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Effectiveness of visual feedback provided by an electromagnetic articulograph (EMA) system: training vowel production in individuals with hearing impairment

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EFFECTIVENESS OF VISUAL FEEDBACK PROVIDED BY AN ELECTROMAGNETIC ARTICULOGRAPH (EMA) SYSTEM: TRAINING VOWEL PRODUCTION IN INDIVIDUALS WITH HEARING IMPAIRMENT

by

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Abstract: An electromagnetic articulograph (EMA) system was used to provide a participant with congenital hearing loss visual biofeedback information on speech production. Five normally hearing listeners reported a change in their perception of the speech sound /æ/ in the various conditions of the study.

Acknowledgements

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Introduction

The history of using visual feedback to understand and correct speech production dates back over two hundred years. In 1803, Erasmus Darwin placed aluminum foil in his mouth and produced vowels to examine how his articulation changed the foil and in 1872 an English dentist named J. Oakley Coles began producing three-dimensional “plates” to show the contact of tongue and hard palate made when saying each of the letters in the alphabet (Fletcher, 1992). The concept of understanding how the tongue moves as a method of speech therapy has since evolved into advanced computer systems that utilize visual biofeedback, visually demonstrating to a person how their tongue is moving in their mouth as it is happening. Using a biofeedback system for therapy can be effective because it elucidates normally ambiguous internal cues like tongue movement and position and allows the user to consciously control these factors (Ball & Code, 1997).

The field of oral deaf education has developed around the idea of teaching speech to children who were born with hearing loss and do not acquire speech from a lack of auditory feedback. In *Speech and the Hearing-Impaired Child: Theory and Practice* (1976), Ling discussed using visual feedback to teach speech with simple visual aids such as mirrors or paper to show the breath stream. He also suggested more complex visual aids such as meters to help a child visualize his pitch or computers that allow a child to interact with a visual display.

In response to Ling’s suggestion, a computer-based speech training program was developed by Osberger, Lippmann, Moeller, & Kroese (1981) with the purpose of aiding educators by drilling students to imitate auditory models, make spontaneous productions based on visual cues, discriminate between auditory signals, and self evaluate intelligibility. Povel and Wansink (1986) also used visual feedback with a computer system called the Vowel Corrector.

In their study, children with hearing impairments received feedback on their vowel production through the position of spots of light on a display screen.

More recently, Massaro and Light (2004) used Baldi, a computer-animated head, to tutor children with hearing loss in speech production of consonants. Baldi was manipulated to present in four different forms to show views of articulator activity within the mouth as well as facial movement during speech. The researchers also used different methods of training such as slowing down Baldi's speaking rate to highlight speech distinctions and having Baldi produce a strong air stream for voiceless consonants versus a limited air stream for voiced consonants.

Some of the benefits Massaro and Light (2004) observed in using Baldi to teach speech were cost effectiveness, easily tailored lessons based on the child's individual needs, and training that could take place outside of the classroom or treatment setting. A computer program is relatively inexpensive and easily transferable because it can be used on computers in the any setting. A disadvantage to this as a form of visual feedback is that a computer program cannot analyze a user's articulator movements and provide feedback for accurate speech production.

In response to the need to provide accurate speech production analysis and visual feedback many computer-based methods of speech therapy have been developed. Glossometry, electropalatography, and electromagnetic articulography are three such examples, all of which analyze the user's tongue position to provide visual feedback on a display. Each of these methods is a unique approach with its own advantages and disadvantages for providing speech therapy to individuals with hearing impairments.

Glossometry works through an artificial plate which the user wears against his hard palate. The plate shines light on the user's tongue which is then detected by photosensors across the plate. From the photosensor measurements of the scattered light on the tongue, the distance between the tongue and sensors can be measured and then displayed for the user on a computer screen. (Ball & Gibbon, 2002). Because the measurements taken are of the tongue's distance from the palate rather than contact, glossometry has traditionally been used to remediate vowel production (Fletcher, Dagenais, & Critz-Crosby, 1991 [2]).

Electropalatography also requires the user to wear an artificial plate against the hard palate and records the tongue's contact with the plate through electrodes on its surface. Similarly to glossometry, electropalatography uses a computer display to show the user's tongue position during therapy (Ball & Code, 1997). As electropalatography measures the tongue's contact on the palate rather than its distance, this method has traditionally been used to remediate consonant production (Fletcher, Dagenais, & Critz-Crosby, 1991 [1]; Dent, Gibbon, & Hardcastle 1995).

In *Vowel Disorders* (2002), Ball and Gibbon discussed how glossometry and electropalatography may be useful for treating vowel errors, but they could not become a widely used therapy with children for financial, availability, and procedural reasons. They explained that the custom-made plates used in glossometry and electropalatography are costly and could only be justified for treating severe speech impairments. Other difficulties with these methods of therapy are that the technology itself is not available in most areas and that the therapy techniques themselves are not suitable for young children.

New computer-based methods of speech therapy are constantly being developed, and one that holds great potential is the Aurora system (Kröger, Pouplier, & Tiede, 2008). The Aurora system is similar to electromagnetic articulography in that it can utilize electrodes on a participant's tongue, but is does not have some of an EMA system's disadvantages like constricted head movement from a helmet. While Aurora has not been used in a published study for speech therapy, Kröger, Pouplier, & Tiede evaluated it for such use and found many benefits to the system. In their evaluation, they wrote that it is “relatively small and easily transported, permits unconstrained participant head movement, and… provides real-time display of receiver coil spatial position” (Kröger, Pouplier, & Tiede, 2008). While this system holds great promise, the Aurora was not ready at the time this study was conducted to be used as a form of visual biofeedback for speech therapy.

For this study, a Carstens AG-100 electromagnetic articulograph (EMA) was used to test if it could potentially be a new method of speech therapy for adults who are deaf or hard of hearing. EMA can be used either to record data from tiny electrodes that can be placed on the tongue, lip, or anywhere else on the face to analyze movement during speech or to give visual feedback on tongue placement through a computer display. The Katz lab at the University of Texas in Dallas (UTD) Callier Center has done extensive research on speech therapy with EMA for adults who have aphasia and Apraxia of Speech (AOS) and have lost much of their ability to articulate speech sounds (Katz, Bharadwaj, & Carstens, 1999; Katz, Bharadwaj, & Stettler, 2006; Katz, et al., 2007). Using EMA, participants with aphasia and AOS were able to improve their speech production on various target consonants and to generalize the therapy to other speech sounds (Katz, et al., 2007).

While adults with AOS and aphasia and adults with congenital deafness experience difficulty producing accurate speech sounds, they have two important differences. First, individuals who have AOS or aphasia have experienced a brain injury while adults who are deaf do not have these cognitive deficits. Second, adults with aphasia and AOS have good access to auditory input which they can use as feedback to guide vocal productions whereas adults who are deaf do not have that auditory feedback.

EMA provides a visual method of speech therapy consisting of a grid, a target circle, and a line displaying movement of the electrode that is attached to the tongue to use for feedback. Theoretically, it does not require auditory feedback from the user and could thus be a method of speech therapy similar to the visual therapy systems of glossometry and electropalatography.

While a promising method of speech therapy, EMA shares some of glossometry and electropalatography's weaknesses. Like the other systems, EMA is not widely available and is probably too invasive to be an effective method of therapy for children. EMA, however, has two great advantages over glossometry and electropalatography. One advantage is that EMA does not require the creation of a custom plate for each user. Not having to create custom plates eliminates a substantial financial burden and also widens its potential use to anyone without advance preparation. Another advantage is that while glossometry is effective for remediating vowels and electropalatography is effective for remediating consonants, EMA can be used to treat both vowels and consonants because it detects electrodes on the tongue as they move within the electromagnetic field without being constrained by the tongue's distance from or contact with the palate.

Purpose

This study was conducted to investigate whether the EMA system could be used to help improve the speech of adults with hearing impairment. The EMA system works by placing a small electrode on a speaker's tongue that allows him or her to see where his or her tongue is during speech on a computer screen.

Previous research in the Katz laboratory suggested that EMA training might be effective in improving speech produced by individuals with AOS resulting from strokes (Katz, Bharadwaj,

& Carstens, 1999; Katz, Bharadwaj, & Stettler, 2006; Katz, et al., 2007). Individuals with AOS have breakdowns in speech motor production, but intact auditory comprehension. In contrast, individuals with profound hearing loss have unimpaired speech motor control, with little or no access to audition. By studying the behavior of individuals who have limited access to hearing, it would be possible to address how visual feedback could be used to assist speech sound production, and whether auditory information is necessary to effectively use EMA, or whether visual information alone is sufficient. The information gained from this experiment will guide future intervention studies involving EMA, and may help improve methods for teaching speech to the deaf.

Methods

The project was reviewed and approved by the human subjects review board at the University of Texas in Dallas.

Participants

The research participant was a twenty-four year old woman with a severe congenital hearing loss who wore binaural hearing aids and communicated primarily through American Sign Language. She was recruited through the University of Texas at Dallas Callier Center and tested at the Katz lab in the University of Texas at Dallas Callier Center.

Five students with normal hearing were recruited from Washington University in St. Louis to listen to the speech sounds produced during the participant's session and report on their perception of the speech sounds.

Equipment

A Carstens AG-100 32-centimeter electromagnetic articulograph system was used to collect data on tongue apex, tongue dorsum, forehead, and upper incisors movement during speech. The EMA was calibrated with the EMA's Art8 program before the session to check electrode functioning. EMA's BioFeedBack V.2.1 program was used to obtain information and provide visual feedback for tongue placement during the session.

Torbot Bonding Cement was used as an adhesive for one electrode to the forehead while Iso-Dent was used to attach electrodes to the tongue and teeth.

A Sony NP-F330 video camera recorder was used to obtain an audio and visual recording of the session. The footage was converted to a WMV file with Windows Movie Maker and separate samples of the participant's speech were created using WaveSurfer.

Procedure

The participant was introduced to an interpreter and given a consent form describing the study. She was then asked questions about her hearing loss and communication mode. The participant was taken into the lab and asked to produce the vowels /i/, /u/, /æ/, and /ɑ/ and consonants /s/ and /ʃ/ for various conditions. During the study, vowels were produced between the phoneme /b/ as /bVb/ and the consonants were produced ending in the vowel /ɑ/ as /Cɑ/.

In the first condition, the participant produced each of the vowels and consonants twelve times as she would normally with her hearing aids on. For the second condition the participant took her hearing aids off and repeated the speech sounds again twelve times.

Next, the participant was connected with the EMA device. This began by placing EMA's 32 inch helmet on her head to create the electromagnetic field used to detect the electrodes. Then, four electrodes were attached to her face and mouth. Torbot Bonding Cement was used to attach one electrode to the participant's forehead and Iso-Dent was used to attach the remaining three electrodes to the participant's tongue dorsum, tongue apex, and upper incisors.

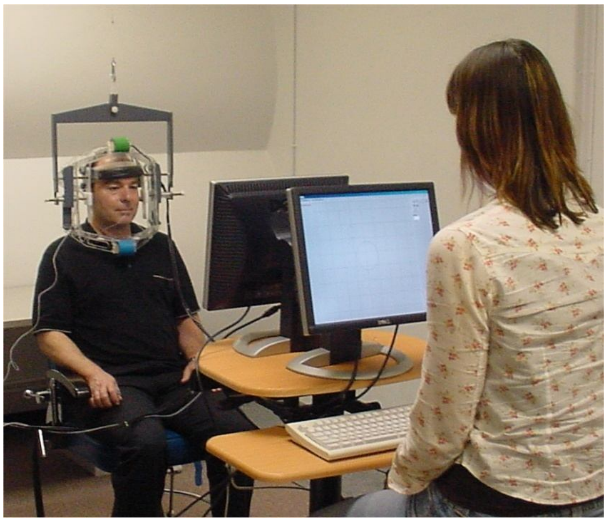

Figure 1A: A participant with AOS working with the EMA system.

For the third condition, the participant produced the same speech sounds twelve times each with the electrodes placed on her tongue. This was to determine if the electrodes' presence, rather than EMA feedback, would affect the participant's speech production.

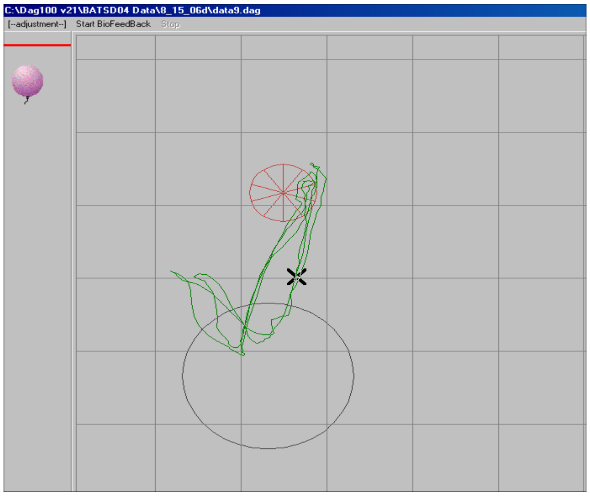

Figure 1B: Visual feedback a participant with AOS used to direct tongue movement.

In the fourth condition, the BioFeedBack V.2.1 program was used to provide visual feedback of the participant's tongue dorsum movement during speech production. The participant would produce the speech sound until a target region could be located and then the experimenter would move the target circle to the appropriate place on the grid for the participant to move her tongue to for correct production. The participant then produced the speech sound and hit the target circle for each sound forty times in two sets of twenty.

Due to the feedback program sometimes counting speech productions multiple times, counting tongue movements that hit the target region without speech, or not counting correct speech productions if the tongue did not hit the target region, the participant produced some of these speech sounds more or less than forty times. /i/ was produced thirty-one times, /u/ was produced 34 times, /æ/ was produced forty times, /ɑ/ was produced thirty-two times, /s/ was produced forty times, and /ʃ/ was produced forty-one times. All of these productions were included in the listener analysis, whether or not the target region was hit.

For the fifth condition, the EMA helmet and electrodes were removed and the participant was asked to produce each speech sound twelve times without her hearing aids.

Digitized speech samples were obtained throughout the session and later presented to five listeners with normal hearing who did not have extensive experience with individuals who have hearing loss. For conditions where the participant was asked to produce twelve speech sounds in a set, only the middle ten speech sounds were used for the listener perception analysis. In the conditions with twenty speech sounds in a set, all available speech sounds were used. While the participant was asked to produce the sounds /i/, /u/, /æ/, and /ɑ/ for vowels, the listeners were asked to choose whether the participant had produced /i/, /u/, /æ/, /ɑ/, or /ʌ/. For consonants, the participant was asked to produce /s/ and /ʃ/, but the listeners were asked to choose from /s/, /ʃ/, /t/, or /d/ as what they perceived the speech sounds to be.

Results

The digitized speech samples obtained from the session were presented to five listeners to determine how the participant's speech sounds would be perceived. For conditions in which the participant was asked to produce /i/, /u/, /ɑ/, or /æ/, listeners were asked to choose from /i/, /u/, /ɑ/, /æ/, or /ʌ/ as the vowel they perceived. When the participant was asked to produce /s/ or /ʃ/, the listeners were asked to choose from /s/, /ʃ/, /t/, or /d/ as the consonant they perceived. Percentages were calculated from the listeners' responses for their perception of each speech sound the participant produced.

Figure 2A: Hearing Aids On

Vowels participant said

Vowels listeners perceived		/i/	/u/	/ɑ/	/æ/
	/i/	**80**	4		
	/u/	20	**84**		
	/ɑ/		2	**86**	
	/æ/			2	**100**
	/ʌ/		10	12	

This confusion matrix shows the listener perception results of the first condition of the study. In this condition, the participant said four vowels (/i/, /u/, /ɑ/, and /æ/) in sets of twelve with her hearing aids on, before working with EMA. Five listeners were presented with each of the speech sounds the participant produced and asked whether they thought she was saying /i/, /u/, /ɑ/, /æ/, or /ʌ/. The results indicate that the majority of the participant's vowel productions were already understandable to inexperienced listeners. When the participant said /i/, the listeners correctly identified the production as /i/ 80% of the time, /u/ was correctly identified 84% of the time, /ɑ/ was correctly identified 86% of the time, and /æ/ was correctly identified 100% of the time.

Figure 2B: Hearing Aids Off

Vowels participant said

Vowels listeners perceived

	/i/	/u/	/ɑ/	/æ/
/i/	**100**	2		
/u/		**94**		
/ɑ/			**94**	**84**
/æ/				12
/ʌ/		4	6	4

This confusion matrix shows the results of the second condition of the study when the participant produced vowels in sets of twelve with her hearing aids off before working with EMA. As in the first condition, when the participant had her hearing aids on, listeners correctly perceived her productions of /i/, /u/, and /ɑ/ the majority of the time. There was a difference, however, in the listeners' perception of the vowel /æ/. When the participant said /æ/ with her hearing aids off, the listeners perceived her as saying /ɑ/ 84% of the time although they had correctly identified her /æ/ productions 100% of the time when her hearing aids were on. This suggests that the participant was affected by the lack of auditory feedback when her hearing aids were removed so that she began producing her /æ/ vowel as /ɑ/.

Figure 2C: Hearing Aids Off, Electrodes Attached

Vowels participant said

Vowels listeners perceived

	/i/	/u/	/ɑ/	/æ/
/i/	**100**			
/u/		**100**		
/ɑ/			**86**	
/æ/			4	**98**
/ʌ/			10	2

The results of the third condition of the study are shown in this confusion matrix. In this condition, the participant said vowels in sets of twelve with her hearing aids off and electrodes attached before working with EMA. The listener perception results of her speech productions resemble those found in the first condition when the participant had her hearing aids on as /i/, /u/, /ɑ/ and /æ/ are correctly identified the majority of the time by the listeners. Unlike the second condition where the participant also had her hearing aids off, /æ/ is identified as /æ/ the majority of the time instead of /ɑ/, with the only change being the attachment of electrodes to the participant's tongue. In this condition, EMA was not on and the participant was not yet receiving visual biofeedback. This suggests that the tactile sensation of electrodes glued to the tongue affected the participant's vowel production.

Figure 2D: Hearing Aids Off, Electrodes Attached, Visual Biofeedback On

Vowels participant said

Vowels listeners perceived		/i/	/u/	/ɑ/	/æ/
	/i/	**100**			
	/u/		**98.18**		
	/ɑ/			**96.67**	6
	/æ/				**93**
	/ʌ/		1.82	3.33	1

This confusion matrix shows the listener perception results of the fourth condition of the study when, the participant produced vowels in two sets of twenty with her hearing aids off and electrodes attached while working with EMA. These results resemble those found in the first and third conditions as /i/, /u/, /ɑ/ and /æ/ were correctly identified by listeners the majority of the time. It cannot be determined if the visual biofeedback improved the participant's speech production as listeners already correctly identified the vowels she produced the majority of the time in the third condition when she had electrodes attached to her tongue but was not receiving biofeedback.

Figure 2E: Hearing Aids Off, Electrodes Off, Visual Biofeedback Off

Vowels participant said

Vowels listeners perceived

	/i/	/u/	/ɑ/	/æ/
/i/	**100**			
/u/		**100**		
/ɑ/			**88**	52
/æ/			8	48
/ʌ/			4	

The listener perception results of the fifth condition of the study are shown in this confusion matrix. In this condition, the participant produced vowels in sets of twelve with her hearing aids off and electrodes off after working with EMA. Listeners correctly identified vowels /i/, /u/, and /ɑ/ the majority of the time as found in the other conditions. Different results were found when the participant produced /æ/, similarly to the results of the second condition where the participant's hearing aids were removed but she did not yet have electrodes attached to her tongue. In this condition, /æ/ was identified by listeners as /æ/ 48% of the time and /ɑ/ 52% of the time. As the only difference between this condition and the second condition is that this occurred after the participant worked with EMA, it seems possible that working with the visual biofeedback affected her vowel production.

Figure 3A: Hearing Aids On

Consonants participant said

Consonants listeners perceived

	/s/	/ʃ/
/s/	30	2
/ʃ/		98
/t/	30	
/d/	40	

This confusion matrix shows the listener perception results of the first condition of the study when the participant produced two consonants (/s/ and /ʃ/) in sets of twelve with her hearing aids on before working with EMA. The five listeners were presented with each of the speech sounds the participant produced and asked whether they thought she was saying /s/, /ʃ/, /t/, or /d/. Listeners correctly identified the participant as saying /ʃ/ 98% of the time but were not as accurate when responding to /s/. When listeners heard the participant say /s/, they identified it as /s/ 30% of the time, /t/ 30% of the time, and /d/ 40% of the time.

Figure 3B: Hearing Aids Off

Consonants participant said

Consonants listeners perceived		/s/	/ʃ/
	/s/	28	4
	/ʃ/		96
	/t/	26	
	/d/	46	

The results in this confusion matrix are for the second condition of the study in which the participant produced consonants in sets of twelve with her hearing aids off before working with EMA. Listeners correctly identified the participant as saying /ʃ/ 96% of the time but were not as accurate when responding to /s/. When listeners heard the participant say /s/, they identified it as /s/ 28% of the time, /t/ 26% of the time, and /d/ 46% of the time.

Figure 3C: Hearing Aids Off, Electrodes Attached

Consonants participant said

Consonants listeners perceived		/s/	/ʃ/
	/s/	8	2
	/ʃ/	30	98
	/t/	36	
	/d/	26	

In this confusion matrix the results are shown for the third condition of the study. In this condition, the participant produced consonants in sets of twelve with her hearing aids off and electrodes attached before working with EMA. Listeners correctly identified the participant as saying /ʃ/ 98% of the time but were not as accurate when responding to /s/. When listeners heard the participant say /s/, they identified it as /s/ 8% of the time, /ʃ/ 30% of the time, /t/ 36% of the time, and /d/ 26% of the time. In the previous two conditions, before the electrodes were attached, listeners did not perceive /s/ as /ʃ/, indicating a possible change in the participant's production of /s/ from the attachment of electrodes.

Figure 3D: Hearing Aids Off, Electrodes Attached, Visual Biofeedback On

Consonants participant said

Consonants listeners perceived	/s/	/ʃ/
/s/	33	0.5
/ʃ/	22.5	99.5
/t/	17	
/d/	27.5	

This confusion matrix shows the listener perception results of the fourth condition of the study in which the participant produced consonants in two sets of twenty with her hearing aids off and electrodes attached while working with EMA. The listeners correctly identified the participant as saying /ʃ/ 99.5% of the time but were not as accurate when responding to /s/. When listeners heard the participant say /s/, they identified it as /s/ 33% of the time, /ʃ/ 22.5% of the time, /t/ 17% of the time, and /d/ 27.5% of the time. While listener perception of the participant's /s/ improved from 8% to 33% in this condition from the last, it is the same as her production in the first and second conditions before EMA use and does not indicate improvement. As in the last condition when electrodes were attached to the participant's tongue, listeners still sometimes perceived /s/ as /ʃ/.

Figure 3E: Hearing Aids Off, Electrodes Off, Visual Biofeedback Off

Consonants participant said

Consonants listeners perceived

	/s/	/ʃ/
/s/	14	8
/ʃ/	22	88
/t/	30	4
/d/	34	

In this confusion matrix the results of the fifth study condition are shown when the participant produced consonants in sets of twelve with her hearing aids off and electrodes off after working with EMA. The listeners correctly identified the participant as saying /ʃ/ 88% of the time but were not as accurate when responding to /s/. When the listeners heard the participant say /s/, they identified it as /s/ 14% of the time, /ʃ/ 22% of the time, /t/ 30% of the time, and /d/ 34% of the time. Despite the electrodes being removed, listeners continued to perceive some of the participant’s /s/ productions as /ʃ/ which indicates a possible change from having experienced the tactile sensation of the electrodes.

Discussion

While the participant’s productions of the consonants /s/ and /ʃ/ and vowels /i/, /u/, and /ɑ/ were not greatly altered by working with EMA, some changes did occur in her vowel production of /æ/. When the participant first produced /æ/ with her hearing aids on, listeners perceived it correctly but when her hearing aids were removed, listeners perceived it as /ɑ/ the majority of the time. Interestingly, once the electrodes from EMA were glued to her tongue, the production if /æ/ was again perceived correctly by the listeners until the electrodes were removed after working with EMA. At this point, her /æ/ production was perceived half the time as either /ɑ/ or /æ/.

There are many possibilities for the difference in the participant's /æ/ production in the hearing aids off conditions before and after EMA use. Factors might be a tendency to change speech just after the loss of auditory feedback or a misperception or miscommunication of the vowel she was being asked to produce. Another difference could be from the vowels themselves as /i/ and /u/ are more distinctive from the other vowels used in this study and less likely to be confused whereas /ɑ/ and /æ/ are similar. Misperception by the listeners, however, does not seem a likely factor as all five had great accuracy in reporting the vowel the participant was producing when she had her hearing aids or the electrodes on.

One possibility is that the participant experienced a "white-coat" effect (Ogedegbe, 2008), improving in her production once the electrodes were attached simply because she was taking part in the study and was connected to a device that she knew could affect speech production. Another possibility is that this participant did not require any visual feedback at all, but was sufficiently aided by the tactile sensation of the electrodes on her tongue as her /æ/ production returned when she was producing vowels with the electrodes even without biofeedback.

While the data received from one participant is by no means conclusive, it does suggest an interesting possibility that visual feedback from devices such as EMA, glossometery, and electropalatography might not be necessary, but simple tactile stimulation on the tongue is enough to create awareness of a person's tongue movement and speech production.

The original intention of the study was to use the various electrodes to gain an accurate view of the participant's tongue movements during speech for later analysis but this data could not be obtained with the available software. Some visual information, while limited, was obtained on the participant's dorsum movement as it was used for feedback during the study.

Conclusion

Over the years, many methods of speech therapy have been developed that focus on visual feedback for individuals who are deaf or hard of hearing. While the results of this study are not statistically significant, they provide interesting data on how individuals who are deaf or hard of hearing can work with an electromagnetic articulograph.

The participant had very good speech to begin with that did not leave much room for improvement. All of the listeners were able to correctly identify the vowels she was trying to produce in almost every condition with the exception of /æ/ after the participant's hearing aids were taken off and when the electrodes were removed from her tongue after the EMA therapy. While there could be many reasons for this discrepancy, it raised the possibility that the tactile sensation of something small placed on the tongue could be enough to promote better speech production.

No problems were experienced by the participant during the course of the study and she was able to successfully navigate her tongue using EMA's visual biofeedback which suggests that other individuals who are deaf or hard of hearing could work with this device and potentially benefit from it as a form of speech therapy. The EMA system also advantages over glossometry and electropalatography as it does not require expensive custom plates to be made for individual users and can be used to remediate both vowels and consonants.

New areas of the field of visual feedback for speech production continue to be explored with computer programs such as Baldi and biofeedback devices such as the Aurora system. The

Baldi program is helpful to individuals with hearing loss as it enables users to visualize articulatory structures and observe the fine details of speech. The program also has the benefit of being cost effective, accessible, and noninvasive which makes it especially viable as a speech therapy tool for children. The Aurora system shows the most promise of succeeding as the latest, most advanced form of visual biofeedback for individuals who are deaf or hard of hearing. It appears more cost effective, less restrictive, and less invasive than glossometry, electropalatography, and electromagnetic articulography. As the Aurora is used in studies for speech therapy and analysis over the next few years, we may see great changes in how visual biofeedback will be used in the future to help individuals who are deaf or hard of hearing.

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