Driving Forces: Mobility and Environmental Language in Children with Cerebral Palsy

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Abstract

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Independent mobility is an important milestone in early childhood that typically emerges alongside communication milestones. Early provision of powered mobility devices for children with physical disabilities has been documented to promote gains in cognitive, motor, and communication domains. Language Environmental Analysis (LENA) has not yet been validated for children with cerebral palsy with physical and/or communication impairments. This study sought to apply LENA to this population while participating in a mobility intervention using adapted ride-on cars. **Methods**: Audio recordings were independently transcribed and coded according to LENA definitions of adult word counts (AWC), conversational turns (CT), and child vocalizations (CV) for a subset of participants (*n*=6) in Communication Functioning Classification System (CFCS) levels I –IV. Accuracy was assessed with inter-rater reliability and Wilcoxon signed-ranks test. Intervention outcomes were assessed using a repeated measures ANOVA for all participants (*n*=12) across the duration of ride-on car use. **Results**: Hand codings and LENA codings achieved high agreement. No statistically significant differences were observed in AWC and CT counts across CFCS levels, and a minimal difference in CV counts was detected between CFCS levels. No significant differences were observed in intervention outcomes. **Discussion**: Results support feasibility of mobility intervention with LENA technology. Further validation of LENA for the CP population is needed. Clinical implications and future directions are discussed.

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Introduction

Cognition is Embodied

Grounded or embodied cognition emphasizes the input of perceptual-motor experience in cognitive development (Lobo et al., 2013). A child's developmental trajectory is no longer conceived of as a direct result of body system maturation; rather, experience shapes development as development enables experience (Anderson et al., 2013; Lobo et al., 2013). Typically developing infants and toddlers are adaptable to their environment and the physical changes of their bodies (Logan et al., 2015). These day-to-day changes instigate larger developmental bursts in a "cascading" effect across domains, including mobility and communication (Adolph & Hoch, 2019; Anderson et al., 2013). This bidirectional relationship between body and experience underlies the concept of grounded cognition.

One of the most crucial milestones in early childhood is self-directed locomotion through crawling or walking. Supporting the framework of grounded cognition, locomotion has profound effects on global development. Locomotion enables an infant to explore new areas, and strengthen, coordinate, and refine motor function. Doing so promotes visual proprioceptive skills that enable object searching and manipulation (Uchiyama et al., 2014; Anderson et al., 2013; Lobo et al., 2013). Active interaction with objects then allows infants to discriminate between and categorize objects, a skill underlying vocabulary acquisition. Placing objects in the mouth promotes vocal play, contributing to the emergence of babbling (Lobo et al., 2013). Ultimately, environmental exploration through self-directed locomotion enables young children to learn about their bodies, objects, surroundings, and other people (Lobo et al., 2013; Adolph & Hoch, 2019).

Several communication skills are facilitated by early motor development, including babbling, referencing, and gesturing (Campos et al., 2000; Lobo et al., 2013). With independent mobility, children can access new objects in their environment (Adolph & Hoch, 2019). These new experiences create opportunities to interact with novel objects, prompting caregivers to use a wider vocabulary (Adolph & Hoch, 2019) and promoting the process of fast-mapping between object and referent (Carey & Bartlett, 1978). Mobility also impacts child-caregiver interactions, enabling children to control their distance from caregivers. This independence alters communication partners, contexts, and linguistic input. Here, negative or corrective behaviors from caregivers may become more prominent with the child's growing independence (Butler, 1986).

Children with Physical Disabilities

As early global and communication development are intricately linked to motor development, it is no surprise that children with physical disabilities are at increased risk of delays in other domains (Halle et al., 2004; Lobo et al., 2013). Social participation for young children relies on appropriate motor, cognitive, linguistic, and sensory functioning. Delays in any of these domains can influence the child's engagement within their environment.

Communication is a domain at the intersection of cognitive, linguistic, and motor development. As such, it can consist of vocalizations, gestures, signs, symbols, spoken words, or any combination of these meaningful signals. Impairments in body structure and function can have direct impacts on activity and participation (WHO, 2001). For example, children with severe physical disabilities are at heightened risk of delayed early communicative signals (Olswang et al., 2014), delayed coordinated joint attention (Feuerstein & Olswang, 2020), unconventional or idiosyncratic communicative behaviors (Sigafoos et al., 2000), and deficits in communication repair strategies (Halle et al., 2004). Any of these differences can contribute to reduced social mobility across social contexts.

Social mobility is the simultaneous use of self-directed locomotion and peer interaction (Logan et al., 2016). Social mobility varies across contexts regardless of age, yet disability status differentiates the frequency of social mobility behaviors. In play, toddlers typically engage in a range of physical activities (e.g., standing, walking, running, etc.), interacting with adults and peers, and combining these behaviors with toys and manual exploration of the environment. Children with physical disabilities engage in fewer physical activities and combine their mobility with objects and peers less frequently than typically developing children. As children with disabilities grow and mobility and social engagement demands increase at home and in the classroom, the gap in social mobility and participation widens (Logan et al., 2016; Raghavendra et al., 2012).

Children with Cerebral Palsy

Cerebral palsy (CP) is one such diagnosis with impacts on multiple domains. It is defined as a non-progressive movement and postural disturbance caused by damage to the central nervous system within fetal development or the first two years of life (Rosenbaum et al., 2007; Paulson & Vargus-Adams, 2017). CP is often accompanied by comorbidities involving sensation, perception, cognition, and communication (Hustad et al., 2010). Risk factors for speech and language delays in this population include persisting primitive reflexes, oral-motor deficits, cognitive impairments, and delayed onsets of vocalizations, babbling, and words (McDonald, 1980). Extant literature suggests that regardless of the subtype of CP, all subsystems for speech (i.e., respiration, phonation, resonance, articulation, and pragmatics) are impacted to some extent (Hustad, 2010). This constellation of system involvement necessitates a team of professionals to optimize function and participation. Early intervention from physical therapists, occupational therapists, and speech-language pathologists is vital in promoting typical milestone acquisition and minimizing the impacts of motor and sensory deficits during natural learning opportunities (Olswang et al., 2013).

Communication profiles of children with CP vary significantly by system involvement (Hustad, 2010). Some individuals may demonstrate various subtypes of dysarthria, a motor speech disorder, with speech intelligibility varying by severity. Others may have concomitant receptive or expressive language disorders, feeding disorders, or cognitive impairments. Bax et al. (2006) estimates that 60% of individuals with CP have communication disorders. Smith & Hustad (2015) report families tend to prioritize mobility needs over communication needs during early intervention. Whether a child uses speech, augmentative and alternative communication (AAC), or a combination, the goal of early SLP intervention is to enable a means of functional communication and social participation.

Characterizing communication profiles of children with CP is clinically valuable in effort to support social participation within caregiver-child dyads. Interaction patterns during free play indicate an element of child passivity, where children allow communication partners to dominate exchanges, rarely initiating, requesting, responding socially, or filling communication turns unless clearly obligated (Light et al., 1985a, b). Pennington & McConachie (2001b) examined maternal control of communication exchanges in relation to a child’s physical dependence on a partner. Severe motor impairments were associated with maternal initiation of communication and limited child repertoires of communicative functions. Fortunately, intervention approaches for this population are moving away from solely improving speech intelligibility and toward supporting high quality communication exchanges, incorporating caregiver training and enriching environmental language (Pennington et al., 2009). Part of this shift may involve early provision of AAC, as there is no prerequisite for age or cognitive level (Cress & Marvin, 2003). Given the range of ages at which AAC intervention may begin, combined with access limitations and misperceptions of AAC's effects on speech development, age estimates at initiation are scant (National Guideline Alliance, 2017; Hidecker, 2010). This high degree of variability emphasizes the need for communication profiles to consider participation and function.

Due to the heterogeneity of the population, numerous efforts have been made to classify individuals exhibiting a wide range of physical and communicative profiles. Classification systems aid interventionists in identifying potential goals and overall participation. Hustad et al. (2010) profiled children by severity of impairment in motor speech, language, and cognition; however, severity of impairment does not always correlate to function or ability to participate in daily activities. For example, a child with CP could have severe motor speech impairments but communicate effectively using a robust AAC system. To better reflect this discrepancy, more recent efforts emphasize participation rather than domain-specific impairments. For the CP population, the Communication Function Classification System (CFCS) reflects communication participation based on sending and receiving messages effectively, regardless of how the individual communicates (Hidecker et al., 2011; Hidecker et al., 2017).

The CFCS supplements the Gross Motor Functioning Classification System (GMFCS) and Manual Ability Classification System (MACS) [Table 1]. These independent but complementary systems provide families and professionals with an operational description of current functional levels of mobility, fine motor skills, and communication (Hidecker et al., 2012). The three are examples of classification systems based on the World Health Organization's International Classification of Functioning, Disability, and Health (WHO-ICF). It is grounded in evidence that a diagnosis alone is not predictive of level of function or need for health services; rather, health conditions must be considered alongside other contextual factors (WHO, 2001). The WHO-ICF provides a framework for understanding disability within an individual's social, environmental, and personal contexts. Initial conceptualizations of CP classifications focused on severity of impairment, aligning with the WHO-ICF's impairments in body structures and functions. Rather, the CFCS centers activity and participation, allowing interventionists to identify participation restrictions and activity limitations, better reflecting proficiency in communication (Hidecker et al., 2011).

Table 1

GMFCS and CFCS Descriptions

Level	**GMFCS**	**CFCS**
I	Walks without limitations across settings. Capable of performing gross motor skills but may have limitations in speed, balance, and/or coordination.	Sends and receives information effectively and timely across communication partners.
II	Walks in most settings with limitations over long distances, uneven terrain, and/or confined spaces. May use hand-held mobility device or wheeled mobility for some settings. Minimal ability to perform other gross motor skills.	Sends and receives information effectively, but slowly across communication partners.
III	Walks using a hand-held mobility device in most indoor settings and wheeled mobility over long distances.	Sends and receives information effectively with select communication partners.
IV	Self-mobility with limitations; may use powered mobility or physical assistance in most settings. May walk or use a body support walker for short distances.	Inconsistently effective in sending and receiving information with select communication partners.
V	Transported in a manual wheelchair in all settings. Limited ability to maintain head and trunk postures against gravity and/or control limb movements.	Seldomly effective in sending and receiving information with select communication partners.

Note: GMFCS: Gross Motor Classification System; CFCS: Communication Function Classification System. Summarized according to Palisano et al. (2007), Paulson & Vargus-Adams (2017), and Hidecker et al., (2011).

Presently, the CFCS is not widely utilized by speech-language pathologists for children with CP in the United States, although Canadian early interventionists apply it to children with and without CP diagnoses (Cunningham et al., 2016). It can be used by families and professionals to describe communicative participation in other populations and help clinicians to understand CP diagnoses in the context of a child's daily life.

Using Powered Mobility Devices to Improve Social Participation

Children with physical disabilities can benefit from assistive devices to experience self-directed locomotion and the developmental bursts associated with it. With evidence of the psychosocial impacts of self-directed locomotion, alternative means of mobility can enable an individual to be more independent and participatory in their environment (Henderson et al., 2008). The use of powered mobility devices (PMDs) is supported by studies indicating the means of self-directed locomotion matter less than the experience itself (Uchiyama et al., 2008; Anderson et al., 2014). Importantly, there is growing evidence that early provision of PMDs is possible and is not hindered by cognitive impairments; as with AAC, there are no cognitive prerequisites to finding appropriate assistive technology (Nilsson & Nyberg, 2003; Beukelman et al., 2012). Although there is evidence for this, it is a recent area of interest contrary to longstanding perspectives among clinicians and researchers (Nilsson & Nyberg, 2003; Beukelman et al., 2012). Further evidence is needed to document best practice.

Children as young as 7, 14, and 23 months have learned to use PMDs successfully (Lynch et al., 2009; Jones et al., 2012; Butler, 1986). Children with neuromotor conditions including spastic quadriplegia and developmental delays have demonstrated success with PMDs (Deitz et al., 2002). Gains in movement, object interaction, and self-initiated communication with caregivers were observed following early PMD training (Butler, 1986; Logan et al., 2015). Additionally, Campos et al. (2000) observed infants to be more attentive and communicative when using self-directed locomotion compared to pre-locomotor infants. In a randomized controlled study, Jones et al. (2012) found receptive communication to improve with PMD-training secondary to greater mobility and fewer requirements for caregiver assistance; although expressive communication did not improve from baseline, receptive communication serves as a marker for language learning that would not be directly limited by gross motor or motor speech impairments. Jones' (2012) study provides important efforts to document language bursts alongside mobility intervention – a goal shared with the current study.

Environmental Language Analysis

Independent navigation of the environment is associated with changes in communication and social interactions (Butler, 1986; Henderson et al., 2008). Following changes in mobility, caregiver-child interactions also undergo unique changes (Anderson et al., 2013). Recent efforts in understanding variables contributing to the proposed Word Gap (Hart & Risley, 1995; Sperry et al., 2018) have inspired interest in environmental language. Technology for automated speech recognition enables extensive speech and language data collection and analysis with remarkably accessible methods. One such technology is Language Environment Analysis (LENA).

LENA provides automated speech and language analysis from naturalistic data collection. LENA records environmental stimuli from a compact recording device, the LENA Digital Language Processor, that fits in a discrete pocket of a toddler vest. Its continuous recording captures and codes child vocalizations, adult words, and conversational turns within a specific radius surrounding the child wearing the device. Child vocalizations (CVs) include distinct speech-related sounds separated by 300ms such as babbling, vowel sounds, and spoken words. Cries, screams, and vegetative sounds are discounted (Gilkerson & Richards, 2009). Adult word counts (AWCs) include tokens of clear words uttered by an adult near the child. Conversational turns (CTs) are operationalized by Hart & Risley’s (1995) criteria of alterations between clear adult and target child vocalizations within 5 seconds of non-vocal behavior (Gilkerson & Richards, 2009). Such measures are examined as markers for communication patterns although they do not capture qualitative information of interactions such as child- or adult-initiation or communicative function (Greenwood et al., 2018).

There is a growing body of evidence validating and using LENA for research and with an increasing focus on intervention (Greenwood et al., 2018). It has been validated for populations including typically developing infants and toddlers (Gilkerson et al., 2017), across various languages in multilingual families (Orena et al., 2019; Gilkerson et al., 2014), in preschool classrooms (Wiggin et al., 2012), and in neonatal intensive care units (Caskey et al., 2014). The focus of validation for atypical development has been on children with hearing loss (Aragon & Yoshinaga-Itano, 2012) and autism spectrum disorder (Oller et al., 2010). Efforts to utilize LENA with other populations with disabilities have been reported for children with Down Syndrome (Thiemann-Bourque et al., 2014), developmental disorders (Bredin-Oja et al., 2018), Fragile X Syndrome (Reisinger et al., 2019), and language delays (Oller et al., 2010). LENA has yet to be validated for or applied to children with CP.

Independent validation efforts of LENA automated counts are important in understanding its application to clinical populations. Ferjan Ramírez et al. (2020) found LENA systematically over-counted CTs when compared to hand coded CTs. Cristia et al. (2021) reported LENA generally underestimated CVs and CTs in typical populations but is largely reliable with AWCs so long as there is no distinction between adult male and adult female speakers. Overall, there is a lack of independent peer-reviewed publications detailing exact methodology in validation efforts, as most LENA studies report validation as the first step in answering a secondary research question (Cristia et al., 2020).

There is a constellation of potential challenges to automatic speech recognition among speakers with neurodevelopmental conditions. The range of profiles and abilities of individuals with CP complicates automated acoustic analysis. First, vowel space and speech rate are primary factors for intelligibility which can be greatly impacted by dysarthric speech (Hustad et al., 2010; Hixon et al., 2014; Turner et al., 1995). Vowel space, vowel duration, voice onset time, and fricative duration are some of the identified sources of variability in automated acoustic analysis of dysarthric speakers (Blaney & Wilson, 2000). Rudzicz et al. (2012) improved the sensitivity of an automated speech recognition software by programming specifically for altered vowel spaces of adult speakers with dysarthria. Additional variability is to be expected for child and adolescent speakers with dysarthria whose vocal tracts are still undergoing development (Hixon et al., 2014). Respiratory and phonatory differences in the CP population may further complicate analysis (Hustad, 2010). Nordberg et al. (2014) documented the high prevalence of such differences among school-aged children with CP, with 68.4% of participants demonstrating dysphonic qualities and 68.4% with respiratory deficits. Automated acoustic analysis is most reliable with consistent vocal quality containing clear formant contrasts and little background noise (Hixon et al., 2014). Dysphonia, associated with motor speech impairments or a history of ventilation, can produce markedly different acoustic profiles that may not be analyzed appropriately by a system normed on non-dysphonic speakers.

Second, LENA captures conversational turns, which can be informative when investigating communication initiations (Greenwood et al., 2018). However, children with complex communication needs, including those with CP, may demonstrate unpredictable communicative attempts that vary in precision and timing secondary to motor speech impairments (Pennington & McConachie, 2001a, b). Therefore, this measure could potentially lack sensitivity to speakers who require more time to initiate or respond. Furthermore, CT counts rely on accurate AWC and CV counts. One of the clinical strengths of LENA technology is to identify potential intervention targets of initiating and responding using AWC, CT, and CV (Greenwood et al., 2018); validation for the CP population is needed in order to reap the full benefits of such technology. The current investigation seeks to begin this validation process through an accuracy assessment with a small sample of the CP population.

LENA and Ride-on Cars

Given the evidence that supports communicative changes with the onset of self-directed locomotion, LENA may provide further insight into the communication interactions of children with CP in the home when independently mobile. This is of particular interest for children with CP who use PMDs such as an adapted ride-on car for play and exploration.

PMDs were provided to children with CP in the current study. Battery-powered ride-on cars were customized for each child’s positioning and driving needs. Without any modifications, these commercially available toy cars are controlled with a foot pedal or button on the steering wheel. As these motor plans may be difficult for children with CP, an easy-to-press large switch that activates with a light touch was installed. Supportive seating was constructed with PVC pipe, swimming kickboards, Velcro, and seatbelts or five-point harnesses. Ride-on cars were operated with a rechargeable 6-volt battery which allows for 45-60 minutes of driving and a maximum speed of 2.5 miles per hour. In the current study, small cars (Fisher Price, East Aurora, NY) were customized for children ages 12-14 months, and three styles of larger cars (Huffy, Dayton, OH; Ballard Pacific, Santa Fe Springs, CA) were customized for children ages 24-48 months.

The current study aims to use LENA technology to measure environmental language of children with CP using ride-on cars for two purposes: 1. to investigate the validity of LENA in capturing and sensitively coding the speech of families and children with CP across CFCS levels using automated speech recognition; 2. to determine whether communication patterns change over time with PMD use.

Research Questions

The developmental bursts associated with increased mobility prompt further investigation of communication-specific development for children with CP while acquiring independent mobility. Adapted ride-on cars offer an affordable intervention that provides broader access to the child's environment. Such newfound independence offers a unique opportunity to examine changes in environmental language and communicative participation as children acquire mobility. This research, rooted in grounded cognition, aims to: 1. contribute to the literature about LENA specific to children with CP; and 2. inform interdisciplinary clinical practice in early intervention. The following research questions were proposed:

Accuracy Assessment. *(1)* Does LENA accurately identify child vocalizations (CVs), perceptually differentiating between communicative and vegetative sounds consistently across CFCS levels? *(2)* Does LENA accurately identify conversational turns (CTs) between caregivers and children with CP consistently across CFCS levels?

Intervention Outcomes. How does communication between caregivers and children with CP change over time with independent mobility using ride-on cars?

Methods

Participants

Nineteen children with cerebral palsy and their families were enrolled in the study and received customized ride-on cars [Table 2]. All participants were then classified into GMFCS and CFCS levels. The study duration was roughly 12 months, with minor variation due to the COVID-19 pandemic and caregiver/child schedules. Seven participants were removed from the dataset with incomplete information and single LENA recordings lost to attrition. Twelve participants finished with enough recordings to be included in analyses. At the time of enrollment, participants ranged from 16 to 49 months of age. Two-thirds of participants were males. No participants were categorized as GMFCS level I, with 33.3% in level II, 50% in level III, and 16.7% in level IV. One participant was categorized into CFCS levels I and II each, with 50% of participants in level III and 33.3% in level IV. Race and ethnicity were caregiver-reported. Two-thirds of participants identified as exclusively White and 8% exclusively Asian, with 25% of the sample identifying as multiracial.

Table 2

Participant Demographics

	Age Range in Months	GMFCS	CFCS	Sex	Race/Ethnicity	No. of Recordings
P1	45-56	III	II	Male	White	7
P2	18-27	IV	IV	Female	White	7
P3	29-35	III	III	Female	White	6
P4 [a]	24	–	–	Male	White	1
P5	37-44	III	I	Male	White, Alaskan Native	10
P6	47-56	II	III	Male	Black, White	7
P7 [a]	26-28	IV	IV	Male	White, Asian	2
P8 [a]	33-37	IV	IV	Female	White	2

P9	49-62	III	III	Female	White	4
P10	18-26	III	IV	Female	Hispanic, Asian	6
P11[a]	48	–	–	Male	White	0
P12	30-37	II	III	Male	Asian	4
P13[a]	36	II	III	Female	White	0
P14[a]	24-25	–	–	Male	Alaskan Native	1
P15	16-27	II	III	Male	White	10
P16[a]	24-26	II	III	Female	Hispanic	2
P17	17-23	II	III	Male	White	3
P18	21-29	IV	IV	Male	White	6
P19	19-28	III	IV	Male	White	6

Note: GMFCS: Gross Motor Classification System; CFCS: Communication Function Classification System.

[a] Enrolled participants excluded from analysis due to low number of recordings.

Ride-on Car Intervention

Ride-on cars [Appendix A] were modified for safety and accessibility to fit the child's motor abilities using a large, easy to press adaptive switch. Custom seating support, such as seatbelts and five-point harnesses, were also added. Caregivers were trained to safely operate the ride-on cars in their homes and communities, and support was provided by the research team for maintenance or repair as needed. Families self-selected when and how often their children used the cars, aside from the days they were completing a language recording, when they were asked to aim for about 30 minutes of car time throughout the day, noting these times on a driving log. Families were given a choice at the end of the study whether to keep the ride-on car or recycle it back to the research lab.

Data Collection

In accordance with LENA guidelines for data collection, participants wore vests with the LENA Digital Language Processor turned on throughout a recording day. Participating families were provided with written and verbal instructions for LENA recording procedures. Recordings occurred about once a month while using the child's ride-on car. Prepaid envelopes were mailed to families in order to return the recorder when indicated. Recordings were processed upon retrieval, then a new recorder was charged and sent back to families for the subsequent month. This process took place throughout the study. Depending on how quickly families returned recordings, families ranged between 3-11 total recordings. The research team captured full audio files, raw LENA metrics for custom analysis, and the proprietary LENA-automated report. The following measures were analyzed across these three data sources:

Table 3

Variable Descriptions

Variable	Definition	Parameters
CFCS Level	Standardized category of communicative independence	Effective sending/receiving of information between familiar and unfamiliar partners in everyday life
LENA AWC	Number of adult-spoken words near a child	Includes vocalizations spoken near and to the key child
LENA CT	Number of turns between adult and child, regardless of if the child or adult initiates the turn	Includes adult- or child-initiated response pairs with a delay ≤5 seconds [Example in Appendix B]
LENA CV	Number of speech-related sounds from the child	Includes speech-related sounds separated by 300ms; excludes vegetative/fixed signal sounds, cries, screams, etc.

Note: CFCS: Communication Function Classification System; AWC: adult word count; CT: conversational turns; CV: child vocalizations. CFCS description based on Hidecker et al. (2011). LENA descriptions based on Gilkerson et al. (2008) and Gilkerson & Richards (2009; 2020).

Hypotheses

Accuracy Assessment

Hypothesis 1a. LENA-coded AWCs, CTs, and CVs will be significantly correlated with hand counts of these same metrics at a rate greater than 80% overall.

Hypothesis 1b. By CFCS level, LENA will have a lower accuracy rate less than or equal to 80% in coding CTs and CVs for children with CP in high CFCS levels (III-IV) secondary to greater reliance on unconventional, idiosyncratic, untimely, or unacknowledged communicative attempts. Children in low CFCS levels will maintain a high correlation between hand and LENA-coded counts.

Intervention Outcomes

Hypothesis 2a. Children in CFCS levels I-II will experience a change in communication patterns over time. This could include a decline in AWCs and CTs with independent navigation enabling increased distance from caregivers. On the other hand, AWCs, and CVs may increase with greater global independence that in turn promotes more communicative opportunities.

Hypothesis 2b. Children in CFCS levels III-IV will experience an increase in AWCs at conclusion of language monitoring compared to baseline, secondary to fluctuations in routine that provide novel opportunities for adult-driven language stimulation. CTs and CVs may increase by the final recordings if there is an increase in AWCs; as a caveat, vocalizations may decrease initially with the acquisition of a new motor skill, thus showing a decline in CTs and CVs over the initial recording period (1-3 months).

Data Analysis

Accuracy Assessment

To examine how accurately LENA identified AWCs, CTs, and CVs for children with CP, raw audio recordings were independently coded by the researcher according to LENA’s definitions. Audio was analyzed using Audacity which enabled adherence to the temporal aspects of LENA definitions. Independent codings were analyzed for agreement with the raw data counts and LENA's automatically generated reports. For this aim, a small sample of participants were randomly selected from three groupings of CFCS levels. Random recording dates were selected, and recordings of less than 6 hours were excluded to improve validity of LENA measures. Recordings were transcribed by two independent raters and coded within 5-minute segments at 3 random time points (in 20-minute increments) during the hour with the most CTs, according to LENA reports. Independently coded reports were generated into Excel files to aid in analysis. Independent raters were graduate and postbaccalaureate speech-language pathology students at the University of Washington. Training on LENA definitions and discussion of agreement were conducted by the graduate researcher to ensure adherence to LENA protocol.

The participant from CFCS I had a full hour of audio from a single day transcribed to aid in operationalizing LENA definitions and intra-rater reliability using the most typical speaker. Participants from CFCS II, III, and IV each had 3 random time points analyzed across 3 random days. The selected participant in CFCS IV was ventilator dependent, which was initially believed to impact CT and CV counts. Thus, two additional participants from CFCS IV, one ventilator-dependent and the other not, were included in audio analysis each with 3 audio segments from a single day of recording. In total, 6 participants contributed to accuracy assessment of 36 5-minute segments of audio. Selected recording days had an average duration of 13.3 hours (*SD*=3.6). Average age was 36.8 months.

Table 4

Accuracy Assessment Demographics

CFCS	**Age in months at selected recording(s)**	**GMFCS**	**Sex**	**Duration of sampled recordings**	**Additional Factors**
I	38	III	Male	60 minutes	Twin
II	45, 46, 48	III	Male	45 minutes	2 siblings
III	47, 49, 54	II	Male	45 minutes	
IV	24, 24, 28	IV	Male	45 minutes	Vent
IV	18	IV	Female	15 minutes	Twin
IV	20	III	Male	15 minutes	Vent

Note: GMFCS: Gross Motor Function Classification System

Inter-rater reliability was calculated across 25% of segments that were coded by both rater 1 and 2. All measures reached 99.0-99.9% reliability for CFCS I. For the remaining segments across CFCS levels, independent ratings achieved 96.8% agreement on AWCs, 98.4% on CTs, and 95.9% on CVs.

Intervention Outcomes

All participants from the ride-on car intervention with at least 3 recordings of a minimum of 4 hours were analyzed for intervention outcomes. Twelve participants met these criteria. Maximum AWC, CT, and CV counts from the first, middle, and last LENA reports were compiled into an Excel file. Middle recordings were defined as either as the exact midpoint for participants with an odd number of recordings or as the longer recording of the two middle dates for participants with an even number of recordings. Average length of audio recordings was 12 hours (*SD*=4.1) Average initial age was 28.8 months (*SD*=8.6) with an average intervention duration of 12.1 months (*SD*=2.1).

Results

Accuracy Assessment

Given the non-normal distribution of 2 related samples, a Wilcoxon signed-rank test was conducted comparing hand-coded against LENA-coded counts of the same segments. Results indicated that coding type did not produce a statistically significant difference in 99.2% of cases.

Only hand-coded CV counts in 2 segments were significantly different than LENA's automatic analysis (*Z* = -1.992, *p* = .046; *Z* = -2.201, *p* = 0.28). Negative Z-scores indicate that in these 2 cases, LENA counts were consistently higher than hand-counted CVs. To clarify whether this difference was due to CFCS level, a post-hoc one-way ANOVA was conducted. This analysis revealed a statistically significant difference in one metric, the LENA-coded CVs, between CFCS groups for one 5-minute segment (*F* (3,2) = 60.198, *p*=.016). Mean CVs of CFCS IV (*n*=3) at this time was 16.33 (*SD*=10.6) compared to CFCS I (*n*=1) with 43 CVs, CFCS II (*n*=1) with 62 CVs, and CFCS III (*n*=1) with 37 CVs.

Intervention Outcomes

A one-way repeated measures ANOVA controlling for age was conducted. Mauchly's Test of Sphericity was met for AWC, CT, and CV. However, multivariate tests revealed no significant effect between subjects of CFCS group, Pillai's trace=.632, *F*(6, 14) =1.078, *p*=.421, η^2=.316. There was also no significant within-subjects effect of time, Pillai's trace=.322, *F*(6, 3) =.238, *p*=.936, η^2=.322, nor an interaction between CFCS group and time, Pillai's trace=1.175, *F*(12, 8) =.949, *p*=.549, η^2=.587.

Discussion

Research Implications

Accuracy Assessment

This is the first study aiming to validate LENA for children with a diagnosis of cerebral palsy. A high degree of accuracy between LENA automated counts and hand-coded counts according to LENA's definitions are meaningful for several reasons. High accuracy, even across children with atypical speech, is key for future applications of this technology to the CP population as well as other populations with communication disorders. Importantly, LENA maintained a high degree of accuracy in coding counts of children with more significantly involved speech presentations, including children who used mechanical ventilation.

It was hypothesized that LENA would maintain high accuracy of CTs and CVs for more typical speakers in lower CFCS levels, with accuracy decreasing as CFCS level increased. This was informally observed. Although not statistically significant in most comparisons, discrepancies in hand-coded and LENA coded counts warrant further discussion. Wilcoxon signed-ranks test showed LENA coded higher AWCs in 66.7% of segments and CTs in 59.5% of segments. Several conditions observed during hand-coding transcription may contribute to this trend. A degree of overestimation of CTs was found by Ferjan Ramírez et al. (2020), highlighting LENA's inability to differentiate child-directed versus overheard speech; CTs in this validation effort were intentionally coded as child-directed, according to Ferjan Ramírez et al.'s findings. The human ear's ability to differentiate live speech of a nearby adult from electronic speech may also be a source of difference. In contexts with little direct vocal interaction between child and a nearby adult yet proximity to television or virtual assistant devices (e.g., Alexa or Siri), LENA overestimated AWCs and CTs. Without the ability to compare transcripts, these observations remain speculative. Regardless, resulting overestimation reflects the advantage of human listeners, yet a lack of statistically significant differences supports LENA's estimations capturing overall trends.

Significant variation in CV counts in two segments by CFCS level reflect the importance of understanding how different motor speech profiles may not be accurately accounted for by automated acoustic analysis. LENA reported higher CV counts than hand-coded counts in 78.6% of segments. Participants in this sample demonstrated a range of phonatory and motor speech presentations. One participant exhibited features of dysarthria that can accompany CP, including inconsistent phonation, segmented speech with equal stress, intermittently harsh vocal quality, fluctuations in volume, and imprecise articulation. Other participants were ventilator-dependent and beginning speaking valve use at the time of the study, one with a co-occurring diagnosis of spina bifida. Given the acoustic differences of dysphonic and dysarthric speech (Ishikawa et al., 2016; Fraser et al., 1998; Rudzicz et al., 2012; Chen et al., 2018), CVs may not be easily recognizable as distinct vocal play by LENA. Participants with inconsistent phonation, a breathy voice, or whisper lack recognizable formant frequencies to be registered as a vocalization (Rudzciz et al., 2012; Chen et al., 2018), which may obscure LENA counts. Ventilation also impacts timing of vocalizations, continuity of phonation, phonatory quality, and place of articulation (Fraser et al., 1998). Given that vocalizations must be made during the expiratory phase of ventilation, this impacts both CT and CV counts. Vocalizations made with non-oral (i.e., pharyngeal or esophageal) placement, with breathy vocal quality, or in the presence of secretions may lead to LENA categorizing emerging vocal play as vegetative in nature. Despite this individual variability, results indicate LENA can be used with the CP population; however, these factors are important to consider in future studies depending on individual participant profiles.

Ferjan Ramírez et al. (2020) identified areas of future validation for LENA, including past 48 months of age. Over the duration of this study, some participants were 48 months of age at enrollment, and more were older by study conclusion. Considering high accuracy rates of children with atypical developmental profiles, this data provides some evidence to support the use of LENA measures to track changes over time past 48 months of age. LENA's age-normed measures of Vocal Productivity and Acoustic Vocal Analysis were not utilized due to atypical development and older ages of some participants. Rather, AWC, CT, and CV trends may be useful past 48 months so long as participants serve as their own controls. This is consistent with other studies applying LENA to children with known developmental delays (Bredin-Oja et al., 2018; Thiemann-Bourque et al., 2014; Reisinger et al., 2019).

Of importance for this study, a full hour of the participant in CFCS I and portions of other participant segments were analyzed during driving time. Initially, it was hypothesized that the mechanical noise from the ride-on car itself could obscure language counts. Vocalizations overlapping with mechanical noise or the child's vocal volume increasing to be heard over noise and distance (thus becoming a "scream") could have resulted in exclusion by LENA. Interestingly, agreement with LENA counts over a full hour of drive time and interrater reliability indicate that mechanical noise did not interfere with language measures. This finding supports further investigation of language metrics during mobility interventions.

Intervention Outcomes

No significant changes in language measures were observed in this feasibility study. This is no surprise given the small sample size with significant individual variability over three timepoints. Participants were instructed only to record LENA samples once a month. Though it was requested that families use the car and record their driving time on LENA recording days, follow-through from families was inconsistent. Otherwise, due to the nature of this feasibility study, families were not told to use the ride-on car at a prescribed frequency. An automated data logger integrated into the ride-on cars indicated that participants averaged one hour of ride-on car use per week. With this low average dose, if environmental language changes had been observed, it would have been difficult to draw any conclusions about mobility and language without controlling for developmental maturation processes. However, LENA can be used to track environmental language changes over time, including during ride-on car use, in future studies.

While naturalistic, the general guideline of one LENA recording anytime each month may have contributed to high variability. Day-to-day routines varied greatly without prescriptive recording dates in this study. For example, without guidelines to pick days with similar routines, some families recorded on a weekday with older siblings at school, and the next over the weekend with recreational activities, more individuals in the home, and varied language contexts. This may be misleading for the purposes of longitudinal tracking with a monthly sampling rate. High between- and within- family variability is consistent with the LENA Natural Language Study's findings (Gilkerson & Richards, 2008). As highlighted by Greenwood et al. (2017), context provides qualitative aspects to LENA's data that is largely quantitative. Their systematic review cites the gap in literature regarding community validation, as most studies occur in the home, clinic, classrooms, and medical settings. The subset of participants from the current validation effort, however, included community contexts with families interacting with friends and neighbors, during travel, and running errands. Future community-based studies should aim to describe recording contexts if not prescribing recording routines.

Clinical Implications

Extant literature indicates early intervention goals for children with CP prioritize self-care and mobility over communication (Smith & Hustad, 2015). This impairment-based approach may be due to caregiver preferences, needs during daily activities (e.g., feeding), or taking a wait-and-see approach for communication. However, nearly 60% of children with CP demonstrate communication impairments (Bax et al., 2006). Smith & Hustad (2015) conclude that most children with CP could benefit from communication-focused intervention, with a significant proportion of those benefitting from AAC during early intervention. Given this discrepancy in practice and evidence, the potential impacts of mobility-focused intervention on communication are a critical area for future investigation.

If independent mobility facilitates novel, varied interactions and opportunities for communication, best practice may incorporate participation-based communication goals. Historically, impairment-based approaches have been utilized across speech, physical, and occupational therapies (Hustad, 2010; Anaby et al., 2017). In speech therapy, dysarthria treatment that aims to remediate neurologically based impairments offer limited evidence (Hustad, 2010; Pennington et al., 2006). Rather, dysarthria treatment is recommended to be compensatory and augmentative in nature (Hustad, 2010). This lends to early intervention moving from impairment-based to participation-based approaches focusing on effective communication rather than subsystem deficits.

Facilitating communication participation may be an indirect outcome of PMD training. The potential for diversifying interaction types and generating novel language opportunities is hopeful for children with complex motor needs. The children in Smith & Hustad's (2015) study who were not receiving AAC intervention but could benefit were all in higher GMFCS levels IV and V, indicating greater neuromuscular involvement. This suggests that children with complex needs may be underserved in communication, especially considering the potential to include communication intervention concurrently with motor intervention.

AAC assessment is often an extensive process evaluating the individual's communication needs potentially spanning motor, cognitive, linguistic, and sensory domains. The American Speech-Language-Hearing Association (ASHA) recommends AAC assessments include informant-based approaches (e.g., caregiver interviews or self-reporting), multi-disciplinary collaboration, and informal, dynamic assessment (ASHA, 2020). Evidence from practice reveals that clinicians use a wide range of informants to shape their evaluations and gather information across domains (Lund et al., 2017). One potential application of LENA technology is to provide supplemental information during AAC assessment in a variety of ways.

LENA's ability to inconspicuously record hours of audio with the compact Digital Language Processor offers a wide observational window. If accessed by SLPs, audio could inform speech intelligibility, partner skills, and current communication breakdowns and repairs. Repair strategies are of interest for children with CP who can take on more passive, respondent communication roles (Halle et al., 2004; Pennington & McConachie, 2001a). This is particularly important for complex communicators to prevent or remedy learned helplessness wherein an individual has learned through unsuccessful attempts that their actions are not related to environmental outcomes (Reichle et al., 1991; Deitz et al., 2002). LENA may also serve as an ecological or participation inventory which can help determine current communicative functions and potential intervention targets (Reichle et al., 1991; Beukelman et al., 2012). Observation across different contexts could aid the SLP in identifying opportunities for more advanced communication. Automated CTs and CVs may provide some insight into participation and interaction patterns with caregivers. Further investigation of LENA capabilities should consider the unique role of such technology in naturalistic observation within AAC use. Evidence of feasibility supports ongoing collaboration between SLPs, PTs, OTs and engineering in the early provision of assistive technology as well as more general interventions focusing on social participation, communication, and mobility.

Limitations

A major limitation is a small sample size and high degree of individual variability among participants. Intervention outcomes are limited by the lack of control of ride-on car use and the lack of a comparison group of children diagnosed with CP who were not assigned to the intervention. Multiple families were lost to attrition, missed recordings, and loss or damage to LENA Digital Language Processors during data collection. Varied recording length likely contributed to potential error sources, as LENA is more reliable with 12–16 hours of audio (Xu et al., 2009). As with many naturalistic studies, the Hawthorne effect may impact adult language when caregivers are aware of being recorded (Ferjan Ramírez et al., 2020). The standard methodology of selecting the hour with the most CTs according to LENA automated reports may have led to biased sampling in the accuracy assessment, as systematically removing segments of overlap may artificially increase accuracy (Cristia et al., 2021). Further, this validation effort did not label every segment coded by LENA, such as speaker and silence tags, and focused solely on AWCs, CTs, and CVs. Doing so enabled a more feasible comparison between LENA counts and clinically relevant language samples. Future validation efforts should follow precise LENA segmentation and labels.

Future Directions

With preliminary evidence that LENA can be used with a high degree of confidence with the CP population, replication is needed. Additionally, clinical diagnoses and characteristics of participants' motor speech profiles would add specificity in application of LENA to children with moderate to severe motor speech disorders. Future intervention studies to document language trends over time with powered mobility should be undertaken while controlling dosage. With proper contextualization, LENA reports could serve as a supplemental informant during

AAC evaluations. Hours of naturalistic recordings could provide an ecological inventory of interaction patterns, partners, and opportunities for aided language stimulation. Such work has the potential to inform participation-based mobility and communication intervention and further elucidate the relationship between these two critical developmental domains in children with disabilities.

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References

Adolph, K. E. & Hoch, J. E. (2019). Motor development: Embodied, embedded, enculturated, and enabling. *Annual Review of Psychology,* 70, 141-64.

American Speech-Language-Hearing Association. (2020, September 16). *Augmentative and Alternative Communication.* ASHA Practice Portal.

Anaby, D., Korner-Bitensky, N., Steven, E., Tremblay, S. Snider, L, Avery, L., & Law, M. (2017). Current rehabilitation practices for children with cerebral palsy: focus and gaps. *Physical & Occupational Therapy in Pediatrics,* 37(1), 1-15. Doi:10.3109/01942638.2015.1126880.

Anderson, D. I., Campos, J. J., Witherington, D. C., Dahl, A., Rivera, M., He, M., Uchiyama, I., & Barbu-Roth, M. (2013). The role of locomotion in psychological development. *Frontiers in Psychology,* 4. Doi: 10.3389/fpsyg.2013.00440.

Aragon, M. & Yoshinaga-Itano, C. (2012). Using Language Environment Analysis to improve outcomes for children who are Deaf or Hard of Hearing. Seminars in Speech and Language, 33(4), 340-353. Doi:10.1055/s-0032-1326918.

Bax, M., Tydeman, C., & Flodmark, O. (2006). Clinical and MRI correlates of cerebral palsy: The European cerebral palsy study. *Journal of the American Medical Association,* 296 (13), 1602-1608. Doi: 10.1001/jama.296.13.1602.

Beukelman, D. R., Mirenda. P., Ball., L. J., Koch Fager, S., Garrett, K. L., Hanson, E. K., Lasker, J. P., Light, J. C., McNaughton, D. B. (2012). *Augmentative and Alternative Communication: Supporting children and adults with complex communication needs.* Baltimore: Brookes Publishing.

Blaney, B. & Wilson, J. Acoustic variability in dysarthria and computer speech recognition (2000). *Clinical Linguistics and Phonetics,* 14(4), 307-327. Doi: 10.1080/02699200050024001.

Bredin-Oja, S. L., Fielding, H., Fleming, K. K., & Warren, S. F. (2018). Estimating vocalization rates in young children with developmental disorders. *American Journal of Speech-Language Pathology,* 27(3), 1066-1072. Doi:10.1044/2018_AJSLP-17-0016.

Butler, C. (1986). Effects of powered mobility on self-initiated behaviors of very young children with locomotor disability. *Developmental Medicine and Child Neurology,* 28, 325-332.

Butler, C. & Darrah, J. (2001). Effects of neurodevelopmental treatment (NDT) for cerebral palsy: an AACPDM evidence report. *Developmental Medicine & Child Neurology,* 43, 778-790.

Campos, J. J., Barbu-Roth, M. A., Hubbard, E. M., Hertenstein, M. J., & Witherington, D. (2000). Travel broadens the mind. *Infancy,* 1(2), 149-219.

Carey, S. & Bartlett, E. (1978). Acquiring a single new word. *Papers and Reports on Child Language Development,* 15, 17-29.

Caskey, M., Stephens, B., Tucker, R., & Vohr, B. (2014). Adult talk in the NICU with preterm infants and developmental outcomes. *Pediatrics,* 133(3), 1-7. Doi:10.1542/peds.2013-0104.

Chen, L., Hustad, K. C., Kent, R. D., & Lin, Y. C. (2018). Dysarthria in Mandarin-speaking children with cerebral palsy: Speech subsystem profiles. *Journal of Speech, Language, and Hearing Research,* 61, 525-548. Doi:10.1044/2017_JSLHR-S-17-0065.

Cress, C. J., & Marvin, C. A. (2003). Common questions about AAC services in early intervention. *Augmentative and Alternative Communication,* 19(4), 254-272. Doi: 10.1080/07434610310001598242.

Cristia, A., Bulgarelli, F., & Bergelson, E. (2020). Accuracy of the Language Environment Analysis System segmentation and metrics: A systematic review. *Journal of Speech, Language, and Hearing Research,* 63, 1093-1105. Doi: 10.1044/2020_JSLHR-19-00017.

Cristia, A., Lavechin, M., Scaff, C., Soderstrom, M., Rowland, C., Räsänen, O., Bunce, J., & Bergelson, E. (2021). A thorough evaluation of the Language Environment Analysis (LENA) system. *Behavior Research Methods,* 53, 467-486. Doi: 10.3758/s13428-020-01393-5.

Cunningham, B. J., Rosenbaum, P., & Hidecker, M. J. C. (2016). Promoting consistent use of the Communication Function Classification System (CFCS). *Disability and Rehabilitation,* 38(2), 195-204. Doi:10.3109/09638288.2015.1027009.

Deitz, J., Swinth, Y., & White, O. (2002). Powered mobility and preschoolers with complex developmental delays. *Journal of Occupational Therapy,* 56, 86-96.

Du, S., Xu, D., Richards, J. A., Hannon, S. M., & Gilkerson, J. (2017). LENA Technical Report: LENA Vocal Productivity measure, LTR-11-1. LENA Research Foundation: Boulder, CO.

Ferjan Ramírez, N., Hippe, D. S., & Kuhl, P. K. (2020). Comparing automatic and manual measures of parent-infant conversational turns: A word of caution. *Child Development,* 1-10. Doi:10.1111/cdev.13495.

Feuerstein, J. L., & Olswang, L. B. (2020). A Randomized Controlled Trial Investigating Online Training for Prelinguistic Communication. *Journal of Speech, Language, and Hearing Research,* 63(3), 827-833.

Feuerstein, J., Olswang, L. B., Greenslade, K., Pinder, G. L., Dowden, P., & Madden, J. (2017). Moving triadic gaze intervention into practice: Measuring clinician attitude and implementation fidelity. Journal of Speech, Language, and Hearing Research, 60(5), 1285-1298.

Fraser, J., Pengilly, A., & Mok, Q. (1998). Long-term ventilator-dependent children: A vocal profile analysis. *Pediatric Rehabilitation,* 2(2), 71-75. Doi:10.3109/17518429809068158.

Gilkerson, J., Coulter, K. K., & Richards, J. A. (2008). LENA Technical Report: Transcriptional analyses of the LENA natural language corpus, LTR-06-2. LENA Foundation: Boulder, CO.

Gilkerson, J., Richards, J. A., Warren, S. F., Montgomery, J. K., Greenwood, C. R., Oller, D. K., Hansen, J. H. L., & Paul, T. D. (2017). Mapping the early language environment using all-day recordings and automated analysis. *American Journal of Speech-Language Pathology,* 26, 248-265. Doi: 10.1044/2016_AJSLP-15-0169.

Gilkerson, J. & Richards, J. A. (2020). LENA Technical Report: A guide to understanding the design and purpose of the LENA system, LTR-12. LENA Foundation: Boulder, CO.

Gilkerson, J., Zhang, Y., Dongxin, X., Richards, J. A., Xu, X., Jiang, F., Harnsberger, J., & Topping, K. (2014). Evaluating language environment analysis system performance for Chinese: a pilot study in Shanghai. *Journal of Speech, Language, and Hearing Research,* 58(2), 445-452. Doi:10.1044/2015_JSLHR-L-14-0014.

Greenwood, C. R., Schnitz, A. G., Irvin, D., Tsai, S. F., & Carta, J. J. (2018). Automated Language Environment Analysis: A Research Synthesis. *American Journal of Speech-Language Pathology,* 27(2), 853-867. Doi:10.1044/2017_AJSLP-17-0033.

Halle, J., Brady, N. C., & Drasgow, E. (2004). Enhancing socially adaptive communication repairs of beginning communicators with disabilities. *American Journal of Speech-Language Pathology,* 13, 43-54.

Hart, B. & Risley, T. R. (1995). Meaningful differences in the everyday experience of young American children. Paul H. Brookes Publishing.

Henderson, S., Skelton, H., & Rosenbaum, P. (2008). Assistive devices for children with functional impairments: impact on child and caregiver function. *Developmental Medicine & Child Neurology,* 50, 89-98. Doi:10.1111/j.1469-8749.2007.02021.x

Hidecker, M. J. C. (2010). AAC use by young children at home. Perspectives on Augmentative and Alternative Communication, 19(1), 5-11. Doi: 10.1044/aac19.1.5.

Hidecker, M. J. C., Cunningham, B. J., Thomas-Stonell, N., Oddson, B., & Rosenbaum, P. (2017). Validity of the Communication Function Classification System for use with preschool children with communication disorders. *Developmental Medicine & Child Neurology,* 59, 526-530. Doi:10.1111.dmcn.13373.

Hidecker, M. J. C., Ho, T. N., Dodge, N., Hurvitz, E. A., Slaughter, J., Workinger, M. S., Kent, R. D., Rosenbaum, P., Lenski, M., Messaros, B. M., Vanderbeek, S. B., Deroos, S., & Paneth, N. (2012). Inter-relationships of functional status in cerebral palsy: Analyzing gross motor function, manual ability, and communication function classification systems in children. *Developmental Medicine & Child Neurology,* 54, 737-742. Doi:10.1111/j.1469-8749.2012.04312.x

Hidecker, M. J. C., Paneth, N., Rosenbaum, P. L., Kent, R. D., Lillie, J., Eulenberg, J. B., Chester, K., Johnson, B., Michalsen, L., Evatt, M., & Taylor, K. (2011). Developing and validating the Communication Function Classification System (CFCS) for individuals with cerebral palsy. *Developmental Medicine and Child Neurology,* 53(8), 704-710. Doi: 10.1111/j.1469-8749.2011.03996.x.

Himmelmann, K., Lindh, K., & Hidecker, M. J. C (2013). Communication ability in cerebral palsy: A case study from the CP register of western Sweden. *European Journal of Paediatric Neurology*, 17, 568-574. Doi:10.1016/j.ejpn.2013.04.005.

Hixon, T. J., Weismer, G., & Hoit, J. D. (2014). *Preclinical speech science: Anatomy, physiology, acoustics, perception.* Plural Publishing.

Hustad, K. C. (2010). Childhood dysarthria: Cerebral palsy. In K. M. Yorkston, D. R. Beukelman, E. A. Strand, & M. Hakel (Eds.), *Management of Motor Speech Disorders in Children and Adults* (pp.3 59-384). ProEd.

Hustad, K. C., Gorton, K., & Lee, J. (2010). Classification of speech and language profiles in 4-year-old children with cerebral palsy: A prospective preliminary study. *Journal of Speech, Language, & Hearing Research,* 53(6), 1496-1513. Doi.org/10.1044/1092-4388(2010/09-0176).

Ishikawa, K., Boyce, S., Kelchner, L., Powell, M. G., Schieve, H., de Alarcon, A., & Khosla, S. (2017). The effect of background noise on intelligibility on dysphonic speech. *Journal of Speech, Language, and Hearing Research,* 60, 1919-1929. Doi:10.1044/2017_JSLHR-S-16-0012.

Jones, M. A., McEwen, I. R., & Neas, B. R. (2012). Effects of power wheelchairs on the development and function of young children with severe motor impairments. *Pediatric Physical Therapy,* 24(2), 131-140. Doi: 10.1097/PEP.0b013e31824c5fdc.

Light, J., Collier, B., & Parnes, P. (1985). Communicative interaction between young nonspeaking physically disabled children and primary caregivers: Part I – discourse patterns. *Augmentative and Alternative Communication,* 1(2), 74-83. Doi: 10.1080/07434618512331273561.

Light, J., Collier, B., & Parnes, P. (1985). Communicative interaction between young nonspeaking physically disabled children and primary caregivers: Part II – communicative function. *Augmentative and Alternative Communication,* 1(3), 98-107. Doi:10.1080/07434618512331273591.

Lobo, M. A., Harbourne, R. T., Dusing, S. C., & McCoy, S. W. (2013). Grounding early intervention: physical therapy cannot just be about motor skills anymore. Physical therapy, 93(1), 94-103.

Logan, S. W., Ross, S. M., Schreiber, M. A., Feldner, H. A., Lobo, M. A., Catena, M. A., MacDonald, M., & Galloway, J. C. (2016). Why we move: Social mobility behaviors of non-disabled and disabled children across childcare contexts. *Frontiers in Public Health,* 4, 204. Doi: 10.3389/fpubh.2016.00204.

Logan, S. W., Shreiber, M., Lobo, M. A., Pritchard, B., George, L., & Galloway, J. C. (2015). Real-world performance: physical activity, play and object-related behaviors of toddlers with and without disabilities. *Pediatric Physical Therapy,* 27 (4), 433-441. Doi:10.1097/PEP.0000000000000181.

Lund, S. K., Quach, W., Weissling, K., McKelvey, M., & Dietz, A. (2017). Assessment with children who need augmentative and alternative communication (AAC): Clinical decisions of AAC specialists. *Language, Speech, and Hearing Services in Schools,* 48, 56-68. Doi: 10.1044/2016_LSHSS-15-0086.

Lynch, A., Ryu, J.C., Agrawal, S., Galloway, J.C. (2009). Power mobility training for a 7-month-old infant with spina bifida. *Pediatric Physical Therapy,* 21: 362-368.

McDonald, E. T. (1980). Early identification and treatment of children at risk for speech development. In R. L. Shiefelbusch (Ed.), *Nonspeech language and communication: Analysis and intervention*, pp. 49-79. Baltimore: University Park Press.

National Guideline Alliance (UK). (2017). *Cerebral palsy in under 25s: Assessment and management.* National Institute for Health and Care Excellence (UK).

Nillson, L. M., & Nyberg, P. J. (2003). Case Report – Driving to learn: A new concept for training children with profound cognitive disabilities in a powered wheelchair. *American Journal of Occupational Therapy,* 57, 229-233.

Nordberg, A., Miniscalco, C., & Lohmander, A. (2014). Consonant production and overall speech characteristics in school-aged children with cerebral palsy and speech impairment. International Journal of Speech-Language Pathology, 16(4),1-10. Doi: 10.3109/17549507.2014.917440.

Oller, D. K., Niyogi, P., Gray, S., Richards, J. A., Gilkerson, J., Xu, D., Yapanel, U., & Warren, S. F. (2010). Automated vocal analysis of naturalistic recordings from children with autism, language delay, and typical development. *Proceedings of the National Academy of Sciences*, 107 (30), 13354-13359. Doi: 10.1073/pnas.1003882107.

Olswang, L. B., Dowden, P., Feuerstein, J., Greenslade, K., Pinder, G. L., & Fleming, K. (2014). Triadic gaze intervention for young children with physical disabilities. *Journal of Speech, Language, and Hearing Research*, 57(5), 1740-1753.

Olswang, L. B., Feuerstein, J. L., Pinder, G. L., & Dowden, P. (2013). Validating dynamic assessment of triadic gaze for young children with severe disabilities. *American Journal of Speech-Language Pathology,* 22, 449-462.

Orena, A. J., Byers-Heinlein, K., & Polka, L. (2019). Reliability of the Language Environment Analysis recording system in analyzing French-English bilingual speech. *Journal of Speech, Language, and Hearing Research,* 62, 2491-2500. Doi:10.1044/2019_JSLHR-L-18-0342.

Palisano, R., Rosenbaum, P., Bartlett, D., & Livingston, M. (2007). GMFCS-E&R: Gross motor function classification system expanded and revised. *CanChild Centre for Childhood Disability Research, McMaster University*; Institute for Applied Health Sciences McMaster University: Hamilton, ON, Canada.

Paulson, A. & Vargus-Adams, J. (2017). Overview of four functional classification systems commonly used in cerebral palsy. *Children,* 4(4), 30. Doi:10/3390/children4040030.

Pennington, L., & McConachie, H. (2001). Interaction between children with cerebral palsy and their mothers: the effects of speech intelligibility. *International Journal of Language and Communication Disorders,* 36(3), 371-393. Doi: 10.1080/13682820110045847

Pennington, L. & McConachie, H. (2001). Predicting patterns of interaction between children with cerebral palsy and their mothers. *Developmental Medicine & Child Neurology,* 43, 83-90. Doi:10.1111/j.1469-8749.2001.tb00720.x

Pennington, L., Smallman, C., & Farrier, F. (2006). Intensive dysarthria therapy for older children with cerebral palsy: findings from six cases. *Child Language Teaching and Therapy,* 22(3), 255-273. Doi: 10.1191/0265659006ct307xx.

Pennington, L., Thomson, K., James, P., Martin, L., & McNally, R. (2009). Effects of It Takes Two to Talk – The Hanen Program for parents of preschool children with cerebral palsy: Findings from an exploratory study. *Journal of Speech, Language, and Hearing Research,* 52, 1121-1138. Doi: 10.1044/1092-4388(2009/07-0187).

Raghavendra, P., Olsson, C., Sampson, J., Mcinerney, R., & Connell, T. (2012). School participation and social networks of children with complex communication needs, physical disabilities, and typically developing peers. *Augmentative and Alternative Communication,* 28(1), 33-43. Doi:10.3109/07434618.2011.653604.

Reichle, J., York-Barr, J., & Sigafoos, J. (1991). *Implementing augmentative and alternative communication: strategies for learners with severe disabilities*. Baltimore: P.H. Brookes Pub.

Reisinger, D. L., Shaffer, R. C., Pedapati, E. V., Dominick, K. C., & Erickson, C. A. (2019). A pilot quantitative evaluation of early life language development in Fragile X Syndrome. *Brain Sciences,* 9(2), 27.

Richards, J. A., Gilkerson, J., Paul, T., & Xu, D. (2008). LENA Technical Report: LENA Automatic Vocalization Assessment, LTR-08-1. LENA Foundation: Boulder, CO.

Rosenbaum, P., Paneth, N., Leviton, A., Goldstein, M., Bax, M., Damiano, D., Dan, B., & Jacobsson, B. (2007). A report: the definition and classification of cerebral palsy April 2006. *Developmental Medicine & Child Neurology Supplement,* 109, 8-14.

Rudzicz, F., Hirst, G., & van Lieshout, P. (2012). Vocal tract representation in the recognition of cerebral palsied speech. *Journal of Speech, Language, and Hearing Research,* 55, 1190-1207.

Sigafoos, J., Woodyatt, G., Keen, D., Tait, K., Tucker, M., Roberts-Pennell, D., & Pittendreigh, N. (2000). Identifying potential communicative acts in children with developmental and physical disabilities. *Communication Disorders Quarterly,* 21(2), 77-86.

Smith, A. L. & Hustad, K. C. (2015). AAC and early intervention for children with cerebral palsy: parent perceptions and child risk factors. *Augmentative and Alternative Communication,* 31(4), 336-350. Doi: 10.3109/07434618.2015.1084373.

Sperry, D. E., Sperry, L. L., & Miller, P. J. (2018). Reexamining the verbal environments of children from different socioeconomic backgrounds. *Child Development,* 90(4), 13030-1318. Doi: 10.1111/cdev.13072.

Thiemann-Bourque, K. S., Warren, S. F., Brady, N., Gilkerson, J., & Richards, J. A., (2014). Vocal interaction between children with Down Syndrome and their parents. *American Journal of Speech-Language Pathology,* 23, 474-485. Doi: 10.1044/2014_AJSLP-12-0010.

Turner, G. S., Tjaden, K., & Weismer, G. (1995). The influence of speaking rate on vowel space and speech intelligibility for individuals with amyotrophic lateral sclerosis. *Journal of Speech and Hearing Research,* 38, 1001-1013. Doi: 10.1044/jshr.3805.1001.

Uchiyama, I., Anderson, D. I., Campos, J. J., Witherington, D., Frankel, C. B., Lejeune, L., & Barbu-Roth, M. (2008). Locomotor experience affects self and emotion. *Developmental Psychology,* 44(5), 1225-1231. Doi:10.1037/a0013224.

World Health Organization (2001). International classification of functioning, disability and health: ICF. World Health Organization.

Wiggin, M., Gabbard, S., Thompson, N., Goberis, D., Yoshinaga-Itano, C. (2012). The school to home link: Summer preschool and parents. *Seminars in Speech and Language,* 33(4), 290-296. Doi:10.1055/s-0032-1326919.

Xu, D., Yapanel, U., & Gray, S. (2009). LENA Technical Report: Reliability of the LENA ™ Language Environment Analysis system in young children’s natural home environment, LTR-05-2. LENA Foundation: Boulder, CO.

Appendix A

Ride-on Car Sample Image

Photo Courtesy of the IMPACT Collaboratory

Appendix B

Sample Conversational Turn Transcript

Call	**Response**	**Response**	**CT Count**
Oh, you got your phone?	Ya	Ring ring ring ring.	2
Hi mommy.	Hi [name], how are you?	I good.	2
Good, what are you doing today?	How you?	I’m very good.	2
Dat good.	Okay.		1
Um, when are you going to see [name]?	Um I uh um two weeks.		1
In two weeks?	Yeah.		1
Oh okay, tell [name] I say hi.	Okay.		1
Okay, bye.	Unintelligible: o ke gɑk		1
Wi wi wi	Hello?	Unintelligible: hʌʔəm	2
Total CTs:			**13**