Studies of Articulatory Feedback Treatment for Apraxia of Speech Based on Electromagnetic Articulography

William F. Katz

Department of Communication Disorders, University of Texas
Dallas, TX

Malcolm R. McNeil

Department of Communication Disorders, University of Pittsburgh
and
Pittsburgh Veterans Administration Healthcare System
Pittsburgh, PA

Abstract

Electromagnetic articulography (EMA) is a method originally designed for the laboratory measurement of speech articulatory motion (Schönle et al., 1987). We describe a novel use of this technology applied to the remediation of apraxia of speech (AOS). In this experimental technique, individuals with AOS are provided with real-time, visual information concerning the movement of the tongue during speech. From information sent via EMA sensors mounted on the tongue, patients are guided into hitting "targets" displayed on a computer monitor, designed to guide correct articulatory placement. The results of several studies suggest that augmented feedback-based treatment is efficacious and that this treatment follows principles of motor learning described in the limb motor literature. Potential challenges facing this type of approach, as well as some new directions, are discussed.

Individuals with apraxia of speech (AOS) typically present with an overall slow rate of speech, extended segment and intersegment durations, abnormal prosody, and consonant and vowel distortions (McNeil, Robin, & Schmidt, 1997; McNeil, Doyle, & Wambaugh, 2000). Based on a review of brain-injured subjects' phonological inventories, phonetic/motor characteristics, speech prosody, target approximation profiles, and "sense of effort," McNeil et al. (1997) defined AOS as a "phonetic-motoric disorder of speech production caused by inefficiencies in the translation of a well-formed and filled phonological frame to previously learned kinematic parameters assembled for carrying out the intended movement." That is, AOS is fundamentally a disorder of the planning and programming of speech movements. Accordingly, and following similar mechanisms identified by earlier researchers (e.g., Darley, 1968; Wertz, LaPointe & Rosenbek, 1984), a number of researchers have begun to use motor learning principles in the treatment of AOS and related disorders.

The application of motor learning principles to AOS has been described in previous issues of *Perspectives* (Austermann Hula, 2007; Ballard, 2001; Maas, 2010, in this issue of *Perspectives*). The purpose of this article is show how some of these principles have been applied during the development and testing of a new form of articulatory-based treatment using electromagnetic articulography (EMA) to provide on- and off-line kinematic feedback.

Potential challenges facing this type of approach, as well as some new directions, also will be discussed.

Basic Principles and Method

A synthesis of studies by Kent (2004) suggests that treatment strategies designed to promote improved postural shaping and phasing of the articulators are efficacious in improving sound production in treated and untreated words, phrases, and sentences produced by individuals with AOS. Clinical investigations of postural shaping techniques have suggested that providing tactile information (or cues) can improve the accuracy of phoneme production in persons with AOS (e.g., Bose, Square, Schlosser, & van Lieshout, 2001). However, clinician-mediated sensory feedback approaches (e.g., Prompts for Restructuring Oral Muscle Phonetic Targets-PROMPT) provide a patient with indirect information concerning the principle moving articulator, the tongue. In order to provide direct information concerning lingual movement for treatment purposes, it is necessary to adapt instrumental techniques such as electropalatography (EPG), ultrasound, and EMA (Bernhardt, Gick, Bacsfalvi, & Adler-Bock, 2005; Hardcastle, Gibbon, & Jones, 1991; Katz, Bharadwaj, Gabbert, & Stettler, 2002).

In the EMA procedure, participants wear a lightweight helmet that produces a low strength electromagnetic field around the head. Small (2 x 2 x 3 mm) receiver sensors are fixed to the surface of the articulators with biocompatible glues. As the receiver sensors move through the alternating magnetic field, currents are induced. These currents are detected by a computer and used to reconstruct a two-dimensional model of articulator position and velocity. A speech signal is recorded and is stored synchronously with kinematic data for subsequent analysis. After recording is completed, the receiver sensors can be removed easily, without subject discomfort.

In feedback applications, the participant is seated in a quiet room wearing the articulograph helmet, with a sensor placed approximately 1 cm from the tongue apex. The participant faces a video monitor that shows a "target region," which corresponds to the correct place of articulation for a given speech motor target (SMT). The participant also views (a) an image of his/her current tongue position, marked with a large "X" and (b) a trace marking the recent path of tongue movement. This trace length can be adjusted by the investigator. The participant's goal is to "hit the target" displayed on the monitor while producing the SMT. In each treatment session, participants typically practice under EMA conditions for a total of approximately 50 min.

Figure 1. An EMA feedback session. A participant wears a Plexiglas helmet with a small, lightweight receiver sensor fixed to various locations on the tongue depending on the goal of treatment. The EMA system provides an image of the participant's tongue tip position on a computer monitor while target gestures are attempted.
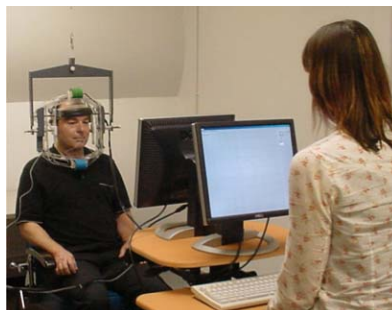
Two types of augmented feedback can be provided, separately or in combination, as chosen by the clinician: Knowledge of Performance (KP) and Knowledge of Results (KR). KP is

information about the nature or specific attributes of the movement pattern. KR is verbal or verbalizable information that tells learners something about the outcome of their actions with respect to the intended goal (see also Maas, this issue). The EMA feedback system can be set to provide predominantly KP by delivering visual and/or auditory rewards when the lingual sensor hits the appropriate targets set for the talker's articulatory space. In most applications, the reinforcement signal is made contingent on a combination of KP and KR. Each time both the correct movement is achieved and this production is deemed to contain a perceptually accurate instance of the given SMT (as determined by the investigator), a visual bar (reward signal) is triggered to move vertically on the monitor.

Clinical Studies/ Empirical Evidence

In a first phase of our research, three case studies suggested that EMA can be used to treat speech motor deficits and oral apraxia in individuals with brain damage after stroke. Katz et al. (1999) examined EMA as a means of remediating /s/, /ʃ/ articulation deficits in the speech of a 68-year-old woman with Broca's aphasia and AOS. Over a 1-month period, the participant was provided EMA visual feedback for tongue tip position during fricative production and a foil treatment in which a computer program delivered voicing-contrast stimuli for simple repetition. The results suggested lasting improvement from the visually guided feedback, while the phonetic contrast treated in the foil condition showed only slight improvement, with a return to baseline 10 weeks later. The findings were considered preliminary evidence that EMA-assisted visual KP can be used to treat place-of-articulation errors in the speech of adults with Broca's aphasia and AOS.

Katz et al. (2002) investigated EMA therapy for a 67-year-old male talker with anomia and AOS subsequent to a left fronto-parietal hemorrhagic CVA. A similar experimental design was employed, with two error-prone speech sounds assigned to EMA treatment (/ʃ/, /tʃ/), and two assigned to a foil treatment condition (/θ/, /f/). Treatment was provided over a 1-month period, in bi-weekly sessions. The results of a perceptual assessment indicated that SMTs treated with EMA were notably improved over baseline levels (/ʃ/, 39%, /tʃ/, 18%), while the SMTs treated in the foil condition showed no evidence of improvement. The /ʃ/ SMT was maintained 6 weeks post-training, while the /tʃ/ target declined near baseline levels. Although this participant's performance was slightly less robust than the first (Katz et al., 1999), the findings were nevertheless considered important because this subject had previously shown very limited improvement on these target phonemes after years of traditional therapy.

It was also of interest to determine whether intervention effects would generalize to buccofacial (or oral) apraxia, the inability to perform voluntary movements of the larynx, pharynx, tongue, lips and cheeks, while automatic or reflexive control of these structures is preserved. Buccofacial (BF) apraxia frequently co-occurs with aphasia and AOS. An ABA design with long-term follow-up was used to investigate two types of therapy for nonverbal oral errors produced by a 65-year-old male with BF apraxia. Over a 1-month period, the participant received (a) structured motor practice for one set of oral gestures ("bite the upper lip," "bite the lower lip") and (b) EMA feedback treatment for a different oral gesture ("touch the upper lip, then the lower lip using the tongue"). The main findings were (a) a mixed pattern of improvement with no long-term maintenance for the gestures treated with structured motor therapy and (b) consistent improvement with long-term maintenance for the gesture treated with augmented visual feedback therapy. The findings suggest that principles of motor learning may provide an improved means of treating a variety of apraxic disorders.

Because these three studies were preliminary, it was not possible to definitively attribute the observed improvement to the treatment alone. Also, these studies did not experimentally manipulate treatment delivery variables, such as the frequency of feedback scheduling, that have been shown to influence acquisition, generalization, and retention of

complex limb movement tasks (Schmidt & Lee, 2005). To address these issues, a second phase of research employed a more rigorous single subject experimental design, a larger number of individuals with AOS and a greater variety of SMTs, tested at high (100%) and low (50%) frequency (VA-RR&D#B3670R, Biofeedback Treatment of Apraxia of Speech Following Stroke).

Figure 2. Sample data from a 63-year old participant with mild aphasia and mild-to-moderate severity AOS (McNeil et al., 2007a). EMA treatment was administered sequentially to four speech motor targets (SMT) groups: Words containing medial /l/, /tʃ/, /st/, and /bl/. Baseline, treatment (shaded), and maintenance phases are labeled for each panel. Treated and untreated (generalization) probe data are shown in the top two panels.
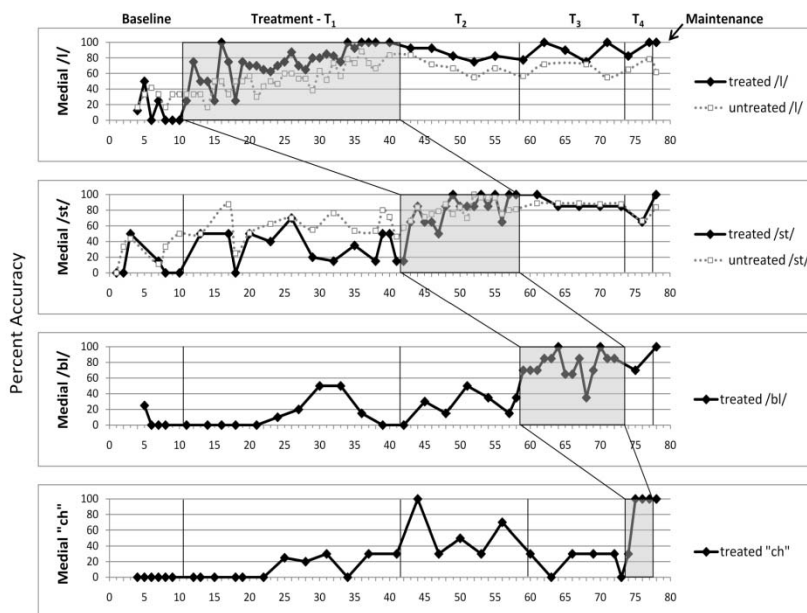

Figure 2 shows representative data from one participant in this study having mild aphasia and mild-to-moderate severity AOS. Treatment was administered sequentially to four groups of SMTs. These were mono- and bi-syllabic words containing the speech sounds /l/, /tʃ/, /st/, and /bl/. For instance, *pillow, color, crawling*, and *relic* were treated items containing word-medial /l/. Frequent (100%) feedback was provided for treated /l/- and /tʃ/-containing words, and infrequent (50%) feedback to /st/- and /bl/-containing words. The treatment criteria were three consecutive sessions with an auditory perceptual accuracy on each treatment probe of ≥ 80%. Generalization to SMTs varying in phonetic contexts was evaluated in 27 untreated stimuli that were both systematically baselined pre-treatment and probed throughout treatment. Intervention yielded evidence for a treatment (acquisition) effect. Sufficiently stable baselines on all treated SMTs allowed attribution of observed effects to the treatment, rather than to other possible sources of change (e.g., spontaneous recovery). Maintenance of treatment effects also was realized for each of the targets, as indicated by high accuracy scores 6 weeks post-treatment (right of each panel). Although the 27 untreated probes are not shown because of space limitations, generalization learning to 26 of the 27 was observed. The results support the efficacy of this technique for this clinical population.

Perceptual analyses have been completed for 14 participants who have finished the protocol. All evidenced positive acquisition and generalization effects. That is, sufficiently stable baselines, compared to the intervention, yielded effects that were attributable to the

intervention, rather than other possible sources of change. In general, three to eight sessions were necessary for criterion to be reached and maintained in the frequent (100%) feedback condition, while five to ten sessions were necessary for the 50% feedback condition. Frequent feedback scheduling (100%) resulted in rapid learning but poorer generalization and long-term retention, while infrequent feedback was associated with slower acquisition, but better maintenance effects.

Individual effect sizes have been computed for the first four complete participant datasets. Effect sizes pooled for these participants have yielded evidence for positive treatment (acquisition) effects and generalization of learning to untreated SMTs within and outside of the traditionally selected targets based on phoneme classes. The averaged *d*-value for the baseline-to-treatment comparison was 2.26 and 3.28 for baseline-to-maintenance for those treated SMTs. The averaged *d*-value for the baseline-to-generalization comparison for untreated stimuli was 1.89. These values are comparable to or exceed other values in the aphasia and AOS treatment literature (e.g., Beeson & Robey, 2006; Wambaugh, Duffy, McNeil, Robin, & Rogers, 2006).

Evaluation

Overall, these data support the notion that augmented feedback-based treatment is efficacious for articulatory errors constituting a broad range of movement targets that result in changes in perceptual improvements of consonants and vowels in American English. Although still in analysis, our larger scale study also supports these generalizations:

Feedback consisting of visual KP plus clinician-provided KR provides superior generalization and maintenance than visual KP alone.

Infrequent feedback (50%) results in greater generalization and maintenance effects than the frequent feedback (100%), consistent with predictions from the limb motor literature regarding the scheduling of feedback frequency.

The data have also presented some puzzles. For example, it is not clear why certain patients obtained better outcomes than others or why certain instances of an SMT improved and others did not (see McNeil et al., 2010, for examples and Katz, McNeil, & Garst, in press, for discussion). For instance, one individual showed cases in which a treated item generalized to an untreated item sharing the same CV context (e.g., *yogurt, yodel*), but did not generalize to other untreated items in the same SMT category (e.g., *yoga*). There were also occasional untreated CV combinations acquired (e.g., *yardage*). There are a number of possible explanations for these patterns, including lexical level issues and motoric/planning demands for segments larger than the CV syllable or smaller than a phoneme. Further research will be necessary to clarify these patterns.

Challenges and New Directions

Clearly, there are equipment size, complexity, and cost issues to be overcome before such systems find their place in the clinic. However, the technology is developing rapidly, with these practical factors rapidly improving. Carstens Medizinelektronik, GmbH, is presently under contract by the German government to develop an easy, cost-effective EMA system targeted to the clinical market (see also Schultz et al., 2006). A Canadian firm (Northern Digital, Inc.) has produced an inexpensive, fleshpoint tracking system that requires no helmet or calibration, and can be used with relatively little training. This system is particularly useful for individuals with postural problems (e.g., from cerebral palsy or TBI) who cannot tolerate wearing a helmet (Vick, 2010). Another cost-effective and simple-to-use tongue-tracking technology is based on a single, permanent-magnet tracking system (BioResearch Associates, Inc.), commonly sold to dental practices (see Dromey, Nissen, Nohr, & Fletcher, 2006). A group

at the University of Texas at Dallas is currently developing specialized, interactive software to be employed across a number of these platforms.

In sum, a first generation of "dinosaur" technologies required to display articulatory movement is quickly giving way to more clinic-friendly techniques. One can envision wireless transducing systems (e.g., Holzrichter & Ng, 2001), stick-on (or spray-on) tongue sensors, and a variety of 3-D imaging and playback displays the near future. However, any such technical breakthroughs will be meaningless without a solid understanding of how visual augmented feedback can be used by to recover speech and without systematically validating each phase-by-phase clinical trial.

In summary, we have presented a new technique, EMA kinematic feedback for the treatment of AOS. The current state of knowledge warrants that additional, systematic clinical trial efficacy research be undertaken. This research should be designed with the following considerations:

The effectiveness should be investigated both in isolation and in combination with other more traditional treatment methods for AOS, including hierarchical treatment methods.

Well-controlled experimental designs should be employed to assess treatment acquisition, generalization, and maintenance including the determination of the optimum schedule of treatment delivery.

Sample size should be increased and the possibility of investigating related disorders should be explored.

William F. Katz is professor of Communication Sciences and Disorders in the School of Behavioral and Brain Sciences at the University of Texas at Dallas. He teaches and directs research in linguistics, speech science, and language disorders. His laboratory at the UTD Callier Center is concerned with the functional and neurological bases of speech production by healthy and brain-damaged talkers.

Malcolm R. McNeil is distinguished professor and department chair at the University of Pittsburgh and Research Career Scientist at the VA Pittsburgh Healthcare System. He teaches and directs research in neurogenic speech and language disorders. Primary research interests are in the assessment of the cognitive mechanisms subtending aphasia and in the nature, diagnosis and treatment of apraxia of speech.

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