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Research Article

Variable Practice to Enhance Speech Learning in Ultrasound Biofeedback Treatment for Childhood Apraxia of Speech: A Single Case Experimental Study

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Purpose: The purpose of this study was to evaluate the role of practice variability, through prosodic variation during speech sound training, in biofeedback treatment for children with childhood apraxia of speech. It was hypothesized that variable practice would facilitate speech sound learning.

Method: Six children ages 8–16 years with persisting speech sound errors due to childhood apraxia of speech participated in a single-subject experimental design. For each participant, 2 speech sound targets were treated with ultrasound visual feedback training: one with prosodic variation (i.e., practicing sound targets in words and phrases spoken fast, slow, loud, as a question, command, and declarative), and one without prosodic variation. Each target was treated for half of the 1-hr session for 14 treatment sessions.

Results: As measured by standardized effect sizes, all participants showed greater change on generalization probes for sound targets treated under the prosodic variation condition with mean effect sizes (d_2) of 14.5 for targets treated with prosodic variation and 8.3 for targets treated without prosodic variation. The average increase in generalization scores was 38% in the prosodic variation condition compared to 31% without.

Conclusions: Ultrasound visual feedback may facilitate speech sound learning and learning may be enhanced by treating speech sounds with explicit prosodic variation.

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Childhood apraxia of speech (CAS) is a pediatric speech sound disorder that results in impaired production of speech sounds along with inconsistent speech output, impaired prosody, and impaired transitioning between sounds and syllables (American Speech-Language-Hearing Association, 2007). Symptoms of CAS can persist well into adolescence; however, for school-age children with CAS whose speech errors have not responded to prior treatments, therapy options are limited. Exploring treatment alternatives, and some of the key components of those treatments that facilitate learning, may provide useful clinical guidance.

Most treatments for CAS involve a strong emphasis on improving speech motor control (Maas, Gildersleeve-Neumann, Jakielski, & Stoeckel, 2014). The theoretical foundation of motor-based treatment for CAS, as derived from schema-based motor learning theory, requires a distinction to be made between acquisition and learning (Maas et al., 2008; Schmidt & Lee, 2011). *Acquisition* refers to performance during practice. For individuals with impaired speech motor systems, acquisition can be a challenge and speech-language pathologists (SLPs) may experience difficulty helping their clients to establish speech movement patterns (particularly movements that have been in error for many years). However, even when clients with CAS are successful in therapeutic settings, acquisition does not necessarily imply that learning has occurred. *Motor learning* is reflected in evidence that the skills that have been successfully trained during speech therapy have generalized (e.g., to untrained words and in tasks in which support is not provided by the clinician) and are retained (over time). The distinction between acquisition and learning has implications for how treatment is delivered. It is important to note that many of the practice and feedback elements that are helpful in facilitating acquisition are not the same elements needed to facilitate learning.

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One approach that has recently been explored for children with persisting CAS is a motor-based ultrasound biofeedback program (Preston, Brick, & Landi, 2013). Similar to most approaches, this treatment is multifaceted. Although there is theoretical motivation for many of the elements of the treatment program (primarily derived from schema-based motor learning; see Maas et al., 2008), each element may or may not, in actuality, contribute to speech motor learning. Therefore, it is important to empirically explore which aspects facilitate positive treatment outcomes. In the following section, an overview of some of the core elements of the treatment approach is provided, followed by a discussion of the theoretical basis for incorporating variable practice (in the form of prosodic variation) during speech sound training for children with CAS.

Ultrasound Biofeedback Treatment for CAS

Real-time visual feedback of the tongue with ultrasound images can facilitate correct productions of lingual speech sounds such as /ɹ/, /s/, /l/, /ʃ/, /tʃ/, and /k/ (Adler-Bock, Bernhardt, Gick, & Bacsfalvi, 2007; Bacsfalvi, 2010; Bacsfalvi, Bernhardt, & Gick, 2007; Bernhardt et al., 2008; Fawcett, Bacsfalvi, & Bernhardt, 2008; McAllister Byun, Hitchcock, & Swartz, 2014; Modha, Bernhardt, Church, & Bacsfalvi, 2008). The visual feedback may help clients to recognize their executed tongue movements and compare those to intended movements, which may enable error detection (and subsequent correction). However, there are a variety of procedures for practicing speech with ultrasound visual feedback.

One ultrasound biofeedback motor learning protocol that has been implemented in prior studies and adapted for a variety of clients with CAS, residual speech errors, and acquired apraxia is a chaining-based procedure designed to facilitate a transition from acquisition to generalization of correct speech movements (Preston et al., 2013; Preston & Leaman, 2014; Preston, Leece, & Maas, 2017; Preston, Maas, Whittle, Leece, & McCabe, 2016; Preston et al., 2014). Acquisition is addressed through initial practice on simple speech movement targets (e.g., two-phoneme combinations such as /kl/ or /ɑɹ/), followed by subsequent practice of these targets within longer and more complex linguistic units. During syllable- and word-level practice, frequent feedback is provided, and the majority of the feedback is in the form of knowledge of performance (or information about movements). Successful attempts at acquiring syllables and words result in progression to more complex linguistic environments (i.e., from monosyllabic words to multisyllabic words, phrases, and self-generated sentences). An example of such a progression would be the following: /ɑɹ/, *tar, guitar, loud guitar*. Targets are designed with chaining principles in mind such that complex targets, such as sentences, include the phrases, words, and phoneme combinations practiced at lower levels (Chappell, 1973; Johnson & Hood, 1988; Young, 1987). As linguistic complexity increases, feedback frequency is reduced and verbal feedback is primarily given in the form of knowledge of results (or information about correctness). In addition, sessions are structured such that only half of the practice involves the visual feedback from the ultrasound, which is intended to encourage generalization.

An initial investigation of an ultrasound biofeedback treatment program for CAS was reported by Preston et al. (2013). In this multiple baseline single-case study of six children ages 9–15 years, treatment targets included consonant–vowel, vowel–consonant, or consonant–consonant sound sequences. Multiple sound sequences were treated for each participant, and all participants acquired at least two treated sound sequences in 18 sessions. The treatment program included a number of elements of motor learning, including practice variability in the form of prosodic variation (i.e., clients were cued to say the targets "faster" or "slower" or "like a question"). However, the design of that study did not incorporate systematic manipulation of these practice elements; therefore, the researchers could not determine which of the factors, or which combination of factors, best facilitated learning of treated sounds in therapy. The present study therefore aimed to isolate one of the motor learning elements—practice variability through prosodic cueing—to evaluate its role on the learning of treated speech sounds in therapy for children with CAS.

Practice Variability

Ultrasound visual feedback of the tongue may facilitate changes in tongue movement for targeted speech sounds or sound sequences. However, practicing speech tasks that require integrating motor commands governing both segmental and prosodic aspects of speech may accelerate motor learning. Predictions from schema-based motor learning theory suggest that practicing movement targets for speech sounds in variable ways should enhance learning (Maas et al., 2008; Schmidt & Lee, 2011), as there is evidence in nonspeech motor tasks that generalization may be better facilitated with variable practice compared to constant practice (Hall & Magill, 1995; Wulf & Schmidt, 1997). Therefore, practicing target segmental patterns in various ways, such as in varying prosodic contexts (e.g., practicing word-initial /ɹe/ in *Rake! Rake? Rake.*) might enable faster learning than practicing the movements in the same way each time (e.g., *Rake. Rake. Rake.*). In some treatment approaches for CAS, such as Dynamic Temporal and Tactile Cueing, variations in prosody are explicitly incorporated in practice (Strand & Debertine, 2000; Strand & Skinder, 1999; Strand, Stoeckel, & Baas, 2006). In a similar manner, Repeated Syllable Transition Training (Ballard, Robin, McCabe, & McDonald, 2010; Murray, McCabe, & Ballard, 2015; Thomas, McCabe, & Ballard, 2014) incorporates variability in prosody through targeting nonwords of varied stress patterns (e.g., weak–strong–weak vs. strong–weak–weak). However, empirical support through systematic manipulation of variable prosodic practice would help to validate the theoretical claims that learning would be enhanced when prosodic variation is included in treatment.

To date, two studies have begun to explore practice variability through prosodic variation in speech therapy. Preston et al. (2014) evaluated speech sound accuracy in eight individuals, ages 10–20 years, with residual speech sound errors who were treated with the chaining-based ultrasound biofeedback program. Each participant was treated on two sound targets for 7 hr each; one target treated with prosodic variation and a separate target treated without prosodic variation. On average, effect sizes measuring generalization were roughly similar across speech sound targets treated with prosodic variation ($d_2 = 3.9$) and targets treated without ($d_2 = 3.6$). The results suggested that prosodic variation in speech practice played a limited role in influencing generalization for children who had residual speech sound errors in the absence of symptoms of CAS. Children with CAS, by contrast, may benefit from intentional practice of speech sounds under varying prosodic conditions, as the integration of speech sounds and prosody is often problematic for children with this disorder (e.g., Shriberg, Aram, & Kwiatkowski, 1997).

In a separate study, Preston et al. (2016) reported on three children with CAS, ages 10–13 years, who were treated under similar procedures. However, in that study, limited acquisition was observed across the three participants, resulting in limited opportunity for participants to engage in variable practice with prosodic cueing. Thus, a comparison of generalization scores between the two conditions was not feasible. The present study therefore sought to test again the contribution of practice variability to learning, but included a modification to the procedures that was designed to accelerate outcomes through a period of auditory perceptual training prior to production training in each session. Justification for this change was indicated by prior studies reporting that auditory perception of speech differs in children with CAS (Froud & Khamis-Dakwar, 2012; Groenen, Maassen, Crul, & Thoonen, 1996; Nijland, 2009) and demonstrating the relative efficacy of perceptual training in improving speech sound accuracy (Rvachew, Nowak, & Cloutier, 2004). The primary aim of the study, however, was to explore how variable practice may contribute to speech sound learning.

Purpose and Hypothesis

The purpose of this study was to evaluate the effect of prosodic variation on speech sound generalization during ultrasound biofeedback therapy in children with CAS. Variable practice on speech sound targets with prosodic cueing was hypothesized to facilitate speech motor learning.

Method

Participants

Six school-age participants with mild-to-moderately-severe CAS participated in the study. All were recruited in the greater Syracuse, New York, area by referrals from local SLPs. Participants attended an initial session during which eligibility for the study was determined. They returned for two additional visits during which further testing was conducted for descriptive purposes and pretreatment baseline data were collected. Participant characteristics are presented in Table 1.

To be eligible for the study, participants were required to score below the 7th percentile on the Goldman-Fristoe Test of Articulation–Second Edition (Goldman & Fristoe, 2000) and to produce speech sound errors in conversational speech. Participants were required to score no lower than 1.33 *SD* below the mean on the Peabody Picture Vocabulary Test–Fourth Edition (Dunn & Dunn, 2007) and on the Wechsler Abbreviated Scales of Intelligence Matrix Reasoning subtest (Wechsler, 2011). All participants also passed a pure-tone hearing screening at 1, 2, and 4 kHz. In addition, participants scored below 25% on at least two pretreatment generalization probes (described below), which were used to monitor generalization of untreated words with target sounds in different word positions. Moreover, on the basis of testing described below, participants were either classified as CAS or non-CAS (i.e., residual speech sound error). Only the participants with CAS are reported here (see Preston et al. [2017] for reports on participants without CAS). CAS diagnosis was not based on a single score but was based on two certified SLPs' determination of CAS features (including prosodic abnormalities, sequencing difficulties, and inconsistency) from recordings of the tasks described below.

Speech Assessments

A repetition task consisting of 15 sentences loaded with late-developing phonemes (/ɹ/ and /s/) was used to evaluate articulatory accuracy and sequencing in connected speech. Percent accuracy of /ɹ/ and /s/ were scored from recordings of this task. The Linguisystems Articulation Test (Bowers & Huisingh, 2011) was also administered to provide an additional sample of speech sound accuracy and consistency.

A multisyllabic word repetition task (Preston & Edwards, 2007) was administered to evaluate lexical stress and segmental accuracy in three- to six-syllable words (e.g., aluminum, stethoscope, accessibility). Percent of words with accurate lexical stress and percent consonants correct were calculated.

Pretreatment stimulability of sounds in error (cf. Miccio, 2002) was measured through imitation of target sounds in four syllables in onset and rhyme positions, each repeated three times. Percent of syllables correct in onset and rhyme positions were calculated.

A maximum performance task was also administered to evaluate speech motor functioning (Rvachew, Hodge, & Ohberg, 2005; Thoonen, Maassen, Gabreëls, & Schreuder, 1999; Thoonen, Maassen, Gabreëls, Schreuder, & de Swart, 1997). This required sustained productions of fricatives /s/, /z/, and /f/ and the vowel /ɑ/, and maximum durations were measured. Maximum repetition rate was computed for repeated productions of monosyllables /pʌ/, /tʌ/, and /kʌ/ and the trisyllable /pʌtʌkʌ/. Performance on these tasks

Table 1. Participant demographic information and results from standardized and nonstandardized assessments.

		Participant					
Measure	**Value**	**Danica**	**Ethan**	**Finn**	**Greg**	**Hannah**	**Isaac**
Age	Years;months	10;7	8;7	9;6	9;7	8;2	16;8
GFTA-2	Standard score	69	75	46	52	83	<40
	Percentile	<1	4	<1	1	4	<1
PPVT-4	Standard score	95	95	111	89	116	96
WASI-II	Matrix Reasoning t score	54	46	43	39	60	40
Sentence repetition	/s/ percent correct	87	84	70	50	91	52
	/ɹ/ Percent correct	0	0	0	2	0	4
LAT	Standard score	62	<59	<61	<61	<58	55
	Inconsistency (out of 12)	6	4	1	1	2	1
Multisyllabic word repetition task	Percent consonants correct	71	72	83	79	85	73
	Percent lexical stress correct	75	65	80	55	65	35
Stimulability probe	/ɹ/ Onset percent correct	0	33	0	0	0	0
	/ɹ/ Rhyme percent correct	25	92	0	0	0	0
	/s/ rhyme percent correct						33
Max performance task	Dysarthria score (out of 2)	0	0	0	0	1	2
	Apraxia score (out of 2)	2	2	2	2	2	2
Emphatic stress task	Percent correct stress	71	46	100	54	100	38
Syllable Repetition Task	Percent consonants correct	88	80	76	86	96	88
	Percent of words with additions	6	17	28	11	6	22
Inconsistency task	Average novel productions	2.9	2.1	1.6	1.5	2	1.5
CTOPP-2	Elision scaled score	4	7	9	10	7	4
	Blending words scaled score	7	12	7	8	7	6
	Phoneme isolation scaled score	7	7	10	7	6	6
Nonword repetition	Percent consonants correct	69	78	86	76	76	74
SAILS	Percent accuracy	/ɹ/ 70	/ɹ/ 100	/ɹ/ 85	/ɹ/ 95	/ɹ/ 75	/ɹ/ 75, /s/ 75
CELF-5	Recalling Sentences scaled score	5	10	11	9	13	8
	Formulating Sentences scaled score	8	8	9	11	10	7
Clinical estimate of severity	On the basis of the clinical judgment	Moderate	Moderate	Mild	Mild	Mild	Moderately severe

Note. GFTA-2= Goldman-Fristoe Test of Articulation–Second Edition; PPVT-4 = Peabody Picture Vocabulary Test–Fourth Edition; WASI-II= Wechsler Abbreviated Scales of Intelligence-II; LAT= Linguisystems Articulation Test; CTOPP-2= Comprehensive Test of Phonological Processing–Second Edition; SAILS = Speech Assessment and Interactive Learning; CELF-5 = Clinical Evaluation of Language Fundamentals–Fifth Edition.

resulted in two separate scores: an apraxia score and a dysarthria score, both of which ranged from 0–2. A score of 0 corresponded to "Not apraxic" or "Not dysarthric," a score of 1 represented "Undefined" for each category, and a score of 2 represented "Apraxic" or "Dysarthric." All participants obtained an apraxia score of 2, corresponding to "Apraxic." In addition, with regard to dysarthria, Hannah obtained a score of 1 (Undefined) and Isaac obtained a score of 2 (Dysarthric).

In addition, the Syllable Repetition Task was administered (Shriberg et al., 2009). Percent consonants correct and percent of items with additions were calculated (Shriberg, Lohmeier, Strand, & Jakielski, 2012).

An emphatic stress task was administered (cf. Shriberg et al., 2010). Participants repeated prerecorded sentences and were scored offline on their ability to correctly imitate contrastive stress (e.g., "*Dan* hates red shoes; Dan *hates* red shoes"). Responses were scored according to the following scale: 0 = Poor prosody, very poor distinction between stressed/unstressed words; 1 = Subtle (mild or moderate) disturbance in prosody, with perhaps some differentiation between stressed and unstressed, but not a good imitation of the sentence; and 2 = Good imitation of the overall prosody of the sentence, clear distinction of the stressed word. The maximum score was 24.

A researcher-developed inconsistency task was administered wherein participants repeated consecutive productions of phonetically challenging words (e.g., *rectangle, computer*). Eight pictures were copied onto a page eight times in rows, and the participant named each as quickly as possible. Phonetic transcriptions of each item were completed offline. The total number of variations of each word was recorded (cf. Marquardt, Jacks, & Davis, 2004; Preston & Koenig, 2011); therefore, a score of 5 on the word *umbrella* indicated five different productions of that word. A variability score for each word was computed and averaged. A score of 1 represented completely consistent productions of the words, whereas a score of 8 represented maximally inconsistent productions (different token produced on every attempt of every word).

Phonological Processing Assessments

The Elision, Blending Words, and Phoneme Isolation subtests of the Comprehensive Test of Phonological Processing–Second Edition (Wagner, Torgesen, Rashotte, & Pearson, 2013) were administered. A nonword repetition task was also administered to assess phonological working memory (Dollaghan & Campbell, 1998). Percent phonemes correct was computed.

In addition, participants completed at least two modules of Speech Assessment and Interactive Learning (Rvachew, 1994) to evaluate their ability to make "goodness judgments" by assessing others' attempts at target words as correct/incorrect. All six participants completed 20 trials each using the /ɹ/ modules; one participant (Isaac) also completed 20 trials of /s/ as this was chosen as a therapy target.

Language Assessments

Language skills were evaluated for descriptive purposes. The Recalling Sentences and Formulated Sentences subtests of the Clinical Evaluation of Language Fundamentals–Fifth Edition (Wiig, Semel, & Secord, 2013) were administered to evaluate expressive language.

Intervention Design

The treatment design included an alternating-treatments, single-subject experimental design (Kearns, 1986) with a baseline phase consisting of multiple baselines across participants. Two treatment conditions were compared per participant and the design was replicated across six participants. For each participant and each speech target, a baseline phase (three to five data points) was followed by a treatment phase of 14 sessions (two sessions per week for 7 weeks), with a maintenance phase of 2 weeks. During the treatment phase, two sound targets were treated each session under different conditions. For each participant, one treated target was randomly assigned to the prosodic variation condition (PROS) and a second target was assigned to the no-prosodic variation condition (No-PROS). This assignment remained constant throughout the treatment phase (i.e., treatment targets were always treated under the same condition). During each 60-min intervention session, 30 min were spent on one treatment target and the other 30 min were spent on the other target in the other condition. The order was counterbalanced each week such that in one session, the order of treatment was PROS then No-PROS, and the treatment order in the other session for the week was No-PROS then PROS. For example, /ɹ/ in onset was assigned to PROS and /s/ in rhyme was assigned to No-PROS for participant Finn. This condition assignment did not change, but the treatment order of PROS (onset /ɹ/) then No-PROS (/s/ rhyme) occurred in one session and No-PROS then PROS occurred in the subsequent session for the week. The order for the week was randomly determined at the beginning of each week.

Generalization Probes and Target Selection

Changes in speech sound accuracy were tracked via percent accuracy on generalization probes, which included word-level items that were untrained. Participants read through the probe lists with no model and no feedback (unless they misread a word). Probes were administered three to five times pre- and posttreatment, as well as at the beginning of every other treatment session. Probes were also re-administered during a scheduled 2-month follow-up visit to evaluate long-term retention. Probes were audio-recorded and scored later by three listeners who were blind to treatment status (i.e., pre-, during, or posttreatment). Scoring was binary (correct/incorrect), and the average rating of the three listeners was used as the participants' score for each session (see the Reliability of Generalization Probe Scores section below for further details).

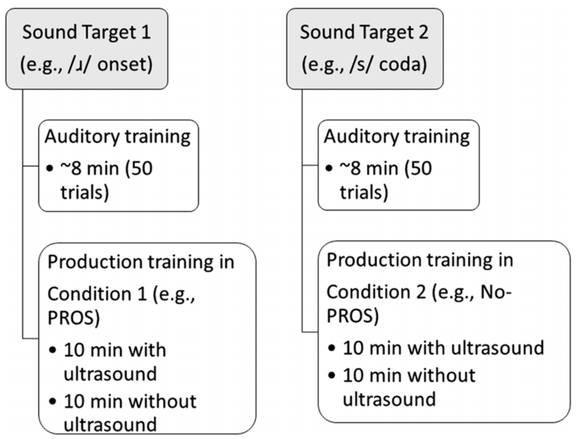
Treatment targets were the sounds that were most frequently in error for each participant on the basis of pretreatment testing. Targets were defined as a phoneme in a syllable position (e.g., /ɹ/ in onset, /s/ in rhyme). The consonant that was most frequently in error (in this study, always /ɹ/ or /s/) was paired with other consonants or vowels to create two-phoneme sequences. For each treatment target, four exemplars were trained. Isaac, for example, practiced /ɹ/ in onsets in the following four exemplars: /ɹæ/, /ɹi/, /bɹ-/, and /tɹ-/. For the same participant, the second target, /s/ rhyme, included exemplars /is/, /aʊs/, /-sp/, and /-st/. Each of these exemplars was then trained during prepractice, but they were embedded within longer words and phrases during structured practice as the child became more successful (see the Structured Practice section below). This procedure of selecting four exemplars was followed to constrain the variability of trained environments of the sounds.

Intervention Procedures

All assessment and treatment sessions were conducted by an SLP certified by the American Speech-Language-Hearing Association. Each treatment session followed a similar time structure. The practice structure varied depending on performance. Each session was divided into two 30-min sections addressing two different treatment targets. The session structure is outlined in Figure 1.

Approximately the first 8 min of each section of therapy involved auditory perception training. This included

Figure 1. Treatment session overview.



listening to recordings of correct and incorrect versions of productions with the target sounds, modeled after Speech Assessment and Interactive Learning (Rvachew, 1994). Using a researcher-developed web-based application, children listened and responded to 50 prerecorded tokens of words containing the target sound produced by a variety of speakers. Participants were instructed to make judgments about correct/incorrect productions (e.g., determining that [ɹoʊp] was an acceptable production of *rope* but a derhoticized production [ɹ̮o̮up] was not acceptable). They received feedback from the computer about their rating (on the basis of researchers' a priori determination of the accuracy of the segments in the recordings). For each phoneme in each word position, there were two to three different modules so that the same items were not presented in each session.

Following auditory training, production training began. Production training on a target lasted 20 min and followed procedures similar to those described elsewhere (Preston et al., 2017; Preston et al., 2016; Preston et al., 2014). The first 10-min period included the use of ultrasound visual feedback whereas the second 10-min period included practice with no visual feedback. During periods when the ultrasound was used, an Echo Blaster 128 ultrasound with a micro convex 6.5 MHz transducer (Articulate Instruments, Ltd, Edinburgh, UK) was placed beneath the chin to provide visual feedback. Children were able to visualize their tongue in real time in sagittal or coronal views (depending on the phoneme being treated and the target movement being trained). For example, in sagittal view /ɹ/ targets were typically trained with a focus on elevating the anterior portion of the tongue (tip, blade, or anterior dorsum), retracting the tongue root toward the pharynx, or lowering the middorsum; additionally, in coronal view elevation of the lateral margins of the tongue and grooving of the midline of the tongue were taught for /ɹ/. When /s/ targets were trained, a coronal view was used to focus on creating a groove in the center while elevating the lateral aspects of the tongue. Descriptions and drawings of preferred tongue shapes were provided and these were compared against the child's productions. Transparencies were placed over the computer screen to draw target tongue shapes for the child to copy. It should be noted that to be counted correct, the production was only required to sound acoustically acceptable to the SLP (regardless of the tongue shape). In addition, the entire sound sequence (e.g., /ɹe/) was required to be correct; thus, errors such as vowel distortions on the treated sound sequences were not acceptable and feedback was provided if necessary to correct vowel errors.

Elicitation/Prepractice

Following auditory training, production training began with the ultrasound in the first 10-min block. Prepractice included verbal and visual instruction to help the participant understand what was required for a correct production of the target movements. A total of 12 correct productions (three correct productions of each of the four variants) were required to advance from prepractice to structured practice. For example, onset /ɹ/ was treated for Isaac, and he was required to correctly produce /ɹæ/, /ɹi/, /bɹʌ/, and /tɹʌ/ three times each. For participants who were readily stimulable, prepractice could be completed in approximately 2 min, allowing for an additional 8 min with the ultrasound and 10 min without the ultrasound in structured practice. For participants who had difficulty acquiring the target sound, the entire 20 min of production training could be spent in prepractice (10 min with the ultrasound and 10 min without). A sample video of prepractice is provided as Supplemental Material S1.

Structured Practice

Once the criterion of 12 correct productions was achieved, the remainder of the 20 min of production training was spent in structured practice. All structured practice occurred in blocks of six attempts. The first attempts were at the syllable level (e.g., six attempts of /ɹi/). If five of six productions were correct, the subsequent block included six attempts at monosyllabic words (e.g., *read* /ɹid/), then multisyllabic words (e.g., *reading*), set phrases (e.g., *I'm reading*), and self-generated sentences (e.g., *I'm reading a new book today*). Hence, all linguistic levels were chained around a core movement towards progressively more complex utterances. If, at any level, fewer than five of six correct attempts were produced, the subsequent attempts returned to syllable-level training on a different target sequence (e.g., /tɹ/).

The structured practice followed the same progression regardless of whether it was during the first 10 min with the ultrasound or the next 10 min without ultrasound. However, during the 10-min periods in which no ultrasound was used, each block of six trials included three trials that required the participant to self-evaluate the accuracy of their production. An example data sheet guiding the structured practice is included in the Appendix.

Condition Differences

Each of the two 30-min sessions involved practicing separate sound targets. The structure during this second half was similar to the first half (auditory training, 10 min of practice with the ultrasound, and 10 min of practice without the ultrasound). The condition differences were during the structured practice stage of treatment. In the PROS condition, participants were told that they were going to practice the target utterances with different prosodic cues or "voices." These variations in prosody were modeled by the SLP for each production and included neutral, question, command, slow, fast, and loud. The relative amount of prosodic variation increased with each linguistic level practiced. Prosodic variation was cued for all monosyllabic words (two different cues were used per block of six trials), multisyllabic words (three cues per six trials), phrases (six cues per six trials), and sentences (six cues per six trials). These cues are shown on the sample data sheet in the Appendix. To maintain similarity in the practice conditions, feedback was provided to the participant only on the accuracy of the target consonants and vowels, not on the prosody.

In the No-PROS condition, the structured practice followed the same progression but with no intentional manipulation of prosody. The target words were modeled with a neutral tone so as not to draw the participants' attention to prosody. Sample videos of the two practice conditions with ultrasound visual feedback are provided as Supplemental Material S2 (no prosody) and Supplemental Material S3 (with prosody).

Treatment Fidelity and Reliability

A research assistant reviewed audio video recordings of two randomly selected sessions per participant. Fidelity to the treatment protocol was assessed by quantifying the frequency with which the SLP gave the prespecified type of feedback. The appropriate verbal feedback was provided 98.6% of the time (*SD* = 1.2%). In addition, interrater reliability between research assistant and the treating SLP's determination of correct/incorrect productions was 94.1% (*SD* = 3.6%).

Reliability of Generalization Probe Scores

Recordings of generalization probes (described above) were randomized and independently scored by three listeners who were blind both to treatment condition and the session in which the generalization probe was administered. Each word from each probe list was scored by each listener as 0 (*incorrect*) or 1 (*correct*) for the perceived accuracy of the target sound. The average rating across listeners was used to evaluate progress. Fleiss kappa, an estimate of reliability across multiple listeners, was 0.56 (95% CI [0.54, 0.57]).

Data Analysis

The primary outcome of interest was performance on the generalization probes in the PROS and No-PROS conditions. Graphical displays of the data are presented by participant. Condition differences were compared primarily with standardized effect sizes, d_2, which is the difference between pre- and posttreatment means divided by the pooled standard deviation of the two phases (Beeson & Robey, 2006). Mean increase in accuracy is also reported as it is a commonly used clinical metric.

Results

Within-Session Performance

For each session, 20 min were spent on prepractice and practice of each treatment target (10 min with the ultrasound and 10 min without). As described above, participants transitioned from prepractice to practice only when the preestablished criteria were met. The number of practice trials, therefore, varied significantly, as some participants remained in the prepractice stage much longer than others. Across the six participants, the mean number of trials completed in the 20 min of practice over 14 sessions was 970 (*SD* = 898, range 0–1,974) for the PROS condition and 1,365 (*SD* = 889, range 126–2,142) in the No-PROS condition. This corresponds to an average of 69 practice trials per session per participant in the PROS condition, and 98 practice trials per session per participant in the No-PROS condition. Supplemental Material S4 includes individual within-session practice data. Isaac was the only participant who failed to advance past the prepractice stage, and this was only for his PROS target; therefore, condition differences for this participant cannot be readily interpreted.

Generalization

Results on generalization probes are first presented by participant, followed by group-level trends. Figure 2 presents percent accuracy on generalization probes, which reflect the average of three listeners. Table 2 summarizes the mean and standardized change from pre- to posttreatment for each participant under each treatment condition.

Danica

Danica demonstrated stable baselines before treatment followed by a strong response to both treatment conditions, with rapid generalization emerging around Sessions 9–10. An increase of 79.2% (d_2 = 46.35) was observed for her targets treated under the PROS condition (from 0.7% to 80.9%). Under the No-PROS condition, an increase of 83.2% (d_2 = 36.64) was observed (from 2.1% to 85.3%). Danica exhibited a slightly larger raw percentage increase in the No-PROS condition, but when accounting for variability in performance, a larger effect size (d_2) was observed under the PROS condition.

Ethan

Ethan also showed a strong response to both treatment conditions. Baselines for both treatment targets were stable with generalization scores steadily increasing. A 92.4% increase (d_2 = 27.5) was observed on generalization probe accuracy for the PROS condition, from 1.2% at baseline to 93.6% posttreatment. A 72% increase (d_2 = 8.71) was observed under the No-PROS condition. Therefore, a larger increase in generalization was observed in the PROS condition.

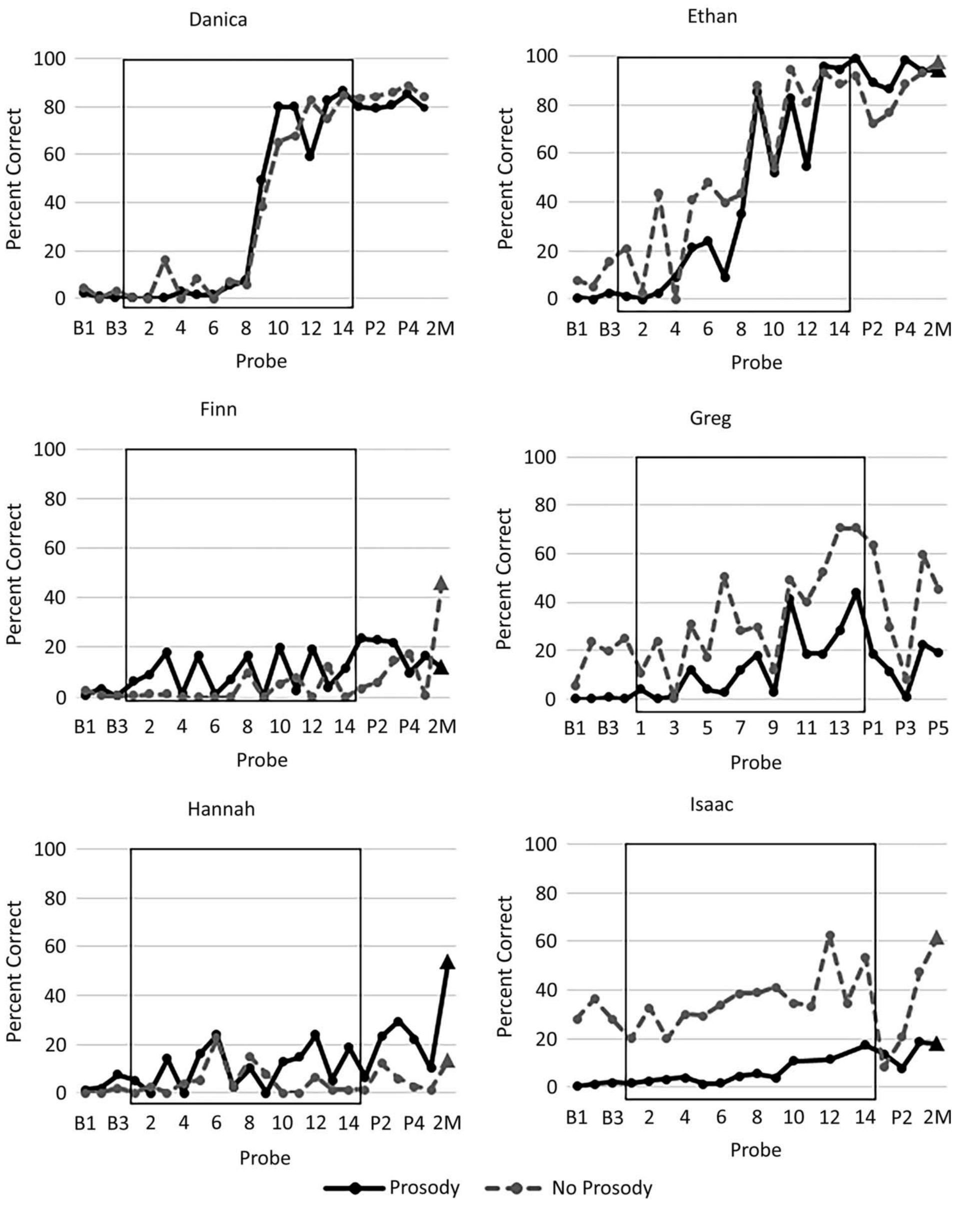
Finn

Finn demonstrated baseline probe scores below 5% for both treatment targets. He showed an increase of 16.7% (d_2 = 3.82) on generalization probes under the PROS condition and a 7.2% increase (d_2 = 1.75) in the No-PROS condition (1.2% pretreatment to 8.4% posttreatment), indicating a greater increase in generalization probe scores under the PROS condition.

Greg

Greg demonstrated a larger standardized effect size under the PROS condition (d_2 = 3.15) than the No-PROS condition (d_2 = 1.42). Prior to treatment, Greg demonstrated a stable baseline with an average of 0.2% accuracy on the generalization probe under the PROS condition, which

Figure 2. Generalization probe data for six participants. Areas enclosed with boxes represent sessions in which treatment occurred. B = Baseline (pretreatment); P = Posttreatment; 2M = 2-month follow-up (represented by triangles). Data reflect the average of three listeners on each probe.



increased 14.4% posttreatment. Under the No-PROS condition, Greg demonstrated some variability in his baseline accuracy, but with a 22.7% mean increase from pretreatment (18.5%) to posttreatment (41.2%). A larger percentage gain was observed under the No-PROS condition; however, when taking variability into account, the standardized effect size was larger for the PROS condition.

Hannah

Both of Hannah's targets were below 5% accurate on the probes before treatment, with stable baselines. Under the PROS condition, Hannah demonstrated an increase of 14.2% (d_2 = 2.27) in generalization probe accuracy from pre- to posttreatment. In the No-PROS condition, an increase of 4.2% (d_2 = 1.51) was observed, indicating a larger increase in generalization under the PROS condition.

Isaac

As can be seen in Table 2, Isaac was one of the poorest responders in both treatment conditions. In the PROS condition, Isaac demonstrated a 12.1% increase (d_2 = 4.00) on generalization probes, from a mean of pretreatment 1.3% to 13.4% posttreatment. A slight decrease of 3.6% (d_2 = −0.19) was observed under the No-PROS condition (from 28.0%

Table 2. Sound targets treated under prosodic variation and no prosodic variation conditions with effect size calculated on generalization probes pre- and posttreatment.

	Prosodic variation							No prosodic variation						
		Pretreatment		Posttreatment					Pretreatment		Posttreatment			
Participant	**Targets**	***M***	**%**	**M**	**%**	**% change**	d_2	**Targets**	***M***	**%**	***M***	**%**	**% change**	d_2
Danica	/ɹ/ rhyme	0.7	0.9	80.9	2.5	79.2	46.35	/ɹ/ onset	2.1 (2.3)	2.3	85.3	2.3	83.2	36.64
Ethan	/ɹ/ rhyme	1.2	1.1	93.6	5.6	92.4	27.5	/ɹ/ onset	12.5 (7.2)	7.2	84.5	9.4	72.0	8.71
Finn	/ɹ/ onset	2.8	2.7	19.5	5.8	16.7	3.82	/ɹ/ rhyme	1.2	1.0	8.4	7.3	7.2	1.75
Greg	/ɹ/ rhyme	0.2	0.3	14.4	8.7	14.2	3.15	/ɹ/ onset	18.5	8.9	41.2	22.7	22.7	1.42
Hannah	/ɹ/ onset	4.1	3.0	18.3	9.6	14.2	2.27	/ɹ/ rhyme	0.5	1.0	4.7	4.5	4.2	1.51
Isaac	/ɹ/ onset	1.3	0.7	13.4	5.3	12.1	4.00	/s/ rhyme	28.0	6.7	25.4	20.9	–3.6	–0.19
Mean (95% CI)		1.7		40.0		38.1 [8.4,67.9]	14.52 [–0.2,29.2]		10.5		41.6		31.0 [1.1,60.8]	8.31 [–3.1,19.7]

Note. d_2 = mean difference of the immediate three to five pretreatment values and three to five posttreatment values, divided by the pooled standard deviation of these pre- and posttreatment values.

to 25.4%); however, there was significantly more variability in his performance on the No-PROS target. As mentioned above, condition differences should be interpreted with caution as he did not advance past the prepractice stage on his PROS target and therefore did not have the opportunity to practice with prosodic variation.

Group Trends

As can be seen in Table 2, all participants showed a larger standardized effect size (d_2) for the prosodic variation condition (average $d_2 = 14.52$) compared to the No-PROS condition average ($d_2 = 8.31$). The magnitude of the difference between the two conditions varied by participant.

The unstandardized percent increase from pre- to posttreatment was 38.1% in the PROS condition compared to 31.0% in the No-PROS condition. All participants showed at least a 12% increase from baseline in generalization probe scores in the PROS condition, but only three of six showed an increase of greater than 12% in No-PROS. When comparing treatment conditions, four of the six participants had an advantage for the PROS condition over No-PROS on unstandardized percent increase with respect to both effect size and raw percentage increase. Two participants, Danica and Ethan, showed particularly strong responses with mean increases greater than 70% in both conditions.

Discussion

It was hypothesized that treating speech sound targets with variable practice in the form of prosodic variation would result in greater speech sound generalization compared to treatment involving constant practice. On the basis of the standardized effect size, there was a consistent trend across all children to show greater improvements for sound targets treated with prosodic variation among the school-age participants with mild-to-moderate CAS treated in this study. The results contradict those from a previous study that showed minimal and inconsistent differences between the practice conditions in children with residual speech sound errors (Preston et al., 2014). However, the role of prosodic variation in practice may be more beneficial for children with speech sound errors associated with CAS compared to those who do not show signs of CAS. It is possible that the prosodic variation was useful to this population because it provided explicit opportunities for children to practice integrating segmental and suprasegmental aspects of speech.

The results are in agreement with predictions from schema-based motor learning theory (Maas et al., 2008; Schmidt & Lee, 2011)—that is, similar to studies of nonspeech motor learning (Hall & Magill, 1995; Wulf & Schmidt, 1997), practice variability was found to enhance generalization. In general, data from the four participants who returned for a 2-month follow-up suggested retention of skills (see triangles in Figure 2).

The implementation of practice variability was relatively straightforward. The clinician simply cued the child to practice words, phrases, and sentences with several different "voices" while providing feedback on articulatory accuracy. This type of practice variability could be easily implemented in many types of treatment for clients with CAS (not just ultrasound); for example, similar strategies are explicitly included in Dynamic Temporal and Tactile Cueing (Baas, Strand, Elmer, & Barbaresi, 2008; Strand & Debertine, 2000; Strand & Skinder, 1999), and it is possible that intentional variations in prosody may contribute to the success observed in that treatment approach. In a similar manner, Repeated Syllable Transition Training (Ballard et al., 2010; Murray et al., 2015; Thomas et al., 2014), which involves intentional practice of nonwords with varied prosodic stress patterns, may benefit children with CAS because of the purposeful integration of segmental and prosodic aspects of speech. Replication of the present results, both within the context of biofeedback treatment (with larger sample sizes) and within the context of other treatment approaches, would be of clinical value.

It should be emphasized that the participants in this study were school-age children with mild-to-moderate impairments related to CAS. It is possible that children who do not fit this profile (e.g., children who are younger or with more severe impairments) might show different responses to treatment or a different magnitude of benefit from practice variability.

Individual Responses to Treatment

As is evident from Figure 2, the two participants who showed strong responses in both conditions (with an advantage from the PROS condition in their standardized effect sizes) were Danica and Ethan. On the basis of the data from Table 1, they were not outliers in age, gender, vocabulary, speech sound accuracy, prosody, phonological processing, or nonverbal reasoning. However, they did show the highest stimulability scores, which may suggest that stimulability accelerates the learning process (Miccio, Elbert, & Forrest, 1999). Although the goal of the study was not to identify treatment responders and nonresponders, further research is clearly needed to identify relevant characteristics that would predict rate of response to treatment.

Isaac demonstrated minimal treatment effect on the basis of unstandardized percent increase, and he was the only participant who failed to meet the criterion to pass the prepractice stage for one of his treatment targets. He was the oldest participant and was qualitatively rated the most severe; he also had the most overt prosodic impairment as evidenced by his performance on the emphatic stress task, and by his lexical stress score on the multisyllabic word repetition task. In addition, he had difficulty sustaining phonemes (e.g., /ɑ/, /s/) during the maximum performance task, which resulted in a dysarthria score of 2. It is possible that some of these aspects of his speech impairment profile contributed to his limited response to the treatment. It may be that more treatment and/or a different type of treatment would be necessary to enhance speech sound learning with children who show limited response.

Last, it should also be noted that there are some interpretive challenges with the results for two participants (Danica and Greg) who showed an advantage for the PROS condition over No-PROS in their standardized effect sizes but not in their raw percent increase on the generalization probes. If raw percent increase were used as the outcome variable, the results would be less consistent. However, standardized effect sizes are generally preferred metrics in single-subject designs as they take into account estimates of variability rather than just mean differences (Beeson & Robey, 2006); therefore, standardized effect sizes were the primary outcome of interest.

Summary and Conclusions

This single-case experimental design provides additional support that ultrasound visual feedback treatment may lead to speech sound learning, as evidenced by generalization and retention, in some children with CAS. The data from this study also support predictions from schema-based motor learning theory that variable practice can increase speech motor learning for children with CAS. The use of prosodic variation during practice can be one way to enhance speech sound learning.

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Appendix

Sample Data Sheet for Structured Practice

Clinician________________Participant ___________ **WITH PROSODIC CUES** Date__________________Session #____

ELICITATION for /ræ/ __ __ __ Elicitation for /brʌ/ __ __ __ Block: B or D (no ultrasound)
ELICITATION for /ri/ __ __ __ Elicitation for /trʌ/ __ __ __

Syllable	Feed-back	Score	Self-Rate	Monosyl Wd	Pros Cue	Feed-back	Score	Self-Rate	Multisyl. Wd	Pros Cue	Feed-back	Score	Self-Rate	Phrase	Pros Cue	Feed-back	Score	Self-Rate	Gener-ated	Pros Cue	Feed-back	Score	Self-Rate
/ræ/	KR,KP			rash	?	KR,KP			ration	slow				rational number	loud				x	?			
	KR,KP				?	KR				slow	KR,KP				?	KR,KP				.	KR,KP		
					?	KR,KP				loud	KR,KP				.	KR,KP				!	KR		
	KR,KP				.	KR,KP				loud	KR				slow					loud			
	KR,KP				.					!					!	KR				slow	KR		
	KR				.	KR				!	KR				fast					fast			
		___/6					___/6					___/6					___/6					___/6	
/ri/	KR,KP			reek	.	KR,KP			recline	.	KR,KP			recline the chair	slow	KR			x	slow	KR		
	KR,KP				.	KR				.					?					loud			
	KR,KP				.	KR,KP				?	KR,KP				.	KR,KP				fast	KR		
					Slow					?	KR				!					!			
	KR,KP				Slow	KR				!					fast	KR,KP				.	KR,KP		
	KR				Slow	KR,KP				!	KR				loud					?			
		___/6					___/6					___/6					___/6					___/6	
/brʌ/	KR,KP			brag	slow	KR,KP			bragging	slow	KR,KP			nonstop bragging	loud	KR,KP			x	fast	KR,KP		
					slow					slow					slow	KR				loud	KR		
	KR,KP				slow	KR				!	KR,KP				fast	KR,KP				?	KR		
	KR,KP				?	KR,KP				!	KR				?					slow			
	KR,KP				?	KR,KP				?					!					!			
	KR				?	KR				?	KR				.					.			
		___/6					___/6					___/6					___/6					___/6	
/trʌ/				truck	.				trucking	.				pick up truck	.	KR			x	loud	KR		
	KR,KP				.	KR,KP				.	KR,KP				?					?			
	KR,KP				.	KR,KP				loud					slow	KR,KP				fast	KR		
	KR,KP				slow	KR				loud	KR				!					!			
	KR,KP				slow	KR,KP				!	KR,KP				fast	KR,KP				.	KR,KP		
	KR				slow	KR				!	KR				loud					slow			
		___/6					___/6					___/6					___/6					___/6	
/ræ/	KR,KP			rap	?	KR,KP			rapidly	slow				rapid decision	!				x	slow			
	KR,KP				?	KR				slow	KR,KP				?	KR,KP				?	KR		
	KR,KP				?	KR,KP				.					fast	KR,KP				!	KR,KP		
	KR,KP				slow	KR,KP				.	KR				slow					loud			
					slow					?	KR,KP				loud					fast			
	KR				slow	KR				?	KR				.	KR				.	KR		
		___/6					___/6					___/6					___/6					___/6	
/ri/	KR,KP			read	.	KR,KP			reading	!	KR,KP			reading book	?	KR,KP			x	fast	KR,KP		
	KR,KP				.					!	KR,KP				.					.			
					.	KR				slow	KR				fast	KR				?	KR		
	KR,KP				?	KR,KP				slow	KR				slow					loud			
	KR,KP				?	KR				.					loud					slow			
	KR				?	KR,KP				.					!	KR,KP				!	KR		
		___/6					___/6					___/6					___/6					___/6	
/brʌ/	KR,KP			broom	slow	KR,KP			broomstick	?	KR,KP			witch on a broomstick	!	KR,KP			x	!	KR,KP		
	KR,KP				slow					?	KR,KP				?					fast			
					slow	KR				loud	KR				slow	KR				slow	KR		
	KR,KP				.	KR,KP				loud	KR				.					.			
	KR,KP				.	KR				.					loud					loud			
	KR				.	KR,KP				.					fast	KR,KP				?	KR		
		___/6					___/6					___/6					___/6					___/6	
/trʌ/	KR,KP			try	?	KR,KP			triangle	slow	KR,KP			triangles on the table	fast	KR,KP			x	!	KR,KP		
	KR,KP				?					slow	KR,KP				loud					fast			
					?	KR				?	KR				?	KR				?	KR		
	KR,KP				slow	KR,KP				?	KR				!					loud			
	KR,KP				slow	KR				!					slow					slow			
	KR				slow	KR,KP				!					.	KR,KP					KR		
		___/6					___/6					___/6					___/6					___/6	