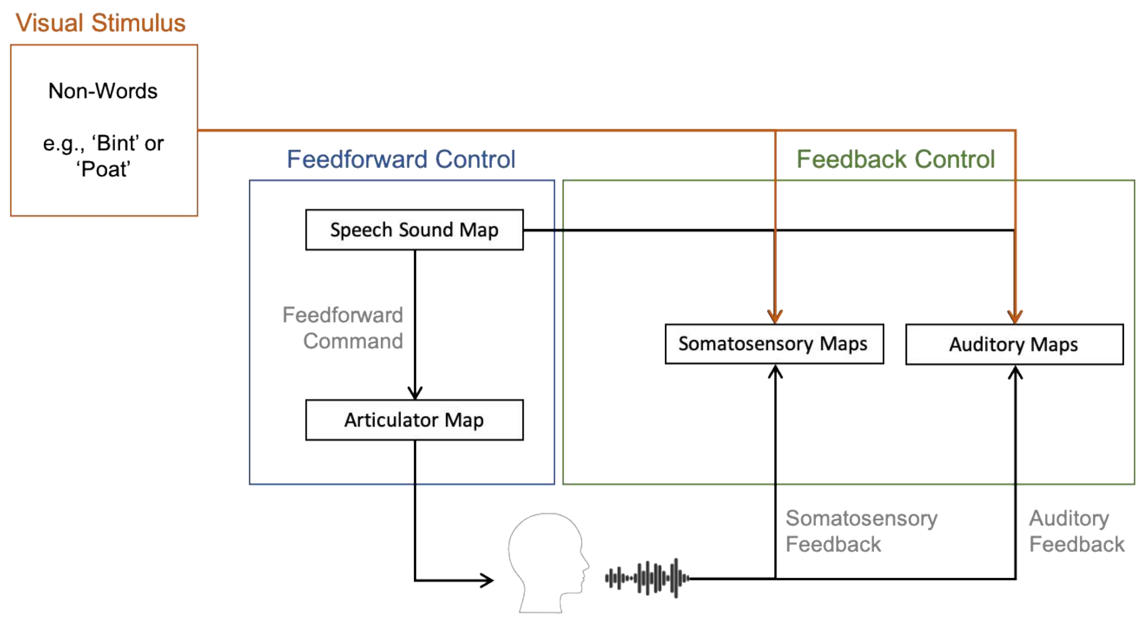


*Figure 2. 1. Schematic of feedforward and feedback reliance for (A) exception words, (B), regular words, (C) pseudohomophones and (D) non-words modified from Guenther, FH. (2016). Neural Control of Speech. Cambridge, MA: MIT Press. *Solid line = primary reliance; Dashed line = possible reliance*

2.1.6.1. Feedback Manipulations during Reading

Few studies have examined the effects of altered auditory feedback on reading performance in TD children (Breznitz, 1997). Breznitz (1997) examined the effects of auditory masking on reading comprehension and decoding performance (real and non-words) in TD children and children with reading impairments. In this study, auditory masking did not impact reading performance in TD children (i.e., no significant change in reading speed, comprehension, or number of decoding errors), but facilitated reading performance in children with reading impairments (i.e., increased reading speed and decreased number of decoding errors). The authors suggested that auditory masking might reduce reliance on impaired phonological skills in children with reading impairments (Breznitz, 1997). Similarly, Rastatter et al. (2007) examined the effects of frequency altered feedback on reading comprehension and reading errors in TD children and children with reading impairments. The authors reported no change in reading comprehension or number of reading errors under frequency altered feedback for TD children. However, children with reading impairments exhibited improved comprehension and reduced number of reading errors under frequency altered feedback. Such results suggest that frequency altered feedback may support phonological processing in children with reading impairments. Taken together, these results indicate that altered auditory feedback during reading may have no impact on TD children but facilitate improved reading in children with reading impairments. How altered auditory feedback might impact reading performance of children with CAS has not yet been investigated.

To date, only two studies have examined the effects of altered somatosensory feedback on reading performance in TD children (Cummine et al., 2021b) and children with CAS (Fleming et al., 2021). Within the context of the print-to-speech model, Cummine et al. (2021b) investigated the role of somatosensory feedback on visual word recognition in TD children using a somatosensory manipulation (i.e., sucking on a lollipop). TD children completed three tasks that varied in reliance on the feedback system: picture categorization, orthographic lexical decision, and phonological lexical decision. The tasks are listed here from no feedback required to feedback required. During an orthographic lexical decision task (LDT), children can primarily utilize feedforward information to identify letter strings that *spell* real words (e.g., real and exception words) versus those that do not (e.g., pseudohomophones and non-words). Conversely, during a phonological LDT, children need to utilize feedback information to identify letter strings that *sound* like real words (e.g., real words, exception words and pseudohomophones) versus those that do not (e.g., non-words).

The authors found that the lollipop facilitated TD children's performance for non-words and regular words in the orthographic-LDT and phonological-LDT, respectively. While the other stimuli types did not meet statistical significance, it is interesting to note that all stimuli, for both reading tasks, showed a pattern of faster response times (ranging from 38 ms - 169 ms) with the lollipop versus without the lollipop. This pattern of findings was considered consistent with the prediction that oral somatosensory information can facilitate silent word recognition tasks Notably, the improvements in word recognition were seen in the absence of effects on a picture categorization task and with negligible changes in accuracy, suggesting the somatosensory manipulation was print-specific and not a general improvement via attention, or speed-accuracy trade-off, for example. These findings provide some evidence that stimulating the oral somatosensory system can modulate word recognition in some contexts. Overall, these findings advance our understanding of the print-to-speech model by providing additional information on the role of peripheral somatosensory information to the visual word recognition process.

In a recent case-control series Fleming et al. (2021), we examined the role of somatosensory feedback on visual word recognition in children with CAS and compared them to the performance of TD children using similar methods as Cummine et al. (2021b). We found that altered somatosensory information (i.e., a large lollipop in the mouth) differentially modulated word recognition in children with CAS. Overall, children with CAS generally exhibited worse performance (i.e., poorer accuracy and slower reaction times) than TD children. However, the lollipop differentially impacted word recognition across tasks and word types for each child with CAS. The performance of one child was substantially impacted when both feedforward and feedback information were enhanced suggesting difficulty integrating feedforward and feedback information. A second child had reduced performance for words that utilized primarily feedback information (e.g., pseudohomophones and non-words) suggesting an impairment in the somatosensory feedback system. Finally, the sensory manipulation had no impact on word recognition in a third child which may indicate the child has an impairment in the feedforward system. These findings underscore that (a) there may be several possible sources for the underlying impairments in CAS; (b) the somatosensory feedback system influences reading performance (Cummine et al., 2016; 2021a; 2021b), and, (c) there is a need to test and relate sensory sensitivity and perception to reading development in CAS. A larger sample size would allow for a more precise interpretation of the role of somatosensory information in CAS. Overall, the results of this study, although tentative due to limited sample size, support the findings from Cummine et al. (2021b), that somatosensory information plays a role in the visual word recognition process, which in turn, can be modulated via somatosensory manipulations. Moreover, it is possible that children with CAS have deficits in different components of the speech production system (i.e., feedforward, feedback or feedforward-feedback integration).

In summary, further work is needed to examine the extent to which altered somatosensory and auditory feedback may impact reading performance in TD children and children with CAS. In addition, the relationship between speech production and reading performance needs to be explored to determine if reading tasks can provide insight into the underlying impairment in CAS.

2.1.7. Summary of Research and Theory for CAS

In summary, CAS is a complex disorder that can affect all levels of speech production. While there has been debate concerning the cause and underlying impairment in CAS, several lines of converging evidence suggest that CAS includes a core deficit in planning and/or programming and a secondary deficit in phonological encoding (Shriberg et al., 2017c). In line with this evidence, the predictions derived from the DIVA model, and related print-to-speech model, warrant systematic investigations to understand if and to what extent manipulations of the feedback system contribute to speech production and reading deficiencies in CAS. Manipulations of the feedback system may shed light on how the feedforward and feedback systems are involved in CAS.

2.2. Practice

In recent decades, evidence-based practice (EBP) has become a standard and key theoretical framework for effective and ethical healthcare. EBP refers to an approach in which current, high-quality available evidence, clinical expertise, and patient preferences and values are integrated into clinical decision-making (ASHA, 2004; Sackett, 1996; Sackett et al., 2000). SLPs are expected to read and evaluate literature (such as prevention, screening, diagnostic procedures, protocols, and measures, as well as efficacy, effectiveness, and efficiency of treatment approaches) and incorporate high-quality evidence into their everyday practice (ASHA, 2004). Nevertheless, despite increasing quantities of, and more convenient access to, clinically relevant research, there is still an immense gap between research and practice. In medicine, it is frequently stated that it takes an average of 17 years for evidence to reach practice (e.g., Hanney et al., 2015; Institute of Medicine, 2001; Morris, Wooding & Grant, 2011). The slow uptake (e.g., Brener et al., 2003; McCurtin & Clifford, 2015; Nail-Chiewtalu & Bernstein Ratner, 2007; Zipoli & Kennedy, 2005) and failure to adopt EBPs (e.g., Dizon et al., 2012; Douglas & Burshnic, 2019; Mickan & Wenke, 2017; O'Connor & Pettigrew, 2009; Olswang & Prelock, 2015) have also been highlighted in the SLP literature. This disconnect appears to be based on the notion that research is misaligned with daily clinical practice. The danger then is that intuition and experience are driving much of the decision-making (Bernstein Ratner, 2006; Furlong et al., 2018). The most frequently reported barriers to implementation of EBP in SLP include a lack of appropriate training and resources, lack of time to engage in EBP (e.g., to read research, to implement new ideas), lack of clinical applicability or useability of evidence, and practice setting constraints (Baker, 2006; Brumbaugh & Smit, 2013; Foster et al., 2015; Furlong et al. 2018; Greenwell & Walsh, 2021; Hoffman et al., 2013; Joffe & Pring 2008; McCurtin & Clifford, 2015; McLeod & Baker, 2014; O'Connor and Pettigrew, 2009; Thome et al., 2020; Wren et al., 2018). These challenges are similar to those reported for CAS (Gomez et al., 2019).

There are, at present, no known studies that have evaluated the use of current best evidence by SLPs for CAS. Some efforts to understand current practices have been made; however, much of the research has been descriptive in nature. Since the ASHA position statement on CAS was released in 2007, there is still considerable variation in the characteristics reported by SLPs as indicative of CAS (Forrest, 2003; Milspaugh & Weiss, 2006; Malmenholt et al., 2017; Meredith & Potter, 2011; Randazzo, 2019; Shakibayi et al., 2019). Moreover, the ASHA position statement appeared to have little impact on improving consensus on CAS characteristics. For treatment, a wide range of approaches with varying treatment intensities are reported, only some of which had any evidence base supporting their use (Gomez et al., 2019; Hoose, 2019; Randazzo, 2019). Only 7% of SLPs felt adequately prepared to treat CAS (Gomez et al., 2019).

However, there has been an unquestioned acceptance of the premise that EBP has to be a priority in SLP in order to improve the quality and cost-effectiveness of care. Some argue that EBP does not "take into account the complexities and realities of clinical practice" (McCurtin & Carter 2015, p.1142), and that SLP practice may be better served by a different approach that recognizes the importance of systemic factors and theory (such as Tonelli, 2006). In disciplines such as occupational therapy, nursing, and social work, theory-guided practice is considered a necessary complement to EBP (e.g., Hinojosa, 2013; Karnick, 2016). Interestingly, Kent (2006) maintains that the field of SLP will be stronger when EBP and theory are enjoined. However, the explicit use of theory in practice in SLP has received no attention.

Among the multitude of definitions of theory, Kerlinger and Lee (2000) define theory as a "set of interrelated constructs, definitions, and propositions that present a systematic view of phenomena by specifying relations among variables, with the purpose of explaining or predicting phenomena" (p. 93). Theory has been described as a "compass" that directs clinical practice (Kent, 2006). It provides SLPs with the means to explain, describe and manage communication disorders. Clinical practice that is not guided by theory runs the risk of being unsystematic and lacking a solid foundation. As Kent (2006) wrote, "If I were to go to a practitioner with a disorder, and that individual told me as a client that he or she had no theory, I would suspect that person's competence. Even for poorly understood disorders, such as childhood apraxia of speech, experienced clinicians have their own theories of the disorder that guide assessment and intervention. The theory may change over time, as theories do, but each theory has an important, if impermanent, value in making sense of all that is known (p. 269)." In other words, SLPs should be able to put into practice what they have learned from theory and do so as part of their everyday practice.

To the best of my knowledge, the explicit use of theory-guided practice (e.g., use of theory or theoretical components as a guiding framework in clinical practice or on the efficacy of theory-based strategies in clinical practice) is not present in the literature. If it is present, it is surprisingly difficult to find given that it is of utmost importance for clinical practice. It has been suggested that SLPs may not be aware of the underlying theories they use (Douglas et al., 2019) or they may not see theory as useful (McCurtin and Carter, 2014). Comparatively, reference to theory-guided practice in other fields such as occupational therapy, nursing and social work, is more prominent and readily accessible. Ultimately a rigorous systematic review is needed.

In sum, the interest in EBP is increasing. However, there is a paucity of published research on the actual understanding and use of EBP in SLP practice for CAS. Furthermore, there have been no discussions on using theory for guiding clinical practice systematically and comprehensively. Thus, it is recommended that further research be undertaken in these areas to better understand and improve clinical management of CAS.

2.3. Summary and Relevance of Proposed Research

CAS is a complex disorder that can affect all levels of speech production, including a core deficit in planning and/or programming and a secondary deficit in phonological encoding (Shriberg et al., 2017c). Research to date has been restricted by a lack of understanding of the cause, underlying mechanism and diagnostic marker for CAS. In the DIVA model, a core deficit in planning and/or programming corresponds to poor feedforward (motor) control, which subsequently leads to reliance on the feedback system. Simulations of the DIVA model have generated testable predictions regarding cause of CAS: (1) reduced or degraded somatosensory information leads to deviant feedforward commands and increased reliance on the feedback system and (2) increased neural noise leads to poor feedforward control and increased reliance on the feedback system. Two ways to examine the extent to which children with CAS utilize auditory and somatosensory feedback during speech production and reading are using behavioural manipulations within the context of the DIVA model and the print-to-speech model.

Even though considerable gains have been made in our understanding of CAS over the past two decades, considerably more work needs to be done to understand the extent to which SLPs use research in their clinical practice for CAS, and more specifically, in the Canadian clinical context. Without understanding current practices, their rationale, and what factors influence current practice, it will be impossible to promote change and adoption of EBPs. When we do have an understanding of the existing practices and why they occur, we can focus our attention and efforts on what can be done to change them. The use of theory-guided practice has been adopted by many other allied health disciplines; however, conspicuously less attention has been paid to the use of theory in SLP. Currently missing is an understanding of the use and usefulness of theories in guiding SLP practice and a clinically focused description of how theory can be incorporated into clinical practice.

CHAPTER 3

Survey Of Speech-Language Pathology Services for Childhood Apraxia of Speech in Canada Raises More Questions than Answers[1]

The following chapter describes an exploratory survey study that was conducted to (a) describe the characteristics of children and young people on SLP caseloads in Canada, (b) describe the diagnostic, assessment, and treatment practices of SLPs in Canada for CAS, and (c) where possible, determine whether or not practices were consistent with the best research recommendations. The results of this study were the impetus for the subsequent paper (Chapter 4) in which I discuss the use of theory to guide practice.

3.1. Abstract

There continues to be uncertainty regarding clinical assessment, diagnosis, and treatment of childhood apraxia of speech (CAS). While there is much emerging clinical research in this area, there remains inconclusive evidence and inconsistent guidance to support and guide speech-language pathologists' (SLPs') clinical decision making and management of CAS. Thus, we surveyed fifty-six (N=56) Canadian SLPs' on their practices with children with CAS. Our descriptive analysis of the SLPs' responses suggests that SLPs' clinical practice varies considerably from one SLP to another. It is within this context that we raise several questions about SLP practices for further study.

Keywords: Childhood apraxia of speech; speech-language pathologists; survey

[1] A version of this chapter has been submitted for publication as "Fleming, C., Cummine, J., & Paslawski, T. (2021). Survey of speech-language pathology services for childhood apraxia of speech in Canada raises more questions than answers."

3.2. Introduction

Childhood apraxia of speech (CAS), also known as development apraxia of speech, is a neurological pediatric speech sound disorder (SSD) that affects a child's ability to make accurate movements when speaking (ASHA, 2007; Terband et al., 2009; Maassen et al., 2010). CAS can occur in isolation with no underlying neurological disorder (i.e., idiopathic CAS), or it can occur with other neurodevelopmental disorders, such as Autism-Spectrum Disorder (ASHA, 2007). When children with CAS speak, they often exhibit inconsistent vowel and consonant errors, have difficulty moving from one sound/syllable to another, and have difficulty using the appropriate stress in syllables/words (for a review, see ASHA, 2007; Murray et al., 2021; Terband et al., 2019). In addition to their difficulties with speech, children with CAS often experience difficulties with: expressive and receptive language; reading, spelling, and writing (i.e., literacy); learning; and fine and gross motor skills (ASHA, 2007; Gillon & Moriarty, 2007; Iuzzini-Seigel, 2019; Lewis et al., 2004; Miller at al., 2019; Murray et al., 2015; Skebo et al., 2013; Teverovsky et al., 2009; Tükel et al., 2015; Zaretsky et al., 2010). Despite an increase in research on CAS over the last several decades, criteria for best practice regarding assessment and differential diagnosis of CAS continue to be debated (Dodd, 2014; Iuzzini-Seigel & Murray, 2017; McCauley & Strand, 2008; Murray et al., 2021). Furthermore, the limited research on treatment efficacy and outcomes has resulted in little consensus among professionals on how best to approach remediation of CAS (for a review, see Maas et al., 2014; Morgan et al., 2018; Murray et al., 2014). Without clear evidence to guide management choices, it can be challenging and confusing for speech-language pathologists (SLPs) to make clinical decisions concerning CAS. The purpose of this work is to explore current practices for assessment, diagnosis, and treatment of CAS in an effort to provide a comprehensive picture of the clinical management process and identify potential areas where the clinical management process can be improved via targeted research, support or information.

Ultimately, the complexity of CAS as a neurodevelopmental disorder, in conjunction with limited research evidence, results in several challenges for SLPs at each stage of the clinical management process. To date, several survey studies have been conducted that attempt to describe and understand the behaviour of SLPs by asking them what they do in clinical practice for children with CAS. Each of these studies has been useful in providing an overview of commonalities with respect to CAS. For example, there is some consensus among SLPs and researchers regarding the characteristics in CAS diagnosis (Forrest, 2003; Malmenholt et al., 2017; Meredith & Potter, 2011; Millspaugh & Weiss, 2006; Shakibayi et al., 2019). After a CAS diagnosis, SLPs often modify or combine aspects of different approaches to produce a hybrid model (Gomez et al., 2019; Hoose, 2019; Randazzo, 2019). The practices utilized by SLPs occasionally had an evidence base supporting their use; however, an overarching theme of these studies seems to revolve around the notion that SLPs' experience issues implementing evidence-based practices (Gomez et al., 2019). To date, there are no reports that examine collective information from all aspects of the clinical management process for CAS (i.e., assessment, diagnosis, and treatment), or that examine management in the Canadian clinical context.

There remains a critical need to understand the clinical practices of SLPs for CAS (Thome et al., 2020; Zipoli & Kennedy, 2005), and specifically in a Canadian context, reflective of our healthcare and education environment, as this has yet to be explored. While many aspects of clinical services for CAS can be seen as similar across contexts, there may be issues of particular concern within national, regional, provincial or local spheres, particularly when looking at policy and system changes. Such endeavours aim to improve clinical research and clinical practice and provide better outcomes for children with CAS. First and foremost, an understanding of the current clinical landscape is necessary to identify potential gaps in the understanding of assessment, diagnosis and treatment of CAS faced by frontline clinicians that could be a target for future research. Second, gathering information from practicing SLPs will also help identify where possible gaps exist with respect to knowledge translation of current evidence-based practices. Targeted efforts could then be made to close these gaps through various translation approaches. As such, the goals of the current exploratory survey were to (a) describe the characteristics of children and young people on SLP caseloads in Canada, (b) describe the diagnostic, assessment, and treatment practices of SLPs in Canada for CAS, and (c) where possible, determine whether or not practices are consistent with the best research recommendations.

3.3. Methods

3.3.1. Ethics Approval and Consent to Participate

The University of Alberta Research Ethics Board approved this study. All participants involved provided informed consent. The survey collected no identifiable information, and the SLPs did not receive any incentives for participation.

3.3.2. Survey and Procedure

To examine the current caseloads and practices of SLPs working with children and young people with CAS, a 49-question survey was developed based upon a review of CAS current literature and modified from Gillon et al.'s (2017) survey on SLP practices with children with Autism Spectrum Disorder. The survey was developed in Google forms and was divided into six sections. The first section gathered demographic information, including education, clinical experience, location, and work setting. The second section addressed the characteristics of children and young people with CAS on SLP caseloads, including gender, age of diagnosis, and co-morbid conditions. The third, fourth, and fifth sections included questions regarding the SLPs' practices for diagnosis, assessment, and treatment, respectively. The final section (not discussed in this paper given the present scope) addressed collaborative practices with parents, educational professionals (e.g., teachers, teaching assistants, and administrators), and other rehabilitation professionals (e.g., occupational and physical therapists). Each section included multiple-choice, checkboxes (for multiple responses within a single question), 5-point Likert scales, and short-answer questions. See Appendix A for a copy of the survey. The survey was disseminated via SLP regulatory body mailing lists, forums, and webpages, as well as on SLP-related social media platforms. Participants were directed to the survey and an informed consent statement using a standard link. Only one response per user (i.e., email) was allowed.

3.3.3. Participants

We received 65 survey responses. The survey was discontinued if respondents indicated they were not SLPs (N=8) or did not work with children with CAS (N=1). A total of 56 completed surveys were received from SLPs who reported working with children with CAS. Respondents included SLPs from 7 provinces and territories (Alberta = 33; British Columbia = 1; New Brunswick = 6; Ontario = 5; Quebec = 8; Saskatchewan = 2; Northwest Territories = 1). The group had varying experience working as an SLP and specifically working as an SLP with children with CAS (Table 3.1). The median number of years practicing as an SLP reported was 10-15 years (mode = < five years), with the median experience working with children with CAS as an SLP = 5-10 years (mode = < five years). The estimated number of children with CAS that services were provided to by the group of SLPs was 1-10 children (53.6%), 11-20 children

(21.4%), 21-30 children (10.7%), and greater than 40 children (14.3%). All SLPs had a master's level degree.

The type of facility where SLPs were employed included educational settings (including early education centers, preschools, and primary or secondary schools; 50%), healthcare settings (including hospitals and community health centers; 26.3%), private practice (18.5%), and daycares (2.2%). The majority of SLPs worked in the city (76.8%) compared to rural settings (23.2%). Seventy-five percent of SLPs reported practicing in English, 16.1% in French, and 8.9% in more than one language (i.e., bilingual service providers).

Almost three-quarters of SLPs (73.2%) reported completing additional training or professional development related to CAS beyond their initial professional training. This included attendance at conferences, workshops, and webinars. Written comments from SLPs suggested that most of this post-degree training was related to treatment approaches for CAS.

Table 3. 1. Characteristics of Speech-Language Pathologists' Working with Children with Childhood Apraxia of Speech (N=56)

	n	%
Years practicing as an SLP		
Under five years	19	33.9
5-10 years	10	17.9
10-15 years	11	19.6
15-20 years	6	10.7
20-25 years	4	7.1
25-30 years	4	7.1
More than 30 years	2	3.6
Years working with children with CAS		
Under five years	22	39.3

5-10 years	18	32.1
10-15 years	5	8.9
15-20 years	2	3.6
20-25 years	4	7.1
25-30 years	4	7.1
More than 30 years	1	1.8
Number of children worked with who have CAS		
1-10 children	30	53.6
11-20 children	12	21.4
21-30 children	6	10.7
More than 30 children	8	14.3

3.3.4. Data Analysis

Descriptive statistics, including means, frequencies, and percentages, were calculated for most survey items. In some cases, the number of responses was less than the number of participants due to skip sequencing (i.e., asking specific questions only to SLPs who gave a particular answer to an opening question). The number of responses could exceed the number of participants when the question allowed multiple responses, and subsequently, the percentages reported for these questions reflect these additional responses. Assessment tools and treatment approaches were coded according to the level of available evidence.

3.4. Results

3.4.1. Children with CAS Receiving SLP Services

The majority of children with CAS on SLP caseloads between 2018 and 2020 were between the ages of 0-4 years (51.3%) and 5-12 years (42.3%), with some children with CAS between the ages of 13-18 years (6.4%). Speech-language pathologists reported supporting more males than females (60.9% versus 39.1%), more monolingual speakers than multilingual/bilingual speakers (61.8% versus 38.2%), and more children from middle socioeconomic backgrounds than high or low socioeconomic backgrounds (46.5% versus 21.8% and 31.7%, respectively).

When asked about the typical age that children received a diagnosis of CAS (Table 3.2), the average age reported was 3.96 years (SD = 0.98). The age of diagnosis most frequently reported was three years (30.1%), followed by four years (25.0%) and five years (19.6%).

Table 3. 2. Typical Age of Diagnosis of Childhood Apraxia of Speech Reported by Speech-Language Pathologists (N=56)

	n	**%**
2 years	1	1.8
3 years	17	30.1
4 years	14	25.0
5 years	11	19.6
6 years	3	6.4
I'm not sure	10	17.9

Speech-language pathologists were asked to report the most common co-morbid conditions for children with CAS (Table 3.3). In order of frequency, the most common co-morbid conditions were other speech/language disorders (24.9%), developmental disability (16.6%), language-literacy disorders (13.9%), and attention-deficit/hyperactivity disorder (ADHD; 12.4%).

Referrals to SLPs for CAS services came from three primary sources: parents (41.1%), educational professionals (26.8%), and other speech-language pathologists (19.6%). Other sources of referrals reported included pediatricians/physicians (8.9%), psychiatrists (1.8%), and audiologists (1.8%).

Table 3. 3. Comorbid Conditions of Childhood Apraxia of Speech Reported by Speech-Language Pathologists

	n	%
Other speech/language disorder	48	24.9
Developmental disability	32	16.6
Language-literacy disorder	25	13.9
Attention-deficit/hyperactivity disorder (ADHD)	24	12.4
Non-verbal oral apraxia	13	6.7
Sensory modulation/integration	11	5.7
Mood disorder	10	5.2
Intellectual disability	9	4.7
Dysarthria	8	4.2
Food allergy/intolerance	7	3.6
Epilepsy	4	2.1
Other	2	1.0
Total	193	100

Note: Other co-morbid conditions listed included gastrointestinal disorder and motor apraxia.

3.4.2. Diagnosis

Of the 56 participants in this study, approximately one half of SLPs (53.6%) reported "always" being involved in the diagnosis of CAS in their region and almost one-third (28.6%) of SLPs reported "often" being involved in the diagnosis of CAS. Nearly one-sixth of SLPs reported "sometimes" (12.5%), rarely (1.8%), or never (1.8%) being involved in the diagnosis of CAS. Of the 54 SLPs involved in the diagnostic process, most reported not usually being involved in a collaborative team for diagnosing CAS. In order of frequency, the most common responses were “never” (38.9%), “rarely” (24.1%), “sometimes” (16.7%), “often” (13.0%), and “always” (7.4%). In addition to SLPs (66.7%), other professionals reported to be responsible for the diagnosis of CAS included pediatricians/physicians (20.5%), psychologists (2.6%), and psychiatrists (1.3%).

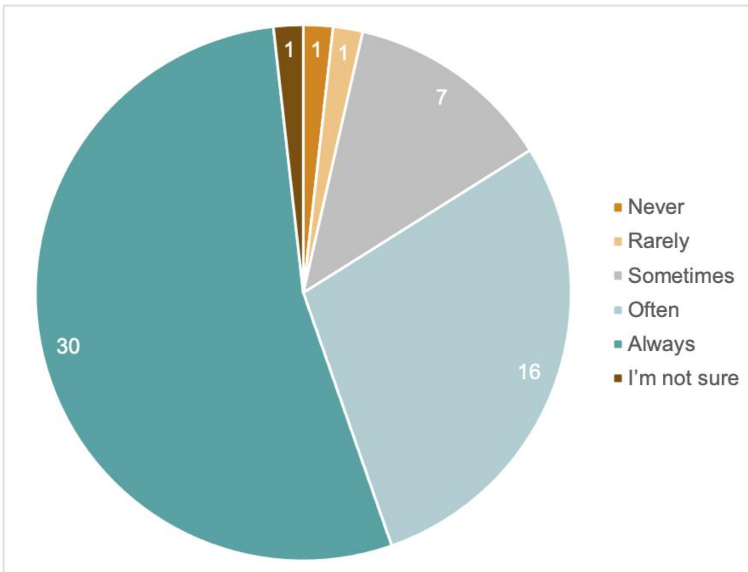


Figure 3. 1. Frequency of participation by speech-language pathologists in the diagnosis of childhood apraxia of speech (N=56)

Speech-language pathologists who reported being involved in the diagnosis of CAS (N=54) were asked which formal assessments (i.e., yields a scaled or standard score) and informal assessments (i.e., does not yield a scaled or standard score) are used in the diagnosis of CAS (not including tests applied to examine other language functions). The formal and informal assessments used by SLPs are listed in Table 3.4, with each assessment tool coded according to its psychometric quality based on Gubiani, Pagliarin and Keske-Soares (2015). [2]

[2] Although several of the assessment tools have been published on extensively and are widely implemented (e.g., MSAP), no known research was found specifically evaluating their validity and reliability.

Table 3. 4. Formal and Informal Assessments used by Speech-Language Pathologists for Diagnosis of Childhood Apraxia of Speech

	n	%	Evidence
Formal Assessments			
Kaufman Speech Praxis Test for Children (KSPT)[1]	28	37.3	V [A]
Dynamic Evaluation of Motor Speech Skill (DEMSS)[2]	17	22.7	R/V [A]
Apraxia Profile (AP)[3]	7	9.3	
Screening Test for Developmental Apraxia of Speech (STDAS)[4]	1	1.3	
None of the above	15	20.0	
Other	7	9.3	
Total	75	100	
Informal Assessments			
Duffy/Mayo Clinic tasks for assessing apraxia of speech[5]	8	14.3	
Madison Speech Assessment Protocol (MSAP)[6]	2	3.6	
None of the above	33	58.9	
Other	13	23.2	
Total	56	100	

Note: V, evidence of validity; R, evidence of reliability.
Other formal assessments listed included a French phonology screening tool. Other informal assessments listed included French speech/apraxia screening tools, motor speech examinations, diadochokinetic rates, Caspari, S. unpublished list of red flags, and the Test of Childhood Stuttering (Gilliam, Logan, & Pearson, 2009).
[1]Kaufman (1995). [2]Strand & McCauley (2019). [3]Hickman (1997). [4]Blakeley (2001). [5]Tasks for Assessing Motor Speech Programming Capacity (Apraxia of Speech; Duffy, 2005) adapted and modified from Wertz, LaPointe, and Rosenbek (1984) and unpublished Mayo Clinic tasks. [6]Shriberg et al. (2010). [A] Gubiani, Pagliarin, & Keske-Soares (2015).

The SLPs who reported being involved in the diagnosis of CAS were asked to identify which criteria they use to diagnose CAS (Figure 3.2). Almost two-thirds of SLPs (64.2%) reported using diagnostic criteria, including the American Speech-Language-Hearing Association (ASHA, 2007) consensus-based feature list (22.6%), Strand's 10-Point Checklist

(Shriberg et al., 2011; 2017a; 13.2%), clinician-developed checklists (13.2%), or a combination of the ASHA feature-list, Strand's 10-Point Checklist, and clinician-developed checklists (15.1%). The remaining one-third of SLPs (35.8%) reported not using specific criteria to diagnose CAS. Of these individuals, 16 SLPs reported not using any criteria and three reported referring to the ASHA feature-list, Strand 10-Point Checklist, and/or clinician-developed checklists but not using specific criteria.

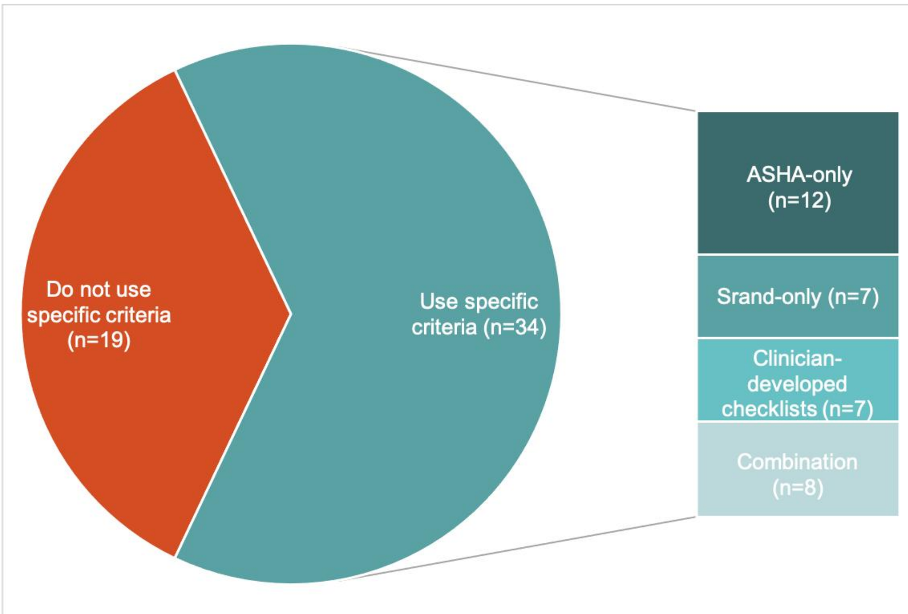


Figure 3. 2. Frequency of use of criteria by speech-language pathologists in the diagnosis of childhood apraxia of speech (n=53)

3.4.3. Assessment

Speech-language pathologists were asked whether they use formal or informal assessments to help determine intervention goals for children with CAS (i.e., for treatment planning; Table 3.5). The most common response from SLPs indicated that formal and informal assessments were "sometimes" (42.9% and 39.2%) used to help determine intervention goals. To a lesser extent, some SLPs reported "often" (17.9% and 21.4%), "rarely" (16.1% and 19.6%), "always" (8.9%), and "never" (12.5%) using formal/informal assessments to help determine intervention goals. As can be seen in Table 3.6, a wide range of assessments were reported by SLPs, including 12 non-language-focused assessments and 20 language-focused assessments. The most common non-language focused assessments were the Kaufman Speech Praxis Test for Children (KSPT; 21.5%), Goldman-Fristoe Test of Articulation (GFTA; 14.8%), Oral Speech Mechanism Screening Examination (OSMSE; 13.3%), and the Dynamic Evaluation of Motor Speech Skill (DEMSS; 11.9%). The most common language-focused assessments reported were the Clinical Evaluation of Language Fundamentals (CELF; 34.3%), Preschool Language Scales (PLS; 9.9%), Expressive One-Word Picture Vocabulary Test (EOWPVT; 7.3%), Peabody Picture Vocabulary Test (PPVT; 6.3%) and Communication Development Inventory (CDI; 5.7%).

Sixty-four percent (64.3%) of SLPs reported "often" or "always" using dynamic assessment (DA). This informal assessment strategy incorporates teaching into assessment and evaluating how this impacts a child's performance, to help determine intervention goals. The remaining SLPs reported "sometimes" (21.4%), "rarely" (7.1%), or "never" (7.1%) using DA.

Table 3. 5. Frequency of Use of Formal and Informal Assessments by Speech-Language Pathologists for Intervention Planning for Children with Childhood Apraxia of Speech (N=56)

	Formal, n (%)	**Informal**, n (%)
Never	8 (14.3%)	4 (7.1%)
Rarely	9 (16.1%)	11 (19.6%)
Sometimes	24 (42.9%)	22 (39.2%)
Often	10 (17.9%)	12 (21.4%)
Always	5 (8.9%)	7 (12.5%)
Total	56 (100.0%)	56 (100.0%)

Table 3. 6. Formal and Informal Assessments used by Speech-Language Pathologists to Determine Intervention Goals for Childhood Apraxia of Speech

Non-Language Focused Assessments	Language-Focused Assessments	Informal Assessment Practices
KSPT	CELF	Speech Analysis
GFTA	PLS	Checklists
OSMSE	EOWPVT	Questionnaires
DEMSS	PPVT	Interviews
AP	CDI	
Other[3]	Other[4]	

Note: KSPT, Kaufman Speech Praxis Test for Children; GFTA, Goldman-Fristoe Test of Articulation; OSMSE, Oral Speech Mechanism Screening Examination; DEMSS, Dynamic Evaluation of Motor Speech Skill; AP, Apraxia Profile; CELF, Clinical Evaluation of Language Fundamentals; PLS, Preschool Language Scales; EOWPVT, Expressive One-Word Picture Vocabulary Test; PPVT, Peabody Picture Vocabulary Test; CDI, Communicative Development Inventories.

Information about the specific skills assessed when determining treatment goals was obtained by asking SLPs to rate how often they assess a particular skill on a 5-point scale (never to always). A detailed list of the specific skills assessed by SLPs is listed in Figure 3.3 in order of frequency of always/often responses. SLPs reported that they:

[3] Other non-language focused assessments (listed by <5% of total respondents) included the Children's Speech Intelligibility Measure (CSIM), Test of Problem Solving (TOPS), Prosody-Voice Screening Profile (PSVP), Verbal Motor Production Assessment for Children (VMPAC), Madison Speech Assessment Protocol (MSAP), Informal Tool for Early Motor Speech (ITEMS), and Inventory of Syllabic Structures in Francophone Children (ISSEF).

[4] Other language-focused assessments (listed by <5% of total respondents) included the Functional Communication Profile, One-Word Picture Vocabulary Test: Receptive (ROWPVT), Receptive-Expressive Emergent Language Test (REEL), Khan-Lewis Phonological Analysis (KLPA), Preschool Language Assessment Instrument (PLAI), Test of Auditory Comprehension of Language (TACL), Test of Narrative Language (TNL), Test of Problem Solving (TOPS) - Elementary or Adolescent, Oral and Written Language Scales (OWLS), Comprehensive Assessment of Spoken Language (CASL), Gray Oral Reading Test (GORT), Test of Integrated Language and Literacy Skills (TILLS), Communication and Symbolic Behavior Scales (CSBS), Comprehensive Test of Phonological Processing (CTOPP), Pragmatic Language Skills Inventory (PLSI), Reynell Developmental Language Scales (RDLS), Test of Adolescent/Adult Word Finding (TAWF), Test of Pragmatic Language (TOPL), Test of Word Reading Efficiency (TOWRE) and Test of Written Language (TOWL).

- Were more likely to assess the production of single-words, volitional/spontaneous speech, receptive language, production of multisyllabic words, alternating movement repetitions, production of words of increasing length/complexity, sequential movement repetitions, production of phrases/sentences, production of single-sounds ("often" and "always" accounted for greater than 80% of responses).
- Were somewhat likely to assess non-speech articulatory postures and sequences, hearing, repetition of words, conversation skills, and well-practiced/automatic speech ("often" and "always" accounted for 51-79% of responses).
- Were less likely to assess literacy development, narrative ability, feeding and swallowing, sensory-motor skills, and executive functions ("often" and "always" accounted for less than 50% of responses).

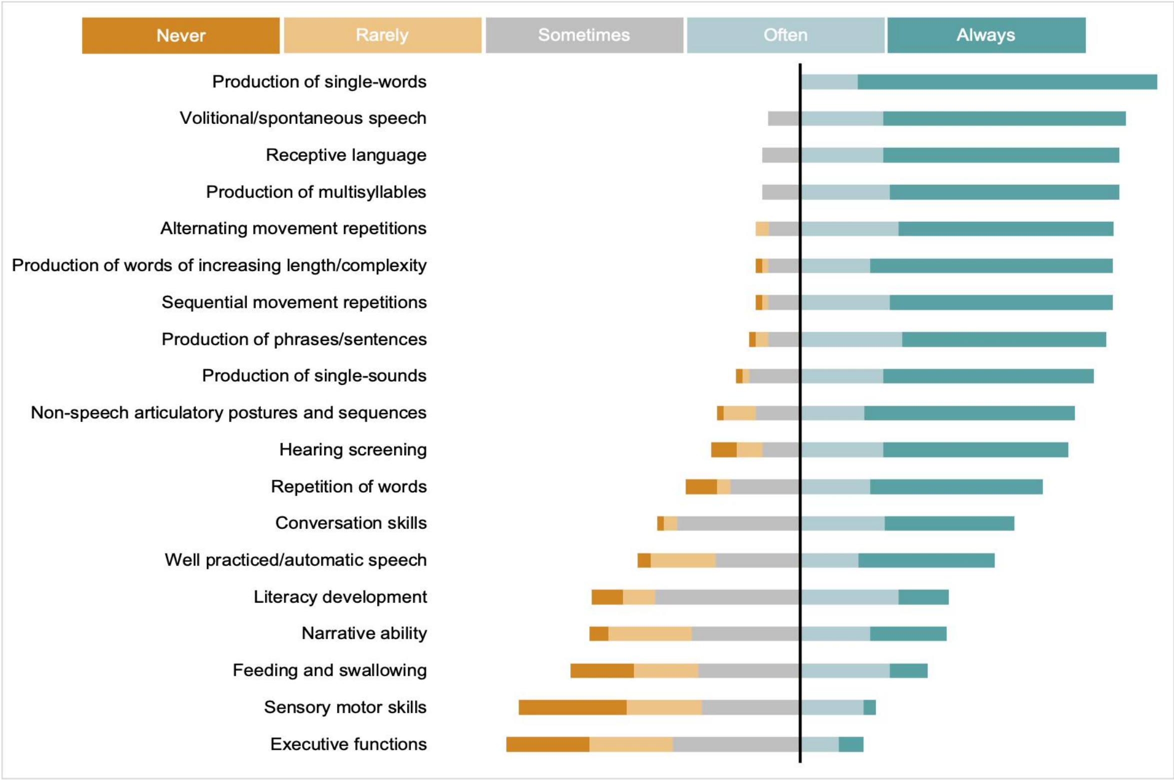


Figure 3. 3. Skills assessed by speech-language pathologists to determine intervention goals for childhood apraxia of speech

Where English was not the first language of the child, over half (55%) of SLPs reported that they did not have access to CAS assessments in the child's native language. Eight percent (8%) reported that they did have access to assessments in the child's native language. The remaining SLPs practiced in English-only (i.e., not applicable; 30.9%). Of the SLPs who reported working with children with CAS whose native language was a language they do not speak or understand, half (50%) reported using an interpreter when conducting assessments. It is not known if these were trained interpreters or untrained bilingual speakers.

3.4.4. Treatment

Fifty-five SLPs reported providing intervention for children with CAS in the 12-month period before the survey. As such, the number of responses for treatment-related questions is 55. The frequency, duration, and intensity of treatment sessions for children with CAS, and the usual period of intervention, reported by SLPs are listed in Table 3.7. The most common frequency, duration, and intensity of treatment sessions provided for children with CAS was 1-2 times per week (77.8%), 30 minutes (40.0%), and 50-100 trials per session (52.7%), respectively. The most common intervention periods were 1-2 years (27.3%) and 2-3 years (25.5%), yet, there was a considerable variation in responses ranging from 1-6 months to more than 5 years.

Children with CAS were more likely to be treated in individual therapy ("sometimes", "often", and "always" accounted for 92.8% of responses) than small group therapy ("never" and "rarely" accounted for 73.6% of responses).

Table 3. 7. Frequency, Duration, and Intensity of Treatment Sessions, and Period of Intervention, for Children with Childhood Apraxia of Speech reported by Speech-Language Pathologists

	N	**%**

Frequency (N=53)		
1-2 times per week	43	82.7
3-4 times per week	5	9.6
Every two weeks	2	3.8
Other	3	5.8
Duration (N=55)		
30 minutes	22	40.0
45 minutes	18	32.7
60 minutes	14	25.5
75 minutes	1	1.8
Intensity (N=55)		
<50	13	23.6
50-100	29	52.7
100-150	10	18.2
150+	3	5.5
Period of Intervention (N=55)		
1-6 months	10	18.2
7-12 months	6	10.9
Between 1 and 2 years	15	27.3
Between 2 and 3 years	14	25.5
Between 3 and 4 years	8	14.5
More than 4 years	2	3.6

SLPs who provided treatment services to children with CAS reported using a wide variety of techniques and approaches. This included motor programming approaches (21.1%), augmentative and alternative communication (AAC; 19.4%), sensory cueing approaches

(18.9%), a combination of motor-programming and sensory cueing approaches (13.2%), rhythmic approaches (11.0%), a combination of motor and linguistic approaches (10.1%), and linguistic approaches (6.2%).

SLPs were more likely to create their own interventions and/or modify commercial/published programs ("sometimes", "often", and "always" accounted for 92.8% of responses) than use commercial programs ("sometimes", "often", and "always" accounted for 56.4% of responses). The commercial/published intervention approaches used by SLPs for CAS are listed in Table 3.8 in order of frequency. Each intervention was coded according to the current scientific evidence regarding effectiveness (emerging, medium, high, or no scientific support) based on previously conducted systematic reviews and randomized controlled trials.

Table 3. 8. Commercial/Published Intervention Approaches used by Speech-Language Pathologists for Childhood Apraxia of Speech

	N	%	Evidence
Dynamic Temporal and Tactile Cueing (DTTC)[1]	30	24.8	++ [A,D,E]
Kaufman Speech to Language Protocol (K-SLP)[2]	26	21.5	
Rapid Syllable Transition Treatment (ReST)[3]	20	16.5	+++ [A,B,D,E,F]
Prompts for Restructuring Oral Muscular Phonetic Targets (PROMPT)[4]	13	10.7	+ [C,E,G]
Integral Stimulation (IS)[5]	9	7.4	*
Touch-Cue Method[6]	5	4.1	
Integrated Phonological Awareness (IPA)[7]	4	3.3	++ [A]
Nuffield Dyspraxia Program (NDP)[8]	2	1.7	+++ [B,D,E,F]
Melodic Intonation Therapy (MIT)[9]	2	1.7	
None of the above	7	5.8	
Other	3	2.5	
Total	121	100	

Note: +, emerging scientific support; ++, medium scientific support; +++ high scientific support; *DTTC is the pediatric adaptation of IS. IS is often used in adults and sometimes the term is used interchangeably with DTTC. Other intervention approaches listed included Charron, L. unpublished literature review, Let's Start Talking (Hodge, 2004; 2007) and Let's Talk Clearly (Hodge, unpublished program).
[A]Murray, McCabe and Ballard (2014). [B]Morgan, Murray, and Liégeois (2018). [C]Namasivayam et al. (2021). [D]Maas, Gildersleeve-Neumann, Jakielski, & Stoeckel (2014). [E]McAllister, Brodén, Gonzalez Lindh, Krüssenberg, Ristic, Rubensson, and Sjogreen (2018). [F]Murray, McCabe, and Ballard (2015). [G]Dale & Hayden (2013).
[1]Strand, Stoeckel and Bass (2006). [2]Kaufman (2013). [3]McCabe, Murray, Thomas, & Evans (2017). [4]Hayden (1984; 2008). [5]Rosenbek et. al. (1973); Strand & Debertine (2000). [6]Bashir, Graham-Jones & Bostwick (1984). [7]Gillon & McNeill (2007); McNeill, Gillon and Dodd (2009). [8]Williams & Stephens (2004). [9]Helfrich-Miller (1984)

3.5. Discussion

In order to understand the clinical diagnostic, assessment, and treatment practices of SLPs working with children with CAS, we conducted an exploratory survey of 56 SLPs in Canada. For the purpose of this paper, we will focus on findings that highlight gaps/challenges in the clinical decision-making process and potentially impact services for children with CAS. We also provide some considerations for potential avenues of future research that may serve to close these gaps.

3.5.1. How is CAS diagnosed?

Diagnosis, in the context of SLP, can be defined as the process of determining the cause or nature of a communication disorder by examination of the signs, symptoms, and results of the available clinical tests. Diagnostic criteria refer to the set of signs, symptoms, and tests used by an SLP to determine the correct diagnosis.

The SLPs in this study reported that the typical age of diagnosis of CAS was between 3 and 5 years of age. This finding is consistent with the notion that diagnosis of CAS under three years of age may be difficult due to the child's inability to attend and focus, or to produce enough speech (at least simple syllables and words) to participate in a motor speech examination (ASHA, n.d., CAS Practice Portal). However, the finding that only half of the respondents reported that SLPs were always involved in the diagnosis of CAS in their region was especially surprising given the critical role that SLPs play with this population. How is this finding to be explained? Moreover, is there any justification for it? This is a necessary avenue of future inquiry. Many of the world's national SLP associations see SLPs as key members of the diagnostic team for CAS (e.g., ASHA, 2007; ASHA, n.d., CAS Practice Portal; SAC, n.d.; 2016). Best practices for CAS highlight the need for an SLP with advanced knowledge, skills, and experience in CAS to be involved in diagnosis (ASHA, 2007; Murray et al., 2021). Given that SLPs are centrally or solely involved in the diagnosis of other SSDs, that the treatment of CAS differs from other SSDs, and that treatment of CAS is guided by decisions made during the diagnostic process, it is necessary for an SLP competent in this area to be central in the diagnosis of CAS. Thus, it is essential to identify whether a child shows symptoms of CAS as this impacts the treatment pathway. While we await additional research to mitigate diagnostic uncertainty in this area, it is imperative that SLPs be involved in the decision-making process to diagnose CAS to the fullest extent allowed by their capacity. Diagnosis is a critical first step for several reasons, including: improving our understanding of CAS; providing a common language to describe CAS; facilitating access to additional supports and funding for services; aiding in treatment planning (i.e., identifying effective, targeted interventions for CAS); and helping children with CAS and their families find support networks.

It is worth mentioning that respondents from Ontario emphasized that SLPs in that province cannot communicate a diagnosis of CAS. In Canada, each province regulates a number of health professions including SLPs under their respective health professions act. Each act contains specific practice statements that outline the scope of practice of SLPs in that province. According to the College of Audiologists and Speech-Language Pathologists (CASLPO, 2018) and the Ontario Regulated Health Professions Act (S.O. 1991, c.18), SLPs practicing in Ontario cannot diagnose CAS, nor can they diagnose any speech, language, and communication disorder. This is not the case elsewhere in Canada. It is not a matter of training; rather, the health professions act in Ontario has controlled the act of diagnosis and restricted SLPs from performing this controlled act (S.O. 1991, c.18, 27 (2) 1.). Although CASLPO recently provided practice advice regarding how to use the term CAS to describe a set of symptoms (CASLPO, 2018; for example, SLPs can communicate findings and symptoms), we do not know to what extent, if at all, this regulation has impacted client care. In the interest of client care, an in-depth review of the nature of collaboration between SLPs and physicians and the opportunities and evidence for expanding the scope of SLPs practice in Ontario would be beneficial.

On a related note, given the complexity of the disorder and the lack of agreement regarding the underlying mechanism of CAS, it is not particularly surprising that several other healthcare professions, including pediatricians, psychiatrists, and neurologists, were reported to be responsible for the diagnosis of CAS. While we acknowledge that a flexible approach is required to support overlapping professional scopes of practice (see the Royal College of Physicians and Surgeons of Canada documents for competencies of developmental pediatricians, 2016, neurologists, 2020, and child and adolescent psychiatrists, 2021, in Canada, respectively), the extent to which these medical professionals have the competence (i.e., knowledge, training, skills, experience, and judgement) and resources required to diagnose CAS (e.g. access to and training in standardized assessments) needs to be explicitly queried. Furthermore, the reason for the participation of multiple healthcare professionals in the diagnosis needs to be determined. For example, the involvement of non-SLPs in the diagnostic process may be due to concerns regarding wait times for SLP services (Moharir et al., 2014; Rvachew and Rafaat, 2014). Unfortunately, we do not yet know the genesis of this finding. In any event, recognition that the diagnostic process for CAS may be collaborative in some practice settings, SLPs, healthcare professionals, and organizations should ensure that all team members have the appropriate knowledge, skills, and experience, as well as the necessary resources, to engage in this process. Additionally, when CAS is suspected, SLPs should be consulted and allowed to conduct a comprehensive assessment to obtain an accurate diagnosis for CAS.

The current gold standard for diagnosing CAS is expert opinion using perceptual assessment of core features (ASHA, 2007; Murray et al., 2021). Although there is no single individual marker that is sufficient for differential diagnosis of CAS from other SSDs, in the interim, there is a general consensus among researchers and SLPs that diagnosis of CAS should be determined using the features of CAS based on the ASHA (2007) consensus-based list and Strand's 10-point Checklist (Murray et al., 2021; Shriberg et al., 2010). Thus, it was surprising to find that 30% of SLPs in this study did not use any criteria for the diagnosis of CAS. Why this is happening needs to be better understood. One possible reason may be related to the debate regarding diagnostic criteria. A key challenge in CAS practice and research is the lack of operationally defined and standardized criteria, overlap of criteria with other SSDs, and uncertainty regarding the number and type of tasks required to elicit these criteria (Iuzzini-Seigel & Murray, 2017; Murray et al., 2015; 2021; Terband, Maassen, et al., 2019; Terband, Namasivayam, et al., 2019). A second hypothesis to be explored is that perhaps the implementation (or lack thereof) of diagnostic criteria is influenced by practice setting. For example, SLPs may be faced with limited access to best evidence which could necessitate making a diagnosis solely based on intuition and clinical experience. A third possibility is that the current criteria for making a diagnosis of CAS perform reasonably well in research settings, however fail to recognize individuals with mild, unclear, or atypical presentations that may be seen in clinical practice settings. Clearly, the approach to mitigating this identified challenge in the diagnostic pathway is contingent upon the fundamental reason that 30% of SLPs reported not using criteria to diagnose CAS. Further research is required to determine if the findings of this study are an accurate reflection of SLP practice and to investigate the barriers and facilitators to the diagnosis of CAS by SLPs in a clinical practice setting.

3.5.2. How is CAS assessed?

Speech-language assessment is a complex process of collecting, integrating, and interpreting information to identify a child's strengths and needs, inform diagnosis, and guide treatment planning (determining the focus, frequency, structure, and length of treatment). For children with suspected CAS, SLPs are currently recommended to complete a comprehensive assessment that combines clinical observations with valid and reliable formal evaluation (Gubiani et al., 2015; Murray et al., 2021; Terband et al., 2019). While many SLPs in this study reported using formal assessments with some evidence of psychometric quality (e.g., the KSPT and the DEMSS), several SLPs also reported using assessments with no valid and reliable protocols (e.g., the AP and the STDAS) or no formal or informal assessment tools at all (n=11; Gubiani et al., 2015). It is also worth noting that there are a number of practices that are commonly implemented by SLPs despite a lack of publicly available evidence demonstrating reliability and validity of the tool for CAS (e.g., Test of Childhood Stuttering, Let's Start Talking, Let's Talk Clearly). This gap between evidence-based recommendations and actual practice is a much-needed avenue for future research. In one scenario, we may need to understand better how SLPs administer assessments in their everyday clinical practice to meet the evidence-based recommendations. For example, the complexities of everyday use of test information may be different across practice settings, and test information could be used both objectively and subjectively to describe the child's communication and behaviours. Alternatively (or perhaps, in conjunction), SLPs and organizations may face significant constraints or use a battery of pre-selected tests for financial or other reasons. Because the protocol for diagnosis is so tightly linked to the treatment approach, targeted research studies on the use of formal and informal assessment tools in diagnosing CAS in everyday clinical practice warrants further investigation.

The SLPs in this study reported conducting comprehensive speech-language assessments to guide treatment planning for children with CAS, including using formal, informal, and dynamic tools and assessing a wide range of skills. They reported more frequently using DA than formal and informal procedures and were routinely assessing skills critical to CAS (e.g., production of single-words, multisyllabic words, and spontaneous speech). Visual analysis of individual response patterns for the use of formal, informal, and DA revealed that the approach taken by each SLP differed. For example, several SLPs reported always using DA and never/rarely using formal or informal assessment, while other SLPs reported often using all three methods. These findings lead us to ask a number of questions: what is the role of testing in everyday clinical practice for children with CAS?; what guides an SLP's decision-making in selecting assessment tools?; what factors contribute to effective clinical decision making for assessment of CAS? Based on the information provided in this study, it remains unclear what approach an SLP takes in the assessment of CAS, how they apply it in practice, and the rationale underlying which procedures are used.

This uncertainty raises several additional questions. For example, to what extent are the types of assessment procedures used by SLPs to guide treatment planning influenced by child or the workplace characteristics? Given the complexity and uniqueness of each child with CAS and increased demands for evidence-based practice, it is important to understand better the factors that contribute to decision-making behind conducting assessments with children with CAS.

3.5.3. How is CAS treated?

The SLPs in this study reported wide variation in treatment dosage for CAS. Treatment dosage, or the total amount of treatment, refers to the frequency (i.e., number of sessions over time), duration (i.e., length of sessions), and intensity (i.e., number of learning trials accomplished during one session) of services (Warren et al., 2007). Current literature suggests that good treatment outcomes are found for children with CAS when treatment is provided 2-3 times per week, 15-60 minutes per session, with at least 60 trials per session (Murray et al., 2014; Namasivayam et al., 2015). Children with CAS often require a greater overall treatment intensity than other SSDs (Edeal & Gildersleeve-Neumann, 2011; Kaipa & Peterson, 2016; Murray et al., 2014; Williams, 2012;). The overall treatment intensity reported by SLPs in this study (1-2 times per week, up to 30 minutes per session, and with 50-100 trials per session) does not appear to be sufficient to achieve optimal treatment outcomes for CAS. There are several possible explanations for these results. One possibility is that SLPs cannot meet the intensity demands due to practice setting constraints, such as size and complexity of caseloads, time, and resources (Brumbaugh and Smit, 2013; Furlong et al., 2018; Joffe and Pring, 2008; Lancaster et al., 2010; McLeod and Baker, 2014; McCurtin and Clifford, 2015). A second possibility is that variations in treatment intensity for CAS reflect a more detailed understanding of the clinical case, such as client and family variables (Baker, 2012; Furlong et al., 2018; Pascoe et al., 2010). Alternatively, variations in treatment intensity may reflect the practice style of the SLP and not the clinical case (e.g., SLPs may be applying a single treatment intensity and schedule across their entire caseload; Brandel & Frome Loeb, 2011; Chiang & Rylance, 2000; Mullen &

Schooling, 2010). A more nuanced understanding of decisions regarding treatment intensity for children with CAS is desperately needed.

Speech-language pathologists reported treating CAS with many different therapies. The prevalence of use of interventions with strong or moderate evidence of effectiveness for CAS in this study was 65%. However, it is clear that several treatment approaches used by SLPs in this study have no known effectiveness. There is very little known about how SLPs choose which treatment approach they offer to individual children with CAS and what factors influence their choices. Clearly, there is a disconnect happening in the dissemination pathway that connects evidenced-based research with practice. While there is some evidence supporting the notion that SLPs prefer intuition and clinical experience (of themselves and colleagues) over evidence (Furlong et al., 2018; Ratner, 2006), a more likely scenario is that there are barriers to treatment services associated with SLP education and training or clinical practice settings. To complicate the matter further, several SLPs in this study also reported that they were more likely to modify published programs, using an eclectic (or hybrid) approach that combines principles/techniques from two or more approaches. A high prevalence of hybrid therapy approaches has been previously reported (Brumbaugh and Smit, 2013; Pascoe et al., 2010). The effectiveness of such hybrid approaches is a fruitful avenue of future work, in addition to the rationales for implementing hybrid approaches (i.e., child, family, and contextual factors; Roulstone et al., 2015).

3.5.4. Limitations

This exploratory survey was conducted to better understand the clinical landscape for CAS in Canada and identify areas in need of future investigation. As a first step, we focused on characterizing the diagnostic, assessment, and treatment practices of SLPs for CAS. However, this leaves several important issues possibly affecting everyday clinical practice unexplored. Follow up descriptive investigation, ideally using interviews or focus groups, is needed to provide insights into the rationale behind clinical decision-making for CAS. In addition, caution should be exercised when interpreting our findings as the barriers and facilitators to diagnosis, assessment, and treatment of CAS by SLPs in clinical practice settings are likely to influence the responses collected here. Given that these barriers and facilitators remain unknown, conclusions about the 'cause' of our findings are hypothetical at this point. Taken together, a more robust understanding of these issues would help provide a fuller picture of the clinical practice of SLPs in Canada concerning CAS.

An additional limitation of this study is the sample size. Our sample represents a small portion of SLPs who may be practicing in the area of CAS. Additionally, there was an over-representation from Alberta, and no representation from Manitoba, Nova Scotia, Prince Edward Island, Newfoundland and Labrador, the Yukon, or Nunavut. Therefore, our sample may not reflect the practices of all SLPs in Canada. The survey was only available in English, potentially limiting our response rate and ability to capture practices in French-speaking communities. Lastly, we cannot report a response rate because we do not know how many people received or saw the survey.

3.6. Conclusion

It is encouraging to find that many SLPs use evidence-based diagnostic, assessment, and treatment practices. Interestingly, SLPs tended to use many practices for which the evidence is limited, unclear, or absent. Without answers to the questions raised by this study, we risk not truly understanding clinical decision-making and services for children with CAS and how to bridge the gap between research and practice so that children with CAS may benefit. Targeted knowledge translation and implementation studies are needed in the area of CAS with all relevant stakeholders to create guidelines that relate to current day-to-day clinical practice and are linked explicitly to supporting evidence. This survey should challenge us to continue to ask questions about clinical practices. Why are we doing what we are doing? Returning to this question should ultimately guide SLPs' decision-making in choosing the right tools to do "the right things right".

CHAPTER 4

What are we doing and why? Using theory to guide practice in speech-language pathology

The following chapter highlights how systematic use of theory in SLP practice would support a shift in our thinking from implicit assumptions to explicit and systematic thinking. It provides a starting point to guide SLPs through a systematic process towards more effective and efficient clinical care. The greater understanding we have of the *what*, *why*, *how*, and *when*, the more likely we are to be intentional, objective, and creative about our approach to managing communication disorders.

4.1. Introduction

"He who loves practice without theory is like a sailor who boards a ship without a rudder and compass and never knows where he may cast" - Leonardo Da Vinci

Speech-language pathologists (SLPs) are health professionals who prevent, identify, assess and treat communication, feeding, and swallowing disorders across the lifespan in order to improve individuals' quality of life and maximize their participation in society (SAC, 2016; CAASPR, 2018). SLPs, along with many other healthcare professionals, face increased pressure to provide services to their clients which integrate the best available evidence, clinical expertise, and patient preferences and values (Sackett, 1996; Sackett et al., 2000; ASHA 2004; 2005). The focus of much of the evidence-based practice (EBP) discussion has been on educational strategies for teaching EBP (e.g., Dollaghan, 2007; Gillam & Gillam, 2008; Goldstein, 2008; Togher et al., 2011) and on the effectiveness of treatment approaches (see the ASHA's National Center for Evidence-Based Practice in Communication Disorders list of evidence-based systematic reviews). Some argue that SLP practice may be better served by a different approach that considers the complexities of clinical practice (Tonelli, 2006; McCurtin & Carter 2015). In disciplines such as occupational therapy, nursing, and social work, theory-guided practice is considered a necessary complement to EBP (e.g., Hinojosa, 2013; Karnick, 2016); however, the role of theory in guiding clinical practice is considerably less prominent in the literature and educational materials of SLP. Yet the dynamic interrelationships between theory, research and practice have never been more apparent. The purpose of this paper is three-fold: (1) to provide a clinically-focused overview of what a theory is, (2) to describe the role of theory in SLP practice, and (3) to provide a clinically relevant checklist for SLPs to apply theory in practice.

Theoretically motivated, or theory-guided, practice is a hallmark of any professional, scientific discipline. It is the questioning approach and commitment to theory shared by clinical SLPs and researchers that differentiates the profession from other technical occupations (Friel-Patti, 1994; Rosenburg & David, 1995; Finn, 2011; Melnyk & Fineout-Overholt, 2011; Orlikoff et al., 2015). I contend that more systematic use of theory in clinical practice would strengthen the field (Kent, 2006) and support SLPs in identifying, describing, understanding and taking into account all of the variables (e.g., client, clinician, setting, etc.) that apply to a clinical case. This approach requires SLPs to comprehensively understand the range of current theories, the evidence supporting each theory, and their application to each individual clinical case. Although theories are explicitly taught in SLP education, it is unclear to what extent SLPs consciously and/or systematically use them in clinical practice. Some of the questions answered in this paper include: What is a theory, and why are theories important? What is the purpose of theory in clinical practice? What does theory look like in action? I offer practical examples to show how theory can be used to guide practice, focusing on childhood apraxia of speech (CAS). Finally, I end with a discussion of how explicit use of theory is necessary for the growth and development of CAS research and practice, particularly in understanding the integration of multiple systems (e.g., sensory, motor, and print). While this paper draws explicitly on SLPs working with children and young people with CAS to provide practical examples and applications, these guidelines can be applied to all populations served by SLPs.

4.2. What is a theory?

In the most general sense, a theory is an organized, coherent set of interconnected statements that define, describe, explain and make predictions about behaviour (Kerlinger and Lee, 2000). Said another way, a theory is a set of statements that explain *what* is going on and *why,* and guides action regarding *what* to change and *how* to change it. The scientific definition of theory should not be confused with everyday use, which is commonly used to describe a hunch, guess or gut feeling (Bordens and Abbott, 2011). Many authors have established the essential ingredients of a "good" theory (e.g., Reynolds, 1971; Bordens and Abbott, 2011). A "good" theory must be logical and coherent and account for most of the scientific data. It has clear definitions of variables and describes the relationship among those variables. A "good" theory needs to be testable, something that can be supported or rejected with new evidence. It must make specific predictions, and it must be clear and straightforward (i.e., parsimonious). Finally, theories, and the constructs and principles they are based on, are dynamic and changing. Ultimately, the test of a "good" theory in clinical practice is how well it accounts for clinical observations, how easily it is understood and how well it supports interactions with specific clients (Bordens and Abbott, 2011).

4.3. Why is theory important?

Theories provide a systematic way to describe, explain and make predictions about communication development and disorders. They help us to better understand our clients and the situations that affect them. Theories are needed to guide SLPs to a greater understanding of the nature of the client's communication disorder and understand the interactions between internal and external factors. Theories inform our understanding of treatment factors and approaches and guide our actions toward helping the client. Any valid diagnostic tool, assessment tool, or intervention approach should be based on a coherent and scientifically supported theory that explains why the tool or approach might be valid or effective. In addition, theories can be used to develop a language for talking with parents, clinicians, and researchers, to aid judgement in novel, atypical, or unclear cases and to inform research and theory development and refinement. The more theories to which SLPs have been exposed, the more likely they are to make sense of client cases, see more connections, and interpret clinical cases more systematically, holistically and comprehensively.

There are many different theories about speech and language development, the complex interrelationships between physical, cognitive-linguistic, social-emotional, and sensory-motor aspects of development, and the origin and nature of communication disorders. The field of SLP draws on theories from many disciplines, including the behavioural and biological sciences (e.g., psychology, biology, neurology) and the physical and health sciences (e.g., acoustics, engineering, medicine, rehabilitation). Theories are integral to SLP because they provide the framework around which we observe, think, and explain things and they provide perspectives for viewing and understanding the clients we see. Such theoretically-guided practice moves beyond intuition/expertise and considering "what works best" (e.g., evidence-based practice) to address a more in-depth understanding of the *why*, *how* and *when* of clinical behaviours.

Communication disorders are highly complex and it is possible to look at a clinical case from multiple perspectives. When an SLP approaches a client from a distinct theoretical standpoint, that is called their *theoretical framework*. A *theoretical framework* comprises the formal theory that an SLP plans to draw upon when making clinical decisions. Often, however, one theory cannot fully address the particular clinical case. Thus, in practice, SLPs may combine one or more formal theories (in part or in whole) and integrate them with information relevant to the particular client population/setting, their own clinical experience, and other scientific evidence (i.e., *conceptual framework*; Ravitch and Riggan, 2017). For the purpose of this discussion, I will refer to theoretical and conceptual frameworks collectively as a "theory" or "theoretical approach". In the next section, I will explore several ways of thinking about how theoretical approaches can be used in practice. Indeed, it is critical to acknowledge that although this discussion focuses explicitly on theory, it is assumed and expected that SLPs are also using evidence.

4.4. What is the purpose of theory in clinical practice?

Spelling out a theory is one of the most important things an SLP can do to provide effective and efficient services that improve clients' lives. An SLP should start by considering what specific theories have been developed that suit the purpose and context of the clinical scenario and that might inform their understanding of the client. Once they have identified the theory(-ies), they should seek to understand the theory and its critical components (i.e., concepts, definitions, relationships, and assumptions) and if the theory is supported by research evidence. Finally, the SLP should specify the reason for selecting the theory or theories they will use.

As previously described, theory can be applied to virtually all aspects of clinical practice. So many possibilities exist that it would be exhaustive to attempt to include every possible scenario. As such, I will illustrate and discuss three possible ways theory can be used in the clinical management process. In each example, theory informs the kinds of questions an SLP should ask and how the SLP might go about answering those questions. In the ideal scenario for all examples, the SLPs' findings refine or generate new theories (indicated by a dashed line).

Before we begin, it is necessary to highlight the clinical process when an SLP does not actively use theory to guide clinical practice (Figure 4.1). In this scenario, the SLP's clinical management practice (i.e., assessment, diagnosis or treatment) is guided by the clinical case. Clinical observations or findings are used to inform their understanding of the client and to determine the next steps. While it is possible in this example that the SLP may use some form of theory to guide the decision process, the lack of an 'active use' of the theory results in much ambiguity about how the decision process unfolded, how findings are interpreted, and the most useful next steps to be taken with the client.

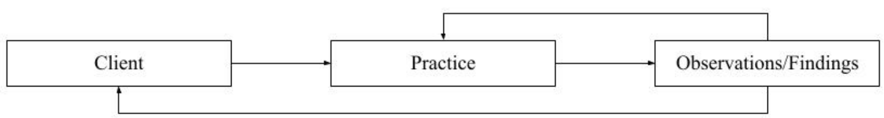


Figure 4. 1. No active use of theory in the clinical management process.

In the example outlined in Figure 4.2, the SLP uses theory to contextualize a clinical case. In doing so, the theory provides a basic structure and understanding of the client and the potential factors contributing to the client's level of functioning. The SLP may then form connections among the characteristics and behaviours of the client and the theory. For example, what does the SLP understand about their client because of the theory? What concepts does the SLP need to understand or capture in order to characterize their client's profile of strengths and weaknesses?

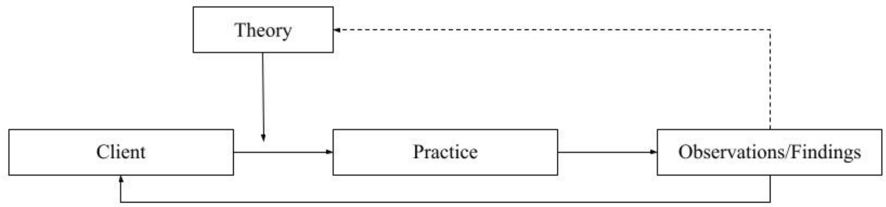


Figure 4. 2. Use of theory to contextualize a clinical case.

In the next scenario (Figure 4.3), the theory is used to inform the choice of assessment, diagnostic, and/or treatment tools or approaches. A theory often specifies the critical components that need to be examined. In addition to being psychometrically sound (i.e., reliable and valid), the measures/tools the SLP chooses should align with the theoretical components they are measuring. Their decision, however, should not be based on availability. As stated by Bordens and Abbott (2011), "if you have chosen a particular measure simply because it is the most readily available or convenient, you should ask yourself whether it really is the best measure" (p. 129). Theory does this by assisting SLPs in answering these questions: What information does the SLP need to obtain during assessment/treatment? Why and how will the SLP gather the information? Why did the SLP choose the specific assessment tools/treatment techniques? Why and how is the particular tool/technique proposed to work? How does the theory predict the client's behaviours?

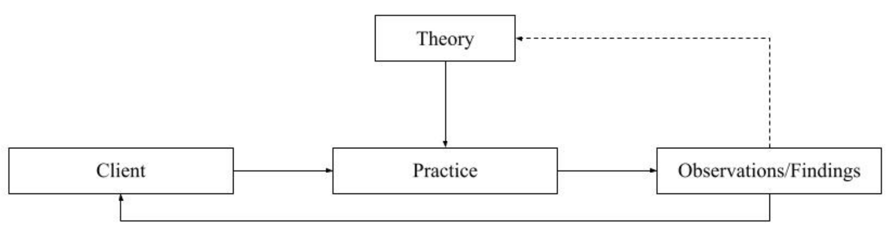


Figure 4. 3. Use of theory to guide assessment, diagnosis and/or treatment.

Theory can also be used as an analytical tool (Figure 4.4). That is, the SLP may organize or interpret their observations/findings within the structure of an existing theory. Ask yourself the following questions: How will the SLP use the information they gather to arrive at a diagnosis or to guide treatment? What characteristics is the SLP looking for to diagnose their client? How does the theory assist in explaining what is happening and why? What behaviour/characteristic is the SLP targeting and how will they remediate or compensate for this behaviour/characteristic? How and when will the SLP modify treatment due to progress or lack of progress?

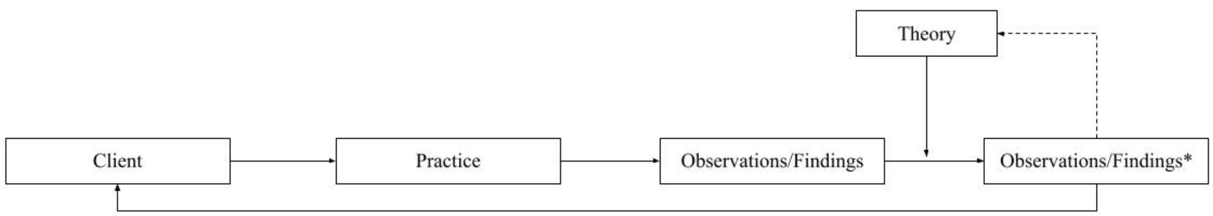


Figure 4. 4. Use of theory to interpret findings.

We acknowledge that the use of theory in practice likely rises, albeit implicitly, as a function of clinical experience as different sources of knowledge are acquired (Kamhi, 1994; 1995; Douglas et al., 2019). For students, novice SLPs, or those who are perhaps uncomfortable with the notion of theory in practice, this process may help them articulate their clinical decisions. On the other hand, for experienced SLPs who may no longer be aware of the theory embedded in their practice (Douglas et al., 2019), this process may support knowledge transfer between expert and novice clinicians.

This exercise aims to apply theory to practice to shift our thinking from implicit assumptions to explicit and systematic thinking. While this is admittedly a simplistic way of looking at theory-guided practice, it provides a starting point to guide SLPs through a systematic process towards increasingly more effective and efficient clinical care, a goal for all clinicians regardless of experience. The greater understanding we have of the *what*, *why*, *how*, and *when*, the more likely we are to be intentional, objective, and creative about our approach to managing communication disorders.

4.5. What does theory look like in action?

4.5.1. Scenario

To illustrate what theory looks like in action, imagine that an SLP observes a 5-year-old child who is difficult to understand and suspects that the child may have CAS. The SLP understands that the current diagnostic gold standard is expert judgement of perceptual speech characteristics that are considered indicative of the underlying breakdown (Murray et al., 2021). After completing a detailed oral mechanism exam and ruling out dysarthria, the SLP designs an assessment that examines the features of CAS (see for a review, Murray et al., 2021; Terband et al., 2019; e.g., the Dynamic Evaluation of Motor Speech Skill (Strand & McCauley, 2019), the speech inconsistency measure (Iuzzini-Seigel, Hogan, & Green, 2017), and the assessment protocol from Murray et al. (2015)). The SLP then assesses the features of CAS proposed to result from a speech-motor deficit using an operationalized checklist (e.g., Murray et al., 2015; Namasivayam et al., 2015; Iuzzini-Seigel & Murray, 2017). The SLP determines that additional information is required and turns to theories of CAS to guide assessment and treatment. The SLP realizes that there are several possible explanations. Among them are that CAS is primarily due to a deficit in transforming an abstract phonological plan into a motor plan and/or program (i.e., motor planning and/or programming; e.g., Shriberg, 2010; Terband et al, 2010; Grigos et al., 2015).

Within the motor planning and/or programming theory of CAS, several possible hypotheses regarding the cause of this deficit have been proposed, including that it is due to impaired feedforward control and subsequent reliance on the feedback system (Terband et al., 2009; 2010) or cerebellar dysfunction (Peter et al., 2020).

4.5.2. Example 1: Core deficit in oral sensitivity or neural noise underlie motor planning and/or programming

Terband et al. (2009; 2010) argue that CAS reflects a deficit in feedforward control. This hypothesis is based on an influential speech acquisition and production model, the Directions Into Velocities of Articulators (DIVA) model (Bohland et al., 2010; Guenther & Vladusich, 2012). A brief description of the DIVA model is as follows, the feedforward (motor) system utilizes stored speech-sound representations to produce speech, and the feedback system utilizes auditory and somatosensory feedback information to produce speech. According to the DIVA model, children with CAS are not able to predict the feedforward commands that will produce a speech sound or speech movement sequence and thus will produce errors in their speech. As a result, the auditory and somatosensory systems are activated to attempt to correct the error. The clinical manifestations of this deficit include deviant coarticulation, speech sound distortions, searching articulation and increased variability. Although the authors acknowledge that this deficit may spread to other systems (e.g., delay in phonological development), the core deficit lies in the speech-motor system (Terband et al., 2010).

Two possible causes of poor feedforward control have been proposed, including (a) reduced or degraded oral sensitivity and (b) increased neural noise (i.e., random electrical fluctuations that impair neural communication). The former predicts that children with CAS will exhibit degraded performance of the somatosensory system and have deviant feedforward commands. The latter suggests that children with CAS will exhibit degraded performance of the auditory and somatosensory feedback systems and have more-or-less intact feedforward commands (Terband et al., 2010). To date, these facets of speech production have not been well studied in CAS. In the absence of strong evidence, the SLP needs to understand and use the guiding principles that are reflected in theory. Otherwise, they run the risk of practicing in ways that are disorganized and inconsistent.

In the example of reduced or degraded oral sensitivity as the cause of CAS, the SLP can draw on evidence from other disciplines, such as dentistry (e.g., Jacobs et al., 1998; Sivapathasundharam & Biswas, 2020), to provide insights into the relationship between oral sensitivity and CAS and to what extent decreased oral sensitivity will impact how the child may respond to treatment. As such, consultation and collaboration with a dentist may be warranted and could open up new avenues for research in CAS, such as direct skills remediation in the somatosensory domain (e.g., oral form recognition and discrimination) or oral sensory-motor stimulation (e.g., vibration, topical stimulation gels). The SLP may use their current knowledge and skills to screen/assess oral-motor skills and feeding and swallowing disorders. The SLP may pay particular attention to how the child responds to tactile cues and the amount of pressure required (e.g., light, moderate, deep) for the child to produce the best/most accurate production. Next, the SLP, continuing to be guided by theory, selects an evidence-based approach to the treatment of CAS that may directly target the somatosensory domain (e.g., Prompts for Restructuring Oral Muscular Phonetic Targets, PROMPT; Dale & Hayden, 2013; Kadis et al., 2014) or enhance sensory input (e.g., Dynamic Temporal and Tactile Cueing, DTTC; Strand et al., 2000; 2006). The SLP may also try to compensate for reduced or degraded oral sensitivity by facilitating the use of auditory feedback (e.g., reduced speech rate; Terband et al., 2010).

On the other hand, if increased neural noise is the cause of CAS, consultation and collaboration with other professionals (e.g., audiology, neurology) may be required to obtain essential information for assessment and treatment. For example, the SLP may need to refer the child to an audiologist for a complete audiological exam to determine if environmental modifications are required to improve access to auditory information (e.g., enhancement of the auditory signal). In addition to treatment that targets the somatosensory domain, the SLP may, within their scope, assess or target the child's ability to localize sounds or discriminate between sounds. A multisensory cueing approach to treatment that involves all of the child's senses may be most appropriate given that the child may not be receiving sufficient feedback from either system (i.e., auditory or somatosensory).

4.5.3. Example 2: Core deficit in sequential processing underlie motor planning and/or programming

Peter and colleagues (2020) contend that children with CAS exhibit impairments in multiple domains (i.e., fine and gross motor, language, and speech) and thus, that the core deficit is not limited to planning and/or programming for speech (Peter et al., 2013). A deficit in sequencing processing (i.e., processing sequentially arranged items) is reported to impact all domains and is consistent with cerebellar dysfunction (e.g., Peter et al., 2013; 2020). The cerebellum is widely assumed to play an important role in sensory, motor, and cognitive domains (see for a review Lawrenson et al., 2018; Marien et al., 2014; Roostaei et al., 2014), and thus a wide variety of clinical manifestations are possible.

In this view, secondary characteristics of CAS are a direct consequence of CAS not comorbidities, and thus, consultation and collaboration with physicians, occupational therapists and physical therapists may be warranted. At present, there are no known assessment tools or treatment programs that have been designed to specifically target sequential processing in the cerebellum for children with CAS. Using the key concepts in the cerebellar hypothesis, the SLP might pay particular attention to tasks that require greater sequential control, such as diadochokinetic (DDK) tasks. For example, greater difficulty with disyllabic ("patapata…") and trisyllabic ("patakapataka…") DDKs compared to monosyllabic ("papapa…") would be expected during the assessment.

The SLP may recognize that tasks such as non-word repetition, non-word reading and spelling (Button et al., 2013; Peter et al., 2012, 2013, 2018; 2020) have been proposed to rely on sequential processing. Still guided by theory, they select an evidence-based approach to CAS treatment that includes these tasks (e.g., Rapid Syllable Transition Training uses non-words; Thomas et al., 2014; McCabe et al., 2017). The treatment program would proceed through a hierarchy of steps that move from simple to more complex sequencing. While more research is needed to fully understand the role of the cerebellum in CAS and determine if and to what extent this type of treatment may lead to structural and functional changes in the cerebellum, theory can still inform the decision-making process for treatment.

As can be seen from the examples above, theory can be used to guide decision-making in the clinical management process. Due to its complexity, in SLP practice there often is not one right answer to what is an acceptable practice. The use of theory strengthens the SLPs ability to deal with ambiguity, complexity, and uncertainty by allowing them to ground and justify their approach. It highlights the notion that a single theory may have one or more hypotheses/predictions about the underlying deficit in CAS that may lead to complementary but differing approaches. Interestingly, the idea that different core deficits (e.g., cerebellum, somatosensory, neural noise) can underlie the same consequences (i.e., CAS) is not a new idea (e.g., Terband et al., 2010; Mailend and Maas, 2021). Engaging in theory throughout the process may lead to alternative and novel but effective ways to manage CAS. Together, these examples highlight how understanding the "why" behind clinical decisions can help the "what" and "how" fall into place.

4.6. What are the challenges of putting theory into practice?

There is very little material in the literature relating to the application of theory to clinical practice. One important concept in understanding the challenges of theory-guided practice is cognitive bias, or the mental "shortcuts" that influence decision-making and client outcomes. Many cognitive biases have been described in the literature (e.g., see for a review, Saposnik et al., 2016; Garrubba et al., 2019). Three of the more salient biases for clinical practice will be explored here, confirmation bias, the framing effect, and the gambler's fallacy. An overreliance on (or lack of active use of) theory may produce a tendency toward a confirmation bias. That is, SLPs may tend to look for evidence to support a theory rather than look for evidence to refute it. The framing bias refers to the fact that clinicians tend to make decisions based on the way information is presented. For example, the SLP's clinical practice and perception of the client is strongly influenced by their theoretical approach instead of by the information itself. Gambler's fallacy refers to our belief that future events are altered by past events when in reality, they are independent. In other words, even if we test a theory with 100 clinical cases, there may still be other clinical cases out there that will disprove or contradict it (i.e., it could still fail on the 101st test). While this is not an exhaustive list of cognitive biases, these are some of the most important to be aware of with respect to theory-guided practice.

4.7. How can theory be used to advance CAS?

Theories are often used to generate new research ideas (Bordens and Abbott, 2011). Research guided by well-developed theories aimed at determining the underlying mechanism is necessary to direct the development and choice of assessment and diagnostic tools, and treatment approaches. For example, the DIVA model sheds light on the key components of speech acquisition and production. This theory has been applied to many questions, including helping to explore the effects of specific underlying deficits. The theory is associated with neurophysiological and neuroanatomical studies of speech acquisition/production and thus offers a framework for hypothesizing about possible loci for deficits. Moreover, the predictions derived from the DIVA model provide new avenues for behavioural studies, such as those that examine if and to what extent sensorimotor manipulations of the feedback system contribute to speech production in children with CAS.

4.8. Conclusion

In summary, this paper describes the importance of using theory in clinical practice. I have discussed how SLPs can use theory to conceptualize clinical problems and guide assessment and treatment practices and I have illustrated how SLPs can apply theory to clinical cases, using CAS as the example. In doing so, I have provided a starting point for further discussion and research. Considerably more work will need to be done to (a) identify the use, usefulness, and perceptions of theory-guided practice in SLP, (b) facilitate the application of theory in clinical practice and (c) identify the barriers of utilizing theory in clinical practice. More broadly, an attempt to assemble and consolidate theories used in SLP for ease of access and to organize and explain theories in a way that makes sense to SLPs may inspire theoretical advances and engage individuals with different theoretical perspectives, and generate new insights. Ultimately, using theory-guided practice to describe, explain, and predict clinical problems will help us answer the questions: what are we doing, why are we doing it and could we be doing something better?

CHAPTER 5

Towards a Better Understanding of Childhood Apraxia of Speech through Disruptions of the Somatosensory and Auditory Feedback Systems: A Clinical Trial Protocol[5]

The following chapter contains a clinical trial study protocol that will be the first to examine predictions within the Directions Into Velocities of Articulators (DIVA; Bohland et al., 2010; Guenther, 1994; 2016; Guenther & Vladusich, 2012) model regarding the cause of CAS by systematically comparing the independent and combined contributions of the auditory and somatosensory feedback systems during speech production and reading.

5.1. Abstract

Background. Childhood apraxia of speech (CAS) impairs a child's ability to plan and/or program the sequential movements required for speech. There is some agreement that CAS is a neurological speech sound disorder that impairs a child's ability to plan and/or program the precise and sequential movements required for speech. However, the cause and underlying mechanism of CAS still remain mostly unknown. Recent computer simulations suggest that CAS may be caused by a breakdown in the somatosensory and/or auditory systems, and thus further behavioural disruptions are required to verify these findings. Furthermore, given that the reading ability is partially dependent on speech production, and that CAS and literacy impairments are highly co-morbid, it is important to explore both of these processes in CAS.

Purpose. The purpose of this study is to provide a theory-based rationale and protocol for a clinical trial to determine the effects of independent and combined somatosensory and auditory disruptions on speech motor behaviors and reading performance in children with and without

[5] A version of this chapter has been submitted as a Clinical Trial Application (CTA) to the Health Canada Office of Clinical Trials, Therapeutic Products Directorate, on February 26, 2020. The CTA was sponsored by The Governors of the University of Alberta.

CAS. This study will address the following research questions (1) What are the effects of manipulations to the somatosensory and/or auditory systems on speech motor behaviours in children with CAS compared to TD children? (2) What are the effects of manipulations to the somatosensory and/or auditory systems on reading performance in children with CAS compared to TD children? (3) Is speech production performance related to reading performance in children with CAS under normal feedback?

Methods. Children with and without CAS (N=40) will complete a comprehensive assessment battery (demographic and health history questionnaire, and tests of hearing, speech, language, and cognition). Each participant will then complete a series of tasks in four conditions: normal feedback, somatosensory alteration-only, auditory masking-only, and combined somatosensory alteration and auditory masking. The four tasks will include: overt repetition (i.e., repeating an unfamiliar syllable or familiar word aloud), orthographic lexical decision (i.e., deciding if a word *spells* a real word or nonword via a button press), phonological lexical decision (i.e., deciding if a word *sounds* like a real word or nonword via a button press) and covert picture categorization (i.e., deciding if a picture of an animal or not animal via a button press). The tasks and conditions are designed to systematically vary reliance on the feedforward and feedback systems. Coarticulation and token-to-token variability, reaction time and accuracy will be measured in task 1; reaction time and accuracy will be measured in tasks 3, 4 and 5. For each dependent variable, mixed analyses of variance (ANOVAs) will be used to test for differences within and between groups.

Significance. Together, these studies will move us closer to an understanding of the core deficit in CAS, and help to inform the development of high-quality procedures for identifying children with CAS (i.e., diagnosis) and tools/protocols for evaluating their strengths and weaknesses (i.e., assessment). In addition, it will inform clinicians who treat children with CAS by ensuring they provide the best possible care and treatment, and inform teachers and specialists who guide reading development.

5.2. Introduction to the Clinical Trial

CAS is a complex disorder that can affect all levels of speech production, including a core deficit in planning and/or programming and a secondary deficit in phonological encoding (Shriberg et al., 2017c). Research to date has been restricted by a lack of understanding of the cause, underlying mechanism and diagnostic marker(s) for CAS. Computer simulations within the Directions Into Velocities of Articulators (DIVA) model of speech acquisition and production (Bohland et al., 2010; Guenther, 1994; 2016; Guenther & Vladusich, 2012) have generated predictions that limitations in feedforward and feedback processing might account for the nature of CAS. Within the context of the DIVA model, a core deficit in planning and/or programming corresponds to poor feedforward (motor) control, which subsequently leads to reliance on the feedback system. Simulations of the DIVA model have generated testable predictions regarding the cause of CAS: (1) reduced or degraded somatosensory information leads to deviant feedforward commands and increased reliance on the feedback system and (2) increased neural noise leads to poor feedforward control and increased reliance on the feedback system (Terband et al., 2009; 2010). In a few behavioural manipulations of the feedback system during speech production, at a group level, children with CAS appear to be unable to compensate for a lack of auditory feedback (Iuzzini-Seigel et al., 2015), altered auditory feedback (Terband et al., 2014), and altered somatosensory feedback (Nijland et al., 2003), suggesting that they may rely on the feedback system to compensate for poor feedforward control. However, at an individual level, the performance of children with CAS is highly variable. Moreover, how a single child with CAS utilizes auditory and somatosensory information is unknown. Therefore, this study will be the first to examine predictions within DIVA regarding the cause of CAS by systematically comparing the independent and combined contributions of the auditory and somatosensory feedback systems.

A second way of examining the contribution of the feedforward and feedback systems is by utilizing silent reading tasks that vary in reliance on these systems within the context of the print-to-speech model (Cummine et al., 2016; 2021a; 2021b; Fleming et al., 2021). In a case-control series, altered somatosensory feedback differentially modulated reading performance in children with CAS suggesting that children with CAS may have deficits in different components of the speech production system (i.e., feedforward, feedback or feedforward-feedback integration; Fleming et al., 2021). Hence, the second part of this study will extend this work to a larger group of children with CAS to determine the extent to which altered feedback may impact reading performance. Finally, using comparable speech and reading tasks will allow us to examine the relationship between speech production and reading performance and thus to determine if reading tasks can provide insight into the underlying impairment in CAS.

5.3. Objectives and Hypotheses

The aim of this paper is to develop a clinical trial study protocol to explore the effects associated with manipulations of the auditory and somatosensory systems during speech production and reading in children with and without CAS in the context of the DIVA model. Using the current knowledge base, we propose procedures to examine the integrity of the feedforward and feedback systems in CAS, data collection, data management and analysis, and methods for the selection of study participants. Such research aimed at understanding the cause and underlying mechanism is critical to the development of assessment tools and treatment approaches for children with CAS. The proposed clinical trial study protocol will aim to address the following research questions:

1. What are the effects of manipulations to the auditory, somatosensory and combined auditory and somatosensory feedback systems on speech motor behaviors in children with CAS in comparison to TD children?

   Hypothesis 1: If the core impairment in CAS is reduced or degraded somatosensory information, it is predicted that children with CAS will be unable to compensate for a lack of auditory feedback due to deviant feedforward commands (Terband & Maassen, 2010). This will lead to deterioration of speech production. Moreover, when feedback in the somatosensory system is altered, minimal deterioration of speech is predicted as auditory feedback can be used to compensate. Finally, it is predicted that a lack of auditory feedback in combination with altered somatosensory feedback will cause further deterioration in speech production (in comparison to a lack of auditory feedback alone) as the child cannot compensate for the perturbation with auditory feedback.

   Hypothesis 2: If the core impairment in CAS is increased neural noise, it is predicted that children with CAS will be able to compensate for a lack of auditory feedback as the child can use intact feedforward commands (Terband & Maassen, 2010). Thus, this will not lead to deterioration of speech production. Moreover, when feedback in the somatosensory system is altered, minimal deterioration of speech is predicted as auditory feedback can be used to compensate. Finally, it is predicted that a lack of auditory feedback in combination with altered somatosensory feedback will not cause further deterioration in speech production in comparison to a lack of auditory feedback alone) as the child can use intact feedforward commands.

2. What are the effects of manipulations to the auditory, somatosensory and combined auditory and somatosensory feedback systems on reading performance in children with CAS in comparison to TD children?

   Hypothesis 3: Reading performance in children with CAS will be impacted to a greater degree by manipulations to somatosensory, auditory, and somatosensory and auditory feedback systems than TD children (i.e., longer reaction time and reduced accuracy). Moreover, children with CAS may exhibit variable performance across tasks and word types that vary in reliance on the feedforward and feedback systems.

3. Is speech production performance related to reading performance in children with CAS under normal feedback?

   Hypothesis 4: Speech production performance (e.g., reaction time and accuracy for overt speech task) will predict reading performance (e.g., reaction time and accuracy for covert reading task) under normal feedback.

Table 5. 1. Hypotheses for speech and reading tasks by group, condition, and variable.

Manipulation	**Overt Repetition**		**Orthographic LDT**		**Phonological LDT**	
	CO-A	**VAR**	**RT**	**ACC**	**RT**	**ACC**
Auditory						
TD	–	–	↑ *(S)*	↓	↑↑	↓↓
CAS – Reduced Som. Info	↑↑ *or* ↓↓	↑↑	↑↑↑ *(S)*	↓↓↓	↑↑↑↑	↓↓↓↓
CAS – Neural Noise	–	–	↑↑ *(S)*	↓↓	↑↑↑	↓↓↓
Somatosensory						
TD	–	–	↓ *(F)*	↑	–	–
CAS – Reduced Som. Info	↑ *or* ↓	↑ *or* ↓	–	–	–	–

CAS – Neural Noise	↑ *or* ↓	↑ *or* ↓	–	–	–	–
Combined						
TD	–	–	↑ *(S)*	↓	↑↑	↓↓
CAS – Reduced Som. Info	↑↑↑ *or* ↓↓↓	↑↑↑	↑↑↑ *(S)*	↓↓↓	↑↑↑↑	↓↓↓↓
CAS – Neural Noise	↑ *or* ↓	↑ *or* ↓	↑↑ *(S)*	↓↓	↑↑↑	↓↓↓

Abbreviations: TD, typically developing; CAS, childhood apraxia of speech; LDT, Lexical Decision Task; CO-A, Coarticulation; VAR, Variability; RT, Reaction Time; ACC, Accuracy; S, slower; F, faster

5.4. Proposed Methods

5.4.1. Participants

Children with CAS and TD children (N=40) will be recruited for this study. The tasks and variables being measured have not yet been used in TD children and thus an adequately sized control group is necessary.

5.4.1.1. Sample Size

A statistical power analysis was performed for sample size estimation using G*Power 3.1.9.3 (Faul et al., 2007) based on data from Nijland et al. (2003), Cummine et al. (2021b) and Fleming et al. (2021). The effect size of the difference for F2 ratios between children with CAS and TD children in Nijland et al. (2003) was 1.23 under normal feedback and 1.27 in the presence of a bite block. Moreover, the effect size of the difference for F2 variability between children with CAS and TD children in Nijland et al. (2003) was 1.24 under normal feedback and 1.33 in the presence of a bite block across multiple utterance positions. Finally, the effect size of the difference for within-subject F2 variability in children with CAS in the presence of a bite block was 1.09.

Assuming a sample size of 20 children with CAS, the effect size of the difference in reaction time between TD children reported Cummine et al. (2021b) and children with CAS reported in Fleming et al. (2021) is 1.40-1.85 under normal feedback and 1.10-1.87 under altered somatosensory feedback (depending on word type and task). Moreover, the effect size of the difference in reaction time under normal feedback versus altered somatosensory feedback for children with CAS is around 1.08 (depending on word type and task).

A study with a large effect size of 1.23, an alpha of 0.05, and a power of 0.80 will require a total sample of 8 for between-subjects measures. A study with a large effect size of 1.08, an alpha of 0.05, and a power of 0.80 will require a total sample of 11 for within-subjects measures. Thus, the proposed total sample size of 40 should be adequate for the main objectives of this study and should allow for comparison of children with and without CAS across the four conditions.

5.4.1.2. Inclusion/Exclusion Criteria

All participants will be between the ages of 6;0 and 17;11, native English speakers, have normal or corrected-to-normal vision, and pass a swallowing screening. Normal hearing in the range of 500-4000 Hz presented at a screening level of 15 dB will also be required based on a pure tone hearing screening.

Children with CAS (N=20) will also meet the following inclusion criteria: typical receptive language, have a SLPs diagnosis of CAS, exhibit three out of three consensus-based characteristics reported by the American Speech-Language-Hearing Association (ASHA, 2007) and exhibit at least four out of 10 characteristics in Strand’s 10-point checklist (Shriberg et al., 2011). If the child has severely impaired speech production (e.g., reduced phonemic and/or phonetic inventories, vowel and prosodic errors, poor speech intelligibility and/or little to no verbal communication), they will also be required to exhibit difficulty with speech motor planning and/or programming based on a score of less than 373 on the Dynamic Evaluation of Motor Speech Skill (DEMSS; Strand et al., 2019). Characteristics of CAS will be rated based on audio-video recordings of administration of the Goldman-Fristoe Test of Articulation (GFTA; Goldman & Fristoe, 2015) and the DEMSS (Strand & McCauley, 2019) using operational definitions for each criterion in Appendix B based on Iuzzini-Seigel et al. (2015).

TD children (N=20) will meet the following inclusion criteria: typical speech, receptive and expressive language, cognition and reading based on age-based standard scores on the GFTA, Khan-Lewis Phonological Analysis (KLPA; Khan & Lewis, 2015), Oral and Written Language Scales (OWLS; Carrow-Woolfolk, 2011), Kaufman Brief Intelligence Test (KBIT; Kaufman & Kaufman, 2004) and Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 2012), respectively. The TD children will be recruited concurrently and matched for gender and chronological age to CAS participants. A TD control group is required as it would be challenging to compare the children with CAS in the current study to previous studies which vary in terms of selected dependent measures, tasks and stimuli, and feedback conditions.

5.4.1.3. Recruitment

Participants will be recruited from established connections, local community groups (e.g., Calgary Apraxia Parent Exchange; Childhood Apraxia Society of Edmonton), private SLPs and clinics, and through acquaintances. The study can also be submitted to Apraxia Kids (previously the CAS Association of North America) for additional recruitment if necessary. Recruitment letters will be given to private SLPs and clinics requesting they circulate the consent to contact and information letter and post a recruitment poster in their facilities (Appendices C and D).

5.4.1.4. Premature Withdrawal/Discontinuation Criteria

Participants that do not meet the study inclusion and exclusion criteria (Appendices E and F) when contacting the study team will not be scheduled for collection. Participants will be immediately withdrawn (i.e., collection stopped) if they (1) do not meet inclusion/exclusion criteria following the comprehensive assessment, (2) are unable to complete the speech or reading tasks, (3) report a desire to discontinue. Participation in the study will be consistent with current public health guidelines regarding COVID-19. If the participant withdraws or their participation is discontinued, their data will be retained for analysis, unless the participant requests the data be destroyed. Any withdrawn participants will be replaced with additional recruitment.

5.4.1.5. Consent and Ethics

Participant consent and/or assent will be obtained according to the Declaration of Helsinki. The experiment will be performed in compliance with the relevant laws and institutional guidelines and will be approved by the applicable research ethics board.

Parental consent and assent will be obtained for all participants 6 to 14 years of age and those 15 to 17 years of age who do not possess decision-making capacity (Appendices G, H and I, respectively). Adolescents 15 to 17 years of age who possess decision-making capacity will be asked to provide informed consent (Appendix J). An adolescent will be deemed to have decision-making capacity if they (a) indicate yes to having typical cognitive abilities on the eligibility questionnaire, (b) appear to understand the relevant information presented (e.g., purpose of the research, foreseeable risks, and potential benefits), and (c) appreciate the potential consequences of any decision they make based upon this information. If any participant who was deemed to have decision-making capacity does not pass the cognitive assessment, consent to continue will be obtained from their parent/guardian

5.4.2. Research Design and Layout

The proposed clinical trial study protocol is a repeated measures quasi-experimental design. This design will allow participants to serve as their own control and thus is helpful to control for variability between subjects (e.g., cognition, age, etc.). In addition, fewer participants are required in comparison to an independent groups design which is important for rare disorders such as CAS.

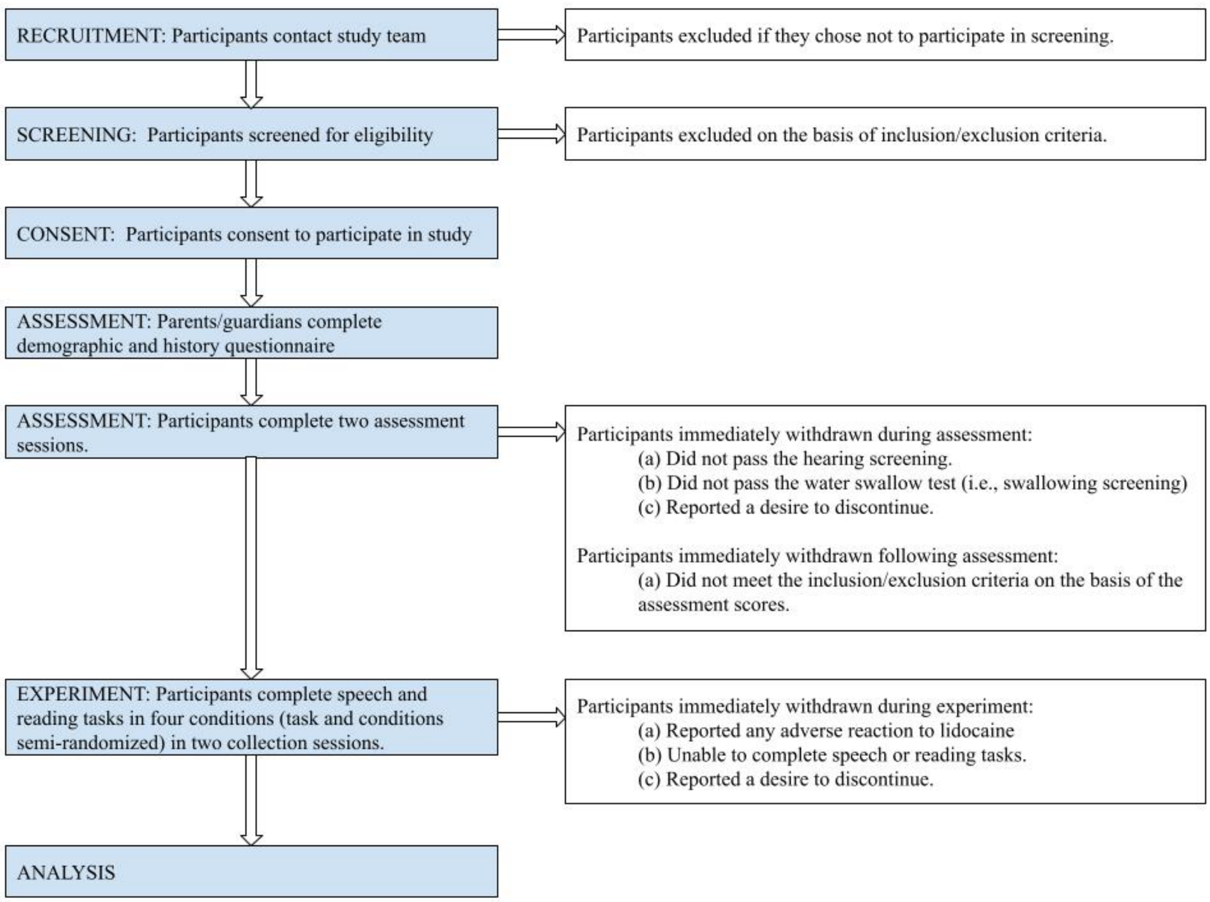


Figure 5. 1. Schematic of the clinical trial protocol study design.

Following assessment, each participant will complete a series of tasks in four conditions: normal feedback, somatosensory alteration-only, auditory masking-only, and combined somatosensory alteration and auditory masking. Each condition will contain four tasks: overt repetition (i.e., repeating an unfamiliar syllable or familiar word aloud), orthographic lexical decision (i.e., deciding if a word *spells* a real word or nonword via a button press), phonological lexical decision (i.e., deciding if a word *sounds* like a real word or nonword via a button press) and covert picture categorization (i.e., deciding if a picture of an animal or not animal via a button press). See Figure 5.1 for a schematic of the clinical trial protocol study design and Figure 5.2 for a schematic of the repeated measures design.

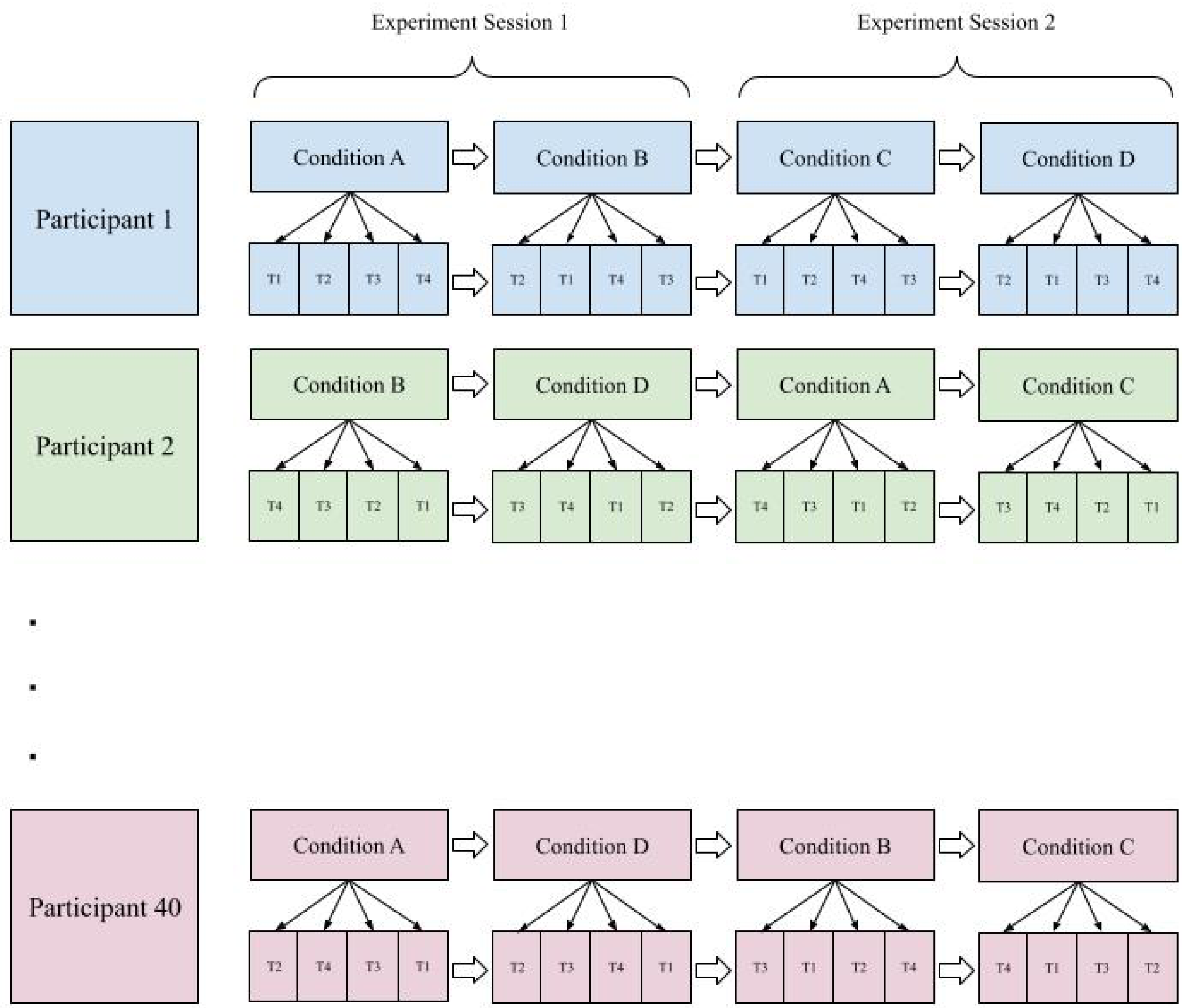


Figure 5. 2. Schematic of the repeated measures design with four semi-randomized conditions (A=Normal feedback, B=Auditory masking-only, C=Somatosensory alteration-only, D=Combined auditory-masking and somatosensory alteration. Abbreviations: T, Task.

5.4.3. Data Collection

5.4.3.1. Assessment Battery

A comprehensive assessment battery will be administered to participants prior to completing the experimental tasks in order to adequately characterize the profile of strengths and weaknesses of each child (see Appendix K for a summary of assessment measures). This will include an assessment of swallowing, hearing, motor speech, articulation and phonology, language, reading and cognition. The assessment tools chosen include those most commonly used in research on CAS and the performance of children with CAS can be compared to a large database of reference data (Shriberg & Strand, 2018). Moreover, the tools selected can be administered across the age range selected for the study. All tests and tools will be administered by an SLP or SLP student according to the respective manual or guidelines. Table 5.2 provides a summary of the assessments described below. Audio and video recordings of the participants' responses to the tests and tasks will be collected.

Table 5. 2. Assessment battery used to obtain case history and measure oral-motor skills, speech, phonological processing, language, literacy, cognition and hearing.

Domain	Tool/Test
Case History	1. Demographic and case history questionnaire
Swallowing	2. Swallowing screening
Hearing	3. Pure tone hearing screening
Oral-Motor	4. Structural-functional oral mechanism exam[1] 5. Diadochokinetic (DDK) Task[2] 6. Tasks for assessing non-verbal oral movement control and sequencing[3]
Speech/Phonology	7. Dynamic Evaluation of Motor Speech Skill[4] (DEMSS)[4] 8. Goldman-Fristoe Test of Articulation – Third Edition (GFTA-3)[5] 9. Khan-Lewis Phonological Analysis – Third Edition (KLPA-3)[6]
Language	10. Oral and Written Language Scales (OWLS)[7]
Literacy	11. Test of Word Reading Efficiency (TOWRE)[8]
Cognition	12. Kaufman Brief Intelligence Test (KBIT)[9]

[1]Shipley and McAfee, 2016; [2]Shriberg et al., 2010; [3]Duffy, 2005, p. 88; [4]Strand & McCauley, 2019; [5]Goldman & Fristoe, 2015; [6]Khan & Lewis, 2015; [7]Carrow-Woolfolk, 2011; [8]Torgesen, Wagner, & Rashotte, 2012; [9]Kaufman & Kaufman, 2004

Case History. The parent or guardian of the participant will be asked to complete the demographic and case history form to the best of their ability (Appendix L). The form will collect demographic and background information (e.g., age, sex, race, ethnicity), and birth, developmental (e.g., motor), speech-language (e.g., diagnosis, age of diagnosis, therapy) and feeding and swallowing history.

Swallowing Screening. A swallowing screening will be administered at the beginning of the assessment. The child will be instructed to drink water from a cup and sustain "ah" before and after. The child will pass the swallowing screening if there is no change in vocal quality following the swallow, no coughing or choking are observed, and/or the parents report no concerns with swallowing. The child will fail the swallowing screening if there is a change in vocal quality following the swallow, coughing or choking are observed and/or the parents report concerns with swallowing. If the child passes, they will be included in the study and assessment will continue. However, if the child fails, they will be excluded from the study and the assessment will not proceed.

Hearing Screening. A standard pure-tone hearing screening will be administered at 15 dB across the speech frequencies of 500, 1000, 2000, and 4000 Hz in both ears based on the Alberta College of Speech-Language Pathologists and Audiologists (ACSLPA) guidelines (ACSLPA, 2015; Appendix M). The child will pass the hearing screening if they respond to at least two of the three present tones at all frequencies. The child will fail the hearing screening if they do not respond to more than one of the three tones at all frequencies.

Oral-Motor. Participants oral-motor skills will be evaluated using a structural-functional oral mechanism exam (adapted from Shipley and McAfee, 2016) supplemented with the Diadochokinesis (DDK) Task in the Madison Speech Assessment Protocol (MSAP) (Shriberg et al., 2010), and tasks for assessing non-verbal oral movement control and sequencing (i.e., non-verbal oral apraxia (NVOA) screening tool; Duffy, 2005, p. 88).

The structural-functional oral mechanism examination (adapted from Shipley and McAfee, 2016 and Shriberg et al., 2010) will be used to evaluate the size, strength, symmetry, range, tone, steadiness, speed, and accuracy of orofacial structures and movements including the face, jaw, velopharyngeal port, palate, tongue, teeth, and lips (Appendix N). The participants will be instructed to perform various tasks (e.g., sustained phonation, alternate between smile and pucker, diadochokinetic rates, etc.) and observations will be judged as normal or abnormal.

Tasks for assessing non-verbal oral movement control and sequencing (Duffy, 2005, p. 88) will be used to evaluate the participants ability to imitate or follow commands for non-speech movements (Appendix O). Participants will be instructed to perform ten tasks (e.g., blow, puff out your cheeks) and performance will be rated on a scale of 1 to 4 (1= inaccurate or only partially accurate, 2= accurate after trial-and-error searching movements, 3= accurate but awkwardly or slowly produced, and 4= accurate, immediate and effortless). NVOA will be diagnosed if the participant performs the task with off-target approximations, obvious errors, or has difficulty alternating movements (Duffy, 2005, p. 88).

Speech/Phonology. Participants' speech will be measured using the Dynamic Evaluation of Motor Speech Skill (DEMSS; Strand & McCauley, 2019), Goldman-Fristoe Test of Articulation – Third Edition (GFTA-3; Goldman & Fristoe, 2015), and the Khan-Lewis Phonological Analysis – Third Edition (KLPA-3; Khan & Lewis, 2015).

The *DEMSS* (Strand & McCauley, 2019) is a 30-minute criterion-referenced assessment of word imitation that will be used to assess speech motor planning and/or programming performance. The *DEMSS* is the only published assessment with adequate evidence of both validity (70% sensitivity and 97% specificity for CAS based on total *DEMSS* score) and reliability (89% for test-retest, 89% for intra-rater and 92% for inter-rater) for diagnosis of children with SSDs (McCauley & Strand, 2008; Strand et al., 2013). During this assessment, children will repeat 60 utterances that vary in length, complexity, and vowel and prosodic content. The *DEMSS* total score will be calculated, as well as score for vowel accuracy, prosodic accuracy, overall accuracy, and consistency.

The Sounds-in-Words subtest of the *GFTA* (Goldman & Fristoe, 2015) is a 20-minute norm-referenced picture-naming task that will be used to assess consonant articulation in single words. Participants will be instructed to name each picture, and the examiner will transcribe and score all responses. The *GFTA* standard score will be calculated.

The *KLPA* (Khan & Lewis, 2015) is a norm-referenced test that is used to evaluate if phonological processes are contributing to the SSD. The *KLPA* uses the participants' responses on the *GFTA* and thus does not require additional test administration. Using the participants' responses from the *GFTA*, the *KLPA* will be scored and the standard score and percent of vowel alterations will be reported.

Language. Participants' receptive and expressive language skills will be measured using the *Oral and Written Language Scales (OWLS;* Carrow-Woolfolk, 2011). The *OWLS* is a norm-referenced tool that will be used to assess receptive and expressive language. On the Listening Comprehension subscale, participants will be instructed to point to one of four pictures that best depicts the meaning of the word read by the examiner. Next, on the Oral Expression subscale, participants will answer questions, finish sentences and generate sentences in response to visual and oral prompts. A standard score for the Listening Comprehension and Oral Expression subscales will be calculated.

Literacy. Participant's literacy skills will be measured using the *Test of Word Reading Efficiency (TOWRE;* Torgesen et al., 2012). The *TOWRE* is a 5-minute assessment of sight word recognition and phonemic decoding. Participants will be instructed to read a list of real words (i.e., sight word recognition subtest) and non-words (i.e., phonemic decoding subtest) as quickly as they can. A scaled score will be calculated for sight word efficiency, phonemic decoding efficiency and total word reading efficiency.

Cognition. The *Kaufman Brief Intelligence Test (KBIT;* Kaufman & Kaufman, 2004) is a norm-referenced tool that will be administered as a measure of participants' verbal and nonverbal cognitive abilities. On the verbal cognitive ability subtest, participants will be instructed to point to the picture that shows the meaning of the word, or the answer to the question provided by the examiner. Moreover, participants will be instructed to point to the picture or say the word that answers the riddle provided by the examiner. On the nonverbal cognitive ability subtest, participants will be instructed to point to the picture or pattern that best fits the relationship or rule provided by the examiner. A standard score will be calculated for verbal nonverbal subtests, as well as a total IQ composite standard score.

5.4.3.2. Experimental Conditions

In the somatosensory alteration-only feedback condition, participants will gargle an oral numbing solution (i.e., Viscous Lidodan 2%). The goal of the oral numbing solution is to numb the lining of the mouth to remove access to somatosensory information. In the auditory masking-only feedback condition, participants will complete tasks while speech noise is presented binaurally. The goal of speech-noise masking is to remove access to auditory feedback. Speech-noise masking will be presented over circumaural headphones calibrated by an audiologist at 65 dB (Iuzzini-Seigel et al., 2015). This level of noise was selected as it was sufficient to effect speech production in children with CAS, and reduces the risk of inducing hearing loss in children (Iuzzini-Seigel et al., 2015). Finally, in the combined somatosensory alteration and auditory masking condition, participants will complete tasks after gargling an oral numbing solution while speech noise is presented binaurally.

The order of the conditions will be semi-randomized across two sessions (two conditions per day) to counteract possible order effects and learning across conditions. The somatosensory alteration condition and combined somatosensory alteration and auditory masking condition will always be completed during different collection sessions and will be presented last during each session so its effects will not interfere with the other conditions. The possible condition orders are as follow (A= normal feedback, B=auditory masking-only, C=somatosensory alteration-only, D=combined auditory-masking and somatosensory alteration): AC-BD, AD-BC, BC-AD, and BD-AC.

Viscous Lidodan 2% Treatment. Viscous Lidodan 2% (i.e., Lidocaine Hydrochloride Oral Topical Solution 2% USP) is a topical anesthetic. The numbing effects of Viscous Lidodan 2% should take effect after five minutes and last around 30 minutes. Each participant will be instructed to swish 15 mL (one tablespoon) of the Viscous Lidodan 2% in their mouth for 60 seconds, then spit into a sink. This amount is the recommended manufacturer dosage. This will occur twice during each collection session. No other topical oral anesthetics are permitted to have been administered in the day before the trial. No details are required on any other medications. The lidocaine will be dispensed by a pharmacist and administered by the research team.

Safety Assessment. Each participant will complete a pre-screening/eligibility questionnaire which asks all participants to report any personal or family history of adverse reactions to anesthetics. This hard-copy questionnaire will be completed by the participant before the informed consent form. It will be reviewed together with the experimenter and participant before collection commences. Any participant reporting a personal or family history of adverse reactions to anesthetics will not be enrolled in the study. Any participant who does not meet all other inclusion/exclusion criteria will not be enrolled.

Participants will be monitored throughout the experiment by research staff for signs of distress or adverse reactions (e.g., redness, itching or swelling of skin, hives, burning, stinging, or any other skin problems, swelling of the neck area, or any difficulty with breathing). A Qualified Investigator will be available via phone/pager during administration of Viscous Lidodan in case of adverse event(s) for assessment, triage, treatment, and/or follow-up as clinically indicated.

If any reactions or adverse effects (i.e., redness, itching or swelling of skin, hives, burning, stinging, or any other skin problems, swelling of the neck area, or any difficulty with breathing) are observed by the experimenters during collection, the Qualified Investigator will be called, and the experimenter will escort the participant to the nearest hospital emergency room. After the collection session is over, the participant will be instructed to report to their nearest emergency room if they experience any reactions or adverse effects. Participants will be informed that they should avoid eating and drinking and exposure to extreme hot or cold temperatures (e.g., food, drink) until complete sensation has returned. The numbness may also increase the risk of unintentional biting (e.g., cheek).

The Qualified Investigator will follow-up with the subject as they deem appropriate. All serious unexpected adverse drug reactions (SUSARs) will be reported to Health Canada as mandated per C.05.014 (1) of the Food and Drug Regulations (FDR).

5.4.3.3. Tasks and Stimuli

In the overt repetition task, participants will be asked to listen to and repeat syllables and word utterances in the context of the carrier phrase “say ---- on green”. All stimuli will be recorded in a soundproof booth by one female English speaker at a sampling rate of 44.1 kHz with 16-bit resolution.

Following Terband et al. (2009), the syllable stimuli will consist of 27 V_1CV_2 utterances using /a/, /i/, and /u/ for the vowels, and /b/, /d/, and /g/ for the consonants (Appendix P). The consonants selected include three places of articulation: bilabial (/b/), alveolar (/d/), velar (/g/); and one manner of articulation: plosive (/b/, /d/, /g/). The vowels selected include three places of articulation: low-central (/a/), high-front (/i/), and high-back (/u/). Each stimulus will be repeated five times generating a total of 135 syllable utterances (Iuzzini-Seigel et al., 2015).

The word stimuli will consist of 60 monosyllabic words balanced for word type (i.e., exception, regular, and non-word), length, frequency of orthographic form, orthographic neighborhood, frequency of orthographic neighbors, unigram frequency, and bigram frequency using the English Lexicon Project (ELP) database (Balota et al., 2007). See Appendix Q for sample stimuli.

In the orthographic lexical decision task (OLDT), participants will be presented with a letter string and instructed to make a decision about whether the letter string *spells* a real word or non-word via a button press (i.e. press the ‘yes’ button if the stimulus spells a real word; press the ‘no’ button if the stimulus does not spell a real word). The word stimuli will consist of 60 monosyllabic words (see Appendix R for sample stimuli) balanced for word type (i.e., exception, regular, pseudohomophone and nonword), length, frequency of orthographic form, orthographic neighborhood, frequency of orthographic neighbors, unigram frequency, and bigram frequency using the English Lexicon Project (ELP) database (Balota et al., 2007).

In the phonological lexical decision task (PLDT), participants will be presented with a letter string and instructed to make a decision about whether the letter string *sounds* like a real word or a non-word via a button press (i.e. press the 'yes' button if the stimulus sounds like a real word; press the 'no' button if the stimulus does not sound like a real word). The word stimuli will consist of 60 monosyllabic words (see Appendix R for sample stimuli) balanced for the same properties stated above.

In the picture categorization task (PC), participants will be instructed to make a decision about whether the picture is of an animal or not via a button press (i.e., press the 'yes' button if the picture is of an animal; press the 'no' button if the picture is not of an animal). Each stimulus set will consist of 50 images from the revised set of Rossion and Pourtois (2004) colored images and will be matched for number of animal and non-animal images.

The order of tasks within each condition will be randomized across all participants. Moreover, the order of the stimuli will be randomized within each task.

5.4.3.4. Procedure

Participants will be scheduled to attend two 90-minute assessment sessions and two 90-minute experimental sessions on separate days. Dividing the assessment and experimental sessions into multiple days will help prevent fatigue and loss of attention. The assessment sessions will be conducted at the participants' home or the Faculty of Rehabilitation Medicine at the University of Alberta Calgary Center Campus, while the experimental sessions will take place at the Faculty of Rehabilitation Medicine Calgary Center Campus.

The assessment session will follow the order outlined in Appendix K. The order of the experimental conditions will be semi-randomized and the order of tasks and stimuli will be randomized across all participants. Randomization is important to counteract possible order effects and learning across conditions.

Participants will be seated in front of a laptop computer with a microphone placed 10 cm away from their mouth. The recorded stimuli and letter strings will be presented using MATLAB software (The MathWorks Inc., 2018) following the sequence depicted in Figure 5.3. Appendices S, T, and U contain the code that will create applications with graphical user interfaces in MATLAB. The overt repetition task and orthographic- and phonological-LDTs were designed to be comparable to allow for comparison of accuracy and reaction time across tasks.

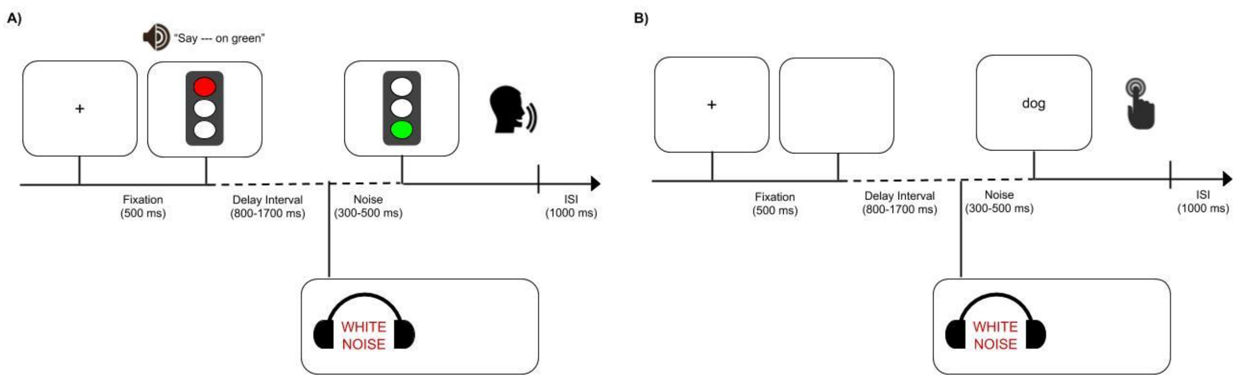


Figure 5. 3. Schematic of one trial in the auditory masking-only condition for the a) overt repetition task and b) orthographic and phonological lexical decision task.

For the overt repetition task, a fixation cross will appear in the center of the screen for a duration of 500 ms. A 'stop' signal will appear and the participant will be presented with a stimulus via headphones in the context of the carrier phrase "say ---- on green". After a variable delay interval of 800-1700 ms, the 'go' signal will appear and the participant will repeat the stimulus. The variable delay will be used to prevent anticipation of trial onset. An interstimulus interval of 1000 ms will follow each stimulus. For the auditory masking-only condition, speech noise will be presented at 65 dB 300-500 ms before the presentation of the ‘go’ signal and continue throughout the participants' response. For the somatosensory alteration-only condition, children will be instructed to swish Viscous Lidodan 2% in their mouth for 60-seconds, then spit into a sink, prior to the start of the task. For the combined somatosensory alteration and auditory masking condition, children will be instructed to swish Viscous Lidodan 2% in their mouth for 60-seconds, then spit into a sink, prior to the start of the task, and speech noise will be presented as described in the auditory-masking only condition. Participant’s productions will be audio and video recorded via a microphone at a sampling rate of 44.1 kHz and a Canon video camera.

For the orthographic and phonological lexical decision tasks, a fixation cross will appear in the center of the screen for 500ms. After a variable delay interval of 800-1700 ms, a letter string will appear and the participant will be instructed to make a decision about whether the letter string spells or sounds like a real word or a non-word via a button press (i.e. press the ‘yes’ button if the stimulus spells or sounds like a real word; press the ‘no’ button if the stimulus does not spell or sound like a real word). An interstimulus interval of 1000 ms will follow each stimulus. The auditory masking-only, somatosensory alteration-only, and combined auditory masking and somatosensory alteration conditions will proceed as described above. Accuracy and reaction time of button presses will be recorded in MATLAB.

For the picture categorization task, a fixation cross will appear in the center of the screen for 500ms. After a variable delay interval of 800-1700 ms, a picture will appear and the participant will be instructed to make a decision about whether the picture is of an animal or not an animal via a button press (i.e., press the ‘yes’ button if the picture is of an animal; press the ‘no’ button if the picture is not of an animal). An interstimulus interval of 1000 ms will follow each stimulus. The auditory masking-only, somatosensory alteration-only, and combined auditory masking and somatosensory alteration conditions will proceed as described above. Accuracy and reaction time of button presses will be recorded in MATLAB.

5.4.4. Data Analysis

5.4.4.1. Reliability of CAS Diagnosis

Two SLPs with experience in motor speech disorders will rate the ASHA (2007) and Strand criteria (Shriberg et al., 2011) for each child with CAS. Inter-rater reliability for the number of criteria will be determined by calculating the intraclass correlation coefficient (ICC).

5.4.4.2. Acoustic Analysis of Syllables in the Overt Repetition Task

Acoustic analysis will be completed using waveform and broadband spectrograms in Praat software version 5.3.5 (Boersma & Weenick, 2019). All coding will be done blindly without knowledge of the group. For each perceptually accurate VCV stimulus trial, the left and right margins of the vowels will be manually placed at the onset and offset of the glottal pulse (i.e., regularly repeating, or periodic, waveform), which will subsequently isolate the consonant. A Praat script will then be used to detect VCV boundaries, and extract the first (F1), second (F2), and third (F3) formant frequencies at the time points of 20%, 50% and 80% of each sounds duration (Maas et al., 2015). Next, a MATLAB script will be used to normalize all formant frequencies using a log10(x) transformation to account for differences within speakers and in the formant frequencies themselves. Data will be examined for outliers and trials greater than 3SD above or below each individual’s mean will be removed from analysis. Finally, the MATLAB script will be used to calculate three dependent variables: coarticulation, token-to-token variability of the consonant and token-to-token variability of the vowels. The formulas for all calculations can be found in Appendix V. These measures were selected as coarticulation and token-to-token variability can be used to index two of the core characteristics of CAS, disrupted movement transitions and inconsistent errors. Moreover, in DIVA simulations of CAS, increased coarticulation and token-to-token variability were predicted as reliance shifts to the feedback system (Terband & Maassen, 2010).

Anticipatory coarticulation on V_1 and C and carryover articulation on C and V_2 will be combined into a composite coarticulation index for analysis. Anticipatory coarticulation (in V_1 and C) will be measured as the absolute differences in mean formant frequencies of each produced sound across all possible vowel contexts (i.e., V_1C/i/ vs. V_1C/u/ vs. V_1C/a/), with subsequent averaging over the three formants to calculate the coarticulation indices, V_1-anticipatory and C-anticipatory (Terband et al., 2009). Carry-over coarticulation (in C and V_2) will be measured as the absolute differences in mean formant frequencies of each produced sound across all possible vowel contexts (i.e., /i/CV_2 vs. /u/CV_2 vs. /a/CV_2), with subsequent averaging over the three formants to calculate the coarticulation indices, C-carry-over and V_2-carry-over (Terband et al., 2009). The final composite coarticulation index will be calculated as the average of anticipatory coarticulation on V_1 and C and carryover articulation on C and V_2.

Token-to-token variability will be calculated for V_1, C and V_2. The token-to-token variability for V_1 and V_2 will be combined into a composite token-to-token variability vowel index for analysis. Token-to-token variability will be measured as the standard deviations in the mean formant frequencies of repeated productions of the same sound (Terband et al., 2009).

5.4.4.3. Reliability of Acoustic Analysis

A second individual with experience in acoustic analysis will segment 10% of the VCV stimulus trials from each condition. The ICC will then be calculated for these trials to determine reliability of acoustic analysis (Iuzzini-Seigel et al., 2015).

5.4.4.4. Analysis of Words in Repetition, Lexical Decision and Picture Categorization Tasks

Reaction time will be measured as the amount of time it takes to respond to a presented stimulus (i.e., from presentation of stimulus to button press). Only accurate responses will be included in analysis of reaction time. Moreover, at the individual level, data will be examined for outliers and trials greater than 3 SD above or below the mean will be removed from analysis. Percent accuracy will be measured as the difference between correct responses and total responses multiplied by 100.

5.4.4.5. Statistical Analysis

All statistical analysis will be performed using SPSS version 25 (IBM Corp., 2017). Simple descriptive statistics (i.e., mean and standard deviation) will be reported for all demographic information, assessment scores and acoustic variables. Independent samples t-tests will be used to test for differences between groups on age and gender variables.

Research Question 1: What are the effects of manipulations to the auditory, somatosensory and combined auditory and somatosensory feedback systems on speech motor behaviors in children with CAS, in comparison to TD children?

For each dependent variable (coarticulation, and consonant and vowel token-to-token variability), mixed analyses of variance (ANOVAs) will be used to test for differences within and between groups if assumptions of normality, homogeneity, and sphericity are met. Normality will be assessed using the Shapiro-Wilk test of normality and homogeneity of variances will be assessed using Levene’s test. Mixed ANOVA’s will be used with type of feedback (normal, auditory-only, somatosensory-only, combined) as a within-subjects factor and group (CAS, TD) as a between-subjects factor. Age will be added as a covariate. Sphericity will be assessed using Mauchly’s Test of Sphericity. If the assumption of sphericity is not met, the estimate of sphericity (i.e., epsilon) will be used to adjust the degrees of freedom for the averaged tests of significance ($\varepsilon > .75$ Huynh-Feldt correction, $\varepsilon < .75$, Greenhouse-Geisser correction). Post hoc analysis will be conducted using the Tukey's honest significant difference (HSD) test. Correction for multiple comparisons using the Bonferroni correction will be made at the ANOVA level (0.05/3=0.017). If assumptions of normality and homogeneity are not met, the Kruskal-Wallis H Test will be performed. Post hoc analysis will be conducted using the Mann-Whitney U test (between-group differences) and Wilcoxon Signed Rank test (within-group differences).

For each dependent variable (coarticulation, and consonant and vowel token-to-token variability), repeated measures ANOVAs will also be used to test for individual differences in speech production across conditions (normal, auditory-only, somatosensory-only, combined).

Research Question 2: What are the effects of manipulations to the auditory, somatosensory and combined auditory and somatosensory feedback systems on reading performance in children with CAS in comparison to TD children?

For each dependent variable (reaction time and percent accuracy), mixed ANOVAs will be used to test for differences within and between groups if assumptions of normality, homogeneity, and sphericity are met (see above). Mixed ANOVAs will be used with type of feedback (normal, auditory-only, somatosensory-only, combined) as a within-subjects factor and group (CAS, TD) as a between-subjects factor. Age will be added as a covariate. Post hoc analysis will be conducted using the Tukey's honest significant difference (HSD) test. Correction for multiple comparisons using the Bonferroni correction will be made at the ANOVA level (0.05/2=0.025). If assumptions of normality and homogeneity are not met, the Kruskal-Wallis H Test will be performed. Post hoc analysis will be conducted using the Mann-Whitney U test (between-group differences) and Wilcoxon Signed Rank test (within-group differences).

For each dependent variable (reaction time and percent accuracy), repeated measures ANOVAs will also be used to test for individual differences in reading performance across conditions (normal, auditory-only, somatosensory-only, combined).

Research Question 3: Is speech production performance related to reading performance in children with CAS?

For each dependent variable (reaction time and percent accuracy), a Pearson correlation will be used to examine the relationship between speech production performance and reading performance by word type (e.g., exception words, regular words, and non-words) if assumptions of normality, linearity and no significant outliers are met. Normality will be assessed using the Shapiro-Wilk test of normality and a scatterplot will be created to check for linearity and outliers. Correction for multiple comparisons using the Bonferroni correction will be made (0.05/6=0.008). If assumptions of normality and linearity are not met, the Wilcoxon Signed Rank test will be performed.

5.5. Contributions of Proposed Research and Conclusion

Together, these studies will move us closer to an understanding of the underlying impairment in CAS through systematic disruptions of the auditory and somatosensory systems during speech production and reading. Comparing performance on speech production and reading tasks may allow us to determine if reading tasks can provide quick and accurate insight into the underlying impairment in CAS. Such an understanding may help to inform the development of high-quality procedures for identifying children with CAS (i.e., diagnosis) and tools/protocols for evaluating their strengths and weaknesses (i.e., assessment). Finally, it will inform clinicians who treat children with CAS by ensuring they provide the best possible care and treatment and inform teachers and specialists who guide reading development.

CHAPTER 6

Discussion

6.1. Summary of Contributions

This doctoral dissertation consisted of three papers that aimed to: (a) describe and examine current SLP services and practices in Canada for childhood apraxia of speech (CAS), (b) provide an orientation to the use of theory in clinical practice, and (c) offer a theory-based rationale and protocol for a clinical trial of somatosensory and auditory disruptions in children with and without CAS. A summary of the main findings of each study are discussed below.

6.1.1. Survey of SLP Practice in Canada

This exploratory study was one of the first that I am aware of to characterize the diagnostic, assessment, and treatment practices of (speech-language pathologists) SLPs in Canada for CAS. The most prominent finding to emerge from this study is that many SLPs used evidence-based diagnostic, assessment, and treatment practices; however, SLPs also tended to use many practices for which the evidence is limited, unclear, or absent. The extent to which these practices were driven by clinical experience, and/or guided theory remains unknown. It is within this context that we raised several questions about SLP practices for CAS for further study. The results of this survey provided the impetus for the following paper regarding theory-guided practice as a potential mechanism to improve the documentation and implementation of SLP practice and services.

6.1.2. Use of Theory to Guide Practice

This paper provided a clinically focused overview of theory and highlighted how theory can be applied to all aspects of clinical practice. It provided a starting point to move SLPs beyond "what works best" to address a more in-depth understanding of the "why" and "how" of clinical behaviours. I argued that theory-guided practice will support SLPs in being intentional, objective, systematic, and creative about their approach to managing communication disorders. While this paper draws explicitly on SLPs working with children and young people with CAS to provide practical examples and applications, these guidelines can be applied to all populations served by SLPs.

6.1.3. Clinical Trial Protocol

This paper explicitly proposes the use of theoretical models of speech and reading to understand CAS. A detailed clinical trial protocol is provided that, at the time of the writing of this, will be the first to examine predictions regarding the cause of CAS within the Directions Into Velocities of Articulators (DIVA) model, and related print-to-speech model, by systematically comparing the independent and combined contributions of the auditory and somatosensory feedback systems during speech production and reading. This clinical trial will move us closer to an understanding of the core deficit in CAS, and help to inform the development of high-quality assessment and diagnostic procedures. Furthermore, one of the most important reasons for understanding the cause of CAS is to devise theoretically motivated interventions that aim to directly target the underlying impairment. Finally, if CAS frequently co-occurs with other development disorders (such as reading impairments), a comprehensive model of CAS needs to be able to explain not only CAS, but also its co-occurrence with other disorders.

Together, these interconnected studies have advanced our understanding of current practices for CAS. The findings indicated that despite growth and advances in CAS, there is still an immense gap between research and practice, with insufficient attention paid to theory. Moreover, the accumulating body of evidence offers limited information regarding the cause and underlying mechanism(s) of CAS and inconclusive evidence and inconsistent guidance to support and guide SLPs' clinical decision-making and management of CAS. These knowledge gaps restrict efforts to improve the quality, efficacy, and effectiveness of CAS services. The following discussion will describe the opportunities, challenges and implications raised by this dissertation.

6.2. Opportunities, Challenges and Implications

As the SLP profession has grown over the past century, evidence-based practice (EBP) has become necessary and expected. SLP licensing and regulatory bodies emphasize EBP practices and require students to learn about theory, understand why theories are important, and learn how to apply theories in practice. For example, the Canadian Alliance of Audiology and Speech-Language Pathology Regulators (CAASPR) identified seven essential competencies required of an SLP upon entry-to-practice in Canada (2018). In the role of "expert", in order to provide safe and effective practice, an SLP must be able to (a) apply knowledge of communication, feeding and swallowing development and disorders to clinical practice, (b) apply knowledge from relevant fields to clinical practice, (c), apply knowledge of hearing, hearing loss and disorders to the auditory system to clinical practice, and finally, (d) use evidence and clinical reasoning to guide professional decisions (CAASPR, 2018). That is, it is imperative that SLPs be able to apply theory *and* use evidence in every aspect of their professional role.

Concerning the use of evidence in practice, the results of the first study provide a tremendous opportunity for clinical growth and effective dissemination practices. Training programs and continuing education activities need to emphasize the use and application of best research evidence and theory, especially for poorly understood disorders such as CAS. The discipline would benefit from more research to address the research-practice gap. Given the limited sample size, further research is required to determine if the findings of this study are an accurate reflection of SLP practice in Canada. If the conversation is to be moved forward, a better understanding of the factors that influence and guide SLPs' clinical decision-making for CAS needs to be developed.

The role of theory in guiding SLP practice is considerably less prominent when surveying the literature and educational materials of SLP than in other allied health disciplines (e.g., nursing, occupation therapy, etc.). This raises several important questions: are SLPs not using theory in practice? Or, are SLPs not making explicit the theories they are using? A reasonable approach to tackle this issue would be to conduct a rigorous systematic review of the literature and a descriptive investigation exploring SLPs' perceptions and opinions of, and attitudes towards, theory-guided practice is required. In addition, a targeted approach that investigates the impact of active vs. non-active implementation of theory-guided practice would provide much needed evidence for the role of theory in the clinical decision-making process.

Despite the potential value of theory, its use in practice presents several challenges. First, SLPs must determine whether a theory is valid. One would need knowledge of theory generation and evaluation to determine what specific criteria to pay attention to. Second, SLPs must understand which theory or theories to apply in a given situation. This presents a challenge for any SLP as these have not been consolidated. It could be argued that an assembly and consolidation of theories used in SLP, in addition to increased ease of access and organization, may inspire theoretical advances, engage individuals with different theoretical perspectives, and generate new insights. A third challenge is that SLPs must understand the theory and its critical components. Without a sound grasp of the underlying theory and its components, it may prevent the SLP from meaningfully applying the theory in practice. Finally, uptake and adoption of theory in practice may be impacted by similar barriers as EBP, such as lack of time, resources, and skills/training. That is, there is an onus on the researchers to explain and describe whether and how theoretical concepts are relevant to specific practice situations. In a similar vein, the active implementation, and subsequent dissemination by way of training, of theory-guided practice by SLPs could serve as a major catalyst in this domain. This can be further facilitated through the definition, operationalization and description of theoretical concepts in measurable terms. Ultimately, research studies are needed to provide evidence of a cause-effect relationship between treatment programs and theoretical concepts. The work outlined here provides a solid foundation to address the challenges of SLP practice for CAS. I am convinced that we can capitalize on the opportunities to integrate theory, research, and practice and promote growth and advancement in CAS.

6.3. Conclusions

This doctoral dissertation advanced our understanding of the current practices in Canada for CAS and highlighted the gaps/challenges in the clinical management of CAS. The application of theory and use of evidence are necessary to provide safe and effective SLP services. Further, theories have been proposed as a way to advance our understanding of CAS. Together, these studies highlight that a step toward advancing our current understanding of CAS and elevating SLP services requires the explicit integration of theory, research, and practice.

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Appendix A. Survey of SLP Practices for CAS

SLP/T Background Information

1. Are you a speech-language pathologist/therapist (SLP/T)? YES/NO (discontinue if "no")
2. Do you work with children and/or adolescents with childhood apraxia of speech (CAS)? YES/NO (discontinue if "no")
3. In what province do you work as an SLP/T? Alberta; British Columbia; Manitoba; New Brunswick; Nova Scotia; Ontario; Prince Edward Island; Quebec; Saskatchewan
4. In what language(s) do you practice as an SLP/T? English; French; Mandarin; Cantonese; Punjabi; Other (please specify)
5. Please select your sex: Male; Female; No response
6. What is your highest educational degree? Bachelor's; Master's; Clinical doctorate (SLP-D); Doctoral degree (PhD); Other (please specify); No response
7. How many years have you been practicing as an SLP/T? Under five years; 5-10 years; 10-15 years; 15-20 years; 20-25 years; 25-30 years; More than 30 years; No response
8. What is your experience in working with children and adolescents with CAS? Recently started; Some experience; A lot of experience; No response
9. Please select the facility that best describes the work setting(s) where you serve children and adolescents with CAS. You may select multiple facilities. For each facility you select, please indicate the (a) number of hours you work with children and adolescents with CAS and (b) the age of children and adolescents with CAS: Hospital; Community Health Center; Day Care; Early Education Center(s); Preschool; Primary or Secondary School(s); Private Practitioner; Other (please specify)
10. What best describes your location of work: City; Rural; Remote; No response
11. Have you completed specific training or professional development regarding CAS (beyond your initial professional study to become an SLP/T? Yes (please specify); No; No response

Characteristics of Children and Young People with CAS on SLP/T's Caseloads

12. Over the last 12-month period, your caseload (of children with CAS) included (select all that apply): Male; Female; Monolingual; Multilingual/bilingual; High socioeconomic backgrounds; Middle socioeconomic backgrounds; Low socioeconomic backgrounds; Those with other significant conditions
13. What is the typical age that children and adolescents with CAS on your caseload receive a diagnosis of CAS? Less than 2 years; 2 years; 3 years; 4 years; 5 years; 6 years; 7 years; 8 years; Greater than 8 years; I'm not sure
14. For children and adolescents on your caseload, select the common co-morbid conditions: Non-verbal oral apraxia (NVOA); Dysarthria; Other speech/language disorders; Developmental disabilities; Mood disorders (e.g., depression, anxiety); Epilepsy; Food allergies/intolerances; Intellectual disability; Attention Deficit Hyperactivity Disorder (ADHD); Sensory

Modulation/Integration Disorder; Language-Literacy Disorder; Other (please specify); Other comments you would like to add:

15. Who primarily refers children and adolescents with CAS for speech-language/therapy services to your work facility or facilities? Parent; Pediatrician/Physician; Educational professional (e.g., principal, teacher); Psychologist; Psychiatrist; Other SLP/T; Social Worker; Other (please specify)

Diagnosis of CAS

16. Do SLP/T's participate in the diagnosis of CAS in your region? Never; Rarely; Sometimes; Often; Always; I'm not sure

17. Are you involved with a collaborative team in the diagnosis of children and adolescents with CAS? Never; Rarely; Sometimes; Often; Always

18. Which professionals are responsible for the diagnosis of children and adolescents with CAS (select all that apply)? A team of professionals; Psychologist; Psychiatrist; Pediatrician/Physician; Speech-Language Pathologist/Therapist; Other (please specify); I'm not sure

19. Which formal assessments (i.e., yields a scaled or standard score) do you use in the diagnosis of CAS in your facility or facilities (not including tests applied to examine other language functions such as vocabulary, expressive and receptive language etc.)? Select all that apply: Apraxia Profile (AP); Dynamic Evaluation of Motor Speech Skill (DEMSS); Kaufman Speech Praxis Test for Children (KSPT); Madison Speech Assessment Protocol (MSAP); Screening Test for Developmental Apraxia of Speech (STDAS); Other (please specify)

20. Which informal assessments (i.e., does not yield a scaled or standard score) do you use in the diagnosis of CAS in your facility or facilities (not including tests applied to examine other language functions such as vocabulary, expressive and receptive language etc.)? Select all that apply: Duffy Motor Speech Exam; Other (please specify)

21. Which criteria do you use to diagnose children and adolescents with CAS (select all that apply)? American Speech-Language-Hearing Association (ASHA) Consensus-Based Feature List (client meets 3/3 criteria); Strand's 10-Point Checklist (client meets 4/10 of the criteria); I do not use specific criteria; Other (please specify)

Assessment for Intervention Planning for Children and Young People with CAS

22. In your role as an SLP/T over the last 12-month period, did you conduct speech-language assessment of children or adolescents with CAS to plan intervention for them? Never; Rarely; Sometimes; Often; Always

23. Do you use standardized norm-referenced assessments, such as those that result in scaled scores, to help determine intervention goals for children and adolescents with CAS? Never; Rarely; Sometimes; Often; Always

24. What standardized norm-referenced non-language focused assessments do you use when determining intervention goals for children and adolescents with CAS (select all that apply)? Apraxia Profile (AP); Children's Speech Intelligibility Measure (CSIM); Dynamic Evaluation of Motor Speech Skill (DEMSS); Kaufman Speech Praxis Test for Children (KSPT); Madison Speech Assessment Protocol (MSAP); Oral Speech Mechanism Screening Examination (OSMSE); Prosody-Voice Screening Profile (PSVP); Screening Test for Developmental Apraxia of Speech (STDAS); Test of Nonverbal Intelligence (TONI); Test of Problem Solving (TOPS);

Verbal Dyspraxia Profile (VDP); Verbal Motor Production Assessment for Children (VMPAC); Wechsler Intelligence Scale for Children (WISC); Wide Range Achievement Test (WRAT); None of the above; Other (please specify)

25. What standardized norm-referenced language-focused assessments do you use when determining intervention goals for children and adolescents with CAS (select all that apply)? Bracken Basic Concept Scale: Expressive (BBCS:E); Bracken Basic Concept Scale: Receptive (BBCS:R); Clinical Evaluation of Language Fundamentals-Preschool (CELF-P); Clinical Evaluation of Language Fundamentals-4 (CELF-4) or any version; Communication Abilities Diagnostic Test (CADeT); Communication and Symbolic Behavior Scales (CSBS); Comprehensive Assessment of Spoken Language (CASL); Emergent Literacy Language Assessment (ELLA); Functional Communication Profile; Goldman-Fristoe Test of Articulation (GFTA); Khan-Lewis Phonological Analysis (KLPA); MacArthur-Bates Communicative Development Inventories (CDI); One-Word Picture Vocabulary Test: Expressive (EOWPVT); One-Word Picture Vocabulary Test: Receptive (ROWPVT); Oral and Written Language Scales (OWLS); Peabody Picture Vocabulary Test (PPVT); Pragmatic Language Skills Inventory (PLSI); Preschool Language Scale (PLS); Receptive-Expressive Emergent Language Test (REEL); Reynell Developmental Language Scales (RDLS); Test of Auditory Comprehension of Language (TACL); Test of Early Language Development (TELD); Test of Language Development (TOLD); Test of Language Competence (TLC); Test of Narrative Language (TNL); None of the above; Other (please specify)

26. Do you use criterion-referenced assessments, such as questionnaires or checklists, to help determine intervention goals for children and adolescents with CAS? Never; Rarely; Sometimes; Often; Always

27. What specific informal assessment practices, such as those you have developed yourself, do you use to help determine intervention goals for children and adolescents with CAS?

28. Do you have access to assessments for children and adolescents with CAS that are in your clients' native language? YES/NO

29. Do you use an interpreter when conducting assessment of children and adolescents with CAS whose native or home language is a language that you do not speak or understand? YES/NO/Not Applicable

30. Dynamic assessment refers to incorporating teaching into assessment and evaluating how this enhances a child's performance. Do you use this assessment method to help determine intervention goals for children with CAS? Never; Rarely; Sometimes; Often; Always

31. How often do you assess the following skills when determining intervention goals for children and adolescents with CAS (Never; Rarely; Sometimes; Often; Always)? Hearing (e.g., screening); Non-speech articulatory postures (e.g., smile) and sequences (e.g., kiss-smile); Sequential movement repetitions (e.g., /puhpuh/); Alternating movement repetitions (e.g., /puhtuhkuh/; Production of single-sounds; Production of single-words; Production of words of increasing length/complexity (e.g., cat, catapult, catastrophe); Repetition of words (e.g., animal animal animal); Production of multisyllables; Production of phrases/sentences; Well practiced/automatic speech (e.g., counting, days of the week); Volitional/spontaneous speech; Receptive language; Literacy development (e.g., phonological awareness, letter-sound knowledge, reading comprehension); Conversation skills (e.g., turn taking, topic maintenance); Narrative ability (e.g., telling a story); Feeding and swallowing; Executive functions; Sensory motor skills

Intervention Practices for Children and Young People with CAS

32. In your roles as an SLP/T over the last 12-month period, did you provide intervention for children or adolescents with CAS? Never (skip to section 5); Rarely; Sometimes; Often; Always

33. What is the most common frequency of intervention you provide for children and adolescents with CAS? 1-2 times per week; 3-4 times per week; 5-7 times per week; Every two weeks; Once a month; Other (please specify)

34. What is the most common duration of a session? 30 minutes; 45 minutes; 60 minutes (1hr); 75 minutes (1.25hrs); 90 minutes (1.5hrs); 105 minutes (1.75hrs); 120 minutes (2hrs)

35. What is the typical number of trials per session (i.e., intensity)? <50; 50-100; 100-150' 150+

36. What is the usual period of intervention that you provide for children and adolescents with CAS?; 1-6 months; 7-12 months; Between 1 and 2 years; Between 2 and 3 years; Between 3 and 4 years; Between 4 and 5 years; More than 5 years

37. Do you work with children and adolescents with CAS in individual therapy sessions? Never; Rarely; Sometimes; Often; Always

38. Do you work with children and adolescents with CAS in small group sessions? Never; Rarely; Sometimes; Often; Always

39. How often (Never; Rarely; Sometimes; Often; Always) do you provide intervention within: A public clinic or hospital; a private clinic; general education classroom; special education classroom; a room outside the classroom; the child's home; other (please specify)

40. What type of intervention approaches do you use with children with CAS? Augmentative and alternative communication (AAC); Motor-programming approaches (i.e., utilize motor-learning principles, including the need for many repetitions of speech movements to help the child acquire skills to accurately, consistently, and automatically make sounds and sequences of sounds); Linguistic approaches (i.e., focus on CAS as a language learning disorder; teach children how to make speech sounds and the rules for when speech sounds and sound sequences are used in language); Motor-programming and linguistic approaches; Sensory cueing approaches (i.e., involve the use of the child's senses, as well as gestures to cue some aspect of the targeted speech sound); Motor-programming and sensory cueing approaches; Rhythmic (prosodic) approaches (i.e., use melody, rhythm and stress patterns to improve functional speech production); Other (please specify)

41. What types of AAC do you use with children and adolescents with CAS? Picture exchange communication system; Sign language; Makaton; Bliss symbols; Computer technology; Visual symbols; Written words; Voice-activated device; Organized communication boards; None of the above; Other (please specify)

42. Do you use published intervention programs or resources for children and adolescents with CAS? Never; Rarely; Sometimes; Often; Always

43. Do you create your own interventions and/or modify commercial programs

44. Which published intervention approaches do you use? Kaufman Speech to Language Protocol (K-SLP); Nuffield Dyspraxia Program (NDP); Rapid Syllable Transition Treatment (ReST); Integrated Phonological Awareness Intervention (IPA); Integral Stimulation (IS); Dynamic Temporal and Tactile Cueing (DTTC); Prompts for Restructuring Oral Muscular Phonetic

Targets (PROMPT); Touch-Cue Method; Melodic Intonation Therapy (MIT); Other (please specify)

Collaborative Practices for CAS

45. To what extent do you work with the following people to build their capacity to support children and adolescents with CAS (Never; Rarely; Sometimes; Often; Always)? Parents; Teachers; Educational para-professionals (e.g., teaching assistants); Educational administration (e.g., principals, program coordinators); Occupational therapists; Physical therapists; Other (please specify)

46. Please list specific approaches you use to build the capacity of teachers to support children and adolescents with CAS.

47. To what extent (Never; Rarely; Sometimes; Often; Always; Not Applicable) do you involve families of children and adolescents with CAS in selecting: The setting(s) of assessment; Assessment measures; Intervention goals; Intervention approaches or programs; The setting(s) of intervention

48. To what extent (Never; Rarely; Sometimes; Often; Always; Not Applicable) do you involve teachers of children and adolescents with CAS in selecting: The setting(s) of assessment; Assessment measures; Intervention goals; Intervention approaches or programs; The setting(s) of intervention

49. Please select the health professionals you would usually collaborate with in working with children and adolescents with CAS (select all that apply): Other SLP/T's; Occupational therapists; Physical therapists; Social workers; Pediatricians/physicians; Audiologists; Nurses; Psychologists; Psychiatrists; Other (please specify); None

Appendix B. Operational Definitions for Childhood Apraxia of Speech Characteristics

ASHA consensus-based feature list[A]	Strand's 10-point checklist[B]	Operational Definition
1. Inconsistent errors on consonants and vowels	n/a	The participant has increased number of errors in repeated productions of the same word (e.g., "cat" is produced as "tat", "cat" and "dat").[C]
2. Lengthened and disrupted co-articulatory transitions between sounds and syllables	1. Difficulty achieving initial articulatory configurations and transitions into vowels	Initiation of utterance or initial speech sound may be difficult for child to produce and may sound lengthened or uncoordinated. Also, child may evidence lengthened or disrupted coarticulatory gestures or movement transitions from one sound to the next.[D]
	2. Syllable segregation	Brief or lengthy pause between syllables which is not appropriate. [D]
3. Inappropriate prosody	3. Lexical stress errors or equal stress	An error in which the appropriate stress is not produced correctly. For example: conDUCT and CONduct have different stress patterns. It is considered an error if the stress is inappropriately equalized across syllables or placed on the wrong syllable. [D]
n/a	4. Slow rate	Speech rate is not typical. It is slower during production of part (e.g., zzziiiiiiper/zipper) or the whole word (e.g., tooommmmmaaatoooo/tomato). [D]
	5. Vowel or consonant distortions including distorted substitutions	A vowel production error in which the vowel is substituted for another phoneme OR in which the vowel is recognizable as a specific phoneme but it is not produced exactly correctly (e.g., not a prototypical production, may sound like it is in between two vowels). It is not considered an error if the vowel is substituted with another phoneme that is consistent with an adult-like model. [D] A consonant production error in which a speech sound is recognizable as a specific phoneme but it is not produced exactly correctly (e.g., an /s/ that is produced with lateralization or dentalization). [D]
	6. Groping (nonspeech)	Prevocalic (silent) articulatory searching prior to onset of phonation, possibly in an effort to improve the accuracy of the production. [D]
	7. Intrusive schwa (i.e., 'uh')	A schwa is added between consonants. For example, it may be inserted in between the consonants in a cluster (e.g., /blu/ becomes /b3lu/). This NOT considered a ''vowel error''. [D]
	8. Voicing errors	A sound is produced as its voicing cognate (e.g., a /p/ that is produced as a /b/). In addition, this could also describe productions which appear to be in between voicing categories (e.g., blurring of voicing boundaries). [D]
	9. Slow diadochokinetic (DDK) rate	Rate of DDKs is slow in comparison to age-based norms.
	10. Increased difficulty with longer or more phonetically complex words	The participant has a disproportionately increased number of errors as the number of syllables increases (as compared to words with fewer syllables). [D]

[A]American Speech-Language-Hearing Association (2007) p. 4. ASHA criteria = 3/3 needed for CAS diagnosis; [B]Shriberg et al. (2011) p. 495. Strand criteria = 4/10 needed for CAS diagnosis; [C]Iuzzini-Seigel et al. (2017); [D]Iuzzini-Seigel et al. (2015)

Appendix C. Sample Recruitment Letter

Dear Sir or Madam:

Re: Research Project Recruitment (Pro000XXXXX)

We are contacting you because you work with children with speech sound disorders. We are looking for individuals/facilities in Calgary, Edmonton and surrounding areas who would circulate an information letter to parents and post an information poster in their facilities regarding a graduate student research study at the University of Alberta.

Childhood apraxia of speech (CAS) disrupts a child's ability to send signals to the mouth (e.g., lips, tongue) to speak. In typical development, information about "how a word sounds", "how a word feels" (i.e., the lips in a rounded position when saying "boo"), and the actual movements of the mouth all work together to produce speech. In childhood apraxia of speech, it is not known whether one of the pieces (i.e., "how it sounds", "how it feels" or the mouth movement) is damaged or whether the pieces are not working together. In addition, given evidence that reading ability is partially dependent on speech production, and that childhood apraxia of speech and literacy impairments are highly co-morbid, it is important to explore both of these processes. One way to learn more about the role that "how it sounds" plays in speech and reading in children with and without CAS is to measure speech production and reading performance in children with and without childhood apraxia of speech in normal conditions, as well as in disrupted conditions, namely presenting noise to cover up information about "how it sounds".

We have received Health Research Ethics Board (HREB) approval from the University of Alberta to run a research study to investigate these claims (Pro000XXXXX). The study will involve **four sessions** that are 90-minutes in length (approximately once a week for four weeks). As part of the study, children with and without CAS will complete a comprehensive assessment, as well as tasks that test their ability to use "how it sounds", "how it feels" and the movements of the mouth in normal conditions, as well as in disrupted conditions. Children who participate will receive $5.00 per session and a copy of their assessment results.

Please contact the study coordinator Cassidy Fleming at [email] or [phone number] if you would like to learn more about the study.

Thank you in advance for considering this request.

Sincerely,

Cassidy Fleming
Speech-Language Pathologist
PhD Candidate
University of Alberta

Dr. Jacqueline Cummine
Principal Investigator
Associate Professor
University of Alberta

Dr. Teresa Paslawski
Co-Investigator
Associate Dean
University of Saskatchewan

Enclosures: Recruitment Poster, Information Letter, Consent to be Contacted by Researcher Form

Appendix D. Sample Consent to be Contacted by Researcher Form

CONSENT TO BE CONTACTED BY RESEARCHER

Title of the Study:	Towards a Better Understanding of Childhood Apraxia of Speech: Disruptions of the Oral Sensory and Auditory Systems (Pro000XXXXX)
Principal Investigator:	Dr. Jacqueline Cummine Associate Professor, Faculty of Rehabilitation Medicine, University of Alberta [email] or [phone number]
Co-Investigator:	Dr. Teresa Paslawski Associate Dean, School of Rehabilitation Science, University of Saskatchewan [email] or [phone number]
Graduate Student Researcher:	Cassidy Fleming, R.SLP PhD Candidate, Faculty of Rehabilitation Medicine, University of Alberta Speech-Language Pathologist [email] or [phone number]

You have been invited to participate in a graduate research study about how the hearing system contributes to how children with and without childhood apraxia of speech speak and read. Study visits would take place at the University of Alberta. You must be located in Calgary and Edmonton and surrounding areas. Please fill out the form below if you are willing to share your contact information to find out more information about the study, including how to give your consent for your child to participate.

I, ________________________________ (your name), authorize ________________________________ (name) to share my name and contact information with the study investigators listed above.

By signing this research consent form, I understand and confirm that:

1. The research investigator may contact me to share additional information about the study
2. This does not mean I am consenting to participate in the study
3. The research investigator needs my name and contact information so that she may give me additional information on the study.
4. This consent is effective as of the date signed and expires on [month day, year].
5. I can revoke this consent at any time.

Name of Individual Providing Consent:	________________________________
Signature of Individual Providing Consent:	________________________________
Date:	________________________________
Preferred Method of Contact (please write phone number or email address):	________________________________

Appendix E. Eligibility Questionnaire – Childhood Apraxia of Speech Group

TOWARDS A BETTER UNDERSTANDING OF CHILDHOOD APRAXIA OF SPEECH			
Inclusion/Exclusion Criteria – Childhood Apraxia of Speech Group			
SUBJECT STUDY ID #:	______________ (e.g., P0###)	SCREENING DATE:	___ ___ / ___ ___ ___ / ___ ___ ___ ___ d d m m m y y y y

Inclusion Criteria

	Yes	No
Does your child have a diagnosis of childhood apraxia of speech?	☐	☐
Was your child's diagnosis given by a speech-language pathologist?	☐	☐
Is your child between the ages of 6 years 0 months and 17 years 11 months?	☐	☐
Is your child's native language English?	☐	☐
Does your child have normal or corrected-to-normal (i.e., contacts or glasses) vision?	☐	☐
Does your child have typical receptive language?	☐	☐
Can your child sound out simple words?	☐	☐

Note: All Inclusion Criteria must be answered YES, to be included in study.

Exclusion Criteria

	Yes	No
Does your child have any difficulty hearing?	☐	☐

Note: All Exclusion Criteria must be answered NO, to be included in study.

	Yes	No
Did the participant meet the eligibility requirements for this study?	☐	☐

Appendix F. Eligibility Questionnaire – Control Group

TOWARDS A BETTER UNDERSTANDING OF CHILDHOOD APRAXIA OF SPEECH			
Inclusion/Exclusion Criteria – Control Group			
SUBJECT STUDY ID #:	________________ (e.g., P0###)	SCREENING DATE:	___ ___ / ___ ___ ___ / ___ ___ ___ ___ d d m m m y y y y

Inclusion Criteria

	Yes	No
Does your child's gender and age match any of the following? *E.g., 7-year-old Male, 8-year-old Female*	☐	☐
Is your child's native language English?	☐	☐
Does your child have normal or corrected-to-normal (i.e., contacts or glasses) vision?	☐	☐
Does your child have typical receptive language?	☐	☐
Does your child have typical expressive language?	☐	☐
Does your child have typical reading skills?	☐	☐
Does your child have typical speech?	☐	☐
Does your child have typical reading skills?	☐	☐
Does your child have average cognition?	☐	☐

Note: All Inclusion Criteria must be answered YES, to be included in study.

Exclusion Criteria

	Yes	No
Does your child have any difficulty hearing?	☐	☐

Note: All Exclusion Criteria must be answered NO, to be included in study.

	Yes	No
Did the participant meet the eligibility requirements for this study?	☐	☐

Appendix G. Sample Parental Consent for Child to Participate in a Research Study

Title of the Study:	Towards a Better Understanding of Childhood Apraxia of Speech: Disruptions of the Auditory and Somatosensory System
Principal Investigator:	Dr. Jacqueline Cummine Associate Professor, Faculty of Rehabilitation Medicine, University of Alberta [email] or [phone number]
Co-Investigator:	Dr. Teresa Paslawski Associate Dean, School of Rehabilitation Science, University of Saskatchewan [email] or [phone number]
Graduate Student Researcher:	Cassidy Fleming PhD Candidate, Faculty of Rehabilitation Medicine, University of Alberta Speech-Language Pathologist [email] or [phone number]

Invitation to Participate: You are being asked to allow your child to be in this graduate student research study about the role of the hearing system (or the auditory system) and the mouth system (or the oral sensory system) in speaking and reading in children.

This form contains information about the study. Before you read it, a member of the study team will explain the study to you in detail. You are free to ask questions if there is anything you do not understand. You will be given a copy of this form for your records.

Purpose of the Study: From this research we wish to learn more about the influence of the hearing and oral sensory system on speaking and reading. One way to learn more about this is to measure speech and reading performance in normal conditions and when hearing information is masked (i.e., by playing noise over headphones) and when oral sensory information is altered (i.e., using an oral numbing mouthwash).

Participation: If you wish for your child to participate in this study, you will be asked to participate in four sessions that will take approximately 1-1.5 hours to complete (4-6 hours total). The study team will send you email or text reminders before your study visits if requested. You will be asked to do the following:

a) Read and complete a pre-screening survey to see if your child is eligible to take part in the study. This should take approximately 5 minutes to complete. The survey will be reviewed by the study team and you will be contacted if your child is eligible.
b) Read and complete a demographic and history survey. This should take you approximately 30 minutes to complete. You do not have to answer any questions that you do not want to answer.
c) Your child will then take part in an assessment. The assessment should take your child approximately 2-3 hours to complete and you can complete it over multiple days. The assessment will include:
    a. A hearing screening (i.e., listening to beeps) to see how well your child hears different sounds. If your child does not pass this screening, then you will be withdrawn from the study. This will take approximately 15 minutes.
    b. An oral exam to get information about the movement, structure, and strength of your child's tongue, mouth and jaw. This will take approximately 25 minutes.
    c. An assessment of your child's speech (i.e., repeating sounds, words and sentences). This will take approximately 45 minutes.
    d. An assessment of your child's understanding and use of language (i.e., pointing to pictures, putting together phrases and sentences). This will take approximately 20-50 minutes.
    e. An assessment of your child's ability to sound out printed words (i.e., reading familiar and unfamiliar words). This will take approximately 10 minutes.
    f. An assessment of your child's verbal and non-verbal thinking skills (i.e., pointing to pictures or answering questions). This will take approximately 15-25 minutes.
d) Your child will then take part in four experiments. Each experiment should take your child approximately 30-45 minutes to complete. Your child will be seated in front of your computer and will complete several

tasks which include 1) repeating unfamiliar syllables, 2) repeating familiar words, 3) making a decision about a series of letters (i.e., “is the stimulus a word or a nonword?”) and 4) making a decision about pictures (i.e., “is the picture of an animal or not?”). We will ask your child to do these tasks four times.

a. The first time, your child will do the tasks with no changes to their hearing.
b. The second time, we will play a noise in your child’s ears using headphones while they do the tasks.
c. The third time, your child will do these tasks after swishing an oral numbing solution in their mouth
d. The fourth time, your child will do these tasks after swishing an oral numbing solution in their mouth and while we play a noise in your child’s ears using headphones.

Benefits: Your child will not benefit directly from being in this study. We hope that the information learned from this study will help us better understand the role of the hearing system in speech and reading and can be used in the future to benefit children with childhood apraxia of speech.

Risks: Your child may experience anxiety or psychological stress during testing. If your child experiences these symptoms, you may ask for a break or choose to stop him/her from participating.

Confidentiality and Anonymity: During this study we will be collecting information (or “study data”) about your child. We will use the data to help answer research questions. The information that you will share will remain strictly confidential and will be used solely for the purposes of this research. The only people who will have access to the research data are the study team.

Data Collected: During this study we will be collecting data about your child. Examples of the types of data we may collect about your child include his/her: name, address, ethnic background, data of birth, age, health conditions, health history, medications, education history, and speech, language, hearing, feeding and swallowing histories. We will also collect data on your child’s current speech, language, cognitive, hearing, and reading abilities, as well as your child’s speech and reading abilities in normal conditions and when the hearing system is altered. Finally, we will collect information about your age, education, occupation and household income. We will get this information by asking you to answer questions and doing the tests outlined in this form. Identifying information will be stored separately in file, and not with the study data.

Data Storage: The study data we collect will be securely stored by the study team during and after the study. Paper surveys will be kept in a locked filing cabinet in the office of the principal investigator at the University of Alberta for a minimum period of 5 years. Electronic copies of the survey will be encrypted and stored on a password protected computer in the department of Communication Sciences and Disorders at the University of Alberta.

Data Usage: Your child’s assessment and experiment data will be coded (with a number) so that it no longer contains his/her name, address or anything else that could identify them. Identifying information (including the demographic and history survey) will be stored separately in file, and not with the study data. Only the study team will be able to link your child’s coded study data to them. Your child’s study data will only be looked at by members of the research team. When the study is done, the assessment and experiment data will be anonymized (i.e., there will be no way to link it back to you ever). The coded written data may be presented, published, and/or reported in a dissertation. The audio- and video- recordings will not be shared in presentations. Results will be published in pooled (aggregate) format. Your answers to open-ended questions on the demographic and history survey may be used verbatim in but neither you (nor your child) will be identified. The coded data may be used to answer research questions in the future, but if we do this it will have to be approved by a Research Ethics Board.

Compensation: Your child will receive a $5.00 honorarium for each study visit (up to a maximum of $20.00). If you choose to withdraw from the study, you will still receive compensation. You will also receive a copy of your child’s assessment results, including the results of their hearing screening, oral exam, speech assessment, language assessment, and reading assessment. If you choose to withdraw from the study before the assessment is completed, you will not receive a copy of the assessment.

Voluntary Participation: Your child is under no obligation to participate. If you decide to allow your child to be in this study, you can change your mind and stop being in the study at any time. Should you choose to withdraw midway through the study, all information/data collected will be destroyed. You can choose to have your child's data withdrawn from the study up to the end of the final experiment session.

Contact Information: If you have any further questions or want more information about the research and/or your participation, you may talk to any member of the study team. Please contact:

Dr. Jacqueline Cummine	Dr. Teresa Paslawski	Cassidy Fleming
Principal Investigator	Co-Investigator	Speech-Language Pathologist
Associate Professor	Associate Dean	PhD Candidate
[email] or [phone number]	[email] or [phone number]	[email] or [phone number]

The plan for this study has been reviewed by a Health Research Ethics Board at the University of Alberta. If you have any questions regarding your rights as a research participant or how the research is being conducted, or you want to talk to someone other than the researchers, you may contact the Research Ethics Office at 780-492-2615.

A copy of the information letter and consent form has been given to you to keep for your records and reference. The study team has kept a copy of the information letter and consent form.

Parental Consent for Child to Participate in a Research Study

Title of the Study:	Towards a Better Understanding of Childhood Apraxia of Speech: Disruptions of the Auditory and Somatosensory System
Principal Investigator:	Dr. Jacqueline Cummine, Associate Professor, University of Alberta [email] or [phone number]
Co-Investigator:	Dr. Teresa Paslawski, Associate Dean, University of Saskatchewan [email] or [phone number]
Graduate Student Researcher:	Cassidy Fleming, Speech-Language Pathologist, PhD Candidate [email] or [phone number]

	Yes	No
1. Do you understand that you have been asked to allow your child to be in a research study?	☐	☐
2. Have you read and received a copy of the study Information Letter?	☐	☐
3. Do you understand the benefits and risks (if any) involved in your child taking part in this research study?	☐	☐
4. Do you understand that your child is free to leave the study at any time without having to give a reason?	☐	☐
5. Has the issue of confidentiality been explained to you?	☐	☐
6. Do you understand who will have access to your child's information, including personally identifiable information?	☐	☐
7. Do you understand that your child will be audio- and video-recorded during the assessment and experimental sessions for analysis by the study team?	☐	☐
8. Do you understand that you and your child may ask any questions you have about the study now or in the future?	☐	☐

Who explained this study to you? ______________________________
Researcher Name

I agree to allow my child ______________________________ to participate in this study.
Child's Name

I have the legal authority to give this consent.

____

Guardian's Name Guardian's Signature Date

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to allow their child to participate.

____

Researcher's Name Researcher's Signature Date

Appendix H. Sample Information Letter and Assent Form (7-10 Years)

Title of the Study:	Towards a Better Understanding of Childhood Apraxia of Speech: Disruptions of the Auditory and Somatosensory System	
Principal Investigator:	Dr. Jacqueline Cummine	[phone number]
Co-Investigator:	Dr. Teresa Paslawski	[phone number]
Graduate Student Researcher:	Cassidy Fleming	[phone number]

We want to tell you about a graduate student research study we are doing. A research study is a way to find out new information about something.

We would like to find out more about the job of the hearing system and the mouth system when children are speaking and reading. You are being asked to join this study because you are 6 to 17 years old.

If you agree to join the study, what will you do?

e) You will be in the study for 4-6 hours on 4 separate days. The study will take place at your home and/or the University of Alberta.
f) We will ask your parent/guardian some questions to see if you are a good fit for this study.
g) We will ask your parent/guardian some questions about your background (e.g., your sex, date of birth, birth history, health history, developmental history, speech-language history, and feeding and swallowing history). They do not have to answer questions you do not want them to answer.
h) We will need you to sit at a computer and take some tests.
    a. We will have you listen to beeps to see how well you hear different sounds. This will take 15 minutes.
    b. We will look in your mouth to get information about the movement, structure, and strength of your tongue, mouth and jaw. This will take 25 minutes.
    c. We will have you repeat sounds, words and sentences. This will take 45 minutes.
    d. We will look at how well you understand language by having you point to pictures and how well you use language by having you talk. This will take 20-50 minutes.
    e. We will have you sound out printed words. This will take 10 minutes.
    f. We will look at your thinking skills by having you point to pictures and answer questions. This will take 15-25 minutes.
i) We will need you to look at a computer and do some tasks. You will repeat words you see on the computer screen, and you will push a button if you see a word that is a real word or made-up word. You will also look at pictures, and you will push a button if you see an animal or not an animal. You will do these tasks four times. This will take 45 minutes.
    a. The first time, you will just sit in front of the computer screen.
    b. The second time, we will play a noise in your ears using headphones while you do the tasks.
    c. The third time, you will do the tasks after swishing an oral numbing solution in your mouth.
    d. The fourth time, you will do the tasks after swishing an oral numbing solution in your mouth and while we play a noise in your ears using headphones.
j) We will record your voice and videotape you during the study.

You will not benefit directly from being in this study. We may learn something that will help other children with childhood apraxia of speech some day. This study may also help us learn more about how children speak and read.

You may feel worried, uneasy, or nervous during testing. You can take a break or choose not to keep going.

You will get $5.00 for each study visit. You will also get a copy of your assessment results.

You do not have to join this study. It is up to you. You can say okay now and change your mind later. All you have to do is tell us you want to stop. No one will be mad at you if you don't want to be in the study or if you join the study and change your mind later and stop.

Before you say **yes or no** to being in this study, we will answer any questions you have. If you join the study, you can ask questions at any time. Just tell the researcher that you have a question.

If you have any questions about this study, please feel free to email Cassidy Fleming.

If you decide to be in the study, then please write your name below.

Would you like to take part in this study?

☐ Yes, I will be in this research study. ☐ No, I don't want to do this.

Child's Name	Child's Signature	Date

Researcher's Name	Researcher's Signature	Date

My signature above signifies that I have discussed this research study with ______________________ using language that is understandable and appropriate for the participant. I believe that I have fully informed him/her of the nature of the study and its possible risks and benefits. I do not believe that the child feels obligated to participate or fears any negative consequences for refusing to participate. I believe the participant understood this explanation and assent to participate in this study.

Appendix I. Sample Information Letter and Assent Form (11-14 Years)

Title of the Study: Towards a Better Understanding of Childhood Apraxia of Speech: Disruptions of the Auditory and Somatosensory System

Study Investigators: Dr. Jacqueline Cummine
Associate Professor, Faculty of Rehabilitation Medicine, University of Alberta
[email] or [phone number]

Dr. Teresa Paslawski
Associate Dean, School of Rehabilitation Science, University of Saskatchewan
[email] or [phone number]

Cassidy Fleming, R.SLP
PhD Candidate, Faculty of Rehabilitation Medicine, University of Alberta
Speech-Language Pathologist
[email] or [phone number]

What is a research study?
A graduate student research study is a way to find out new information about something. Children do not need to participate in a research study if they don't want to participate

Why is the research being done?
You are being asked to take part in in this graduate student research study about the job of the hearing system when children are speaking and reading. One way to learn more about the influence of this system on speaking and reading is to measure speech production and reading performance when auditory information is removed (i.e., playing noise over headphones) and when oral sensory information is altered (i.e., using an oral numbing mouthwash).

If I join the study, what will happen to me?

a) You will be in the study for 4-6 hours over 4 days. The study will take place at your home and/or the University of Alberta.
b) We will ask your parent/guardian some questions to see if you are a good fit for this study.
c) We will ask your parent/guardian some questions about your background (e.g., your sex, date of birth, birth history, health history, developmental history, speech-language history, and feeding and swallowing history). They do not have to answer questions you do not want them to answer.
d) We will need you to sit at a computer and take some tests.
    a. We will have you listen to beeps to see how well you hear different sounds. This will take 15 minutes.
    b. We will look in your mouth to get information about the movement, structure, and strength of your tongue, mouth and jaw. This will take 25 minutes.
    c. We will have you repeat sounds, words and sentences. This will take 45 minutes.
    d. We will look at how well you understand language by having you point to pictures and how well you use language by having you talk. This will take 20-50 minutes.
    e. We will have you sound out printed words. This will take 10 minutes.
    f. We will look at your thinking skills by having you point to pictures and answer questions. This will take 15-25 minutes.
e) We will need you to look at a computer and do some tasks. You will repeat words you see on the computer screen, and you will push a button if you see a word that is a real word or made-up word. You will also look at pictures, and you will push a button if you see an animal or not an animal. You will do these tasks two times. This will take 45 minutes.
    a. The first time, you will just sit in front of the computer screen.

b. The second time, we will play a noise in your ears using headphones while you do the tasks.
c. The third time, you will do the tasks after swishing an oral numbing solution in your mouth.
d. The fourth time, you will do the tasks after swishing an oral numbing solution in your mouth and while we play a noise in your ears using headphones.

f) We will record your voice and videotape you during the study.

Will this study help me?
You will not benefit directly from being in this study. We hope that the information learned from this study will help us better understand how children speak and read.

Will any part of this study hurt?
You may feel worried, uneasy, or nervous during testing. You can take a break or choose not to keep going.

Do my parents know about this study?
We will talk to your parents about your participation in this study as well. You can talk this over with them before you decide.

Who will see the information collected about me?
The information collected about you during this study will be kept safely locked up. Nobody will see it or read it except the people doing the research. The study information about you will not be given to your parents unless you say it is okay. The researchers won't tell your friends or anyone else.

What do I get for being in the study?
You will get $5.00 for each study visit. You will also get a copy of your assessment results.

Do I have to be in the study?
You do not have to be in the study. No one will be upset if you don't want to do this study. If you don't want to be in this study, you just have to tell us. It's up to you. You can also take more time to think about being in the study.

Who can I contact if I have questions about the study?
You can ask any questions that you may have about the study. If you have a question later that you didn't think of now, either you can call or have your parents call or email Cassidy Fleming. You can also take more time to think about being in the study and also talk some more with your parents about being in the study.

If you have any questions regarding your rights as a study participant or how the research is being conducted, or you want to talk to someone other than the researchers, you may contact the University of Alberta Research Ethics Office at 780-492-2615.

A copy of the information letter and assent form has been given to you to keep. The study team has kept a copy of the information letter and assent form.

Assent to Participate in a Research Study

Title of the study: Towards a Better Understanding of Childhood Apraxia of Speech: Disruptions of the Auditory and Somatosensory System

Investigators: Cassidy Fleming (R.SLP, PhD Candidate), Dr. Jacqueline Cummine, and Dr. Teresa Paslawski

Email Address(es):

Phone Number(s):

Signatures

If you decide to be in the study, then please write your name below. You can change your mind and stop being part of the study at any time. All you have to do is tell the person in charge. It's okay. The researchers and your parents won't be upset with you

Would you like to take part in this study?

☐ Yes, I will be in this research study. ☐ No, I don't want to do this.

Child's Name	Child's Signature	Date

Researcher's Name	Researcher's Signature	Date

My signature above signifies that I have discussed this research study with _______________________ using language that is understandable and appropriate for the participant. I believe that I have fully informed him/her of the nature of the study and its possible risks and benefits. I do not believe that the child feels obligated to participate or fears any negative consequences for refusing to participate. I believe the participant understood this explanation and assent to participate in this study.

Appendix J. Sample Information Letter and Consent Form (15-17 Years)

Title of the Study: Towards a Better Understanding of Childhood Apraxia of Speech: Disruptions of the Auditory and Somatosensory System

Study Investigators:
Dr. Jacqueline Cummine
Associate Professor, Faculty of Rehabilitation Medicine, University of Alberta
[email] or [phone number]

Dr. Teresa Paslawski
Associate Dean, School of Rehabilitation Science, University of Saskatchewan
[email] or [phone number]

Cassidy Fleming, R.SLP
PhD Candidate, Faculty of Rehabilitation Medicine, University of Alberta
Speech-Language Pathologist
[email] or [phone number]

Why am I being asked to take part in this research study? You are being asked to be in this graduate student research study about the role of the hearing system (or the auditory system) and the mouth system (or the oral sensory system) in speaking and reading in children.

This form contains information about the study. Before you read it, a member of the study team will explain the study to you in detail. You are free to ask questions if there is anything you do not understand. You will be given a copy of this form for your records.

What is the reason for doing the study? From this research we wish to learn more about the influence of the hearing system on speaking and reading. One way to learn more about this is to measure speech and reading performance in normal conditions and when hearing information is masked (i.e., by playing noise over headphones) or when oral sensory information is altered (i.e., using an oral numbing mouthwash).

What will I be asked to do while I am in the study? If you wish to participate in this study, you will be asked to participate in four online sessions that will take approximately 1-1.5 hours to complete (4-6 hours total). The study team will send you email or text reminders before your study visits if requested. You will be asked to do the following:

k) Read and complete a pre-screening survey to see if you are eligible to take part in the study. This should take approximately 5 minutes to complete. The survey will be reviewed by the study team and you will be contacted if you are eligible.
l) Have your parent/guardian read and complete a demographic and history survey. This should take them approximately 30 minutes to complete. They do not have to answer any questions that they/you do not want to answer.
m) You will then take part in an assessment. The assessment should take approximately 2-3 hours to complete and you can complete it over multiple days in a 3-week period. The assessment will include:
    a. A hearing screening (i.e., listening to beeps) to see how well you hear different sounds. If you do not pass this screening, then you will be withdrawn from the study. This will take approximately 15 minutes.
    b. An oral exam to get information about the movement, structure, and strength of your child's tongue, mouth and jaw. This will take approximately 25 minutes.
    c. An assessment of your speech (i.e., repeating sounds, words and sentences). This will take approximately 45 minutes.
    d. An assessment of your understanding and use of language (i.e., pointing to pictures, putting together phrases and sentences). This will take approximately 20-50 minutes.

e. An assessment of your ability to sound out printed words (i.e., reading familiar and unfamiliar words) This will take approximately 10 minutes.
f. An assessment of your verbal and non-verbal thinking skills (i.e., pointing to pictures or answering questions). This will take approximately 15-25 minutes.

n) You will then take part in two experiments. Each experiment should take you approximately 30-45 minutes to complete. You will be seated in front of your computer and will complete several tasks which include 1) repeating unfamiliar syllables, 2) repeating familiar words, 3) making a decision about a series of letters (i.e., "is the stimulus a word or a nonword?) and 4) making a decision about pictures (i.e., "is the picture of an animal or not?"). We will ask you to do these tasks two times.
   a. The first time, you will do the tasks with no changes to their hearing.
   b. The second time, we will play a noise in your ears using headphones while you do the tasks.
   c. The third time, you will do the tasks after swishing an oral numbing solution in your mouth.
   d. The fourth time, you will do the tasks after swishing an oral numbing solution in your mouth and while we play a noise in your ears using headphones.

What are the benefits to me? You will not benefit directly from being in this study. We hope that the information learned from this study will help us better understand the role of the hearing system in speech and reading and can be used in the future to benefit children with childhood apraxia of speech.

Will any part of this study hurt? You may experience anxiety or psychological stress during testing. If you experience these symptoms, you may ask for a break or choose to stop participating.

Confidentiality and Anonymity: During this study we will be collecting information (or "study data") about you. We will use the data to help answer research questions. The information that you will share will remain strictly confidential and will be used solely for the purposes of this research. The only people who will have access to the research data are the study team.

What data will we be collecting? During this study we will be collecting study data about you. Examples of the types of data we may collect about you include your: name, address, ethnic background, data of birth, age, health conditions, health history, medications, education history, and speech, language, hearing, feeding and swallowing histories. We will also collect data on your current speech, language, cognitive, hearing, and reading abilities, as well as your speech and reading abilities in normal conditions and when the hearing system is altered. Finally, we will collect information on your parent/guardians including their age, education, occupation and household income. We will get this information by asking you and your parent/guardian to answer questions and doing the tests outlined in this form. Identifying information will be stored separately in file, and not with the study data.

How will the study data be stored? The study data we collect will be securely stored by the study team during and after the study. Paper surveys will be kept in a locked filing cabinet in the office of the principal investigator at the University of Alberta for a minimum period of 5 years. Electronic copies of the survey will be encrypted and stored on a password protected computer in the department of Communication Sciences and Disorders at the University of Alberta for a minimum period of 5 years.

How will the study data be used? Your study data will be coded (with a number) so that it no longer contains your name, address or anything else that could identify you. Identifying information (including the demographic and history survey) will be stored separately in file, and not with the study data. Only the study team will be able to link your coded study data to you. Your study data will only be looked at by members of the research team.

When the study is done, the data will be anonymized (i.e., there will be no way to link it back to you ever). The coded <u>written</u> data may be presented, published, and/or reported in a dissertation. The audio- and video-recordings will not be shared in presentations. Results will be published in pooled (aggregate) format. Your answers to open-ended questions on the demographic and history survey may be used verbatim but neither you (nor your child) will be identified. The coded data may be used to answer research questions in the future, but if we do this it will have to be approved by a Research Ethics Board.

Will I be paid to be in the study? You will receive a $5.00 honorarium for each study visit (up to a maximum of $20.00). If you choose to withdraw from the study, you will still receive compensation. You will also receive a copy of your assessment results, including the results of your hearing screening, oral exam, speech assessment, language assessment, and reading assessment. If you choose to withdraw from the study before the assessment is completed, you will not receive a copy of the assessment.

Do I have to take part in the study? You are under no obligation to participate. If you decide to be in this study, you can change your mind and stop being in the study at any time. Should you choose to withdraw midway through the study, all information/data collected will be destroyed. You can choose to have your data withdrawn from the study up to the end of the final experiment session.

What if I have questions? If you have any further questions or want more information about the research and/or your participation, you may talk to any member of the study team. Please contact:

Dr. Jacqueline Cummine	Dr. Teresa Paslawski	Cassidy Fleming
Principal Investigator	Co-Investigator	Speech-Language Pathologist
Associate Professor	Associate Dean	PhD Candidate
[email] or [phone number]	[email] or [phone number]	[email] or [phone number]

The plan for this study has been reviewed by a Health Research Ethics Board at the University of Alberta. If you have any questions regarding your rights as a research participant or how the research is being conducted, or you want to talk to someone other than the researchers, you may contact the Research Ethics Office at 780-492-2615.

A copy of the information letter and consent form has been given to you to keep for your records and reference. The study team has kept a copy of the information letter and consent form.

Consent to Participate in a Research Study

Title of the Study:	Towards a Better Understanding of Childhood Apraxia of Speech: Disruptions of the Auditory and Somatosensory System
Principal Investigator:	Dr. Jacqueline Cummine, Associate Professor, University of Alberta [email] or [phone number]
Co-Investigator:	Dr. Teresa Paslawski, Associate Dean, University of Saskatchewan [email] or [phone number]
Graduate Student Researcher:	Cassidy Fleming, Speech-Language Pathologist, PhD Candidate [email] or [phone number]

	Yes	**No**
1. Do you understand that you have been asked to be in a research study?	☐	☐
2. Have you read and received a copy of the study Information Letter?	☐	☐
3. Do you understand the benefits and risks (if any) involved in taking part in this research study?	☐	☐
4. Do you understand that you are free to leave the study at any time without having to give a reason?	☐	☐
5. Has the issue of confidentiality been explained to you?	☐	☐
6. Do you understand who will have access to your information, including personally identifiable information?	☐	☐
7. Do you understand that you will be audio- and video-recorded during the assessment and experimental sessions for analysis by the study team?	☐	☐
8. Do you understand that you may ask any questions you have about the study now or in the future?	☐	☐

Who explained this study to you? ______________________________

Researcher Name

I agree to participate in this study.

____

Participant's Name   Participant's Signature   Date

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to allow their child to participate.

____

Researcher's Name   Researcher's Signature   Date

Appendix K. Assessment Battery

Domain	Instrument	Age Range	Time*	Measures/Purpose
History	Case History Form	All	n/a	Obtain demographic and history information.
Hearing	Pure-Tone Hearing Screen	All	15 mins	Pass or fail bilateral hearing screening at 15dB in the range of 500-4000Hz
Structural-Functional Exam	Oral Mechanism Exam (OME)	Can follow simple directions	20 mins	Obtain information regarding size, strength, symmetry, range, tone steadiness, speed and accuracy of orofacial movements
	Non-Verbal Oral Apraxia (NVOA) Screen	Can attempt imitation of non-speech movements	5 mins	Presence or absence of NVOA
Motor Speech	Dynamic Evaluation of Motor Speech Skill (DEMSS) [A]	Can attempt imitation of simple words or phrases	30 mins	Vowel Accuracy Prosodic Accuracy Overall Accuracy Consistency DEMSS Total Score
Articulation/ Phonology	Goldman-Fristoe Test of Articulation (GFTA-3) [B]	2;0-21;11	5-15 mins	Sounds-in-Words Standard Score
	Khan-Lewis Phonological Analysis (KLPA-3) [C]	2;0-21;11	n/a	Standard Score Percent Occurrence Vowel Alterations
Language	Oral and Written Language Scales (OWLS-II) [D]	5;0-21;11	20-50 mins	Listening Comprehension Standard Score Oral Expression Standard Score
Reading	Test of Word Reading Efficiency (TOWRE-2) [E]	6;0-24;11	5-10 mins	Sight Word Efficiency Scaled Score Phonemic Decoding Efficiency Scaled Score Total Word Reading Efficiency Index Scaled Score
Cognition	Kaufman Brief Intelligence Test (KBIT-2) [F]	4;0-90;0	15-25 mins	Verbal Standard Score Nonverbal Standard Score IQ Composite Standard Score

* Total administration time is 115-170 minutes (1 hour 55 minutes; 2 hours 50 minutes). [A]Strand & McCauley (2019); [B]Goldman & Fristoe (2015); [C]Khan & Lewis (2015); [D]Carrow-Woolfolk (2011); [E]Torgesen et al. (2012); [F] Kaufman & Kaufman (2004)

Appendix L. Demographic and History Questionnaire

Date: ___________________	Researcher Initials: ______	Participant ID: ___________

CAS Study Demographics and Child History Questionnaire+	
1.	Sex: ☐ M ☐ F
2.	Date of Birth (mm/dd/yyyy): ____
BACKGROUND	
3.	What is your child's ethnic group? ☐ Not Hispanic or Latino ☐ Hispanic/Latino (Spanish, Mexican, Puerto Rican, Dominican, Colombian)
4.	What is your child's race (select all that apply)? ☐ Native Hawaiian or Other Pacific Islander ☐ Asian (Filipino, Korean, Laotian, Vietnamese, Japanese, Chinese) ☐ African American/Black ☐ American Indian/Alaskan Native ☐ Caucasian/White ☐ Other: ____
5.	Have any family members had any speech, language, hearing problems or learning difficulties (grandparents, parents, siblings etc.)? Speech: ☐ Yes ☐ No ☐ Don't Know Language: ☐ Yes ☐ No ☐ Don't Know Hearing: ☐ Yes ☐ No ☐ Don't Know Learning: ☐ Yes ☐ No ☐ Don't Know If "yes", please describe below (including who). If "yes" to learning difficulties, please describe the type of difficulties (e.g., reading, writing, arithmetic, etc.) ____ ____ ____
6.	Relationship of guardian 1 to the child (e.g., mother, father): ______________________
7.	What is the highest level of education obtained by guardian 1? ☐ Professional (e.g., Master, doctoral, medical, and law degrees, and the like.) ☐ 4 year college graduate (e.g., Bachelor degrees) ☐ 1-3 years college (includes business schools) ☐ High school graduate ☐ 10-11 years of school ☐ 7-9 years of school ☐ < 7 years of school

8. What is guardian 1's occupation?

____
____

9. Relationship of guardian 2 to the child (e.g., mother, father): ____________________

10. What is the highest level of education obtained by guardian 2?

- ☐ Professional (e.g., Master, doctoral, medical, and law degrees, and the like.)
- ☐ 4 year college graduate (e.g., Bachelor degrees)
- ☐ 1-3 years college (includes business schools)
- ☐ High school graduate
- ☐ 10-11 years of school
- ☐ 7-9 years of school
- ☐ < 7 years of school

11. What is guardian 2's occupation?

____
____

BIRTH HISTORY

12. Gestation age at time of delivery: _________ weeks ☐ Don't know

13. Birth weight: ________ lb ________ oz ☐ Don't know
Birth length: ________ inches OR ________ cm ☐ Don't know

14. During the delivery and birth of the child:

Were there any significant complications?

☐ Yes ☐ No ☐ Don't Know

Did the child have any medical problems at or shortly after birth?

☐ Yes ☐ No ☐ Don't Know

For any "yes" answers, please describe below.

____
____
____
____

HEALTH HISTORY

15. Has your child has any major medical problems (e.g., congenital abnormalities, disorders of the nervous, circulatory, respiratory, digestive, or musculoskeletal systems)?

☐ Yes ☐ No ☐ Don't Know

If "yes", please explain below.

____
____
____

16. Has your child ever had any vision/eye problems?

☐ Yes ☐ No ☐ Don't Know

If "yes", please explain below.

____

____

____

17. Has your child ever had any hearing problems?

☐ Yes ☐ No ☐ Don't Know

If "yes", please explain below.

____

____

____

Has your child had ear infections?

☐ Yes ☐ No ☐ Don't Know

If yes, how often? ______________________________

DEVELOPMENTAL HISTORY

18. Was English the first language your child learned to speak?

☐ Yes ☐ No

If "no", how old was your child when he/she first learned to speak English?

____

19. Does your child speak another language?

☐ Yes ☐ No

If "yes", what other languages does your child speak?

____

If "yes", has English been the primary language spoken in the home?

____

20. At what age did your child start babbling?

__________ months **or** __________ years ☐ Don't know

21. At what age did your child say his/her first words?

__________ months **or** __________ years ☐ Don't know

22. At which age did your child produce his/her first word combinations (i.e., put two or more words together) for example "mommy shoes"

__________ months **or** __________ years ☐ Don't know

23. Does your child have difficulty with any gross motor skills (i.e., the child's use of his/her body in various activities such as sitting, walking, balance, etc.)?

☐ Yes ☐ No

If "yes", please explain below.

If "yes", do these difficulties interfere with your child's daily function?

☐ Yes ☐ No

24. Does your child have difficulty with any fine motor skills (i.e., the child's use of his/her hands, including drawing, manipulating objects, using a pencil etc.)?

☐ Yes ☐ No

If "yes", please explain below.

If "yes", do these difficulties interfere with your child's daily function?

☐ Yes ☐ No

25. Handedness

☐ Right ☐ Left ☐ Mixed ☐ Not yet established

26. What is the highest level of school that your child has completed (check one):

☐ None
☐ Preschool
☐ Kindergarten
☐ 1st grade
☐ 2nd grade
☐ 3rd grade
☐ 4th grade
☐ 5th grade
☐ 6th grade
☐ 7th grade
☐ 8th grade
☐ 9th grade
☐ 10th grade
☐ 11th grade
☐ 12th grade

27. Do you ever feel your child has significant attention problems?

☐ Yes ☐ No ☐ Don't Know

28. Have any of your child's teachers ever told you your child has significant attention problems?

☐ Yes ☐ No ☐ Don't Know

29. Has your child ever been diagnosed with ADHD?

☐ Yes ☐ No ☐ Don't Know

30. Has your child ever been diagnosed with a learning problem or disorder?

☐ Yes ☐ No ☐ Don't Know

31.	Has your child ever received speech/language therapy? ☐ Yes ☐ No ☐ Don't Know If yes, please complete questions 37-41.
32.	Has your child ever been diagnosed with a hearing problem? ☐ Yes ☐ No ☐ Don't Know
33.	Has your child ever been diagnosed with any other mental, behavioral, or neurodevelopmental disorders? ☐ Yes ☐ No ☐ Don't Know
34.	Has your child ever received special tutoring or "pull-out instruction"? ☐ Yes ☐ No ☐ Don't Know
35.	Has your child ever had an Individualized Education/Program Plan (IEP/IPP)? ☐ Yes ☐ No ☐ Don't Know
36.	Has your child ever received any other evaluation or therapy (please select all that apply): Physical therapy ☐ Yes ☐ No ☐ Don't Know Occupational therapy ☐ Yes ☐ No ☐ Don't Know Counseling ☐ Yes ☐ No ☐ Don't Know Other: ____
For any "yes" answers (questions 27-36), please explain below: ____ ____ ____ ____ ____	
SPEECH-LANGUAGE HISTORY	
37.	What is your child's speech, language or communication diagnosis? ____ ____ ____ ____ ____ ____
38.	When was your child diagnosed (age of diagnosis)? _____________ years
39.	Who diagnosed your child (i.e., title such as speech-language pathologist)? ____ ____ ____ ____
40.	Is your child currently receiving speech therapy? ☐ Yes ☐ No

If “yes”:

How long as your child been in speech therapy?

____

How often does your child receive speech therapy per week (frequency)?

____

What is the length of your child’s therapy speech sessions?

____

What are your child’s current speech therapy goals?

____

If “no”:

When did your child last receive speech therapy?

____

How often was your child receiving therapy per week (frequency)?

____

What was the length of your child’s speech therapy sessions?

____

41. Has your child ever had a hearing evaluation/screening?

☐ Yes ☐ No ☐ Don't Know

If “yes”, what were you told?

____

____

FEEDING AND SWALLOWING HISTORY

42. How was your child fed as an infant?

☐ Breast ☐ Bottle ☐ Combination of breast and bottle ☐ Tube fed

43. How long did your child receive:

- Breast milk: ____
- Bottle: ____

44. Did your child have any difficulties with feeding as an infant (e.g., sucking, weight gain, sleeping cycles, temperament, feeding tube)?

☐ Yes ☐ No ☐ Don't Know

If “yes”, please explain below.

____

____

____

45.	Did your child have any difficulties transitioning from bottle to finger foods/spoon feeding? ☐ Yes ☐ No ☐ Don't Know If "yes", please explain below. ____ ____ ____
46.	At what age did your child eat from a spoon? _________ months **or** _________ years ☐ Don't know
47.	How long does a meal usually take? _________ minutes ☐ Don't know
48.	What kinds of foods does your child eat? ☐ Liquids ☐ Thickened liquids ☐ Pureed ☐ Mashed ☐ Ground ☐ Chopped ☐ Bite-sized pieces ☐ Table foods (whatever your family is eating)
49.	Does your child consume an adequate amount and variety of: Liquids: ☐ Yes ☐ No ☐ Don't Know Fruits: ☐ Yes ☐ No ☐ Don't Know Vegetables: ☐ Yes ☐ No ☐ Don't Know Grains: ☐ Yes ☐ No ☐ Don't Know Dairy: ☐ Yes ☐ No ☐ Don't Know Meats: ☐ Yes ☐ No ☐ Don't Know If "no", please explain below. ____ ____ ____
50.	Does your child take any nutritional supplements? ☐ Yes ☐ No ☐ Don't Know If "yes", please explain below. ____ ____
51.	How is your child positioned during feeding? ☐ Sitting in a chair ☐ Sitting in a wheelchair ☐ Held on lap ☐ Reclined ☐ Lying down ☐ Other (please specify): ____________________________
52.	What utensils does your child use? ☐ Bottle ☐ Spoon ☐ Sippy cup

	☐ Cup (no lid) ☐ Straw
53.	Does your child display any of the following behaviors related to feeding/swallowing? ☐ Frequent coughing/choking related to feeding ☐ Gagging/vomiting related to feeding ☐ Refusal behaviors (e.g., head turning) related to feeding ☐ Difficulty accepting foods of certain textures ☐ Difficulty chewing ☐ Holding food in mouth ☐ Difficulty chewing ☐ Noisy breathing ☐ Tongue thrust ☐ Other (please specify): ______________________________________
54.	Has your child has a swallow assessment/study completed by a speech-language pathologist? ☐ Yes ☐ No ☐ Don't Know If "yes": Where: ____ When: ____ What were the results? ____ ____ ____
55.	Additional comments or concerns related to feeding and/or swallowing? ____ ____ ____ ____ ____

+Adapted from the (1) Pediatric Imaging, Neurocognition and Genetics Study. (2011). PING study demographics and child health history version 6. Retrieved from http://ping-dataportal.ucsd.edu, (2) American Speech-Language-Hearing Association. (n.d.). Pediatric clinical assessment template (liquids, semi-solid and solid foods). Retrieved from https://www.asha.org/uploadedFiles/Pediatric-Feeding-Template-Liquid-Pureed-Solid.pdf and (3) American Speech-Language-Hearing Association. (n.d.). Swallowing and feeding team referral plan. Retrieved from https://www.asha.org/uploadedFiles/ASHA/Practice_Portal/Clinical_Topics/Pediatric_Dysphagia/Pediatric-Dysphagia-resources.pdf.

Appendix M. Hearing Screening Form

TOWARDS A BETTER UNDERSTANDING OF CHILDHOOD APRAXIA OF SPEECH			
Hearing Screening[+]			
SUBJECT STUDY ID #:	________________ (e.g., P0###)	SCREENING DATE:	___ ___ / ___ ___ ___ / ___ ___ ___ ___ d d m m m y y y y

Tester Name: ________________________________

Tester Role: ☐ SLP ☐ SLP Student

Tester Signature: _____________________________

If the parent/guardian answers 'yes' to any of the following questions, the participant should not be screened.

Does the participant have a current ear infection? ☐ Yes ☐ No
Does the participant have pain or swelling of the ear? ☐ Yes ☐ No
Does the child have drainage and/or blood from the ear? ☐ Yes ☐ No

Right Ear [Frequency (Hz)]												**Left Ear [Frequency (Hz)]**											
500			**1000**			**2000**			**4000**			**500**			**1000**			**2000**			**4000**		

(P = Pass, F = Fail)

Screening Outcome: ☐ Pass ☐ Fail

[+]Adapted from the Alberta Health Services Hearing Screening Audiology Consultation form (CH-0370).

Appendix N. Structural-Functional Oral Mechanism Exam Screening Protocol

TOWARDS A BETTER UNDERSTANDING OF CHILDHOOD APRAXIA OF SPEECH			
Orofacial Examination Task[A] with Diadochokinesis Task (DDK)[B]			
SUBJECT STUDY ID #:	________________ (e.g., P0###)	SCREENING DATE:	___ ___ / ___ ___ ___ / ___ ___ ___ ___ d d m m m y y y y

Instructions: Check and circle each item noted. Include descriptive comments in the right-hand margin.

Evaluation of Face **Comments**

_______ symmetry: normal/droops on right/droops on left ____

_______ abnormal movements: none/grimaces/spasms ____

_______ mouth breathing: yes/no ____

_______ other: ____

Evaluation of Jaw and Teeth

Tell client to open and close mouth.

_______ range of motion: normal/reduced ____

_______ symmetry: normal/deviates to right/deviates to left ____

_______ movement: normal/jerky/groping/slow/asymmetrical ____

_______ TMJ noises: absent/grinding/popping ____

_______ other: ____

Observe dentition.

_______ occlusion (molar relationship): normal/neutroclusion (Class I)/ distoclusion (Class II)/ mesioclusion (Class III)/ ____

_______ occlusion (incisor relationship): normal/overbite/underbite/crossbite ________________________

_______ teeth: all present/dentures/teeth missing (specify) ____

_______ arrangement of teeth: normal/jumbled/spaces/misaligned ________________________________

_______ hygiene: ____

_______ other: ____

Evaluation of Lips

Tell client to pucker.

_______ range of motion: normal/reduced ____

_______ symmetry: normal/droops bilaterally/droops right/droops left ________________________________

_______ strength (press tongue blade against lips): normal/weak ___________________________________

_______ other: ____

Tell client to smile.

_______ range of motion: normal/reduced ____

_______ symmetry: normal/droops bilaterally/droops right/droops left ________________________________

_______ other: ____

Tell client to puff cheeks and hold air (air leaking?).

_______ lip strength: normal/reduced ____

_______ nasal emission: absent/present ____

_______ other: ____

Evaluation of Tongue

_______ surface color: normal/abnormal (specify) ____

_______ abnormal movements: absent/jerky/spasms/writhing/fasciculations ____________________________

_______ size: normal/small/large ____

_______ frenum: normal/short ____

_______ other: ____

Tell client to protrude the tongue.

_______ excursion: normal/deviates to right/deviates to left ___________________________________

_______ range of motion: normal/reduced ____

_______ speed of motion: normal/reduced ____

_______ strength (push tongue depressor away with tongue): normal/reduced _________________________

_______ other: ____

Tell client to retract tongue.

_______ excursion: normal/deviates to right/deviates to left ___________________________________

_______ range of motion: normal/reduced ____

_______ speed of motion: normal/reduced ____

_______ other: ____

Tell client to move tongue tip to the right.

_______ excursion: normal/incomplete/groping ____

_______ range of motion (touch tongue to stick held at right side): normal/reduced ______________________

_______ strength (child pushes finger with tongue outside of cheek): normal/reduced ____________________

_______ other: ____

Tell client to move the tongue tip to the left.

_______ excursion: normal/incomplete/groping ____

_______ range of motion (touch tongue to stick held at left side): normal/reduced ______________________

_______ strength (child pushes finger with tongue outside of cheek): normal/reduced ____________________

_______ other: ____

Tell client to move the tongue tip up.

_______ movement: normal/groping ____

_______ range of motion (touch tongue to stick held at upper lip): normal/reduced ______________________

_______ other: ____

Tell client to move the tongue tip down.

_______ movement: normal/groping ____

_______ range of motion (touch tongue to stick held at lower lip): normal/reduced ______________________

_______ other: ____

Observe rapid side-to-side movements.

_______ rate: normal/reduced/slows down progressively ____

_______ range of motion: normal/reduced on left/reduced on right ______________________________

_______ other: ____

Evaluation of Pharynx:

_______ color: normal/abnormal ____

_______ tonsils: absent/normal/enlarged ____

_______ other: ____

Evaluation of Hard and Soft Palates/Respiration and Phonation:

_______ color: normal (white/pink) /abnormal ____

_______ rugae: normal/very prominent ____

_______ arch height; width: normal/high/low; normal/narrow/wide______________________________

_______ growths: absent/present (describe) ____

_______ fistula: absent/present (describe) ____

_______ clefting: absent/present (describe) ____

_______ uvula: normal/bifid/deviates right/deviates left ___________________________________

_______ gag reflex: normal/absent/hyperactive/hypoactive ______________________________

_______ other: ____

Tell client to phonate using sustained /ɑ/.

_______ symmetry of movement: normal/deviates right/deviates left __________________________

_______ nasality: absent/hypernasal ____

_______ stable pitch/intensity: ____

_______ other: ____

Tell client to phonate using intermittent, repeated /ɑ/.

_______ symmetry of movement: normal/deviates right/deviates left __________________________

_______ coordination of movement: normal/abnormal ______________________________________

_______ nasality: absent/hypernasal ____

_______ ability to control respiration and phonation: _____________________________________

_______ other: ____

Tell client to "repeat as fast and as steadily as possible". Make sure you provide a model for these tasks.

Stimulus	Number of Syllables in 5 Seconds			Sounds were Accurate?	Production was Rhythmic?
	Trial 1	Trial 2	Trial 3		
puh					
tuh					
kuh					
puhtuh					
puhkuh					
tuhkuh					
puhtuhkuh					
pattycake					

[A]*Adapted from Form 6-1 Assessment in Speech-Language Pathology: A Resource Manual, Third Edition, 2004, Delmar Learning.* [B]*Adapted from the Madison Speech Assessment Protocol (MSAP).*

Appendix O. Tasks for Assessing Nonverbal Oral Movement Control and Sequencing

TOWARDS A BETTER UNDERSTANDING OF CHILDHOOD APRAXIA OF SPEECH			
Tasks for Assessing Nonverbal Oral Movement Control and Sequencing[+]			
SUBJECT STUDY ID #:	________________ (e.g., P0###)	SCREENING DATE:	___ ___ / ___ ___ ___ / ___ ___ ___ ___ d d m m m y y y y

Instructions: Ask the patient to perform the following tasks. If he or she fails to respond to a command, use imitation. The following code can be used to score responses:

4. Accurate, immediate, effortless
3. Accurate but awkwardly or slowly produced
2. Accurate after trial and error searching movements
1. Inaccurate or only partially accurate; important component missing or off target

NR. No Response

V. Accompany or substituted vocalization or verbalization (e.g., patient says "cough" instead of coughing)

P. Perseverative response

Item	**Command**	**Imitation**
1. Cough		
2. Click your tongue		
3. Blow		
4. Bite your lower lip		
5. Puff out your cheeks		
6. Smack your lips		
7. Stick out your tongue		
8. Lick your lips		
9. Bite your lower lip and then click your tongue		
10. Smack your lips and then cough		

[+]Duffy (2005), p. 88

Appendix P. Syllable Stimuli for Speech Repetition Task

1. /aba/
2. /abi/
3. /abu/
4. /ada/
5. /adi/
6. /adu/
7. /aga/
8. /agi/
9. /agu/
10. /ibi/
11. /ibu/
12. /iba/
13. /idi/
14. /idu/
15. /ida/
16. /igi/
17. /igu/
18. /iga/
19. /ubu/
20. /uba/
21. /ubi/
22. /udu/
23. /uda/
24. /udi/
25. /ugu/
26. /uga/
27. /ugi/

Appendix Q. Sample Word Stimuli for Speech Repetition

Word List A

go	bet	heb	goke	watch	check	sirt	gurt
he	form	nup	blim	should	nurse	tuze	hilk
fast	seem	casp	carm	friend	make	pheem	koze
hang	plus	drot	cruf	young	year	shost	lish
most	deep	jize	fesk	here	coat	toard	mult
one	land	nilk	flum	light	take	spult	sish
some	skill	pibe	fraz	large	rest	yept	snum
took	start	quem	glon				

Word List B

is	tin	ket	gark	where	three	rame	tring
so	will	moz	nume	bring	cream	scaz	strit
find	bank	chon	plog	might	side	sleg	yate
head	same	fabe	spof	wood	king	bris	vode
move	near	lafe	warb	learn	feet	clus	stek
our	back	pime	zine	two	part	fibe	snan
talk	twist	heep	prost	look	pie	frit	naze
show	write	lurt	sment				

Appendix R. Sample Stimuli for Lexical Decision Tasks

Word List A

are	jay	blak	bok	wall	found	milc	trud
me	zone	gess	lem	would	white	kamp	stul
book	fine	weel	blam	come	those	gole	rabe
four	miss	fone	drid	school	song	heet	stoon
hold	note	chek	glek	earth	blew	bair	frant
much	leap	mete	lete	front	meat	brane	chish
post	street	shur	wude	know	hot	chare	shron
ton	chair	skab	vate				

Word List B

ask	beam	hed	dap	walk	speak	nyse	mupe
no	dive	durt	mig	world	hard	dait	plud
both	rose	keap	bliz	great	hole	cair	swak
from	pack	feal	dife	night	next	berd	whift
kind	life	doun	grus	has	road	layt	thulk
none	change	noze	hime	good	sky	shaip	snept
put	smile	shud	kobe	floor	pan	flore	greal
they	board	yung	lote				

Word List C

be	up	sed	fem	want	short	neel	serb
of	raw	caik	nid	touch	match	looz	sloz
bowl	mile	tirn	brev	group	voice	hoam	tork
give	just	gaim	drut	small	loud	rong	theal
last	team	hazz	hade	have	real	fome	slust
old	grip	paje	loze	first	huge	drinc	dreen
she	desk	sope	nern	love	join	focks	bloan
there	crowd	werk	pife				

Word List D

do	sum	gud	gan	work	treat	nues	skob
we	crop	bote	nop	taste	share	lize	tage
done	east	maik	boke	house	must	coph	whug
grow	race	groe	dabe	their	page	kost	twack
mind	left	kase	hish	could	wire	bern	swuim
once	joke	roal	mide	live	clue	bocks	risty
such	while	taip	plig	what	set	klaps	grold
the	count	yeer	rone				

Appendix S. MATLAB Script for Speech Repetition Task

```
function varargout = Task1(varargin)
% TASK1 MATLAB code for Task1.fig
%      TASK1, by itself, creates a new TASK1 or raises the existing
%      singleton*.
%
%      H = TASK1 returns the handle to a new TASK1 or the handle to
%      the existing singleton*.
%
%      TASK1('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in TASK1.M with the given input arguments.
%
%      TASK1('Property','Value',...) creates a new TASK1 or raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before Task1_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to Task1_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help Task1

% Last Modified by GUIDE v2.5 26-Feb-2020 13:25:49

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @Task1_OpeningFcn, ...
                   'gui_OutputFcn',  @Task1_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before Task1 is made visible.
function Task1_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to Task1 (see VARARGIN)

% Choose default command line output for Task1
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

clc
clear


% UIWAIT makes Task1 wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Nothing
function varargout = Task1_OutputFcn(hObject, eventdata, handles)

varargout{1} = handles.output;
```

```
% --- Executes on button press in whitenoise.
function whitenoise_Callback(hObject, eventdata, handles)

global whitenoise

noise = uigetfile('*.mp4','Select the Audio File');
[y,Fs] = audioread(noise);
whitenoise = audioplayer(y,Fs);
set(handles.checkbox2,'Value', 1);


% --- Executes on button press in graphics.
function graphics_Callback(hObject, eventdata, handles)

global A B C

folder = uigetdir('C:','Select the path for the graphics files');
files = dir([folder,'/*.PNG']);
num = length(files(not([files.isdir])));

farray = cell(num,1);
audio = cell(num,1);
for i = 1:num
   farray{i} = files(i).name;
end
fnames=natsortfiles(farray);

A = imread(char(fnames(2)));
B = imread(char(fnames(3)));
C = imread(char(fnames(1)));


% --- Executes on button press in audio.
function audio_Callback(hObject, eventdata, handles)

global num audio Fs fnames

folder = uigetdir('C:','Select the path for the audio files');
files = dir([folder,'/*.mp4']);
num = length(files(not([files.isdir])));

farray = cell(num,1);
audio = cell(num,1);
for i = 1:num
   farray{i} = files(i).name;
end
fnames=natsortfiles(farray);
for i = 1:num
   [y,Fs]=audioread([folder,'/',fnames{i}]);
   audio{i}=y(:,1);
end
set(handles.checkbox1,'Value',1)


% --- Executes on button press in start.
function start_Callback(hObject, eventdata, handles)

global num counter A B C t1 t2 t3 t4 t5 cond whitenoise ButtonPressTime order audio Fs recording Trial...
         Word WhiteNoiseTime GreenLightTime Fsr started

date_Callback(hObject, eventdata, handles)

started = 0;
Fsr = 44100;
order = randperm(num);
Word = string(zeros(num,1));
Trial = [1:num]';
counter = 1;
ButtonPressTime = zeros(num,1);
WhiteNoiseTime = zeros(num,1);
GreenLightTime = zeros(num,1);

t1 = 2;    % 0.5
```

```
t2 = 2;     % 1
t3 = [2000,3000];    % [300,500] GreenLightTime
t4 = [2000,3000];    % [800,1700] WhiteNoiseTime
t5 = 0.5;   % extra space after red light appears before recording plays

imshow(C) % show cross
pause(t1)
imshow(B) % show red light
pause(t5) % half second pause
sound(audio{order(counter)},Fs)    % plays audio
pause(t2)   % extra pause - makes spacing better

WNtime = randi([t4])/1000;
pause(WNtime);
WhiteNoiseTime(counter) = WNtime;

   if cond == 2
      play(whitenoise)
   elseif cond == 4
      play(whitenoise)
   else
   end

GLTime = randi([t3])/1000;
pause(GLTime);
GreenLightTime(counter) = GLTime;

imshow(A)
tic;
started = 1;

recording = audiorecorder(Fsr,16,1);

record(recording);  % record


% --- Executes on selection change in condition.
function condition_Callback(hObject, eventdata, handles)

global cond
cond = get(handles.condition, 'Value');


% --- Nothing
function condition_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
   set(hObject,'BackgroundColor','white');
end


% --- Nothing
function word_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
   set(hObject,'BackgroundColor','white');
end


% --- Nothing
function checkbox1_Callback(hObject, eventdata, handles)


% --- Nothing
function checkbox2_Callback(hObject, eventdata, handles)


% --- Executes on button press in response.
function response_Callback(hObject, eventdata, handles)

global ButtonPressTime counter t1 t2 t3 t4 t5 A B C whitenoise num cond order audio Fs Trial...
   fnames Word recording PN SN WhiteNoiseTime GreenLightTime Fsr started

if started == 1
elapsedtime = toc;
```

```
ButtonPressTime(counter) = elapsedtime;
Word(counter) = fnames(order(counter));


stop(recording)                    % record
recaud{counter} = getaudiodata(recording);     % record

% Trial
    if cond == 2
        condition = 'WN';
    elseif cond == 3
        condition = 'NWN';
    elseif cond == 4
        condition = 'Somat+WN';
    elseif cond == 5
        condition = 'Somat+NWN';
    else
    end
    dateandtime = get(handles.date,'String');
    name = 'Recording%i_Participant%03d_Session%03d_REP_%s_%s.wav';
    name1 = sprintf(name,counter,PN,SN,condition,dateandtime);
    audiowrite(name1,recaud{counter},Fsr);

stop(whitenoise)
started = 0;

if counter < num
    counter = counter + 1;
    pause(t2)
    imshow(C)
    pause(t1)
    imshow(B)
    pause(t5)
    sound(audio{order(counter)},Fs);% plays audio
    pause(t2)   % extra pause - makes spacing better

    WNtime = randi([t4])/1000;
    pause(WNtime);
    WhiteNoiseTime(counter) = WNtime;

    if cond == 2
      resume(whitenoise)
    elseif cond == 4
      resume(whitenoise)
    else
    end

    GLTime = randi([t3])/1000;
    pause(GLTime);
    GreenLightTime(counter) = GLTime;

    imshow(A)
    tic;
    started = 1;

    recording = audiorecorder(Fsr,16,1);

    record(recording);  % record

else
    sentence = 'Good Work! Close window and select Start to try again.';

    ParticipantNumber = string(zeros(num,1));
        for i = 1:num
            ParticipantNumber(i) = PN;
        end
    SessionNumber = zeros(num,1);
        for i = 1:num
            SessionNumber(i) = SN;
        end
    Task = string(zeros(num,1));
        for i = 1:num
            Task(i) = 'REP';
        end
    Condition = string(zeros(num,1));
```

```
        for i = 1:num
            Condition(i) = condition;
        end

    filename = 'Participant%03d_Session%03d_REP_%s_%s.txt';
    filename1 = sprintf(filename,PN,SN,condition,dateandtime);

    Results = table(ParticipantNumber,SessionNumber,Task,Condition,Trial,Word,WhiteNoiseTime,GreenLightTime,ButtonPressTime);
    writetable(Results, filename1);
    msgbox(sentence,'Complete!');
end
end


% --- Executes on key press with focus on figure1 or any of its controls.
function figure1_WindowKeyPressFcn(hObject, eventdata, handles)

switch eventdata.Key
    case 'n'
        response_Callback(hObject, eventdata, handles)
    otherwise
end


function parnum_Callback(hObject, eventdata, handles)

global PN

partnum = get(handles.parnum, 'String');
PN = str2num(partnum);


function sesnum_Callback(hObject, eventdata, handles)

global SN

sessnum = get(handles.sesnum, 'String');
SN = str2num(sessnum);


function date_Callback(hObject, eventdata, handles)

nowdate = datestr(now, 'mm_dd_yyyy_HHMM');
set(handles.date, 'String', nowdate);


% --- Executes during object creation, after setting all properties.
function date_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

Appendix T. MATLAB Script for Orthographic and Phonological Lexical Decision Tasks

```
function varargout = Task2Rev2(varargin)
% TASK2REV2 MATLAB code for Task2Rev2.fig
%      TASK2REV2, by itself, creates a new TASK2REV2 or raises the existing
%      singleton*.
%
%      H = TASK2REV2 returns the handle to a new TASK2REV2 or the handle to
%      the existing singleton*.
%
%      TASK2REV2('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in TASK2REV2.M with the given input arguments.
%
%      TASK2REV2('Property','Value',...) creates a new TASK2REV2 or raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before Task2Rev2_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to Task2Rev2_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help Task2Rev2

% Last Modified by GUIDE v2.5 26-Feb-2020 10:37:41

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @Task2Rev2_OpeningFcn, ...5
                   'gui_OutputFcn',  @Task2Rev2_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before Task2Rev2 is made visible.
function Task2Rev2_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to Task2Rev2 (see VARARGIN)

% Choose default command line output for Task2Rev2
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

clear
clc

% UIWAIT makes Task2Rev2 wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = Task2Rev2_OutputFcn(hObject, eventdata, handles)

varargout{1} = handles.output;
```

```
% --- No output
function word_Callback(hObject, eventdata, handles)


% --- Executes during object creation, after setting all properties.
function word_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in wordfile.
function wordfile_Callback(hObject, eventdata, handles)

global num text answer docname
folder = uigetfile('*.xlsx','Select the Excel File Containing the Words');
docname = folder;
[answer,text] = xlsread(folder);
num = length(text);


% --- Executes on button press in noisefile.
function noisefile_Callback(hObject, eventdata, handles)

global p
noise = uigetfile('*.MP3','Select the Audio File');
[y,Fs] = audioread(noise);
p = audioplayer(y,Fs);
set(handles.checkbox1,'Value', 1);


% --- Executes on button press in start.
function start_Callback(hObject, eventdata, handles)

global num cond counter p text order time correct incorrect t1 t2 t3 t4 ReactionTime Word Trial...
        Response Accuracy WhiteNoiseTime WordTime started

date_Callback(hObject, eventdata, handles) % gets date

order = randperm(num);
ReactionTime = zeros(num,1);
Word = string(zeros(num,1));
Response = string(zeros(num,1));
WhiteNoiseTime = zeros(num,1);
WordTime = zeros(num,1);
Trial = [1:num]';
Accuracy = string(zeros(num,1));
counter = 1;
time = 0;
correct = 0;
incorrect = 0;
started = 0;

t1 = 2;   % 0.5 cross fixation
t2 = 2;     % 1 ISI
t3 = [2000,3000];    % [800,1700] WhiteNoiseTime
t4 = [2000,3000];     % [300,500] WordTime

set(handles.word,'string','')
pause(t2)
set(handles.word,'FontSize',300)
set(handles.word,'string','+')
pause(t1)
set(handles.word,'string','')
set(handles.word,'FontSize',30)

WNtime = randi([t3])/1000;
pause(WNtime);
WhiteNoiseTime(counter) = WNtime;

    if cond == 2
      play(p)
    elseif cond == 4
```

```
      play(p)
    else
    end

    WTime = randi([t4])/1000;
    pause(WTime);
    WordTime(counter) = WTime;

set(handles.word,'string',text{order(counter)})
tic;
started = 1;


% --- Executes on selection change in condition.
function condition_Callback(hObject, eventdata, handles)

global cond
cond = get(handles.condition, 'Value');


% --- Executes during object creation, after setting all properties.
function condition_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in real.
function real_Callback(hObject, eventdata, handles)

global counter num p cond text order answer t1 t2 t3 t4 ReactionTime Word Response Trial...
            Accuracy WhiteNoiseTime WordTime PN SN docname started

if started == 1
elapsedtime = toc;
ReactionTime(counter) = elapsedtime;
Word(counter) = text(order(counter));
Response(counter) = 'Word';

stop(p)

if answer(order(counter)) == 1
    Accuracy(counter) = 'Yes';
else
    Accuracy(counter) = 'No';
end

started = 0;
set(handles.word,'string', '')
if counter < num
    counter = counter + 1;
    pause(t2)
    set(handles.word,'FontSize',300)
    set(handles.word,'string', '+')
    pause(t1)
    set(handles.word,'string','')
    set(handles.word,'FontSize',30)
    WNtime = randi([t3])/1000;
    pause(WNtime);
    WhiteNoiseTime(counter) = WNtime;

    if cond == 2
        resume(p)
    elseif cond == 4
        resume(p)
    else
    end

    WTime = randi([t4])/1000;
    pause(WTime);
    WordTime(counter) = WTime;

    set(handles.word,'string',text{order(counter)})
    tic;
```

```
    started = 1;
else
    sentence = 'Good Work! Close window and select Start to try again.';

        if cond == 2
            condition = 'WN';
        elseif cond == 3
            condition = 'NWN';
        elseif cond == 4
            condition = 'Somat+WN';
        elseif cond == 5
            condition = 'Somat+NWN';
        else
        end

    ParticipantNumber = string(zeros(num,1));
        for i = 1:num
            ParticipantNumber(i) = PN;
        end
    SessionNumber = zeros(num,1);
        for i = 1:num
            SessionNumber(i) = SN;
        end
    Task = string(zeros(num,1));
        for i = 1:num
            Task(i) = 'LDT';
        end
    Condition = string(zeros(num,1));
        for i = 1:num
            Condition(i) = condition;
        end

    dateandtime = get(handles.date,'String');
    filename = 'Participant%03d_Session%03d_LDT_%s_%s_%s.txt';
    filename1 = sprintf(filename,PN,SN,condition,docname,dateandtime);

    Results = table(ParticipantNumber, SessionNumber, Task, Condition,Trial, Word, Response, WhiteNoiseTime, WordTime, ReactionTime,Accuracy);
    writetable(Results,filename1);
    msgbox(sentence,'Complete!');
end
end


% --- Executes on button press in nonreal.
function nonreal_Callback(hObject, eventdata, handles)

global counter num p cond text order answer t1 t2 t3 t4 ReactionTime Word Response Trial...
                Accuracy WhiteNoiseTime WordTime PN SN docname started

if started == 1
elapsedtime = toc;
ReactionTime(counter) = elapsedtime;
Word(counter) = text(order(counter));
Response(counter) = 'Non-word';

stop(p)

    if answer(order(counter)) == 0
        Accuracy(counter) = 'Yes';
    else
        Accuracy(counter) = 'No';
    end

started = 0;
set(handles.word,'string', '')
if counter < num
    counter = counter + 1;
    pause(t2)
    set(handles.word,'FontSize',300)
    set(handles.word,'string', '+')
    pause(t1)
    set(handles.word,'string','')
    set(handles.word,'FontSize', 30)
    WNtime = randi([t3])/1000;
    pause(WNtime);
```

```
    WhiteNoiseTime(counter) = WNtime;

    if cond == 2
      resume(p)
    elseif cond == 4
      resume(p)
    end

    WTime = randi([t4])/1000;
    pause(WTime);
    WordTime(counter) = WTime;

    set(handles.word,'string',text{order(counter)})
    tic;
    started = 1;
else
    sentence = 'Good Work! Close window and select Start to try again.';

        if cond == 2
            condition = 'WN';
        elseif cond == 3
            condition = 'NWN';
        elseif cond == 4
            condition = 'Somat+WN';
        elseif cond == 5
            condition = 'Somat+NWN';
        else
        end

    ParticipantNumber = string(zeros(num,1));
        for i = 1:num
            ParticipantNumber(i) = PN;
        end
    SessionNumber = zeros(num,1);
        for i = 1:num
            SessionNumber(i) = SN;
        end
    Task = string(zeros(num,1));
        for i = 1:num
            Task(i) = 'LDT';
        end
    Condition = string(zeros(num,1));
        for i = 1:num
            Condition(i) = condition;
        end

    dateandtime = get(handles.date,'String');
    filename = 'Participant%03d_Session%03d_LDT_%s_%s_%s.txt';
    filename1 = sprintf(filename,PN,SN,condition,docname,dateandtime);

    Results = table(ParticipantNumber, SessionNumber, Task, Condition,Trial, Word, Response, WhiteNoiseTime, WordTime, ReactionTime,Accuracy);
    writetable(Results,filename1);
    msgbox(sentence,'Complete!');
end
end


% --- Executes on button press in checkbox1.
function checkbox1_Callback(hObject, eventdata, handles)


function figure1_WindowKeyPressFcn(hObject, eventdata, handles)

switch eventdata.Key
    case 'b'
        real_Callback(hObject, eventdata, handles)
    case 'n'
        nonreal_Callback(hObject, eventdata, handles)
    otherwise
end


% code for participant number
function parnum_Callback(hObject, eventdata, handles)
```

```
global PN

partnum = get(handles.parnum, 'String');
PN = str2num(partnum);

% --- Executes during object creation, after setting all properties.
function parnum_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% code for session number
function sesnum_Callback(hObject, eventdata, handles)

global SN

sessnum = get(handles.sesnum, 'String');
SN = str2num(sessnum);



% --- Executes during object creation, after setting all properties.
function sesnum_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


function date_Callback(hObject, eventdata, handles)

nowdate = datestr(now, 'mm_dd_yyyy_HHMM');
set(handles.date, 'String', nowdate);


% --- Executes during object creation, after setting all properties.
function date_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

Appendix U. MATLAB Script for Picture Categorization Task

```
function varargout = Task3(varargin)
% TASK3 MATLAB code for Task3.fig
%      TASK3, by itself, creates a new TASK3 or raises the existing
%      singleton*.
%
%      H = TASK3 returns the handle to a new TASK3 or the handle to
%      the existing singleton*.
%
%      TASK3('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in TASK3.M with the given input arguments.
%
%      TASK3('Property','Value',...) creates a new TASK3 o r raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before Task3_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to Task3_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help Task3

% Last Modified by GUIDE v2.5 13-Aug-2020 11:47:21

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @Task3_OpeningFcn, ...
                   'gui_OutputFcn',  @Task3_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before Task3 is made visible.
function Task3_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to Task3 (see VARARGIN)

% Choose default command line output for Task3
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes Task3 wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = Task3_OutputFcn(hObject, eventdata, handles)

varargout{1} = handles.output;


% --- Executes on button press in imagefile.
```

```
function imagefile_Callback(hObject, eventdata, handles)

global num fnames

folder = uigetdir('C:','Select the path for the graphics files');
files = dir([folder,'/*.JPG']);
num = length(files(not([files.isdir])));

farray = cell(num,1);
audio = cell(num,1);
for i = 1:num
    farray{i} = files(i).name;
end
fnames=natsortfiles(farray);




% --- Executes on button press in noisefile.
function noisefile_Callback(hObject, eventdata, handles)

global p

noise = uigetfile('*.MP3','Select the Audio File');
[y,Fs] = audioread(noise);
p = audioplayer(y,Fs);
set(handles.checkbox1,'Value', 1);


% --- Executes on selection change in condition.
function condition_Callback(hObject, eventdata, handles)

global cond

cond = get(handles.condition, 'Value');

% --- Executes during object creation, after setting all properties.
function condition_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


function parnum_Callback(hObject, eventdata, handles)

global PN

partnum = get(handles.parnum, 'String');
PN = str2num(partnum);


% --- Executes during object creation, after setting all properties.
function parnum_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


function sesnum_Callback(hObject, eventdata, handles)

global SN

sessnum = get(handles.sesnum, 'String');
SN = str2num(sessnum);


% --- Executes during object creation, after setting all properties.
function sesnum_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

```
% --- Executes on button press in start.
function start_Callback(hObject, eventdata, handles)

global num cond counter p order time correct incorrect t1 t2 t3 t4 ReactionTime Image Trial...
        Response Accuracy WhiteNoiseTime ImageTime A fnames started

date_Callback(hObject, eventdata, handles) % gets date

order = randperm(num);
ReactionTime = zeros(num,1);
Image = string(zeros(num,1));
Response = string(zeros(num,1));
WhiteNoiseTime = zeros(num,1);
ImageTime = zeros(num,1);
time = zeros(num,1);
Trial = [1:num]';
Accuracy = string(zeros(num,1));
counter = 1;
time = 0;
correct = 0;
incorrect = 0;
started = 0;

t1 = 2;   % 0.5 cross fixation
t2 = 2;   % 1 ISI
t3 = [2000,3000];    % [800,1700] WhiteNoiseTime
t4 = [2000,3000];     % [300,500] ImageTime


pause(t2)
imshow(A) % displays cross image
pause(t1)
cla(handles.image, 'reset')
set(handles.image, 'XColor', [0.94 0.94 0.94])
set(handles.image, 'YColor', [0.94 0.94 0.94])


WNtime = randi([t3])/1000;
pause(WNtime);
WhiteNoiseTime(counter) = WNtime;

   if cond == 2
     play(p)
   elseif cond == 4
     play(p)
   else
   end

   WTime = randi([t4])/1000;
   pause(WTime);
   ImageTime(counter) = WTime;

imshow(imread(char(fnames(order(counter))))) % show image of interest
tic;
started = 1;


% --- Executes on button press in checkbox1.
function checkbox1_Callback(hObject, eventdata, handles)


% --- Executes on button press in real.
function real_Callback(hObject, eventdata, handles)

global counter num p cond order answer t1 t2 t3 t4 ReactionTime Image Response Trial...
           Accuracy WhiteNoiseTime ImageTime PN SN docname A fnames started

if started == 1
elapsedtime = toc;
ReactionTime(counter) = elapsedtime;
Image(counter) = fnames(order(counter));
Response(counter) = 'Animal';

stop(p)
```

```
if strcmp(char(fnames(order(counter))),'Alligator003 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Bear021 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Bird028 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Cat049 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Cow068 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Deer071 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Dog073 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Duck081 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Fish089 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Fly093 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Fox098 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Frog100 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Giraffe103 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Gorilla108 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Horse121 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Lion140 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Lobster142 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Monkey145 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Mouse149 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Ostrich159 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Racoon183 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Rooster191 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Seahorse200 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Sheep202 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Snake209 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Swan223 .jpg') == 1
    Accuracy(counter) = 'Yes';
elseif strcmp(char(fnames(order(counter))),'Tiger233 .jpg') == 1
    Accuracy(counter) = 'Yes';
else
    Accuracy(counter) = 'No';
end

started = 0;
cla(handles.image, 'reset')
set(handles.image, 'XColor', [0.94 0.94 0.94])
set(handles.image, 'YColor', [0.94 0.94 0.94])
if counter < num
    counter = counter + 1;
    pause(t2)
    imshow(A) % displays cross
    pause(t1)
    cla(handles.image, 'reset')
    set(handles.image, 'XColor', [0.94 0.94 0.94])
    set(handles.image, 'YColor', [0.94 0.94 0.94])
    WNtime = randi([t3])/1000;
    pause(WNtime);
    WhiteNoiseTime(counter) = WNtime;
```

```
    if cond == 2
        resume(p)
    elseif cond == 4
        resume(p)
    else
    end

    WTime = randi([t4])/1000;
    pause(WTime);
    ImageTime(counter) = WTime;

    imshow(imread(char(fnames(order(counter))))) % show image of interest
    tic;
    started = 1;
else
    sentence = 'Good Work! Close window and select Start to try again.';

        if cond == 2
            condition = 'WN';
        elseif cond == 3
            condition = 'NWN';
        elseif cond == 4
            condition = 'Somat+WN';
        elseif cond == 5
            condition = 'Somat+NWN';
        else
        end

    ParticipantNumber = string(zeros(num,1));
        for i = 1:num
            ParticipantNumber(i) = PN;
        end
    SessionNumber = zeros(num,1);
        for i = 1:num
            SessionNumber(i) = SN;
        end
    Task = string(zeros(num,1));
        for i = 1:num
            Task(i) = 'PC';
        end
    Condition = string(zeros(num,1));
        for i = 1:num
            Condition(i) = condition;
        end

    dateandtime = get(handles.date,'String');
    filename = 'Participant%03d_Session%03d_LDT_%s_%s_%s.txt';
    filename1 = sprintf(filename,PN,SN,condition,docname,dateandtime);

    Results = table(ParticipantNumber, SessionNumber, Task, Condition,Trial, Image, Response, WhiteNoiseTime, ImageTime, ReactionTime,Accuracy);
    writetable(Results,filename1);
    msgbox(sentence,'Complete!');
end
end


function nonreal_Callback(hObject, eventdata, handles)

global counter num p cond text order answer t1 t2 t3 t4 ReactionTime Image Response Trial...
        Accuracy WhiteNoiseTime ImageTime PN SN docname A fnames started

if started == 1
elapsedtime = toc;
ReactionTime(counter) = elapsedtime;
Image(counter) = fnames(order(counter));
Response(counter) = 'Non-Animal';

stop(p)

if strcmp(char(fnames(order(counter))),'Alligator003 .jpg') == 1
    Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Bear021 .jpg') == 1
    Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Bird028 .jpg') == 1
    Accuracy(counter) = 'No';
```

```
elseif strcmp(char(fnames(order(counter))),'Cat049 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Cow068 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Deer071 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Dog073 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Duck081 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Fish089 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Fly093 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Fox098 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Frog100 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Giraffe103 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Gorilla108 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Horse121 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Lion140 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Lobster142 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Monkey145 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Mouse149 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Ostrich159 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Racoon183 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Rooster191 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Seahorse200 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Sheep202 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Snake209 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Swan223 .jpg') == 1
   Accuracy(counter) = 'No';
elseif strcmp(char(fnames(order(counter))),'Tiger233 .jpg') == 1
   Accuracy(counter) = 'No';
else
   Accuracy(counter) = 'Yes';
end

started = 0;
cla(handles.image, 'reset')
set(handles.image, 'XColor', [0.94 0.94 0.94])
set(handles.image, 'YColor', [0.94 0.94 0.94])
if counter < num
   counter = counter + 1;
   pause(t2)
   imshow(A) % displays cross image
   pause(t1)
   cla(handles.image, 'reset')
   set(handles.image, 'XColor', [0.94 0.94 0.94])
   set(handles.image, 'YColor', [0.94 0.94 0.94])
   WNtime = randi([t3])/1000;
   pause(WNtime);
   WhiteNoiseTime(counter) = WNtime;

   if cond == 2
     resume(p)
   elseif cond == 4
     resume(p)
   end

   WTime = randi([t4])/1000;
```

```
    pause(WTime);
    ImageTime(counter) = WTime;

    imshow(imread(char(fnames(order(counter))))) % show image of interest
    tic;
    started = 1;
else
    sentence = 'Good Work! Close window and select Start to try again.';

        if cond == 2
            condition = 'WN';
        elseif cond == 3
            condition = 'NWN';
        elseif cond == 4
            condition = 'Somat+WN';
        elseif cond == 5
            condition = 'Somat+NWN';
        else
        end

    ParticipantNumber = string(zeros(num,1));
        for i = 1:num
            ParticipantNumber(i) = PN;
        end
    SessionNumber = zeros(num,1);
        for i = 1:num
            SessionNumber(i) = SN;
        end
    Task = string(zeros(num,1));
        for i = 1:num
            Task(i) = 'PC';
        end
    Condition = string(zeros(num,1));
        for i = 1:num
            Condition(i) = condition;
        end

    dateandtime = get(handles.date,'String');
    filename = 'Participant%03d_Session%03d_LDT_%s_%s_%s.txt';
    filename1 = sprintf(filename,PN,SN,condition,docname,dateandtime);

    Results = table(ParticipantNumber, SessionNumber, Task, Condition,Trial, Image, Response, WhiteNoiseTime, ImageTime, ReactionTime, Accuracy);
    writetable(Results,filename1);
    msgbox(sentence,'Complete!')
end
end


function figure1_WindowKeyPressFcn(hObject, eventdata, handles)

switch eventdata.Key
    case 'b'
        real_Callback(hObject, eventdata, handles)
    case 'n'
        nonreal_Callback(hObject, eventdata, handles)
    otherwise
end

function date_Callback(hObject, eventdata, handles)

nowdate = datestr(now, 'mm_dd_yyyy_HHMM');
set(handles.date, 'String', nowdate);


% --- Executes during object creation, after setting all properties.
function date_CreateFcn(hObject, eventdata, handles)

if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on button press in cross.
function cross_Callback(hObject, eventdata, handles)
```

```
global A

folder = uigetfile('*.png','Select the cross graphic');
A = imread(folder);
```

Appendix V: Calculations

Obtained from Terband et al. (2009), p. 1608-1609

Legend for Calculations

Parameter/function	Description
CA	Coarticulation index
VAR	Variability index
V_{1_j} $j = \{/a/,/i/,/u/\}$	Vowel 1
C_k $k = \{/b/,/d/,/g/\}$	Consonant
V_{2_l} $l = \{/a/,/i/,/u/\}$	Vowel 2
$W_{j,k,l} = \left\{V_{1_j}, C_k, V_{2_l}\right\}$	W = list of all possible words (e.g. $W_{1,1,1}$ is /aba/; $W_{2,k,l}$ are all words beginning with /i/.)
$S = \left\{V_{1_j}, C_k, V_{2_l}\right\}$	S = list of all speech sounds
$F_{i,m}\left(S\langle W_{j,k,l}\rangle\right)$ $i = \{F1, F2, F3\}$ $m = \{beginning, middle, end\}$	Formant i at measurement point m of speech sound S in the context of word W. (Note that the formant values measured in Hz were normalized using a log10(x)-transformation.)
$StDev = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x}^2)}{n-1}}$	Standard deviation of set x with number of elements n

Calculations

Mean formant frequency

$$V_1: F_i\left(V_{1_j}\langle W_{j,k,l}\rangle\right) = \frac{1}{3}\sum_{m=1}^{3} F_{i,m}\left(V_{1_j}\langle W_{j,k,l}\rangle\right)$$

$$C: F_i\left(C_k\langle W_{j,k}\rangle\right) = \frac{1}{3}\sum_{m=1}^{3} F_{i,m}\left(C_k\langle W_{j,k}\rangle\right)$$

$$V_2: F_i\left(V_{2_l}\langle W_{k,l}\rangle\right) = \frac{1}{3}\sum_{m=1}^{3} F_{i,m}\left(V_{2_l}\langle W_{k,l}\rangle\right)$$

Anticipatory coarticulation

$$V_1: CA\left(V_{1_j}\langle W_{j,k}\rangle\right) = \frac{1}{3}\sum_{i=1}^{3}\frac{1}{3}\sum_{l,l\prime=1}^{3}\left(F_i\left(V_{1_j}\langle W_{j,k,l}\rangle\right) - F_i\left(V_{1_j}\langle W_{j,k,l\prime}\rangle\right)\right) \text{ } with\ l \neq l'$$

$$C: CA\left(C_k\langle W_{j,k}\rangle\right) = \frac{1}{3}\sum_{i=1}^{3}\frac{1}{3}\sum_{l,l\prime=1}^{3}\left(F_i\left(C_k\langle W_{j,k,l}\rangle\right) - F_i\left(C_k\langle W_{j,k,l\prime}\rangle\right)\right) \text{ } with\ l \neq l'$$

Carry-over coarticulation

$$C: CA\left(C_k\langle W_{k,l}\rangle\right) = \frac{1}{3}\sum_{i=1}^{3}\frac{1}{3}\sum_{j,j\prime=1}^{3}\left(F_i\left(C_k\langle W_{j,k,l}\rangle\right) - F_i\left(C_k\langle W_{j\prime,k,l}\rangle\right)\right) \text{ } with\ j \neq j'$$

$$V_2: CA\left(V_{2_l}\langle W_{k,l}\rangle\right) = \frac{1}{3}\sum_{i=1}^{3}\frac{1}{3}\sum_{j,j\prime=1}^{3}\left(F_i\left(V_{2_l}\langle W_{j,k,l}\rangle\right) - F_i\left(V_{2_l}\langle W_{j\prime,k,l}\rangle\right)\right) \text{ } with\ j \neq j'$$

Token-to-token variability in mean formant frequency

$$V_1: VAR(V_{1_j}) = \tfrac{1}{3}\sum_{i=l}^{3} StDev\left\{F_i\left(V_{1_j}\langle W_{j,k,l}\rangle\right)\right\} \text{ } with\ k, l = 1, \ldots 3$$

$$C: VAR(C_k) = \tfrac{1}{3}\sum_{i=l}^{3} StDev\left\{F_i\left(C_k\langle W_{j,k,l}\rangle\right)\right\} \text{ } with\ j, l = 1, \ldots 3$$

$$V_2: VAR(V_{2_l}) = \tfrac{1}{3}\sum_{i=l}^{3} StDev\left\{F_i\left(V_{2_l}\langle W_{j,k,l}\rangle\right)\right\} \text{ } with\ l, k = 1, \ldots 3$$

Appendix W. Sample Subject Screening and Enrollment Log

TOWARDS A BETTER UNDERSTANDING OF CHILDHOOD APRAXIA OF SPEECH
Subject Screening and Enrollment Log

Subject Study ID #:		Met Eligibility Criteria	For Subjects Eligible and Signing Consent		Was subject enrolled in the study?	If subject is excluded – Reason for exclusion
			Date of Consent	Study Number		
1		☐ Yes ☐ No			☐ Yes ☐ No	
2		☐ Yes ☐ No			☐ Yes ☐ No	
3		☐ Yes ☐ No			☐ Yes ☐ No	
4		☐ Yes ☐ No			☐ Yes ☐ No	
5		☐ Yes ☐ No			☐ Yes ☐ No	
6		☐ Yes ☐ No			☐ Yes ☐ No	
7		☐ Yes ☐ No			☐ Yes ☐ No	
8		☐ Yes ☐ No			☐ Yes ☐ No	
9		☐ Yes ☐ No			☐ Yes ☐ No	
10		☐ Yes ☐ No			☐ Yes ☐ No	
11		☐ Yes ☐ No			☐ Yes ☐ No	
12		☐ Yes ☐ No			☐ Yes ☐ No	

Appendix X. Sample Subject Visit Tracking Log

TOWARDS A BETTER UNDERSTANDING OF CHILDHOOD APRAXIA OF SPEECH
Subject Visit Tracking Log

Subject Study ID #		Visit # 1 Date	Visit # 2 Date	Visit # 3 Date	Visit # 4 Date	Visit # 5 Date	Date and Reason if Early Termination
Example **#P001**	Projected:		*4/07/10*	*5/02/10*	*6/02/10*		
	Actual:	*04/01/10*	*4/06/10*	*5/02/10*	*6/03/10*		
	Projected:						
	Actual:						
	Projected:						
	Actual:						
	Projected:						
	Actual:						
	Projected:						
	Actual:						
	Projected:						
	Actual:						
	Projected:						
	Actual:						