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Electropalatography and ultrasound in vowel remediation for adolescents with hearing impairment

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Abstract

The purpose of this study was to investigate the use of electropalatography (EPG) and ultrasound in the remediation of vowels in adolescents with hearing impairment. Three adolescents with severe hearing impairment participated in a 6-week vowel remediation programme using electropalatography (EPG) and dynamic two-dimensional ultrasound as adjuncts to speech therapy. Pre- and post-therapy speech productions were evaluated in terms of vowel formant values, EPG tongue-palate contact patterns and phonetic transcription. Notable changes were observed for all vowels across speakers, with most changes in the direction of the adult English targets. Transcription, acoustic and EPG tongue-palate contact results did not necessarily converge across vowels or speakers. Visual feedback as provided by EPG and ultrasound can be facilitative in promoting vowel development in adolescents with hearing impairment. Further research is required to evaluate the stability of changes, the relative impact of ultrasound and EPG and the relationship between phonetic transcriptions, tongue-palate contact and acoustic information about vowels.

Keywords: *Electropalatography, ultrasound, adolescents, hearing impairment, visual feedback, vowel intervention.*

Introduction

The present study investigated the use of electropalatography (EPG) and ultrasound imaging in vowel remediation for three adolescents with severe hearing impairment. There are relatively few reports on vowel development and remediation, possibly because vowels tend to be more quickly acquired than consonants, even by children with hearing impairment (Osberger & McGarr, 1982). However, several studies have reported vowel production difficulties in speakers with hearing impairment. Stoel-Gammon and Otomo (1986) noted that 8-month-olds with hearing impairment produced fewer vowel distinctions than age-matched hearing babies. In their study of 192 speakers with hearing impairment (aged 8–20 years), Hudgins and Numbers (1942) described a number of vowel mismatches: substitutions (their example, J*a*ne for J*o*hn), splitting of diphthongs into two separate vowels, diphthongization (their example, "do you" as "do-ee you-ee"), and nasalization. Using EPG, Dagenais and Critz-Crosby (1992) observed that the tongue movements and positions for vowels in 10 children with normal hearing differed significantly from those of 10 children with hearing impairment, with speakers with hearing impairment showing less vertical range, less distinctive between-vowel tongue shapes and more within-vowel variability than the hearing speakers. Ryalls and Larouche (1992) also observed greater variability in vowel production in speakers with hearing impairment.

Few studies have been conducted concerning vowel remediation in speakers with hearing impairment. Because the present study utilized visual feedback, only those studies evaluating visual feedback displays are discussed here. Most earlier studies evaluated the impact of acoustic displays on speech habilitation (treatment), reporting generally positive results (e.g., Boothroyd, Archambault, Adams, & Storm, 1975; Bridges & Huckabee, 1970; Houde, 1980; Stevens, Nickerson, & Rollins, 1983). Researchers have also used articulatory visual feedback in speech habilitation for vowels, using a number of different tools, such as, glossometry, ultrasound and EPG (e.g., Bernhardt, Gick, Bacsfalvi, & Ashdown, 2003; Fletcher, Dagenais, & Critz-Crosby, 1991; Fletcher, McCutcheon, Smith, & Smith, 1989; Klajman, Huber, Neumann, Wein, & Bockler, 1988; Shawker & Sonies, 1985; Tudor & Selley, 1974).

With glossometry, the client wears a custom-fit acrylic pseudopalate, much like a dental appliance,

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that has four pairs of light-emitters and receivers (diode photosensors). Hardware and software outside the speaker's mouth calculate and display distances between the tongue and the sensors during articulation. Fletcher et al. (1989) evaluated the use of glossometry in a 3-week study with a 12-year-old with profound hearing loss. After daily practice with the glossometer, the client showed greater differentiation of tense-lax vowel pairs, although tongue placement remained variable. Fletcher et al. (1991) targeted the four point vowels (/i, æ, u, ɑ/) in a 1-month (15–20 session) glossometry study with six students aged 4 to 16 years with profound hearing impairment. Results were mixed but suggested that glossometric feedback could facilitate improvement in tongue position and vowel accuracy.

To view tongue position and movements with ultrasound, an ultrasound transducer is placed against the underside of the chin, above the larynx. Dynamic two-dimensional ultrasound displays a series of relatively strong white successive images that approximate the tongue's position and movements on a screen in real time (see Figure 1). The images are a result of the refraction of ultrasound waves when they pass from tissue into air just above the tongue's surface. The transducer can be turned to allow imaging along either the mid-sagittal or coronal planes. In a study using two-dimensional ultrasound, Klajman et al. (1988) evaluated vowel remediation in 18 deaf children aged 8–17 years. One to four vowels were targeted per child for up to 10 minutes per vowel. Post-treatment, six children produced the vowels accurately, ten showed closer approximations and two showed no change.

EPG requires the user to wear a custom-fit pseudopalate. The palate contains electrodes that record the timing and location of the tongue's contact with the palate. This allows display of tongue-palate contact patterns for the majority of English lingual phones on a computer monitor (see Figure 2 and Gibbon, 2006, regarding Cleftnet UK). For vowels, EPG shows lateral tongue margin contact in the palatal and velar regions of the oral cavity. Lax vowels generally have less contact overall than tense vowels, and appear retracted in comparison (compare /u/ and /ʊ/ in Figure 2). The tense vowels are higher, and show a more advanced tongue root than their lax counterparts (compare /u/ and /ʊ/ post-treatment in Figure 2 for Purdy). Most EPG studies have focused on consonants. However, Bernhardt et al. (2003) targeted English high vowels in four adolescents with severe hearing impairment during three of 14 treatment sessions, using EPG or ultrasound independently in different sessions. Three participants showed significant gains in vowel production, although had not yet mastered the vowels.

The few studies using articulatory feedback for vowel remediation suggest that such feedback can have positive treatment effects. However, studies have been limited in terms of treatment time, participant number and evaluation measures. The present study was undertaken to investigate more in-depth the effects of EPG and ultrasound use in speech habilitation for vowel production in three speakers with hearing impairment by focusing only on vowels in treatment and by using three types of measures to evaluate results: phonetic transcription, acoustic analysis and EPG tongue-palate contact patterns. It was predicted that, post-treatment, vowels would be closer to the target acoustically, in terms of EPG tongue-palate contacts and in terms of phonetic transcription, with greater gains for trained than untrained vowels. Based on the Dagenais and Critz-Crosby (1992) study, it was expected that vowels might also show less variability post-treatment. Because none of the three participants had learned all high vowels, particularly the tense-lax distinction, these were treatment targets, with the lax vowel /ɛ/ being an untreated comparison target.

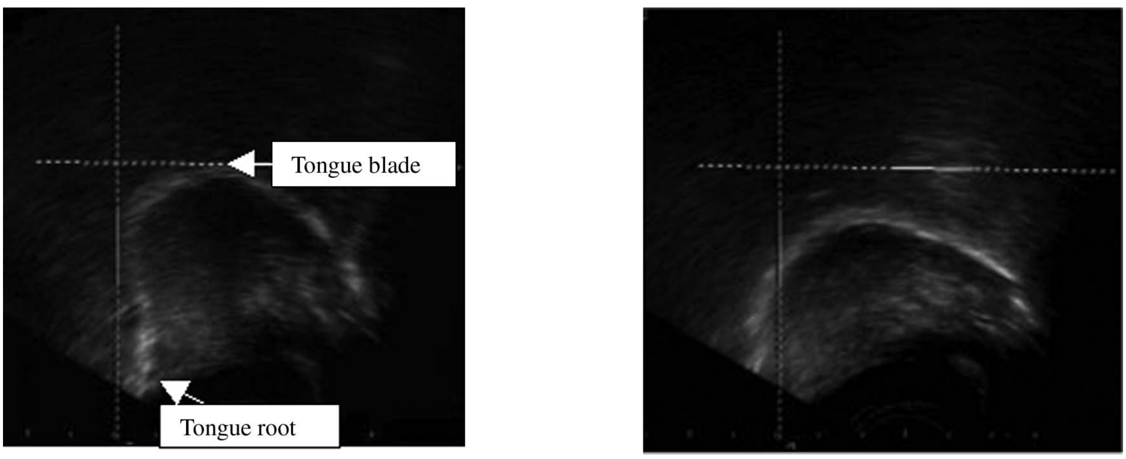

Figure 1. Mid-sagittal ultrasound displays of the English tense vowel /u/ (left), and /ʊ/ (right). The tongue tip is on the right of the image. Note the comparatively high tongue body and advanced tongue root of /u/ compared with /ʊ/.

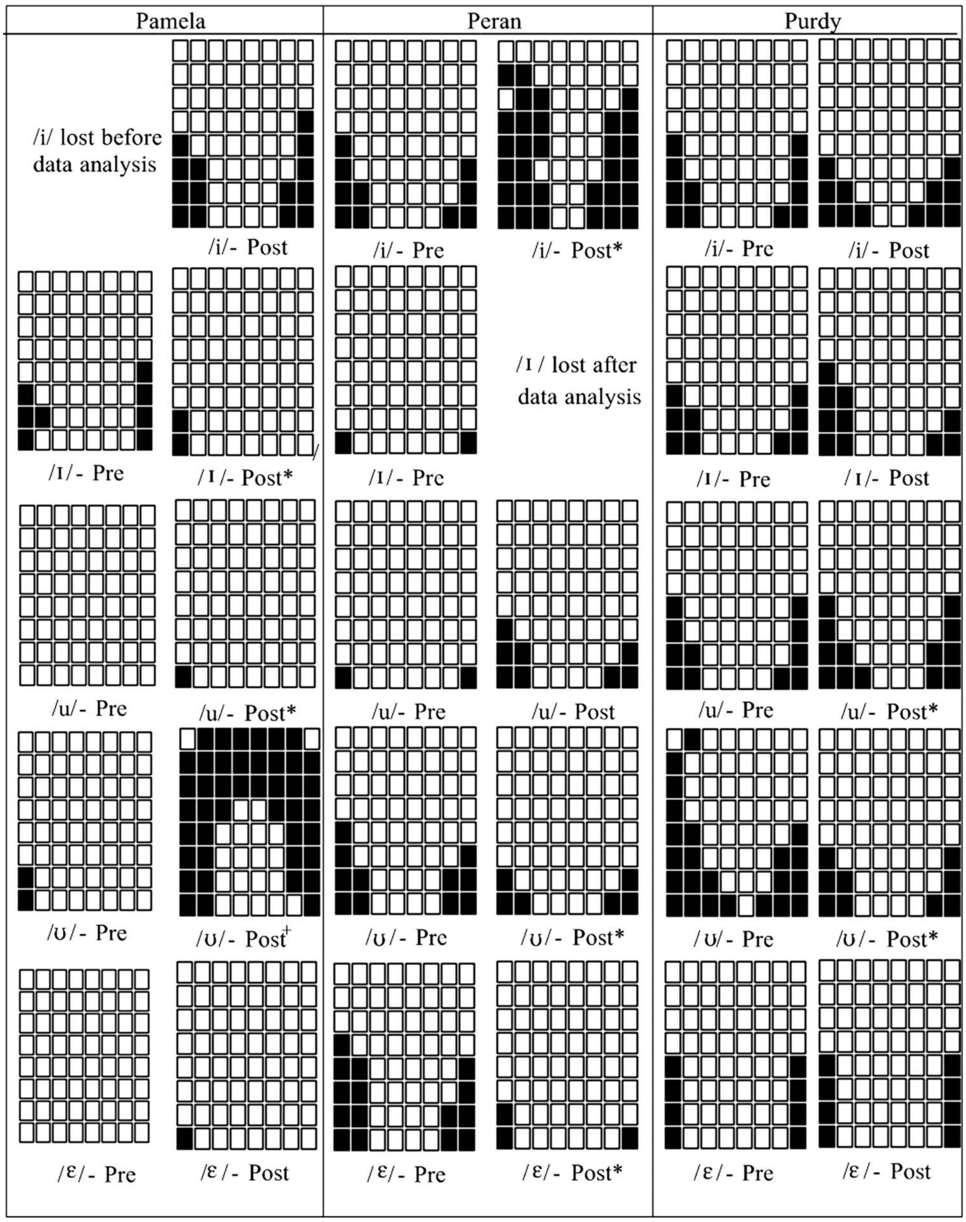

Figure 2. EPG contact patterns (black) for one sample vowel (maximum point) for each participant pre- and post-treatment. The upper two rows represent the alveolar region, the middle three rows the palatal region and the lower three rows, the velar region. * = notable improvement towards the adult target. + = notable change away from the adult target.

Method

Participants with hearing impairment

Three 18-year-olds from an oral programme for the deaf and hard of hearing participated in the study. All three participants (pseudonyms Pamela [female], Purdy [male] and Peran [male]) were diagnosed with severe- to-profound sensorineural hearing loss before the age of 2;6 years. Aided thresholds for the three participants were in the moderate to severe range (sloping downwards towards the high frequencies). Although all three participants came from families that speak English as a second language, only Pamela speaks the family's mother tongue. All participants speak western Canadian English, which is similar to Standard American English with the exceptions of (a) /u/, which is produced as a high round central vowel, (b) /ɔ/, which is produced only before the consonant /r/ and (c) the limited appearance of "Canadian raising" (in which the onsets of the diphthongs /aʊ/ and /aɪ/ become mid vowels when they precede voiceless obstruents). These students had participated in the Bernhardt et al. (2003) study, and thus were familiar with EPG and ultrasound. Pre-treatment transcriptions (Table I) by the first two authors showed relatively accurate production of /ɪ/ and /ɛ/ by Pamela, /u/ and /ʊ/ by Peran, and /ɪ/ by Purdy.

Reference speakers with normal hearing

Speech samples were collected from two young adults in the local area (one female, one male) to gain acoustic reference data. In addition, EPG data

Table I. Transcription ratings for electropalatography (EPG) and ultrasound (US) audio-recordings for all participants (Mean, SD).

		Pamela		Peran		Purdy	
Vowel	Tool	Pre	Post	Pre	Post	Pre	Post
i	EPG	n/a	n/a	2.3, .46	1.3, .23	2.9, .1	2.6, .49
	US	1.7, .48	1.4, .52	3.0, .0	2.4, .5	2.6, .1	1.7, .67
ɪ	EPG	1.2, .18	1.0, .0	2.7, .67	1.8, .66	1.0, .0	1.1, .1
	US	1.3, .7	1.0, .0	2.4, .97	1.3, .48	1.0, .0	1.0, .0
u	EPG	3.0, .0	1.6, .49	1.5, .67	1.1, .66	2.6, .47	1.8, .68
	US	2.6, .84	1.8, .65	1.0, .0	1.0, .0	2.7, .27	2.4, .49
ʊ	EPG	1.0, .18	1.3, .23	2.6, .5	2.0, .44	1.8, .18	1.3, .46
	US	2.0, .0	1.7, .48	1.0, .0	1.0, .0	1.8, .18	1.5, .28
ɛ	EPG	1.3, .23	1.8, .77	2.9, .1	2.9, .49	1.9, .84	1.5, .5
(un-trained)	US	1.3, .67	1.2, .4	2.6, .8	2.2, .91	2.7, .23	1.5, .72

Note: Vowels were pronounced in CVC words *heap*, *hip*, *hoop*, *put*, *pep* 10 times each in the carrier phrase *I'm a* ____. Transcriptions were coded using a three-point scale: 1 = phonetic match with adult target, 2 = phonemic match, 3 = non-match phonetically. Numbers represent averages and standard deviations over the 10 tokens.

were collected from one male and one female adult from the area. These data were collected as basic age-matched reference information for Canadian speech for the region, as recommended by Hillenbrand, Getty, Clark and Wheeler (1995), who note that speech production can change over a period of several decades and can vary by geographical region. The reference data are included in Tables III–V and represent the average of ten tokens for each vowel, a similar amount to that collected for the study participants.

Equipment

A WIN-EPG (2002 version) system was used for EPG assessment and training with a Dell Computer and Windows 1998. The WIN-EPG is designed for use on a Windows operating system and uses Articulate Assistant 1.10 as the built-in EPG software. Both the participants and their two SLPs had custom-fit artificial palates. Two kinds of ultrasound machines were used in the study. An Aloka Pro-Sound SSD-5000 ultrasound machine with a 6 MHz UST-9118 180-degree convex array EV transducer was used for both assessment and treatment. A portable Sonosite 180 Plus ultrasound machine with a Sonosite C15/4-2 MHz MCX convex array transducer was used only for treatment, i.e., when the larger machine was unavailable or when an ultrasound machine was taken to the participants' school. (The two machines provide very similar images.) Clarity of the image was enhanced on ultrasound by adjusting the range and gain (e.g., range of 11, gain of 60 on the Aloka Pro-Sound) and coating the transducer with water-soluble ultrasound gel. During EPG data collection, speech was audio-recorded using the WIN-EPG with a table-top Radio Shack microphone (model 33-3009) placed four inches from the mouth. During ultrasound data collection, audio and video data were recorded onto digital videotape using a Shure microphone (model SM58) placed 10 inches from the mouth.

General assessment and treatment procedures

Vowels were elicited in real CVC words collected pre- and post-treatment during both EPG and ultrasound data collection. Data were collected independently for EPG and ultrasound in order to reduce interference in speech production from having a simultaneous palate and ultrasound probe during assessment. This also provided a means to determine whether speech production would differ in the two conditions. Consonants in the words were chosen so as to limit co-articulatory influence on tongue position for the vowels (/h/, /p/, and in one case, /t/, as in *heap*, *hip*, *hoop*, *put*, *pep*). These monosyllables were produced in the carrier phrase *I'm a hoop*, which the participants could pronounce easily, and which contained a neutral vowel schwa as the last vowel before the vowel of interest. Each sentence was read ten times in a row, with the EPG palate in the participant's mouth for the EPG recording and with the ultrasound probe on a stand beneath the chin for ultrasound recordings. Sentence stimuli were not randomized in order to reduce the need to re-instruct the speakers frequently about the intended vowel target and to increase the speed of a very tedious task for speakers with a disability. (Unfortunately, the speech sample data for Pamela's pre-treatment /i/ were lost prior to analysis and, in addition, Peran's /ɪ/ data were lost due to technician error after analysis).

Treatment took place twice a week for 6 weeks, and was conducted by the first and second authors of the study, both certified speech-language pathologists (SLPs). One of the weekly treatment sessions was at the Interdisciplinary Speech Research Laboratory (ISRL) at the university for 1 to 1.5 hours, and the other 45-minute session took place in the participants' high school. The first author took the portable ultrasound into the school for some of the school therapy sessions. All sessions had some individual and some group instruction. Each session began with an awareness component, i.e., the participants were given phonetic instruction about the vowel quadrilateral, the differences between tense and lax vowels and the articulatory components of the vowel targets. The SLPs then demonstrated the vowels using either ultrasound or EPG separately, with both still and moving images. Each student was asked to explain the articulatory parameters of the vowel and the differences between his or her production and the target. The vowels were practised first in isolation and then in syllables, words and phrases, with focus on the tense-lax distinction within sessions, using for example, minimal pairs or functional vocabulary. Home practice with a family member or school assistant and without visual feedback was encouraged for targets achieved within sessions (although the homework was not completed each time by all participants). (For further information on treatment procedures, see Bernhardt et al., 2003, 2005a, b.) Following the treatment, acoustic, EPG and phonetic transcription analyses were conducted as described below. No ultrasound measurements were made, because of the difficulty in obtaining stable measurements for that technology (Stone, 2005). In addition, it was difficult to find an adequate method of head stabilization for the participants at the time of data collection.

Acoustic analysis

The audio-recordings of the vowels were transferred from the ultrasound recordings to a Macintosh computer using Adobe Premiere 1.0 (2004) as the video editing software and stored on the hard drive. Only ultrasound recordings were chosen for the acoustic analysis. Although there can be some noise from the scanner, it was considered that the ultrasound recordings might have less distortion than recordings using EPG pseudopalates. The waveforms of the vowels were extracted into Praat (version 4.2.05, Boersma & Weenink, 2005). Each vowel was analysed by a research assistant who had training on Praat and who was unconnected with the study. Vowel formant frequencies were obtained by first displaying the waveform of each vowel in Praat on the computer. Using the cursors from Praat, the target vowel was selected from each word and marked by hand. Once this was completed, Praat scripting was used to find the first three formants in each vowel. The 50% point was selected. All of the vowels were checked by the first author to determine that Praat scripting was accurate and that no incorrect formant choice had been made. Where discrepancies arose, these were corrected manually by the research assistant or first author. Average F1 and F2 values over the 10 tokens were calculated at each measurement location for each vowel pre- and post-treatment for the participants. Ten percent of all formant values were re-evaluated by the first author to assess inter-observer reliability. There was 85% exact agreement between the assistant's F1, F2 and F3 values and the first author's. Areas of disagreement (within a margin of error of 75 Hz) were primarily due to weak signals in several audio files, making formants difficult to see. Disagreements were arbitrated by a phonetician unconnected with the study.

For acoustic analyses shown in Figures 3–5, F2-F1 × F1 was plotted because this method is reported to be a better mapping to spatial locations in the oral cavity (Ladefoged & Maddieson, 1996).

EPG analysis

For purposes of tongue-palate contact analysis, the WIN-EPG analysis software (Articulate Assistant v1.10) was used. This system provides quantitative information on contact patterns in alveolar, palatal and velar regions (see Wrench, 2006, for more information). In general, the alveolar region represents the two upper rows, the palatal region, the middle three rows and the velar region the bottom three rows, with the black squares indicating tongue contact (see Figure 2). A second research assistant unconnected with the study extracted the target vowels, and selected the point of maximum tongue-palate contact. The numbers presented by the program were checked visually by the first author and research assistant with 100% agreement between observers. Average values were calculated for each vowel for each participant pre- and post-treatment.

Table II. Average vowel formant values for the three participants 10 months prior (from Bernhardt et al., 2003) and pre- and post-treatment, compared with values for two hearing adults.

Vowel	Pamela			Peran			Purdy			Hearing	Hearing
F1, F2	Prior	Pre	Post	Prior	Pre	Post	Prior	Pre	Post	female	male
/i/ F1	520	468	455	322	397	333	298	379	333	514	388
F2	2119	2470	2480	1968	1966	1859	2005	1776	1930	2964	2233
/ɪ/ F1	463	605	609	339	347	329	374	464	420	914	633
F2	2205	2101	2097	1943	1903	1868	1962	1716	1704	2251	1748
/u/ F1	576	430	503	314	389	450	316	356	346	621	435
F2	1222	1018	1055	989	962	940	1584	817	1118	1418	1165
/ʊ/ F1	539	607	648	322	424	448	301	367	461	708	507
F2	1131	1348	1299	932	1528	1615	1217	1430	1426	1796	1121
/ɛ/ F1	877	979	967	376	409	736	485	462	558	996	774
F2	1920	1875	1913	1989	1775	1519	1794	1534	1406	1942	1596

Note. The values listed from the two young hearing adults were collected in the Interdisciplinary Speech Research Laboratory at the University of British Columbia as local acoustic reference data.

In terms of reference data, velar contact for the hearing male EPG reference data showed the highest percentage for /i/ and /u/, followed by /ɪ/, with very little for /ɛ/ and /ʊ/. Vowels /ɪ/, /i/, and /u/ also had observable palatal contact, while /ɛ/ and /ʊ/ had none (see Tables IV – V).

Phonetic transcription

Speech sample data for transcription came from recordings conducted during both EPG and ultrasound assessments. Trained transcribers were used (the first and second authors of the paper), in keeping with the finding of Assmann, Neary and Hogan (1982), that untrained listeners can have orthographic and labelling difficulties in evaluating vowels. Although the two transcribers were also the SLPs for the study, bias was reduced by using Ladefoged's (2004) phonetic training CD as a reference for comparison with each of the vowels of the participants. Reliability between transcribers was 88%. Differences in transcriptions related to degree of /r/-colouring, raising, lowering, fronting or backing. Consensus transcriptions were arrived at by referring to the Ladefoged (2004) CD. These consensus transcriptions were then coded on a three-point scale for quantitative analysis (as opposed to a two-point measure indicating accurate versus inaccurate). The three-point scale (as utilized in Bernhardt et al., 2005a; Ertmer & Maki, 2000) provided a means to show partial matches with the target (a rating of "2"). A score of "1" reflected accurate articulation of the vowel (phonetically acceptable match). A score of "2" was given for broad transcription phonemic matching, i.e., narrow phonetic deviation was considered acceptable, e.g., /i/ realized as [ɪ]. A score of "3" indicated that the phone produced was not perceived as a match in eitherbroad (phonemic) or narrow (phonetic) transcriptions, e.g., /i/ -> [ɪ]. Average ratings were calculated for each vowel pre- and post-treatment for each speaker. Ultrasound and EPG transcriptions are reported separately because of concern that speech produced with EPG palates may sound more unnatural.

Results and discussion

Observations are presented and discussed within speaker, and then followed by a general summary. Note that Table II also includes acoustic data from the post-treatment recordings of a previous study (Bernhardt et al., 2003) as an indication of observable change over time across participants. These earlier data are for reference only and are not discussed in the current paper.

Pamela

All of Pamela's vowels except /i/ (for which EPG data were lost) showed change on some dimension in the present study, although no vowel showed changes on all measures. The most-improved vowel appeared to be /u/, which showed improvement in both transcription (Table I) and acoustic data (Table II). A scatter plot (Figure 3) mirrors the change in tongue position when measured with formants. The higher F1 post-treatment reflects movement of the tongue away from the central pre-treatment position. The EPG contact data, however, did not show notable change for /u/. Pamela's artificial palate appears relatively short (i.e., does not extend very far back into the oral cavity), meaning that the tongue-palate contact may not have been visible for post-treatment /u/.

For Pamela, limited changes had been expected for the lax vowels, because pre-treatment transcriptions showed a high degree of accuracy, and /ɛ/ was untreated. Minimal or no changes were noted in transcription or acoustics in accordance with that prediction, although EPG contact data showed notable change (see Table III and Figure 2). The /ɪ/

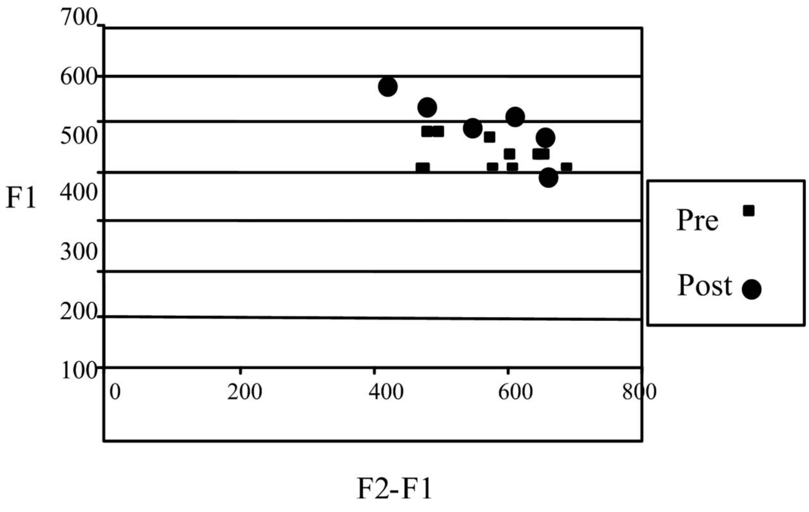

Figure 3. An acoustic plot of Pamela's /u/ (F2-F1 × F1). Note the higher F1 post-treatment.

Table III. EPG tongue-palate contact data for Pamela.

Vowel	Tongue contact area	Hearing female	Pre-Tx mean (SD)	Pre-Tx range	Post-Tx mean (SD)	Post-Tx range
/ɪ/	Palatal	.091	.034 (.026)	.0–.083	.0[a]	.0[a]
	Velar	.408	.433 (.074)	.25–.5	.185 (.089)	.083–.292
/u/	Palatal	.054	.0	.0	.0	.0
	Velar	.454	0.017 (.029)	.0–.083	.033 (.047)	.0–.125
/ʊ/	Palatal	.0	.0	.0	.731 (.123)	.583–1
	Velar	.142	0.046 (.041)	0–.083	0.496 (.172)	.375–.958
/ɛ/	Palatal	.0	.0	.0	.0	.0
	Velar	.167	.0	.0	.12 (.252)	.0–.083

Note: Palatal and velar contact numbers are mean maximum values for 10 pre- and 10 post-treatment (Tx) tokens. Vowels were analysed with WIN-EPG in words *heap*, *hip*, *hoop*, *put* and *pep* in the phrase *I'm a* ______. Data for /i/ were irretrievable. Reference data are included for one adult hearing female from the local area. [a]Based on nine tokens.

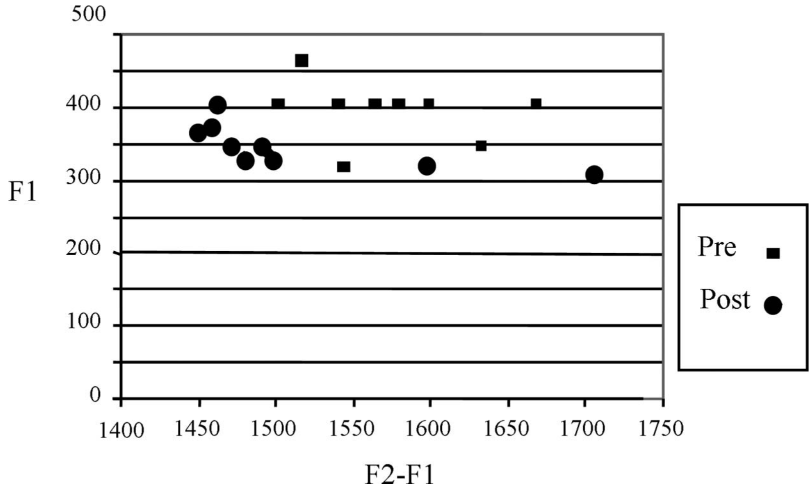

Figure 4. An acoustic plot of Peran's /i/ (F2-F1 × F1). Note the lowering of F1 and F2 and the reduced variability post-treatment.

Table IV. EPG tongue-palate contact data for Peran.

Vowel	Tongue contact area	Hearing male	Pre-Tx mean (SD)	Pre-Tx range	Post-Tx mean (SD)	Post-Tx range
/i/	Palatal	.375	.196 (.127)	.042–.417	.475 (.069)	.375–.583
	Velar	.692	.583 (.075)	.417–.667	.646 (.066)	.542–.75
/ɪ/	Palatal	.091	.233 (.123)	.083–.417	.258 (.101)	.167–.458
	Velar	.408	.546 (.079)	.417–.667	.454 (.108)	.333–.667
/u/[a]	Palatal	.054	.0 (.0)	.0	.004 (.013)	.0–.042
	Velar	.454	.170 (.127)	.042–.458	.314 (.065)	.125–.375
/ʊ/	Palatal	.0	.554 (.127)	.333–.708	.013 (.028)	.0–.083
	Velar	.142	.675 (.058)	.583–.792	.271 (.141)	.042–.05
/ɛ/	Palatal	.0	.188 (.087)	.125–.417	.208 (.076)	.083–.333
	Velar	.167	.375 (.1)	.25–.5	.375 (.098)	.25–.5

Note: Palatal and velar contact numbers are mean maximum values for 10 pre- and 10 post-treatment (Tx) tokens. Vowels were analysed with WIN-EPG in words *heap*, *hip*, *hoop*, *put* and *pep* in the phrase *I'm a* ______. Reference data are included for one hearing adult male from the local area. [a]Based on 11 tokens.

and /ɛ/ velar contacts and the /ɪ/ palatal contacts approximated the adult target more closely post-treatment, but the /ʊ/ contacts varied more from the adult target post-treatment. The tongue placement changes for /ɛ/ were negligible post-treatment, and may have reflected random variation, i.e., no generalization effect. Overall, for the front lax vowels, results were in keeping with expectations. For the back vowel, /ʊ/ pre-therapy, there was little or no EPG contact (similar to the adult reference participant) and the EPG recordings matched the adult target (rating of "1"). However, the ultrasound recordings showed deviation from the adult target (Table I), suggesting the vowel might show some post-treatment improvement overall. Post-treatment, changes in acoustics and transcription were insignificant, but there was a negative change in terms of EPG contacts; the consonant /t/ in the word *put* may have caused her tongue to move forward for the vowel as she was trying to make a difference in production.

The divergence in results between EPG contact patterns and transcription/ acoustic results occurred across all measurable vowels in Pamela's data. Contact pattern changes thus do not necessarily imply a change in the acoustic signal.

Peran

Peran showed change on some dimension (transcription, EPG, acoustic) across all vowels, with /i/ showing improvement on all measures. Among the front vowels, transcription data for both EPG and ultrasound recordings revealed notable changes for /i/ and /ɪ/ (see Table I) but not for the untrained vowel /ɛ/. Acoustic data (Table II) appeared to converge with transcription data for /i/ but not for /ɪ/ or /ɛ/. Figure 4 reflects the change in tongue position for the vowel /i/. The lowering of F1 reflects a higher tongue body and movement of the tongue away from a more central position as expected. In terms of EPG contact (see Table IV and Figure 2), changes in palatal and velar contacts were observed for only one front vowel (/i/) plus the two back vowels, /u/ and /ʊ/. Furthermore, less variability in range of contacts was seen for each of these vowels post-treatment.

Pre-treatment expectations were that Peran's front vowels /i/ and /ɪ/ would improve, with some possible generalization to the untrained vowel /ɛ/. Expectations were met for transcription and to a certain extent for acoustic and EPG data. Peran's high back vowels, which were considered accurate pre-treatment, were not expected to show much change. However, both back vowels did show change in EPG contact, in the direction of the adult target, although these changes were apparently not sufficient to trigger perceptible acoustic differences. Overall, Peran's formant data changed in the expected direction. The exceptions were F2 for /i/ and /ʊ/, which appeared to change in the opposite direction, which was surprising in that the transcriptions and EPG data for /i/ showed notable improvement. The decrease in variability post-treatment was also in keeping with pre-treatment predictions concerning vowels of the hearing impaired.

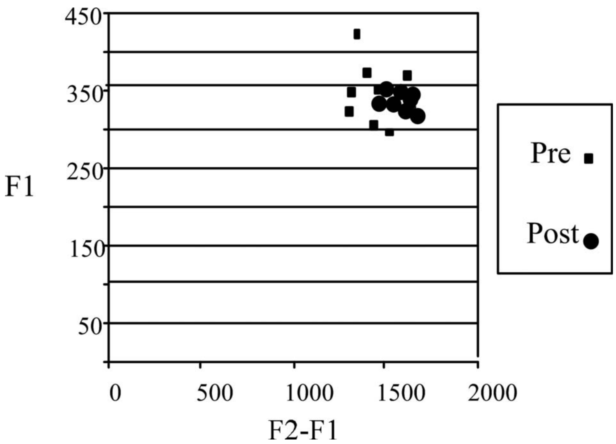

Figure 5. An acoustic plot of Purdy's /i/ (F2-F1 × F1). Note the change for F2 and reduced variability post-treatment.

Purdy

Purdy also showed positive change across vowels (see Tables I, II and V). Transcription data for both EPG and ultrasound revealed changes, but for different vowels. The EPG transcription data showed change in the direction of the adult target for the vowel /u/, while ultrasound transcription data showed improvement for /i/ and /ɛ/. Formant changes in trained vowels /i/ and generalization target /ɛ/ matched the direction of change in the transcription data. Figure 5 displays the change in F2 that reflects a change in position on the front-back dimension for /i/. Among the back vowels, /u/ changed less than /ʊ/ for the acoustic data.

For EPG contact data (Table V and Figure 2), all of the noted changes were in the direction of the male reference data except for /i/, which showed a trend in the opposite direction for both palatal and velar contacts. However, the acoustic and transcription data showed improvement for /i/, suggesting that Purdy could approximate the acoustic quality of /i/ with an individual contact pattern. Overall less variability of the contacts was seen for his vowels post-treatment.

In summary, few changes were expected for Purdy's vowel /ɪ/, which was relatively accurate

Table V. EPG tongue-palate contact data for Purdy.

Vowel	Tongue contact area	Hearing male	Pre-Tx mean (SD)	Pre-Tx range	Post-Tx mean (SD)	Post-Tx range
/i/	Palatal	.375	.025 (.029)	.0 – .083	.004 (.013)	.0 – .042
	Velar	.692	.525 (.040)	.458 – .583	.496 (.053)	.417 – .542
/ɪ/	Palatal	.091	.0	.0 – .0	.017 (.022)	.0 – .042
	Velar	.408	.441 (.029)	.417 – .5	.358 (.069)	.25 – .458
/u/[a]	Palatal	.054	.012 (.020)	.0 – .042	.0 (.0)	.0 – .0
	Velar	.454	.417 (.068)	.333 – .5	.242 (.068)	.125 – .333
/ʊ/	Palatal	.0	.079 (.633)	.0 – .208	.025 (.040)	.0 – .125
	Velar	.142	.467 (.122)	.292 – .667	.362 (.059)	.292 – .458
/ɛ/	Palatal	.0	.334 (.033)	.0 – .083	.029 (.02)	.0 – .042
	Velar	.167	.304 (.059)	.208 – .375	.221 (.048)	.167 – .333

Note: Palatal and velar contact numbers are mean maximum values for 10 pre- and 10 post-treatment (Tx) tokens. Vowels were analysed with WIN-EPG in words *heap*, *ship*, *hoop*, *put* and *pep* in the phrase *I'm a* ______. Reference data are included for one hearing adult male from the local area. [a]Based on seven tokens for *hoop* pre-treatment.

pre-treatment; change was observed only for EPG contacts, which were in the direction of the adult reference data, in keeping with expectations. Purdy's post-therapy productions of all other vowels showed expected change in terms of transcriptions, acoustics and in at least one tongue-palate contact change per vowel. The lack of similarity between Purdy's EPG contact patterns for /i/ and those of the adult reference speaker probably reflects the variability among speakers in terms of typical contacts for any target vowel. Purdy's productions post-therapy for these vowels, as expected, generally revealed less variability, although his production of /ɪ/ was more variable post-intervention in EPG contacts.

General summary

The current study was not designed as a comparison of EPG or ultrasound, but employed both equally, with the view that the complementary displays might be facilitative for vowel production. The 6-week study incorporating visual feedback did appear to have at least a short-term impact on the vowel production of the three adolescents (see Tables I–V and Figures 2–5). Eight of the 15 vowels (five vowels across three speakers) showed gains, which suggests that outcomes were not spurious, but were at least in part influenced by the treatment methodology. Quantitative and qualitative data collection is currently underway to determine whether gains in this study were temporary or stable.

In terms of individual vowels, /i/ showed improvement for all three speakers, with prominent gains for Purdy and Peran across all measures. For many speakers with sensorineural hearing impairment, vowels with high second and third formants such as /i/ are challenging; thus, the improvement for /i/ was noteworthy. All three participants also showed changes in EPG contact patterns for /ʊ/, although none of those changes matched transcription ratings or acoustic measures (except for F1 for Purdy). The untrained /ɛ/ generally showed less gains than other vowels across speakers, but this was not a remarkable difference. Overall, changes across vowels might reflect an increased awareness of the whole vowel space, and the need to use greater tongue movements in the oral cavity.

Variability in vowel production was noted to be another key issue for speakers with hearing impairment (Dagenais & Critz-Crosby, 1992; Ryalls & Larouche, 1992). In the present study, variability changes were noted for some vowels, usually in the direction of reduced variability post-treatment, another positive change, especially when coupled with improvement in accuracy.

Because the SLPs for the study were also the transcribers, it was important to have instrumental measurements undertaken by assistants external to the study, i.e., EPG and acoustic data, to compare with the phonetic transcriptions. For Peran, transcriptions accorded improvement to /ɪ/ whereas the other data did not confirm this, but for all other improvements noted in transcriptions across the three speakers, there were changes either acoustically or in terms of EPG, lending credibility to the transcription data. Some changes in EPG contacts and/or acoustic data did not reflect changes in transcriptions. Whether these were spurious, indicated incipient change or reflected real differences in evaluation methods cannot be known without follow-up studies. Differences among transcription, acoustic and EPG data have been reported previously. For example, Hardcastle, Gibbon and Jones (1991) reported that some speakers were able to produce consonants that were transcribed as accurate or near-accurate with tongue-palate configurations that were very different from typical productions. The use of different types of measures provided varying perspectives on the vowel production outcomes, with observation of possible subtle changes in EPG contact patterns that were not audible. However, more empirical studies are needed to learn about the articulatory and acoustic interactions of vowel production.

While EPG and ultrasound appear to offer valuable visual feedback, it is important to note that they are only one component of speech habilitation. Visual feedback cannot take the place of instruction based on knowledge of phonology and phonetics and speech-language pathology training and experience, but it does appear to show promise as an adjunct to treatment. Future clinical studies could vary the amount of type of time with and without different technologies to evaluate the effects of different types and intervals of treatment across different populations. Overall, the present case-based study suggests that further exploration of EPG and ultrasound is warranted, both independently and together, both to learn more about speech production from various perspectives, and to determine ultimate efficacy of such visual feedback approaches. Future research, eventually including randomized control trials may provide the field with more definitive answers on such technologies. In the interim, case data such as are presented here, provide insights into the potential of alternate treatments.

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