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Extensions to the Speech Disorders Classification System (SDCS)

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Abstract

This report describes three extensions to a classification system for pediatric speech sound disorders termed the Speech Disorders Classification System (SDCS). Part I describes a classification extension to the SDCS to differentiate motor speech disorders from speech delay and to differentiate among three subtypes of motor speech disorders. Part II describes the Madison Speech Assessment Protocol (MSAP), an approximately two-hour battery of 25 measures that includes 15 speech tests and tasks. Part III describes the Competence, Precision, and Stability Analytics (CPSA) framework, a current set of approximately 90 perceptual- and acoustic-based indices of speech, prosody, and voice used to quantify and classify subtypes of Speech Sound Disorders (SSD). A companion paper, Shriberg, Fourakis, et al. (2010) provides reliability estimates for the perceptual and acoustic data reduction methods used in the SDCS. The agreement estimates in the companion paper support the reliability of SDCS methods and illustrate the complementary roles of perceptual and acoustic methods in diagnostic analyses of SSD of unknown origin. Examples of research using the extensions to the SDCS described in the present report include diagnostic findings for a sample of youth with motor speech disorders associated with galactosemia (Shriberg, Potter, & Strand, 2010) and a test of the hypothesis of apraxia of speech in a group of children with autism spectrum disorders (Shriberg, Paul, Black, & van Santen, 2010). All SDCS methods and reference databases running in the PEPPER (Programs to Examine Phonetic and Phonologic Evaluation Records; [Shriberg, Allen, McSweeny, & Wilson, 2001]) environment will be disseminated without cost when complete.

Keywords

apraxia; articulation; dysarthria; genetics; phonology

Overview

The long-term goal of the Phonology Project, Waisman Center, University of Wisconsin-Madison is to develop and validate the a system for etiologic classification of pediatric speech sound disorders of currently unknown origin termed the Speech Disorders Classification System (SDCS; Shriberg, 1980, 1982a, 1982b, 1993b, 1994b, 1997b, 2010; Shriberg, Austin,

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Lewis, McSweeny, & Wilson, 1997; Shriberg & Kwiatkowski, 1982; Shriberg, Tomblin, & McSweeny, 1999). Rationale for the SDCS is that classification by etiology, a so-called medical model of classification, is needed for speech sound disorders (SSD) to participate in the continuing advances in genomic and other biomedical sciences. Specifically, the assumption is that next-generation personalised medicine for assessment, treatment, and eventual prevention of diseases and disorders will require international classification systems based on biological phenotypes (Helmuth, 2003; Shriberg, 2010; Threats, 2006).

The three extensions to the SDCS described in this paper are motivated by public health goals, as well as findings from epidemiological studies of speech-language disorders supporting the explanatory-predictive power of biological factors, relative to social and environmental risk and protective factors (e.g. Campbell et al., 2003; Harrison & McLeod, 2009; McLeod & Harrison, 2009; Reilly et al., 2007; Roulstone, Miller, Wren, & Peters, 2009; Roulstone, Wren, Miller, & Peters, 2009; Zubrick, Taylor, Rice, & Slegers, 2007). Dykens, Hodapp, and Finucane (2000), discussing intellectual disorders, includes extensive comparative discussion of etiological versus ‘mixed group’ approaches to classification.

Comparative discussion of alternative proposals to classify children with SSD based on linguistic (e.g. Broomfield & Dodd, 2004; Dodd, Holm, Crosbie, & McCormack, 2005), psycholinguistic (e.g. Stackhouse & Wells, 1997, 2001), or the present etiological constructs is beyond the scope of this report. Each classification proposal has strengths and limitations relative to theory and practice in SSD, with each fulfilling the important role of generating research that tests the validity of the primitives, postulates, and predictions of each classification proposal. The eventual value of alternative conceptual and methodological frameworks will be determined by the impact of empirical findings, theory, and practice, towards an integrated account of speech sound disorders of currently unknown origin.

The paper is divided into three sections. Part I includes a brief description of the SDCS and rationale for modification and extensions based on research and applied needs for children with motor speech disorders of currently known and unknown origins. Part II describes an assessment instrument, the Madison Speech Assessment Protocol (MSAP), that provides the speech, prosody, and voice data needed for typologic and etiologic classification of children’s prior and current speech status. Part III describes an analytic approach to translate MSAP findings to the most likely classification(s), using a set of risk factors and diagnostic markers organized by three constructs termed the Competence, Precision, and Stability Analytics (CPSA) framework.

Part I. Motor speech disorders modifications to the SDCS

Shriberg (2010) provides the most recent detailed description of the primary elements of the SDCS, excepting the extensions described in this report. The two branches of the SDCS in figure 1, termed the Speech Disorders Classification System-Typology (SDCS-T) and the Speech

Disorders Classification System-Etiology (SDCS-E), were developed to address research and applied needs with children who have SSD of currently unknown origin. The following brief summary of the discussion in Shriberg (2010) includes rationale for the revised motor speech disorder section of the SDCS shown in figure 1.

Speech Disorders Classification System-Typology (SDCS-T)

The left arm of the SDCS shown in figure 1 includes classification categories for four types of speech sound disorders based on a speaker’s age and current and/or prior speech errors. *Normal (ized) Speech Acquisition* (*NSA*) is assigned to speakers of any age with typical or normalised speech. *Speech Delay (SD)* includes 3- to 9-year-old children with significant speech sound deletions and substitutions that typically normalise with treatment. The extended type of speech sound disorder discussed in the next section, *Motor Speech Disorder* (*MSD*), includes children with significant speech sound deletions, substitutions, and distortions that may not completely normalise with treatment. *Speech Errors (SE)* includes speakers with speech sound distortion errors (typically on sibilants and/or liquids) that are not associated with the risk domains and adverse social, academic, and vocational consequences documented for SD and MSD, but may also persist throughout the lifespan. Technically, whereas age and speech characteristics are sufficient for the typologic distinctions among NSA, SD, MSD, and SE and their later normalization histories, subroutines in the SDCS-E software described in the following sections are needed to differentiate MSD from SD.

The bottom row in the SDCS-T arm of the SDCS includes classification assignments for children older than 9 years of age that indicate present and prior speech status. The classification *Persistent Speech Disorder* (*PSD*) is the cover term for misarticulations that persist past this developmental period generally taken to be the terminus point for phonetic-phonologic development. Suffixes to PSD are used to indicate the histories of each of the three types of SSD: PSD-SD, PSD-MSD, and PSD-SE.

Speech Disorders Classification System-Etiology (SDCS-E)

The right arm of figure 1, Speech Disorders Classification System-Etiology (SDCS-E), provides the conceptual framework and working terms for eight etiologic subtypes within SD, MSD, and SE (and their possible persistence after 9 years as PSD-SD, PSD-MSD, or PSD-SE). A set of working terms (and their abbreviations) is used for the eight subtypes of SSD shown in figure 1.

Speech Delay (SD)—The etiologic hypothesis for Speech Delay (SD) is that it includes three individual and overlapping causes, each with one or more distal and proximal origins with risk and protective factors in both genetic and environmental domains. The three etiologic subtypes of SD are those associated with (a) cognitive-linguistic processing constraints that may be, in part, *gen*etically transmitted (*SD-GEN)*; (b) auditory-perceptual processing constraints that are the consequence of the fluctuant conductive hearing loss associated with early recurrent *o*titis *m*edia with *e*ffusion *(SD-OME);* and (c) affective, temperamental processing constraints associated with *d*evelopmental *p*sychosocial *i*nvolvement *(SD-DPI).* Shriberg (2010) reviews research findings supporting the validity and clinical utility of these three subtypes of speech delay. As above, although there may be lifetime residuals of each subtype, the general perspective on research findings is that children or adolescents eventually normalise the significant speech features that define each of the three subtypes.

Motor Speech Disorder (MSD)—Prior versions of the SDCS-E included two subtypes of speech delay termed *Speech Motor Involvement* (*SMI*): a subtype with planning/programming constraints consistent with *a*praxia *o*f *s*peech (Speech Delay-Apraxia of Speech [*SD-AOS*]) and a subtype consistent with possibly subclinical *dys*arthria (Speech Delay-Dysarthria [*SD-DYS*]). Notice that both of these subtypes were subordinated under Speech Delay. Two considerations have motivated a change to elevate Motor Speech Disorders to the superordinate classification level shown in figure 1, SDCS-E. First, persisting speech disorder in adults with inherited and de novo genetic disruptions, especially in emerging follow-up studies of speakers with early diagnoses of apraxia of speech (e.g. Jakielski, 2008;Shriberg, Potter, & Strand, 2010), are not consistent with the concept of a speech delay. Rather, for such speakers in both research and clinical contexts (e.g. counseling parents, treatment planning), the persistence of significant speech and/or prosody-voice deficits is consistent with the construct of motor speech *disorder* rather than speech *delay*.

A second rationale for the MSD extension to the SDCS is the need for an additional classification alternative that is sensitive to motor speech disorder (MSD), but not specific for classical subtypes of either apraxia or dysarthria. There are many literature descriptions of children with neurodevelopmental differences affecting speech that are either not readily classified as apraxia of speech (MSD-AOS) or dysarthria (MSD-DYS) or do not appear to be a reasonable fit to either classification (e.g. Bishop, 2002; Bradford, Murdoch, Thompson, & Stokes, 1997; Cheng, Chen, Tsai, Chen, & Cherng, 2009; Gaines & Missiuna, 2007; Hill, 2001; Powell & Bishop, 1992; Newmeyer et al., 2007; Rechetnikov & Maitra, 2009; Vick et al., 2009; Visscher, Houwen, Scherder, Moolenaar, & Hartman, 2007; Zwicker, Missiuna, & Boyd, 2009). As described later, a subclassification of MSD in figure 1 termed *Motor Speech Disorder-Not Otherwise Specified* (*MSD-NOS*) provides the cover term needed for speech, prosody, and voice behaviours that are consistent with motor speech impairment (e.g. slow rate, imprecise consonants), but are not specific for apraxia or dysarthria.

Speech Errors (SE)—Last, the two subtypes of *Speech Errors* (*SE*) included in the SDCS-E provide classifications for English speakers who have transient or persistent distortions of sibilants (SE-/s/) and/or rhotics (SE-/r/). Persistent speech sound distortions in American English such as dentalised /s/, lateralised /s/, and derhotacised /r/ currently are viewed as having some social consequences (e.g. Crowe Hall, 1991; Mowrer, Wahl, & Doolan, 1978; Silverman & Falk, 1992; Silverman & Paulus, 1989), but for speech genetics research, it is necessary to identify and typically exclude speakers with these subtypes of SSD from those meeting criteria for SD. Elsewhere we suggest that the causal origins of such distortions and their natural histories remain of considerable theoretical interest (Flipsen, Shriberg, Weismer, Karlsson, & McSweeny, 2001; Karlsson, Shriberg, Flipsen, & McSweeny, 2002; Shriberg, 1994; Shriberg, Flipsen, Karlsson, & McSweeny, 2001).

It is important to underscore four aspects of SDCS terminology. First, the current etiologic classification terms are not intended to be used in clinical practice until validated by empirical findings. As with SD-GEN, SD-OME and SD-DPI, the terms MSD-AOS, MSD-DYS, MSD-NOS and SE-/s/ and SD-/r/ are used only as interim place holders until cross-validation studies warrant integration with extant and emerging systems for classification of diseases and disorders.

Second, as discussed in the following section, although the suffix *GEN* is used to denote the most common form of SSD proposed to be heritable (SD-GEN), genetic substrates clearly contribute to each of the three subtypes of SD and three subtypes of MSD. As indicated in the right arm of figure 1, the SDCS assumes that both genetic and environmental risk and protective factors contribute to the origin and persistence of each etiologic subtype of SSD.

Third, although Childhood Apraxia of Speech (CAS) has become the accepted term for MSD-AOS, we use MSD-AOS in research contexts that include adults with neurogenetic forms of AOS and children and adults with acquired AOS. For clarity in most other contexts, however, it is simply efficient to use CAS.

Last, and perhaps most in need of clarity, the SDCS subtypes shown in figure 1 are not mutually exclusive. Multiple causal pathways involving multiple domains are, by definition, the rule in complex developmental disorders. Children at risk for genetically-transmitted SSD (i.e. SD-GEN) can also have a sufficient transient conductive hearing loss associated with recurrent otitis media with effusion to be at risk for SD-OME. A slash convention is used for classification of speakers who meet risk criteria for more than one subtype (e.g. SD-GEN/OME; MSD-AOS/DYS; SD-DPI/MSD-NOS).

Genetic and environmental hypotheses

Table 1 includes hypotheses about genetic and environmental risk factors for each of the eight subtypes of SSD shown in figure 1. As noted previously, contemporary goals for the SDCS include its potential to provide more precise phenotypes for SSD than have been used to date in genetic studies of SSD and other verbal domains (language, reading, spelling: for a review see Lewis et al., 2006). The last two columns in table 1 indicate the central etiologic and speech processing distinctions among the three types of speech sound disorders (SD, MSD, and SE) and among subtypes within each type. We have proposed a variant of attunement theory termed *speech attunement* to account for sociodemographic differences observed in children with the two proposed subtypes of SE (Shriberg, 1975,1994;Shriberg, Paul, Black, & van Santen, 2010), but will not have further need to refer to these subtypes in the present report.

The primary risk factors for the three subtypes of SD listed in table 1 are posited to include both genetic and environmental substrates. As indicated previously, although the affix GEN is used with the SD stem for the first classification in table 1 (i.e. SD-GEN), each of the three subtypes of SD is presumed to have both genetic and environmental antecedents. The genetic contribution in each case is posited to be from many (polygenic) sources, rather than from one major gene (monogenic). As observed with other normally-distributed traits, the assumption is that SD-GEN, SD-OME, and SD-DPI result from contributions from multiple genomic and environmental sources that place children at risk for the three types of processing deficits shown in the right-most column of table 1.

In contrast to the three subtypes of SD in table 1, the three subtypes of MSD are hypothesised to have monogenic or oligogenic origins. Oligogenic causal pathways include the genetic contributions of a small group of genes, with one or a few having proportionally more influence on the phenotype. Such origins could include the possibility of the same genes expressing differently in two or more of the three MSD subtypes, or different major genes or small groups of genes for each MSD subtype. As shown in table 1, deficits in one or more aspects of sensorimotor speech processes are posited for each of the three MSD classifications, with a clear need for research to identify the core processes associated with each classification.

Part II. The Madison Speech Assessment Protocol (MSAP)

Despite or perhaps as a consequence of the many theoretical perspectives on speech sound disorders in the past and present centuries, there is no consensus on a standardised assessment protocol for research and practise. As indicated previously, discussion of alternative theoretical proposals that would motivate alternative assessment protocols consistent with each perspective is beyond the scope of this report. The SDCS requires a protocol comprised of tests and tasks that can be administered to participants of all ages, that provides information on speech, prosody, and voice status using perceptual and acoustic methods, and that is time efficient for research and practise. The following sections describe the assessment instrument developed to meet these goals, termed the Madison Speech Assessment Protocol (MSAP).

Description

Table 2 includes descriptive information on the MSAP measures that assess relevant risk factors and correlates of speech sound disorders (cognitive, language, behavioural, developmental) and the measures that assess a speaker's speech, prosody, and voice. The measures were either selected from the literature or developed locally or with collaborators over several decades of research. The MSAP is significantly influenced by the form and content of the research protocol used by Barbara Lewis and colleagues, including the concept of four age-based variants of the protocol (preschool, school-age, adolescent, adult) and includes several audio-recorded speech tasks from Lewis' protocol. The fixed sequence of administration of each MSAP task within each age group was developed and tested to optimise examiner efficiency and examinee interest and compliance. Abbreviations and acronyms for all MSAP tasks are used for efficiency in the present text, tables, and figures.

The MSAP measures were assembled to yield information on the risk factors for and correlates of SD, MSD, and SE, and to quantify the *competence, precision*, and *stability* of participants' speech production (described in Part III). Table 2 includes brief descriptions of the goals of each measure and the number and type of stimuli. As shown in figure 2, the MSAP samples speech (a) using imitative and spontaneous evocation modes; (b) within four linguistic contexts, including sounds, syllables, words, and utterances; and (c) in simple and complex phonetic and phonological contexts. As discussed subsequently, several MSAP tasks evoke repeated tokens of word types to quantify stability of productions over repeated trials.

Administration

An unpublished laboratory document titled the Phonology Project Laboratory Manual (hereafter, the *laboratory manual*) provides information on each MSAP measure and detailed directions for administration. Goals are to maximise the validity of MSAP data by standardising administration procedures, including information on examiner responses to potentially invalidating participant behaviours. The *Goldman-Fristoe Test of Articulation-2* (*GFTA-2*; table 2) is the only speech measure for which the examiner records responses in the conventional way during administration. Participant responses to all other tests and tasks are scored off-line by the examiner or research staff. Eliminating the need for scoring of MSAP speech tasks during administration allows examiners to focus on the task of obtaining representative responses from participants, particularly children and adolescents with significant cognitive or behavioural challenges. All collaborative research projects with examiners using the MSAP for the first time have included at least one trial administration, followed by detailed feedback to ensure examiner compliance with guidelines in the laboratory manual.

The auditory stimuli for all of the imitative speech tasks described in table 2 are presented by computer. The auditory stimuli for five of the MSAP tasks (Lexical Stress Task [LST], Challenging Words Task [CWT], Vowel Task 1 [VT1], Vowel Task 2 [VT2] and Vowel Task 3 [VT3]) are accompanied by colorful illustrations. Game-like activities and individualised cumulative incentives are used to obtain and sustain attention and motivation to complete the protocol in one or two assessment sessions. Tasks up to and including the Sustained Consonant Task (SCT) listed in table 2 are administered in the first approximately one hour of assessment, with the remaining MSAP tasks administered to younger children in a second session also lasting approximately one hour. Assessment of participants older than six years of age is typically completed in one approximately two-hour session. Digital recordings of participants' responses to the MSAP have been made in quiet environments using contemporary audio and video systems. The laboratory manual and other laboratory documents (Chial, 2003;Shriberg et al., 2005) include detailed information on optimizing digital recordings for transcription, prosody-voice coding, and acoustic analyses.

Data reduction

The laboratory manual also includes extensive information on the software environment for data reduction and statistical analyses termed PEPPER (Programs to Examine Phonetic and Phonologic Evaluation Records; [Shriberg, Allen, et al., 2001]). The following sections are brief summaries of methods and procedures.

Perceptual methods—Audio and video playback of participants' responses to the MSAP tasks for transcription and prosody-voice coding is accomplished using laptop computers configured with customised audio-video players in the PEPPER environment and standard external desk-top speakers. The players provide waveform displays of the audio stimuli and participant responses. Narrow phonetic transcription of segmental information is completed using a set of symbols and transcription conventions (Shriberg & Kent, 2003) supplemented by laboratory manual guidelines for transcription in the PEPPER environment. The data reduction section of the manual includes procedures for glossing, formatting, and transcribing each of the 15 MSAP speech tasks in table 2. Coding of a speaker's prosody and voice characteristics is obtained from the conversational speech sample using procedures described in McSweeny and Shriberg (2001), Shriberg (1993), Shriberg, Kwiatkowski, and Rassmussen (1990), and supplemented in the laboratory manual. All transcription and prosody-voice coding completed by transcribers is checked for clerical errors by an assistant who enters the transcripts for PEPPER analyses.

Acoustic methods—Acoustic analyses of responses to each MSAP speech task are completed by analysts following procedural instructions for segmentation, formant measures, and spectral measures developed in prior research (Flipsen et al., 2001; Flipsen, Tjaden, Weismer, & Karlsson, 1996; Karlsson et al., 2002; Shriberg, Flipsen, et al., 2001), supplemented by instructions in the laboratory manual. The analysts use a series of screen displays to segment speech sounds and pauses and set formant values. The screen displays provide utilities to derive and store frequency, amplitude, and duration values. Figure 3 illustrates some of the screen displays in PEPPER that facilitate high-throughput acoustic analyses. As indicated in the legend, the electronic version allows enlargement of text and graphic elements within the figure.

Risk factor and correlates methods—The software environment includes databasing procedures to organise and analyse findings from each of the relevant MSAP measures in Table 2, including raw and standardised scores for the tests and tasks using reference databases. The laboratory manual includes detailed procedures to code other risk factors and correlates information (e.g. medical history, speech mechanism exam findings) using a 3-category ordinal system ('0' = within normal range; '1' = marginal positive, and '2' = positive [i.e. affected for the variable]). The manual includes procedures to derive composite values for some risk factors/correlates in the same domain (e.g. middle ear history composite: highest score on *excessive ear wax, number of episodes of otitis media with effusion in first two years of life*, or other middle ear variables based on the preliminary system described in Shriberg & Kwiatkowski, 1994).

Part III. The Competence, Precision, and Stability Analytics (CPSA) Framework

The software organises findings from the perceptual, acoustic, and case records data using an organizational matrix termed the Competence, Precision, and Stability Analytics (CPSA) framework. CPSA data provide a theory-neutral profile of a speaker's or a group of speakers' averaged speech, prosody, and voice status. The framework was designed to quantify and make readily accessible the large amounts of data available from participants' responses to the MSAP. Research and applied aims include the use of CPSA output for typologic classification (SDCS-T), diagnostic classification (SDCS-E), phenotyping for genetic research (Shriberg, 1993), and clinical decision making (e.g. treatment planning). As discussed previously, a primary goal of recent research using the SDCS has been to differentiate children with MSD from those with SD, and the added challenge of differentiating among MSD-AOS, MSD-DYS, and MSD-NOS (e.g. Shriberg, Potter, & Strand, 2010) and within subtypes of MSD-DYS. The CPSA framework, shown in table 3 and described in the sections to follow, provides the analytic constructs and quantitative methods for these research and applied goals.

The 10 linguistic domains in the CPSA framework

The rows of the CPSA matrix in table 3 organise MSAP findings into those reflecting traditional segmental and suprasegmental *tiers,* with the two tiers, respectively, including three and seven linguistic *domains.* The three segmental tier domains organise responses to the MSAP measures by vowels (monophthongs/diphthongs), consonants, and measures that derive scores from both vowels and consonants. The seven suprasegmental tier domains are subordinated within the two constructs of prosody (phrasing, rate, stress) and voice (loudness, pitch, laryngeal quality, resonance). These seven domains were developed from a series of studies of speakers with SSD of known and unknown origin (Shriberg, Kwiatkowski, & Rasmussen, 1990;McSweeny & Shriberg, 2001). Thus, as described in the following sections, for each of the 10 linguistic domains in the matrix shown in table 3, the CPSA provides information that profiles a speaker’s competence, precision, and stability.

Competence indices

The 30 Competence indices (i.e. the antonym of constructs such as *severity of impairment, handicap*) in table 3 quantify a speaker’s mastery of the phonetic and phonological features of the ambient English dialect. For clarity, statistical efficiency, and positive impact on clinical stakeholders, all competence indices are labeled in the positive direction, with higher scores indicating better performance. The primary purpose of competence indices is to provide descriptive detail associated with the SDCS-T classifications reviewed in Part I (figure 1). Competence indices are useful for both independent and dependent variable needs in research and practise (e.g. Percentage of Consonants Correct, Intelligibility Index). Some competence indices are also both sensitive to and specific for etiologic classification of speech sound disorders (e.g. some of the measures of vowel competence in table 1 are sensitive to and specific for subtypes of MSD [e.g. Shriberg, Paul, et al., 2010;Shriberg, Potter, & Strand, 2010]). All competence indices are obtained using the perceptual methods of phonetic transcription and prosody-voice coding, following the rationale that definitional criteria for competence are determined by a social group’s consensual perceptual criteria.

Precision indices

Speech precision (i.e. the antonym of constructs such as *imprecise, distorted*) in the CPSA framework indexes spatial and temporal features of speech production relative to a speaker’s age and gender. Unlike the titles of the competence indices, which indicate the variables they assess, titles for the precision and stability indices are based on a directional hypothesis associated with their potential as diagnostic markers for one of the three SD and three MSD subtypes of SSD. For example, Reduced Vowel Space is posited to be a diagnostic marker of MSD, but non-specific for MSD-AOS or MSD-DYS and hence currently an MSD-NOS index (to be discussed).

Unlike competence indices, precision and stability indices are obtained from MSAP tasks using both perceptual and acoustic data reduction methods. For the perceptually-based indices included in the three segmental domains in table 3, lowered precision is consistent with the construct of an inappropriate distortion in which a speech sound may be phonemically correct, but phonetically variant from the normative value expected in the phonetic context in question. In clinical speech pathology, certain speech sound distortions of the phonemes of each language have been, by consensus, included with phoneme deletions and phoneme substitutions as speech sound errors. A system in Shriberg (1993; Appendix) differentiates clinically-significant distortions of American English using six phonetic features (place, manner, voicing, additions, duration, and force) and organises them by whether or not the distortion is conventionally classified as an error in clinical speech pathology and whether or not it commonly occurs in the conversational speech of American English speakers. Perceptual methods use diacritic symbols to capture such allophonic detail (e.g. a backed vowel, a lengthened vowel, a vowel onglide, a spirantised stop, a weak stop), whereas acoustic methods provide continuous data on the precision of parameters of frequency, amplitude, duration, laryngeal quality (e.g. jitter, shimmer, harmonic-to-noise ratio), and resonance (e.g. F2 lowering for nasopharyngeal resonance [Fourakis, Karlsson, Tilkens, & Shriberg, 2010]). Together with stability indices and risk factors to be discussed next, such information provides the primary data for differentiating SD and SE from NSA, MSD from SD, and for differentiating among subtypes of SD and MSD.

Stability indices

The analytic construct of stability (the antonym of constructs such as *inconsistency*, *variability*) has an extensive history in research in motor skill development and performance. To enable stability estimates at different levels of complexity, several of the MSAP tasks require participants to produce multiple tokens of each stimulus item (for example, see table 2: Vowel Tasks 1, 2, and 3; Challenging Words Task; Rhotics and Sibilants Task). For the analytic framework in table 3, stability is indexed by subtracting the coefficient of variation (standard deviation divided by the mean) from 1.00. Stability measures can provide information on the similarity of performance across tokens of a speech type (e.g. all occurrences of /i/ in a speech sample), across members of a speech class (e.g. all front vowels in a speech sample), and across repeated measures (i.e. all tokens of a speech type in two or more speech samples obtained on the same or different days). As with the constructs of competence and precision, a speaker's stability in each of the 10 linguistic domains in table 3 is estimated by standardizing the speaker's raw scores using the raw scores of speakers with typical speech of the same gender and chronological, intellectual, or language age from the reference database.

Multiple sources and sub-indices

Multiple sources—As discussed previously and illustrated in figure 2, CPSA data for each of the precision and stability markers in table 3 are typically obtained from more than one MSAP task. The entries in table 4 indicate how the information obtained in the MSAP is used to provide information for CPSA from multiple sources, reflecting the different speech processing demands in the 15 MSAP speech measures. As shown in table 4, the software computes index and sub-index (see next section) information from as many as seven different MSAP tasks. For an example of an index that is obtained from multiple MSAP sources, see table 4, Vowels and Consonants Precision indices: Increased % of Phoneme Distortions.

Subindices—An additional feature of the CPSA framework software not shown in this report is its extensive use of subindices to describe and classify performance on each of the primary markers. Some subindex examples include Reduced Vowel Space, which includes sub-indices of vowel space computed using eight alternative metrics; Lowered F1 sub-indices, which are available at the level of individual vowels; and Slow Speech Rate, which includes subindices for several rate units (e.g. syllables, phonemes) at each of four utterance length categories (e.g. two to four word utterances, five to seven word utterances and so forth). As with the multiple source data, information from subindices is useful for exploratory data analyses toward optimum description and explanation of a speaker's competence, precision, and stability. Eventually, such complexities in the current SDCS will be pruned to retain only the most informative MSAP tasks, indices, and subindices of speech, prosody, and voice for diagnostic classification and other descriptive-explanatory needs.

Criterion for a positive marker

As described, the PEPPER software computes z-scores on each index and subindex, using user-selected databases that standardise a speaker's raw scores by age and gender. Preliminary studies of alternatives to classify a z-score for a marker as *positive* (affected) supported a decision to consider a z-score of lower or greater than one standard deviation from the mean of the reference group (i.e. < −1.00 or > 1.00 depending on the expected direction of deficit) on any one or more index or subindex from any one or more MSAP sources as sufficient to code the index as positive. This liberal criterion likely yields false positives (i.e. compared to more stringent criteria such as 1.25 or 1.50 standard deviation units) particularly as the software currently includes no false discovery rate corrections. The plus or minus 1.00 standard deviation criterion is maximally sensitive to validation goals of identifying all possible true positives for each of the SDCS-E subtypes in diagnostic accuracy studies. Later studies are expected to use improved statistical algorithms to maximize the diagnostic accuracy of the etiologic classification studies described in the following section.

Etiologic classification of children with SSD using the SDCS

As described to this point, the SDCS was developed as an assessment tool to classify a child's speech competence (i.e. NSA vs. SE, SD, or MSD) and to identify the most probable etiologic subtype for children with SD or MSD. SE studies have reported findings supporting the hypothesis that residual speech distortions differ acoustically depending on whether a speaker with Persistent Speech Disorder (PSD) had a history of SD or SE (Flipsen et al., 2001; Karlsson et al., 2002; Shriberg, Flipsen, et al., 2001). Studies supporting the risk factors and candidate markers of the three proposed subtypes of SD are summarised in Shriberg (2010). Consistent with the goals of the present report, the following discussions focus on MSD extensions to the SDCS.

Table 5 is a summary list of the speech, prosody, and voice indices that ongoing research suggests are sensitive to and specific for the three MSD classifications in figure 1 and table 1. The MSD-NOS indices in table 5, as defined, are not specific for any currently identified subtype of MSD. Recent studies (Shriberg, Paul, et al., 2010;Shriberg, Potter, & Strand, 2010) present the first diagnostic findings for motor speech sound disorders using the MSD extensions to the SDCS. Table 6 is a summary of the tabular entries in Table 5 that provides quantitative information on several relevant features of the CPSA markers of MSD. Four observations about the entries in table 5 and as summarised in table 6 warrant comment.

First, the current number of candidate speech, prosody, and voice markers for each of the MSD classifications in table 6 includes 25 indices for MSD-AOS, 12 for MSD-DYS, and 20 for MSD-NOS, with the smaller number of MSD-DYS indices reflecting the limited literature in childhood dysarthria. At present, the putative markers within each classification are weighted equally in their potential diagnostic accuracy. Studies in process seek to identify additional potential markers and determine which have the highest diagnostic accuracy, the highest reliability, and are most efficient relative to the number and type of MSAP sources needed to score a speaker as positive for the marker.

A second observation about the information in table 6 is that it currently does not include potential risk markers for MSD subtypes from the case history and MSAP tasks, including structural and functional examination of the oral mechanism. Exploratory and confirmatory studies in progress will determine which historical and performance information captures unique classification variance.

A third observation is that the distribution of MSD subtype marker entries in table 5 and summarised in table 6 is spread across the 30-cell CPSA matrix (i.e. 10 linguistic domains x the three analytic constructs). Notice that the MSD-AOS markers include linguistic domains from both segmental and suprasegmental tiers, and primarily address speech stability (23/25, 92%). In comparison, the MSD-DYS markers are primarily suprasegmental (11/12, 92%) and all address speech precision (12/12, 100%). Of the 20 MSD-NOS markers, which are nonspecific for either MSD-DYS or MSD-AOS, approximately half are segmental (8/20, 40%) and all address speech precision (20/20, 100%).

Last, as indicated in table 5 and table 6, proportionally more of the putative markers for MSD subtypes are obtained using acoustic (75%) than perceptual (25%) data reduction methods. Use of the SDCS requires skills in both methods, including the two types of perceptual methods (narrow phonetic transcription and prosody-voice coding) and acoustic analysis. A companion paper provides estimates of the relative reliabilities of each of the three data reduction methods.

Research with the SDCS

The purpose of the present paper was to report on three extensions to a system used to describe and classify speech sound disorders. As cited in the text, the extended SDCS has been used recently to address substantive questions about the speech status of children with galactosemia and autism spectrum disorders. Studies in process address speech status questions in a number of complex neurodevelopmental disorders including several syndromes (Down, Fragile X, Joubert, Velocardiofacial) and in phenotype studies of persons with point mutations and other disruptions in *FOXP2* and several candidate genes for persons with idiopathic apraxia of speech. When completed for dissemination, the SDCS running in the PEPPER environment will be available without cost from the Phonology Project website: http://www.waisman.wisc.edu/phonology/

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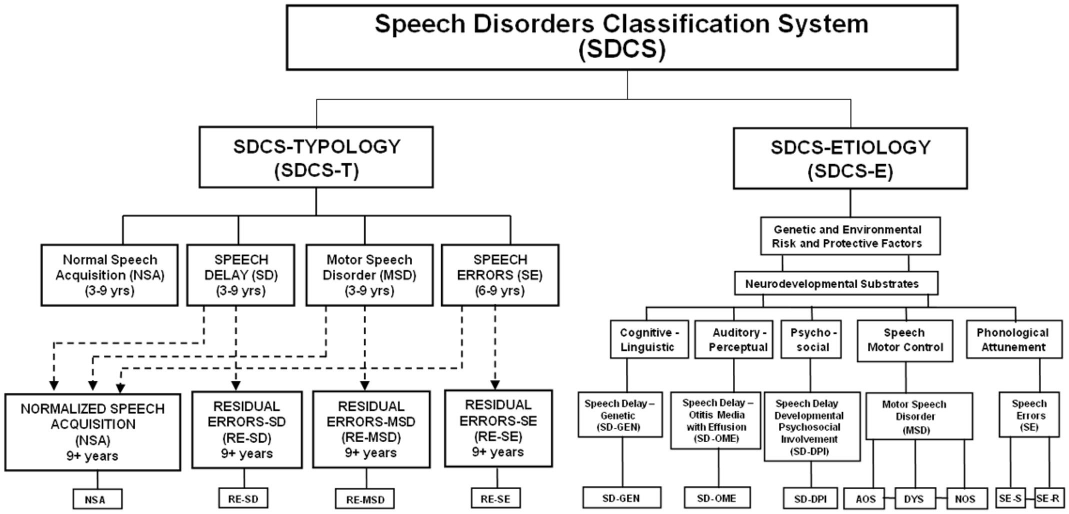

Figure 1.

A framework for causality research in childhood speech sound disorders.

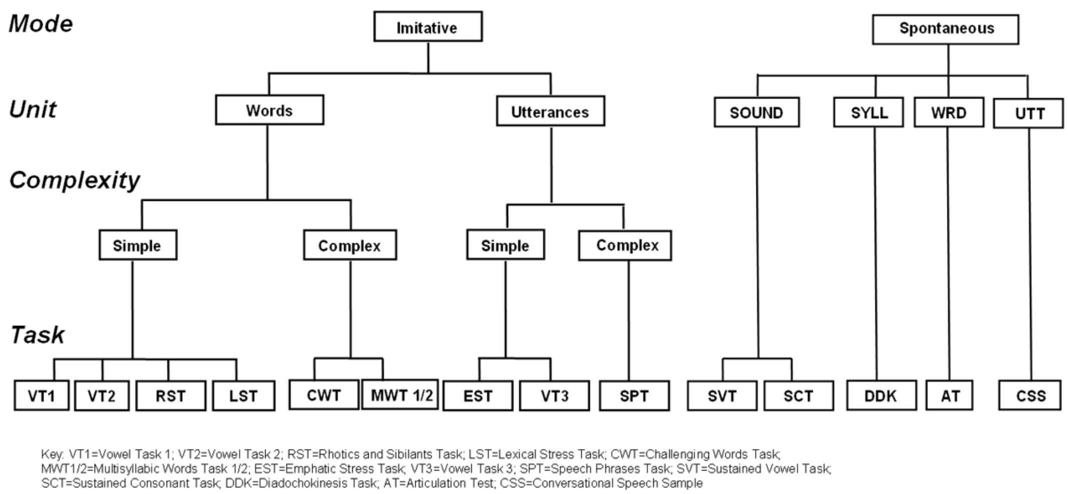

Figure 2.
The Madison Speech Assessment Protocol (MSAP) speech sampling context hierarchy.

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Figure 3.

Sample display of the three windows viewable during acoustic analysis: the phonetic transcript window, the waveform window, and the acoustic analysis window. For acoustic analysis, the transcript window provides information on the coded utterances (displayed to the right of the numeric utterance), any Prosody-Voice Screening Profile (PVSP) codes used, the phoneme perceptually transcribed, and the phonemes marked for acoustic analysis (highlighted using a color code). The example displayed is the first coded utterance in a conversational sample. Data for the segmented utterance and all segmented phonemes can be viewed in the acoustic analysis window using a scrolling function to include views of onset and offset times for the utterance and each individual phoneme, pauses, characteristic F0, Mean F0, minimum and maximum F0, characteristic amplitude, and F1–F3. The moment data for a segmented fricative is displayed in the upper right corner of the acoustic analysis window. The electronic version of the figure allows enlarged views of these sample screens.

Table 1

Working terms for eight putative etiological subtypes of speech sound disorders of currently unknown origin and their genetic and/or environmental risk factors (distal causes) and associated affected processes (proximal causes).

No.	Type	Subtype	Abbreviation	Risk Factors	Processes Affected
1	Speech Delay	Speech Delay–Genetic	SD-GEN	Polygenic/Environmental	Cognitive-Linguistic
2		Speech Delay–Otitis Media with Effusion	SD-OME	Polygenic/Environmental	Auditory-Perceptual
3		Speech Delay– Developmental Psychosocial Involvement	SD-DPI	Polygenic/Environmental	Affective-Temperamental
4	Motor Speech Disorder	Motor Speech Disorder–Apraxia of Speech	MSD-AOS	Monogenic? Oligogenic?	Speech-Motor Control
5		Motor Speech Disorder–Dysarthria	MSD-DYS	Monogenic? Oligogenic?	Speech-Motor Control
6		Motor Speech Disorder-Not Otherwise Specified	MSD-NOS	Monogenic? Oligogenic? Polygenic? Environmental?	Speech-Motor Control
7	Speech Errors	Speech Errors-Sibilants	SE-/s/	Environmental	Speech Attunement
8		Speech Errors-Rhotics	SE-/r/	Environmental	Speech Attunement

Table 2

The 25 tests and tasks in the Madison Speech Assessment Protocol (MSAP).

Measure	Speech Task	Acronym	Age Group[a]				Description and Goal	Stimuli
			1	2	3	4		
Goldman-Fristoe Test of Articulation-2 (2nd ed.)[b]	X	GFTA-2	X	X	X		The Sounds-in-Words section of the GFTA-2 provides supplementary production phonology information at the single word level.	34 picture plates (53 target words)
Audiological and (optionally) Acoustic Immittance Screening Task[c]		None	X				Audiologic and acoustic immittance screening data provide status on hearing and middle ear functioning at the time of assessment and supplement case history information.	Pulsed pure tones presented at 500, 1000, 2000, and 4000 Hz at 20 dB for the audiologic screening
Conversational Speech Sample	X	CSS	X	X	X	X	The CSS is the primary data source for production phonology, including segmental and suprasegmental (PVSP) data. It can also be used to obtain language production data.	If needed, pictures or books are used to evoke spontaneous conversational speech.
Lexical Stress Task	X	LST	X	X	X	X	The LST provides perceptual and acoustic information on a participant's ability to realize lexical stress in two-syllable words produced in imitation in a carrier phrase.	24 pictured two-syllable words (e.g., "chicken"), including 8 trochees, 8 iambs, and 8 spondees; recorded stimulus for each word in the carrier phrase "Say ___"
Challenging Words Task	X	CWT	X	X	X	X	The CWT provides information on a participant's ability to correctly sequence and produce sounds in 12 challenging words containing a variety of consonants (mostly Early- and Middle-8 sounds) and vowels in imitation. Multiple repetitions provide information on the stability of productions.	12 pictured words (e.g., "helicopter"), each presented 3 times; recorded stimulus for each token
Vowel Task 1	X	VT1	X	X	X	X	VT1 provides information on the 4 corner vowels /i, æ, u, e/ in single words produced in imitation. Multiple repetitions provide information on the stability of productions.	4 pictured CVC words (e.g., "bat"), each presented 4 times; recorded stimulus for each token
Vowel Task 2	X	VT2	X	X	X	X	VT2 provides information on the 11 non-corner vowels and diphthongs in single words produced in imitation. Multiple repetitions provide information on the stability of productions.	11 pictured CVC words (e.g., "bite"), each presented 4 times; recorded stimulus for each token
Vowel Task 3	X	VT3		X	X	X	VT3 provides information on vowels in 5 sentences produced in imitation. Multiple repetitions provide information on the stability of productions.	5 pictured sentences (e.g., "He has a blue pen"), each presented 4 times; recorded stimulus for each token
Syllable Repetition Task		SRT	X	X	X	X	The SRT provides information on speech processing in two- (CVCV), three- (CVCVCV), and four-syllable (CVCVCVCV) nonsense words using four	Recorded stimulus for each of the 18 nonsense words (e.g., "bamana")

Measure	Speech Task	Acronym	Age Group[a] 1	2	3	4	Description and Goal	Stimuli
							Early-8 consonants /b, d, m, n/ and a single low back vowel /a/ to minimize articulatory challenges.	
Nonword Repetition Task [d]		NRT	X	X	X	X	The NRT provides information on speech processing using nonsense words.	Recorded stimulus for each of 16 nonsense words — four each of 1-syllable, 2-syllable, 3-syllable, and 4-syllable words (e.g., "teIvak")
Emphatic Stress Task	X	EST	X	X	X	X	The EST provides information on a participant's ability to realize emphatic stress within short sentences. In each of the four trials for each of 2 sentences, a different word is stressed.	Recorded stimuli for two 4-word sentences (e.g., "May I see PETE"), repeated 4 times each
Rhotics and Sibilants Task	X	RST		X	X	X	The RST provides information for /r/ and /s/ productions obtained in imitated single words embedded in the carrier phrase "Say ___ again."	Recorded stimuli for 10 words (e.g., "soon," "bird"), each repeated four times
Multiyllabic Words Task 1	X	MWT1	X	X			MWT1 provides information on single words selected to represent difficult articulatory sequences. It assists in evaluating phonological planning, sound sequencing, and transitions from one sound to another. The MWT1 includes 25 single words for children age 3;0 to 11;11.	Recorded stimulus for each of 25 words (e.g., "animal")
Multisyllabic Words Task 2	X	MWT2			X	X	See description for MWT1. MWT2 includes 20 single words for participants age 12;0 and up.	Recorded stimulus for each of 20 words (e.g., "emphasis")
Speech Phrases Task [e]	X	SPT	X	X	X	X	The SPT provides information on 25 two- and three-word phrases selected to represent difficult articulatory sequences. It assists in evaluating phonological planning, sound sequencing, and transitions from one sound to another.	Recorded stimulus for each of 25 phrases (e.g., "big farm house")
Diadochokinesis Task	X	DDK	X	X	X	X	The DDK task provides information on a participant's ability to coordinate rapid, accurate, and rhythmic alternating movements of the lips and tongue within a single place of articulation and across 2 and 3 places of articulation (bilabial, alveolar, and velar).	Two 1-consonant syllable strings (e.g.,"papapa"), three alternating 2-consonant syllable strings, one alternating 3-consonant syllable string, and the word "pattycake"
Sustained Vowel Task	X	SVT	X	X	X	X	The SVT provides information on a participant's respiratory-laryngeal capacity and laryngeal quality.	The vowel /a/
Sustained Consonant Task	X	SCT	X	X	X	X	The SCT provides information on a participant's respiratory-laryngeal capacity.	The consonant /f/

Measure	Speech Task	Acronym	Age Group[a]				Description and Goal	Stimuli
			1	2	3	4		
Orofacial Examination Task		OET	X	X			The OET provides information on the structure and function of the speech mechanism.	None
Oral and Written Language Scales [f]		OWLS	X	X	X	X	The OWLS provides information on language comprehension and production.	Two books of picture plates, one each for the comprehension and production subtests
Woodcock-Johnson III Tests of Achievement [g]		WJ-III				X	The WJ-III provides information on language skills in adults in the areas of Letter-Word Identification Test 1) and Word Attack (Test 13). [Optional tests include: Test 7 – Spelling; Test 9 - Passage Comprehension; Test 11 – Writing Samples)	Test 1: Single letters and increasingly difficult words (e.g., "provincial") are displayed for participant's to pronounce. Test 13: Single letters and increasingly difficult nonwords (e.g., "fronkett") are displayed for participant's to pronounce.
Kaufman Brief Intelligience Test (2nd ed.) [h]		KBIT-2	X	X	X	X	The KBIT provides information on cognitive functioning using scores from the KBIT2's three verbal and nonverbal subtests.	Two books of picture plates are used for all of the nonverbal and some of the verbal test items
Case History Form		CHF	X	X	X	X	The CHF provides risk factor information on a participant's medical, social, academic, hearing, family aggregation, and speech-language history.	None
Case History Interview		CHI	X	X	X	X	The CHI supplements and clarifies the information collected on the participant's CHF.	None
Examiner Checklist		EC	X	X	X	X	The EC provides information on the examiner's impressions of selected aspects of the participant's behavior and psychosocial development/affect.	None

[a] Age group1: Preschool=3;0–5;11; Age group 2: School-age=6;0–11;11; Age group 3: Adolescent=12;0–17;11; Age group 4: Adult=18;0+

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Table 3

Candidate diagnostic markers of subtypes of Speech Delay (SD) and subtypes of Motor Speech Disorders (MSD) in the Competence, Precision, and Stability Analytics (CPSA) framework.

Segmental	***Competence***	***Precision***	***Stability***
1. Vowels	Percentage of Non-rhotic Vowels/Diphthongs Correct	**Reduced Vowel Space**	**Less Stable Vowel Space**
	Percentage of Rhotic Vowels/Diphthongs Correct	**Lengthened Vowels**	**Less Stable F1**
	Percentage of Phonemic Diphthongs Correct	**Distorted Rhotics**	**Less Stable F2**
	Percentage of Vowels Correct: CSS [a]	**Reduced Pairwise Vowel Duration Variability**	**Less Stable Vowel Duration**
	Percentage of Vowels Correct: AT[b]		**Less Stable Rhotic Distortions: F3-F2**
	Percentage of Non-rhotic Vowels/Diphthongs Correct Revised		Less Stable Vowel Errors
	Percentage of Rhotic Vowels/Diphthongs Correct Revised		
	Percentage of Phonemic Diphthongs Correct Revised		
	Percentage of Vowels/Diphthongs Correct Revised: CSS		
	Percentage of Vowels/Diphthongs Correct Revised: AT		
	Percentage of Relative Non-rhotic Vowel/Diphthong Distortions		
2. Consonants	Percentage of Consonants in Inventory	Nasal Emissions	Less Stable Consonant Errors
	Percentage of Consonants Correct: CSS	Reduced % Glides Correct	**Less Stable Sibilant Centroids**
	Percentage of Consonants Correct: AT	**Lowered Sibilant Centroids**	
	Percentage of Consonants Correct- Revised: CSS	**Lengthened Cluster Durations**	
	Percentage of Consonants Correct- Revised: AT		
	Percentage of Consonants Correct in Complex Words: MWT		
	Relative Omission Index		
	Relative Substitution Index		
	Relative Distortion Index		
3. Vowels and Consonants	Speech Disorders Classification System	Increased Percentage of Phoneme Distortions	Less Stable Whole Word Errors
	Intelligibility Index	**Syllable/Word Segregation: Increased % Between/Within-Word Pauses**	Less Stable % Phonemes Correct in Complex Words
	Percentage of Structurally Correct Words		
Suprasegmental			
Prosody			
4. Phrasing	Percentage Appropriate Phrasing	Increased Repetitions and Revisions	**Reduced Speech-Pause Duration Variability Ratio**

Segmental	*Competence*	*Precision*	*Stability*
5. Rate	Percentage Appropriate Rate	**Slower Speaking Rate**	**Less Stable Speaking Rate**
		Slower Articulation Rate	**Less Stable Articulation Rate**
6. Stress	Percentage Appropriate Stress	**Reduced Lexical Stress**	**Less Stable Lexical Stress**
		Increased Lexical Stress	**Less Stable Emphatic Stress**
		Reduced Emphatic Stress	**Less Stable Sentential Stress**
		Reduced Sentential Stress	
Voice			
7. Loudness	Percentage Appropriate Loudness	**Reduced Vowels-Consonants Intensity Ratios**	**Less Stable Vowels-Consonants Intensity Ratios**
		Increased Vowels-Consonants Intensity Ratios	
8. Pitch	Percentage Appropriate Pitch	**Lowered Fundamental Frequency Mean**	**Less Stable Mean Fundamental Frequency**
		Raised Fundamental Frequency Mean	
		Lowered Fundamental Frequency Range	
		Increased Fundamental Frequency Range	
9. Laryngeal Quality	Percentage Appropriate Laryngeal Quality	**Increased Jitter**	**Less Stable Jitter**
		Increased Shimmer	**Less Stable Shimmer**
		Reduced Harmonics-to-Noise Ratio	**Less Stable Harmonics-to-Noise Ratio**
		Increased % Breathy Utterances	
		Increased % Rough Utterances	
		Increased % Strained Utterances	
		Increased % Break/Shift/Tremorous Utterances	
10. Resonance Quality	Percentage Appropriate Resonance Quality	Increased % Nasal Utterances	**Less Stable: Nasal: Lowered F1: /a/**
		Nasal: Lowered F1:/a/	**Nasopharyngeal: Less Stable F2: High Vowels**
		Increased % of Nasopharyngeal Utterances	
		Nasopharyngeal Lowered F2:High Vowels	

Note. Bold entries indicate candidate marker analysis completed using acoustic data reduction methods.

[a] See Table 2 for key to abbreviations.

[b] AT=Articulation Test, a generic term for alternative articulation tests, including the Goldman-Fristoe Test of Articulation (2nd ed.), Sounds-in-Words section.

Table 4

Speech sources (14) within the Madison Speech Assessment Protocol (MSAP) for indices and candidate markers in the Competence, Precision, and Stability Analytics (CPSA).

		MSAP Sources[a]												
Domain	**Descriptors & Markers**	**CSS**	**CSS24**	**VT1**	**VT2**	**AT[b]**	**MWT1/2**	**SVT**	**CWT**	**RST**	**VT3**	**SPT**	**EST**	**LST**
Competence														
Vowels	% of Non-rhotic Vowels/Diphthongs Correct	X												
	% of Rhotic Vowels/Diphthongs Correct	X												
	% of Phonemic Diphthongs Correct	X												
	% of Vowels Correct	X												
	% of Vowels Correct: AT					X								
	% of Non-rhotic Vowels/Diphthongs Correct Revised	X												
	% of Rhotic Vowels/Diphthongs Correct Revised	X												
	% of Phonemic Diphthongs Correct Revised	X												
	% of Vowels/Diphthongs Correct Revised	X												
	% of Vowels/Diphthongs Correct Revised: AT					X								
	% of Relative Non-rhotic Vowel/Diphthong Distortions	X												
Consonants	% of Consonants in Inventory	X												
	% of Consonants Correct	X												
	% of Consonants Correct: AT					X								
	% of Consonants Correct- Revised	X												
	% of Consonants Correct- Revised: AT					X								
	% of Consonants Correct in Complex Words: MWT						X							
	% of Relative Omission Index	X												
	% of Relative Substitution Index	X												
	% of Relative Distortion Index	X												
Vowels & Consonants	Speech Disorders Classification System	X												
	Intelligibility Index	X												
	% of Structurally Correct Words	X												
Phrasing	% of Appropriate Phrasing	X												

Domain	Descriptors & Markers	MSAP Sources[a]												
		CSS	CSS24	VT1	VT2	AT[b]	MWT1/2	SVT	CWT	RST	VT3	SPT	EST	LST
Rate	% of Appropriate Rate	X												
Stress	% of Appropriate Stress	X												
Loudness	% of Appropriate Loudness	X												
Pitch	% of Appropriate Pitch	X												
Laryngeal Quality	% of Appropriate Laryngeal Quality	X												
Resonance Quality	% of Appropriate Resonance Quality	X												
		MSAP Sources												
Domain	**Descriptors & Markers**	**CSS**	**CSS24**	**VT1**	**VT2**	**AT**	**MWT1/2**	**SVT**	**CWT**	**RST**	**VT3**	**SPT**	**EST**	**LST**
Precision														
Vowels	**Reduced Vowel Space**		X	X										
	Lengthened Vowels		X	X	X									
	Distorted Rhotics		X		X					X				
	Reduced Pairwise Vowel Duration Variability		X											
Consonants	Nasal Emissions	X				X	X							
	Reduced % Glides Correct	X				X	X					X		
	Lowered Sibilant Centroids		X			X	X			X				
	Lengthened Cluster Durations		X			X	X					X		
Vowels & Consonants	Increased % of Phoneme Distortions	X				X	X		X	X	X		X	
	Increased Syllable/Word Segregation		X			X	X					X		
Phrasing	Increased Repetitions and Revisions		X											
Rate	**Slower Speaking Rate**		X											
	Slower Articulation Rate		X											
Stress	**Reduced Lexical Stress**								X					
	Increased Lexical Stress								X					
	Reduced Emphatic Stress												X	
	Reduced Sentential Stress		X											
Loudness	**Reduced Vowels-Consonants Intensity Ratios**		X	X	X	X								X
	Increased Vowels-Consonants Intensity Ratios		X	X	X	X								

		MSAP Sources[a]												
Domain	**Descriptors & Markers**	**CSS**	**CSS24**	**VT1**	**VT2**	**AT[b]**	**MWT1/2**	**SVT**	**CWT**	**RST**	**VT3**	**SPT**	**EST**	**LST**
Pitch	**Lowered Fundamental Frequency Mean**		X	X										
	Raised Fundamental Frequency Mean		X	X										
	Lowered Fundamental Frequency Range		X	X										
	Increased Fundamental Frequency Range		X	X										
Laryngeal Quality	**Increased Jitter**		X	X				X						
	Increased Shimmer		X	X				X						
	Reduced Harmonics-to-Noise Ratio		X	X				X						
	Increased % Breathy Utterances													
	Increased % Rough Utterances		X											
	Increased % Strained Utterances		X											
	Increased % Break/Shift/Tremorous Utterances		X											
Resonance Quality	Increased % Nasal Utterances		X											
	Nasal: Lowered F1:/a/		X											
	Increased % of Nasopharyngeal Utterances		X											
	Nasopharyngeal: Lowered F2: High Vowels		X											
		MSAP Sources												
Domain	**Descriptors & Markers**	**CSS**	**CSS24**	**VT1**	**VT2**	**AT**	**MWT1/2**	**SVT**	**CWT**	**RST**	**VT3**	**SPT**	**EST**	**LST**
Stability														
Vowels	**Less Stable Vowel Space**		X	X										
	Less Stable F1		X	X										
	Less Stable F2		X	X										
	Less Stable Vowel Duration		X	X	X									
	Less Stable Rhotic Distortions: F3-F2		X		X					X				
	Less Stable Vowel Errors	X		X	X		X		X		X			
Consonants	Less Stable Consonant Errors	X					X		X	X				
	Less Stable Sibilant Centroids		X			X	X			X				
Vowels & Consonants	Less Stable Whole Word Errors	X		X	X				X	X	X			
	Less Stable % Phonemes Correct in Complex Words	X					X		X		X			

Domain	Descriptors & Markers	MSAP Sources[a]												
		CSS	CSS24	VT1	VT2	AT[b]	MWT1/2	SVT	CWT	RST	VT3	SPT	EST	LST
Phrasing	**Reduced Speech-Pause Duration Variability Ratio**		X											
Rate	**Less Stable Speaking Rate**		X											
	Less Stable Articulation Rate		X											
Stress	**Less Stable Lexical Stress**								X					X
	Less Stable Emphatic Stress												X	
	Less Stable Sentential Stress		X											
Loudness	**Less Stable Vowels-Consonants Intensity Ratios**		X	X	X									X
Pitch	**Less Stable Mean Fundamental Frequency**		X	X										
Laryngeal Quality	**Less Stable Jitter**		X	X				X						
	Less Stable Shimmer		X	X				X						
	Less Stable Harmonics-to-Noise Ratio		X	X				X						
Resonance Quality	**Less Stable: Nasal: Lowered F1: /a/**		X											
	Nasopharyngeal: Less Stable F2: High Vowels		X											

Note. Bold entries indicate candidate marker analysis completed using acoustic data reduction methods.

[a] See Table 2 for key to abbreviations.

[b] AT=Articulation Test, a generic term for alternative articulation tests, including the Goldman-Fristoe Test of Articulation (2nd ed.), Sounds-in-Words section.

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Table 5

Candidate CPSA Markers for Motor Speech Disorders-Apraxia of Speech (MSD-AOS), Motor Speech Disorders-Dysarthria (MSD-DYS), and Motor Speech Disorders-Not Otherwise Specified (MSD-NOS).

Motor Speech Disorders-Apraxia of Speech (MSD-AOS)		
Segmental	***Precision***	***Stability***
1. Vowels		**Less Stable Vowel Space**
		Less Stable F1
		Less Stable F2
		Less Stable Vowel Duration
		Less Stable Rhotic Distortions: F3-F2
		Less Stable Vowel Errors
2. Consonants	Reduced % Glides Correct	Less Stable Consonant Errors
		Less Stable Sibilant Centroids
3. Vowels & Consonants		Less Stable Whole Word Errors
		Less Stable % Phonemes Correct in Complex Words
Suprasegmental Prosody		
4. Phrasing	Increased Repetitions and Revisions	**Reduced Speech-Pause Duration Variability Ratio**
5. Rate		**Less Stable Speaking Rate**
		Less Stable Articulation Rate
6. Stress		**Less Stable Lexical Stress**
		Less Stable Emphatic Stress
Voice		**Less Stable Sentential Stress**
7. Loudness		**Less Stable Vowels-Consonants Intensity Ratios**
8. Pitch		**Less Stable Mean Fundamental Frequency**
9. Laryngeal Quality		**Less Stable Jitter**
		Less Stable Shimmer
		Less Stable Harmonics-to-Noise Ratio
10. Resonance Quality		**Less Stable: Nasal: Lowered F1: /a/**
		Nasopharyngeal: Less Stable F2: High Vowels
Motor Speech Disorders-Dysarthria (MSD-DYS)		

Motor Speech Disorders-Apraxia of Speech (MSD-AOS)		
Segmental	***Precision***	***Stability***
Segmental	*Precision*	*Stability*
1. Vowels/Diphthongs		
2. Consonants	Nasal Emissions	
3. Vowels/Diph & Consonants		
Suprasegmental Prosody		
4. Phrasing		
5. Rate		
6. Stress		
Voice		
7. Loudness		
8. Pitch	**Lowered Fundamental Frequency Mean**	
	Lowered Fundamental Frequency Range	
9. Laryngeal Quality	**Increased Jitter**	
	Increased Shimmer	
	Reduced Harmonics-to-Noise Ratio	
	Increased % Breathy Utterances	
	Increased % Rough Utterances	
	Increased % Strained Utterances	
	Increased % Break/Shift/Tremorous Utterances	
10. Resonance Quality	Increased % Nasal Utterances	
	Nasal: Lowered F1:/a/	
Motor Speech Disorders-Not Otherwise Specified (MSD-NOS)		
Segmental	*Precision*	*Stability*
1. Vowels/Diphthongs	**Reduced Vowel Space**	
	Lengthened Vowels	
	Distorted Rhotics	
	Reduced Pairwise Vowel Duration Variability	
2. Consonants	**Lowered Sibilant Centroids**	

Motor Speech Disorders-Apraxia of Speech (MSD-AOS)		
Segmental	***Precision***	***Stability***
	Lengthened Cluster Durations	
3. Vowels/Diph & Consonants	Increased Percentage of Phoneme Distortions	
	Syllable/Word Segregation: Increased % Between/Within Word Pauses	
Suprasegmental Prosody		
4. Phrasing		
5. Rate	**Slower Speaking Rate**	
	Slower Articulation Rate	
6. Stress	**Reduced Lexical Stress**	
	Increased Lexical Stress	
	Reduced Emphatic Stress	
Voice	**Reduced Sentential Stress**	
7. Loudness	**Reduced Vowels-Consonants Intensity Ratios**	
	Increased Vowels-Consonants Intensity Ratios	
8. Pitch	**Raised Fundamental Frequency Mean**	
	Increased Fundamental Frequency Range	
9. Laryngeal Quality		
10. Resonance Quality	Increased % of Nasopharyngeal Utterances	
	Nasopharyngeal: Lowered F2: High Vowels	

Note. Bold entries indicate candidate marker analysis completed using acoustic data reduction methods.

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Table 6

Candidate Precision and Stability markers in the Competence, Precision, and Stability Analytics (CPSA) cross-tabulated by subtype of motor speech disorder and data reduction method (perceptual, acoustic).

Subtype[a]	Candidate CPSA Marker								
	Precision			Stability			Total		
	Perceptual	Acoustic	Total	Perceptual	Acoustic	Total	Perceptual	Acoustic	Total
MSD-AOS	2	0	2	4	19	23	6	19	25
MSD-DYS	6	6	12	0	0	0	6	6	12
MSD-NOS	2	18	20	0	0	0	2	18	20
Total MSD	10	24	34	4	19	23	14	43	57

[a]MSD= Motor Speech Disorder; AOS=Apraxia of Speech; DYS=Dysarthria; NOS=Not Otherwise Specified