Influence of a Standard Electropalatography Artificial Palate Upon Articulation

A Preliminary Study

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Key Words

Electropalatography · Artificial palate · Articulation

Abstract

Objective: This study investigated the influence of a standard electropalatography (EPG) palate upon speech articulation in 3 normal speakers under standard EPG testing conditions. **Patients and Methods:** Three adult females aged 26, 31 and 34 years read the experimental phrase ‘say CV again’ 5 times under 3 experimental conditions: normal speech (without a palate in situ), 45 min after EPG palate insertion and 3 h after EPG palate insertion. Consonants and vowels commonly used in EPG research were studied and included /t/, /s/ and /f/ in the /i/, /a/ and /u/ vowel environments. Perceptual and acoustic analysis of the data was completed. **Results:** The results revealed varied patterns of adaptation across the 3 participants. Perceptual analysis suggested that 2 of the participants adapted to the presence of the palate; however, 1 did not. The presence of the palate resulted in significant changes to consonant duration for all 3 participants. Spectrally, production of /t/ was unaffected by the presence of the palate, while articulation of fricatives varied across the participants. **Conclusion:** Paired with a previous study examining the effects of an EPG palate upon speech

articulation [McLeod S, Searl J: Am J Speech Lang Pathol 2006;15:192–206], the present data suggest that researchers and clinicians alike should be aware of the potential perturbing effects of the palate.

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Introduction

Electropalatography (EPG) is now a relatively common approach in the assessment and treatment of speech articulation disorders, particularly in the UK and Australia. This technique has provided valuable insight into the tongue-palate speech articulation characteristics of both children [1–3] and adults [4–11] and has consistently resulted in positive treatment outcomes for children with articulation disorders [12–14]. Use of EPG requires that participants wear an individually moulded, acrylic artificial palate that resembles an orthodontic retainer. The artificial palate is approximately 1–2 mm thick and fits snugly against the contours of the hard palate, attaching via wires to the teeth.

When the artificial palate is initially inserted, most participants exhibit distorted speech articulation and/or increased salivation. It is generally accepted by EPG researchers that individuals require between 45 min and 3 h of desensitisation to adapt to the presence of the palate within the mouth [8, 15, 16]. However, EPG studies do not report detailed comparisons of speech articulation

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prior to, and following, artificial palate insertion. Generally, participants are considered to have *adapted* when (1) speech articulation is observed by the examining researcher to have returned to a similar level of articulatory precision as without the palate in situ and (2) excess salivation has ceased.

The lack of research data formally examining the perceptual and acoustic effects of the EPG palate upon speech articulation has attracted criticism. Weismer and Bunton [17] stated that 'the demonstrated influence of pseudo-palates on articulatory behaviour makes it difficult to evaluate the generalizability of findings from electropalatographic studies of speech production' (p. 2882). This seems a particularly pertinent issue as, in recent times, EPG has been used to make inferences about underlying speech motor control processes in healthy and neurologically impaired speakers [18]. Given the potential influence of the palate upon articulation, careful analysis of the effects of the appliance, both perceptually and acoustically, is required to ensure that valid interpretations can be drawn from the findings of EPG research studies.

A recent investigation has provided initial data to address the lack of research in this area. McLeod and Searl [1] examined adaptation to an EPG palate in 7 adult speakers of Australian English over a 5-hour period on day 1 (inclusive of 2 h with the palate removed) and a 3- to 4-hour period on day 2. Spectral and durational analyses were conducted on the consonants /s/ and /t/ during production of the phrases /ə ti/ and /ə si/. Spectral analysis revealed that initially, the palate negatively affected consonant articulation; however, articulation normalised following 60 min and 2 h adaptation for /t/ and /s/ respectively. There was no significant change to measures of consonant duration across time periods for either consonant. Perceptually, one expert rater (not blinded to the study purpose) completed 2 ratings upon listening to a counting (1–20) and short reading task. The rater was asked to provide a yes/no judgement in response to the question 'Is this person wearing an EPG palate?' and to rate speech naturalness and distortion on an 11-point equal interval scale. The findings indicated that impairment to speech naturalness and distortion was minimal; however, the expert rater was able to determine accurately that the participant was or was not wearing a palate in 76% of cases for the counting task and 81% of cases for the reading of the rainbow passage.

The study by McLeod and Searl [1] has provided a valuable first step towards improved understanding of the effect of standard EPG palates upon speech production. However, much remains to be examined. For ex-

ample, how do naive listeners perceive speech articulation with an EPG palate in situ? Such data are required for research to conclude that influences upon speech naturalness are minimal. Furthermore, a wider variety of consonants, including variation in place and manner of articulation, should be investigated to provide further confirmation of the minimal perturbing effects of the EPG appliance. Therefore, this study aims to extend the work of McLeod and Searl [1] and undertake detailed perceptual and spectral analysis of 3 individuals' articulation of /t/, /s/ and /ʃ/ across the conditions of normal speech (without the palate in situ) and the commonly used adaptation times of 45 min and 3 h.

Method

Participants

Three females aged 31, 26 and 34 years participated in the study. They are henceforth referred to as participant 1 (P1), participant 2 (P2) and participant 3 (P3) respectively. All exhibited normal dental occlusion and reported normal hearing and no history of neuromotor or speech disturbance. They were selected through previous participation in EPG studies conducted by the Motor Speech Research Centre, University of Queensland [4–6]. There were no special criteria for selection, only that individuals had not participated in an EPG investigation for a period of 2 or more years and were available for re-assessment using EPG. A period of 2 years was chosen to minimise the effects of any previous periods of adaptation to the appliance.

Data Collection

Nine CV words embedded within the carrier phrase 'say CV again' were repeated 5 times under 3 speaking conditions by each participant. Consonants and vowels commonly used in EPG research were studied and included /t/, /s/ and /ʃ/ in the /i/, /a/ and /u/ vowel environments. This resulted in 45 phrases per speaker for each speaking condition. The experimental stimuli were presented in random order across the 3 conditions.

The 45 experimental phrases were read and recorded at 3 speaking conditions: (1) normal speech (without the artificial palate in situ), (2) 45 min following the insertion of the palate, and (3) 3 h following insertion of the artificial palate. The participants were required to wear the artificial palate for the entire duration of data collection (approximately 3 h) and during this time were instructed to converse as much as possible while going about their daily work activities. Speech was recorded using a head-mounted microphone (Sony ECM-3 Electret condenser microphone) positioned approximately 5 cm from the mouth. The microphone signal was captured at a sampling rate of 44 kHz with a Sony Digital Audio Tape recorder. All testing was conducted in a sound-treated room under standard test conditions.

A custom-made artificial palate was worn by each of the participants. This palate was the standard EPG artificial palate employed in all investigations that use the Windows EPG system. Each palate was approximately 1–2 mm thick and was moulded to fit the contours of the hard palate. Two sets of wire clasps held

the palate in place on the roof of the mouth. The posterior wire clasps fitted over the molars and the anterior clasps were placed between the lateral incisors. Two sets of wires that ran along the outside of the teeth and out the corners of the mouth connected the artificial palate to a data interface and computer terminal.

Perceptual Analysis

A compact disc was generated containing a randomised presentation of the participants' productions of the experimental phrase. The compact disc consisted of a total of 405 stimuli with a 6-second period of silence between each production (9 phrases $\times$ 5 repetitions $\times$ 3 speaker conditions $\times$ 3 speakers). The recorded phrases were presented to 5 naive listeners, all females aged between 20 and 25 who were undergraduate students of speech-language therapy at the University of Canterbury, Christchurch, New Zealand. All naive listeners reported normal hearing.

The listeners were asked to complete a rating of the speech stimuli using a procedure similar to that of Weismer and Bunton [17]. The raters were instructed 'You will hear a series of repetitions of the phrase, say ___ again; please listen carefully and decide if you think the speaker is wearing an artificial palate or not, then place a tick in the appropriate column (yes/no) beside the phrase number'. Only the phrases with 80% inter-judge agreement (i.e. in which 4 out of 5 of the listeners responded similarly) were included in the analysis of results [17]. These were termed 'consistently' judged and amounted to 253 of the total 405 productions (63% of the total number of phrase recordings).

Acoustic Analysis

The CV portion of each phrase recording was subjected to acoustic analysis using a commercially available computer system (Kay CSL 4300B). These audio signals were digitised at a rate of 20 kHz, using 16 bits of quantisation. Measures employed previously in articulatory perturbation studies were used to determine the effect of the artificial palate upon speech production [17, 19]. The measures included were as follows:

(i) *Durational measures*: an amplitude-by-time display of the CV waveforms was employed in the analysis of all durational measures. For /t/, voice onset time (VOT) was measured from the beginning of the burst to the onset of periodicity associated with the subsequent vowel. For /s/ and /f/, duration was measured from the onset of frication noise to the beginning of periodicity for the subsequent vowel [19].

(ii) *Consonant spectra*: for /t/, /s/ and /f/ spectral analysis of the centroid frequency (M1) and kurtosis of the distribution (M4) was conducted [20]. These moments reflect the concentration and peakedness respectively of the spectral energy distribution during consonant production [20]. For determination of /t/ spectra, a 20-ms section of the consonant was selected beginning at the onset of the burst. Spectral analysis of /s/ and /f/ was completed using a 50-ms window as positioned at the midpoint of the consonant amplitude-by-time waveform. Spectral characteristics of each consonant were determined on the basis of long-term spectral analysis. The long-term spectral analysis display of each consonant was created through an averaging of individual Fast Fourier Transform computations performed every 23 ms across the entire duration of the consonant [21]. A full Hamming window was used.

Fig. 1. Percentage of repetitions judged correctly at the no palate condition, that is, the naive listeners correctly judged that participants *were not* wearing the EPG palate.

Reliability

Re-analysis of 20% (81 repetitions) of the acoustic data set was conducted for reliability purposes. To determine intra-judge reliability, the investigator who performed the initial measurements also performed the second set of reliability measures. To determine inter-judge reliability, an investigator not involved in performing the original measures performed the second set of reliability measures. Pearson's product moment correlations were conducted to test the reliability between the first and second set of measures. For intra-judge reliability, the correlation between the first and second set of measures for consonant duration was 0.998, with an average absolute between-measure difference of 1.95 ms. For M1 and M4, the correlation was 0.965 and 0.97, with average absolute differences of 189 Hz and -0.043. The correlation between the first and second judges for consonant duration was 0.996, with an average absolute difference of 5.62 ms. For M1 and M4, the inter-judge correlations were 0.972 and 0.95, with average absolute differences of 305 Hz and 0.64 respectively.

Statistical Analysis

Statistical analysis was completed using Friedman Repeated Measures Analysis of Variance on Ranks at $\chi^2 < 0.01$ (adjusted for multiple comparisons). Normality and homogeneity of variance could not be assumed; therefore, the non-parametric statistical test was chosen. Post-hoc analysis was completed using α -adjusted Tukey pairwise multiple comparison procedures at $p < 0.05$.

Results

Perceptual Analysis

Figure 1 shows the percentage of phrase repetitions, by consonant, correctly judged to have been spoken without the palate in situ during the no palate condition. As ex-

Fig. 2. Percentage of repetitions judged correctly at the 45-minute (a) and 3-hour (b) conditions, that is, the naive listeners correctly judged that participants *were* wearing the EPG palate.

pected, naive listeners correctly identified that the speakers were not wearing an artificial palate during the no palate condition. Only production of the consonant /s/ for P1 and P3 demonstrated any reduction from 100% correct judgment, though the percentage correct identification did not drop below 89%. Figures 2 and 3 contain the percentage of repetitions judged correctly and incorrectly at the 45-minute and 3-hour conditions. The results show that for P1 the naive listeners correctly identified that the participant *was wearing* an artificial palate at both the 45-minute and 3-hour conditions. These results indicated that P1 did not adapt to the presence of the artificial palate. In contrast, the results showed that P2 and P3 exhibited high levels of percentage incorrect judgement by the 3-hour stage. That is, the naive listeners incorrectly indicated that the participants were not wear-

Fig. 3. Percentage of repetitions judged incorrectly at the 45-minute (a) and 3-hour (b) conditions, that is, the naive listeners incorrectly judged that participants *were not* wearing the EPG palate.

ing a palate when they were. These results indicate that P2 and P3 likely adapted, perceptually, to the presence of the palate.

Temporal Analysis

Consonant Duration

Table 1 contains individual mean and grouped results for measures of consonant duration. Overall, P1 and P3 exhibited reduced durations at both the 45-minute and 3-hour conditions. In contrast, P2 demonstrated no changes across the conditions. Statistical analyses of the results confirmed these observations, with both P1 and P3 demonstrating a significant reduction in overall consonant duration following 3 h of adaptation ($p < 0.05$).

Analysis according to phoneme type indicated that P1 articulated the 3 consonants with a significantly reduced

Table 1. Means of durational measures in milliseconds for each participant for both individual sounds and collapsed across consonant

		No palate	45 min	3 h	χ^2	p
P1	/t/	103 (11) ^a	79 (14) ^b	86 (13) ^{a, b}	14.29	<0.001**
	/s/	204 (20) ^a	156 (15) ^b	167 (18) ^b	26.53	<0.001**
	/f/	209 (18) ^a	163 (14) ^b	174 (15) ^b	26.53	<0.001**
	overall	172 (52) ^a	134 (41) ^b	142 (43) ^c	66.18	<0.001**
P2	/t/	139 (9) ^a	116 (21) ^b	122 (9) ^b	12.40	0.002*
	/s/	215 (11) ^a	222 (13) ^{a, b}	228 (20) ^b	9.73	0.008*
	/f/	215 (21)	218 (19)	228 (13)	6.53	0.038
	overall	190 (39)	185 (53)	193 (53)	5.20	0.074
P3	/t/	100 (18) ^a	82 (11) ^b	82 (10) ^b	14.40	<0.001**
	/s/	186 (20)	197 (29)	180 (28)	4.13	0.127
	/f/	191 (19)	190 (19)	183 (14)	1.86	0.395
	overall	159 (46) ^a	156 (57) ^{a, b}	147 (51) ^b	11.64	0.003*

** p < 0.001; * p < 0.01. Overall = Mean and standard deviation values collapsed across consonant. For /t/, VOT was measured as an indicator of consonant duration. Means exhibiting different corresponding letters in superscript were statistically significant using α -adjusted post-hoc analysis at p < 0.05.

Table 2. Mean centroid frequency (M1) in hertz for each participant for both individual sounds and collapsed across consonant

		No palate	45 min	3 h	χ^2	p
P1	/t/	2,446 (1,439)	2,704 (1,367)	2,653 (827)	0.933	0.627
	/s/	8,528 (481) ^a	5,236 (1,433) ^b	4,961 (1,283) ^b	22.53	<0.001**
	/f/	3,893 (332) ^a	2,982 (858) ^b	2,944 (928) ^b	14.53	<0.001**
	overall	4,956 (2,766) ^a	3,641 (1,673) ^b	3,581 (1,462) ^b	22.91	<0.001**
P2	/t/	5,935 (651)	5,013 (909)	5,350 (1,002)	2.80	0.247
	/s/	7,598 (1,058) ^a	5,669 (1,802) ^b	6,666 (1,401) ^b	12.93	0.002*
	/f/	3,373 (330) ^a	3,691 (465) ^{a, b}	3,967 (452) ^b	12.13	0.002*
	overall	5,635 (1,901)	4,791 (1,434)	5,328 (1,500)	6.58	0.037
P3	/t/	3,192 (1,738)	2,376 (1,155)	2,334 (1,530)	5.20	0.074
	/s/	7,695 (1,175)	6,655 (1,339)	6,833 (1,645)	4.93	0.085
	/f/	3,467 (432) ^a	2,420 (905) ^b	3,463 (740) ^a	13.86	<0.001**
	overall	4,785 (2,409) ^a	3,817 (2,318) ^b	4,227 (2,370) ^{a, b}	13.14	<0.001**

** p < 0.001; * p < 0.01. Overall = Each participant's combined means across all consonants (i.e. 30 trials). Means exhibiting different corresponding letters in superscript were statistically significant using α -adjusted post-hoc analysis at p < 0.05.

duration 45 min after insertion (p < 0.05), with fricatives maintaining the reduced duration 3 h after insertion. P3 articulated /t/ with a reduced duration at both the 45-minute and 3-hour conditions; however, P3's fricative durations remained unchanged across the 3 conditions (p > 0.05). The results for P2 revealed variable patterns

of segment durations according to phoneme type. Significant reductions (p < 0.05) in the duration of both /t/ and /s/ were observed at the 3-hour condition. In contrast, the results for /f/ demonstrated a trend towards increased duration following both 45 min and 3 h of adaptation.

Table 3. Mean kurtosis of the spectral distribution (M4) for each participant for both individual sounds and collapsed across consonant

		No palate	45 min	3 h	χ^2	p
P1	/t/	2.37 (5.10)	0.60 (3.56)	-0.46 (1.51)	3.60	0.165
	/s/	7.45 (4.56) ^a	-1.19 (0.73) ^b	-1.29 (0.53) ^b	22.53	<0.001**
	/f/	1.29 (1.73)	1.15 (2.51)	1.18 (3.04)	5.20	0.074
	overall	3.70 (4.82) ^a	0.19 (2.69) ^b	-0.14 (2.26) ^b	24.14	<0.001**
P2	/t/	0.69 (1.60)	-0.74 (0.95)	-0.33 (1.43)	5.73	0.057
	/s/	1.05 (1.87) ^a	-0.82 (0.84) ^b	-0.14 (2.06) ^b	12.13	0.002*
	/f/	0.76 (0.92)	0.17 (0.52)	0.17 (0.69)	3.33	0.189
	overall	0.83 (1.49) ^a	-0.47 (0.90) ^b	-0.10 (1.48) ^b	18.98	<0.001**
P3	/t/	-0.11 (2.28) ^a	0.64 (2.07) ^b	1.93 (4.14) ^b	14.36	<0.001**
	/s/	1.31 (2.35)	0.02 (2.70)	1.33 (4.25)	3.60	0.165
	/f/	0.87 (1.22)	1.03 (2.02)	0.12 (0.37)	1.86	0.395
	overall	0.73 (2.04)	0.56 (2.27)	1.11 (6.44)	0.05	0.975

** p < 0.001; * p < 0.01. Overall = Each participant's combined means across all consonants (i.e. 30 trials). Means exhibiting different corresponding letters in superscript were statistically significant using α -adjusted post-hoc analysis at p < 0.05.

Spectral Analysis

Centroid Frequency (M1)

Table 2 contains individual and grouped consonant results for M1. Statistical analysis of the collapsed consonant data indicated that P1 demonstrated a significant reduction (p < 0.05) in M1 between the no palate and 45-minute conditions and that this reduction was maintained at the 3-hour condition (p < 0.05). Analysis of P1's individual consonant results revealed a significant reduction in M1 for fricatives (p < 0.05) at both the 45-minute and 3-hour conditions. P1's production of /t/ was unaffected with similar (p > 0.01) M1s observed across the sampling periods.

While, overall, P2 exhibited similar M1 values across conditions, fricative production was affected. Analysis revealed a significant reduction in M1 for /s/ at both the 45-minute and 3-hour conditions. However, a significant increase in M1 was observed for /f/ at the 3-hour period. For P3, M1 values appeared to reflect a process of adaptation with a significant difference overall between the no palate and 45-minute conditions (p < 0.05), yet no significant differences in M1 (p > 0.05) between the no palate and 3-hour conditions. This pattern was statistically significant for /f/ with a trend towards similar results observed for /s/. P3's data for /t/ were similar across the sampling periods (p < 0.01).

Kurtosis (M4)

Table 3 contains individual participants' mean and standard deviation values for kurtosis (M4) for both individual consonants and collapsed across consonants. Overall, a similar pattern emerged for P1 and P2, both of whom demonstrated a significant reduction (p < 0.05) in M4 at the 45-minute and 3-hour conditions. Similarly, when individual consonants were examined, both P1 and P2 exhibited significant reductions (p < 0.05) in M4 for /s/ when the no palate condition was compared with both the 45-minute and 3-hour conditions, indicating a reduction in the 'peakedness' of the spectral distribution. In contrast, the overall results for P3 revealed similar M4 values across the conditions. When individual consonants were examined, P3 exhibited a significant increase in M4 for /t/ (p < 0.05) at both the 45-minute and 3-hour conditions.

Discussion

Perceptual Analysis

The perceptual component of the study required the listeners to perceive the presence or absence of an EPG palate in speech samples. Presumably, if the speakers successfully adapted to the EPG palate, the listeners would be unable to perceive the presence of the palate. The results from the participants showed a clear delineation be-

tween P1 and both P2 and P3. In the case of P1, the results demonstrated that adaptation did not occur (perceptually) across /t/, /s/ and /f/ as the listeners correctly identified the absence/presence of the EPG palate with greater than 80% accuracy across all sampling periods. In contrast, both P2 and P3 were found to adapt to the palate, as evidenced by low percentage correct identification scores at 45 min and, in particular, 3 h after insertion of the palate. Overall, there was no clear pattern in regard to adaptation by consonant type for any of the participants. They were judged to have either adapted to the palate across all consonants types (P2 and P3) or not (P1).

The current finding that 1 of the 3 participants did not adapt to the presence of the palate compares favourably with the results of McLeod and Searl [1], who also reported that approximately one third (i.e., 2 of 7) of their participants exhibited poor adaptation (perceived as unnaturalness and articulatory distortion). Therefore, it appears that while the majority of individuals are able to adapt their speech to the presence of an EPG palate, some participants exhibit difficulty, or do not adapt, even following extended adaption time periods.

Temporal Analysis

The combined results of the temporal analysis for the 3 consonant types revealed the following major patterns: (1) the duration of consonant articulation generally remained either unchanged or decreased across the 3 sampling periods, (2) the durations of /s/ and /f/ were more variable than /t/, and (3) consonant duration at 45 min did not commonly differ significantly from the durations at the 3-hour sampling period.

Across all participants, VOT of /t/ decreased following insertion of the EPG palate. This result is consistent with previous articulatory perturbation studies that reported a reduction in both VOT [19] and stop gap duration [22] of /t/ upon insertion of thick and thin artificial palates. However, the present results do not closely align with those of McLeod and Searl [1], who reported no changes to stop gap duration preceding /t/ in their study of 7 speakers of Australian English. Although the measures are not identical, it was surprising to find dissimilar results. The long VOT values reported in the current investigation, ranging from 82 to 139 ms across the participants, most likely reflect the common finding of long VOTs among female speakers [23, 24]. Interestingly, the present study was confined to female speakers, while McLeod and Searl [1] considered 3 female and 4 male speakers. It is possible that gender differences across the 2 studies contributed to the differing results. Regarding

the current study findings of reduced VOT with palate insertion, 2 explanations are offered. Firstly, it is possible that adaptation to the palate may have been accompanied by increases in speaking rate, which would have resulted in a decrease in /t/ VOT at the 45-minute and 3-hour conditions. While speaking rate was not measured in the present study, this explanation appears unlikely as similar reductions in duration were not found for the remaining 2 consonants. Alternatively, it is possible that reduced VOT for /t/ reflects speaker-specific temporal adjustments undertaken to maintain the perceptual integrity of /t/ articulation.

The durational data for articulation of /s/ and /f/ was less consistent across the participants. P1 and P3 demonstrated reduced durations across the sampling periods, however not to the same extent as found for VOT. Conversely, P2 demonstrated a slight increase in /s/ and /f/ duration across time. It is possible that the variable consonant durations for /s/ and /f/ were related to the articulatory precision required for fricative production. Specifically, /s/ requires a complex lingual gesture to be maintained in the alveolar region [25], the point at which an EPG palate is often at its thickest. It is therefore possible that the individual variation observed reflects speaker-specific temporal adjustments undertaken as part of the adaptive process.

The findings of reduced /t/ duration and variable fricative durations demonstrate that the insertion of an EPG palate resulted in temporal articulatory changes for the 3 participants studied. While these durational changes occurred, it was obvious to the group of naive listeners that only P1 was wearing an EPG palate at the 45-minute and 3-hour conditions. Therefore, it is possible that each speaker made compensatory adjustments to consonant duration in an attempt to adapt to the presence of the EPG palate. P2 and P3 were successful in this undertaking; however, P1 was not. Further, it would seem that the temporal adjustments required to produce perceptually acceptable articulation may be participant-dependent, reflected through the variation observed across the participants in the current study.

Spectral Analysis

Clear patterns in the spectral composition of /t/ and /s/ were found across the 3 participants. However, individual variation existed for /f/ articulation. An adaptation continuum appeared to exist with /t/ least susceptible spectrally to the perturbing influence of the palate, followed by /f/ and /s/ respectively. Following 3 hours with the palate in situ, all participants generally articulated /t/

with similar centroid frequency and kurtosis of the spectral distribution compared to the no palate condition. The finding of a limited effect of the palate upon the spectral characteristics of /t/ was consistent with previous research [1, 19, 22]. In the light of the consistent reduction in the duration of /t/ across sampling periods, the lack of change in the acoustic spectrum would suggest that the palate has a greater influence on the temporal features of /t/ rather than its spectral features.

Similar to previous studies [1, 19, 22], the insertion of the EPG palate resulted in a reduced centroid frequency and greater spread of spectral energy across frequencies during /s/ production for both P1 and P2. These acoustic results are generally thought to be associated with a posterior shift in the place of articulation and shorter, wider fricative constrictions [26]. In contrast, P3 demonstrated little change to any spectral parameters of /s/ with the palate in situ. This lack of change would suggest that minimal articulatory changes were required to produce /s/ accurately with the palate in situ. Alternatively, if any strategic articulatory reorganisation was required for production of /s/, it was completed prior to the 45-minute assessment condition.

Given the pattern of spectral findings for /s/, it is important to consider why P1 and P2 exhibited changes in /s/ spectra, whereas P3 did not. While not directly measured in the present study, it was informally observed that P3 exhibited a wider and flatter hard palate than either P1 or P2, who both exhibited smaller mouths and a high palatal arch. The differences in structural morphology of the 3 participants may have allowed the individual with a greater articulatory space to articulate /s/ more easily in the presence of an EPG palate. In addition, the role of oral sensation in producing speech with an EPG palate in situ should not be overlooked. It is possible that a continuum of susceptibility to oral perturbation exists, with some individuals exhibiting heightened sensation and, therefore, poorer adaptive abilities or, alternatively, reduced (while still within a normal range) oral sensation resulting in greater adaptive ability.

The spectral results for /f/ varied across the participants; however, P1 exhibited the greatest changes in production, followed by P2, then P3. For P1, similar spectral findings for /f/ were achieved to /s/, likely indicating that strident fricatives, in general, were articulated with a retracted tongue position and/or wider fricative groove with the palate in situ. In contrast, the results for P2 were unusual, with the participant exhibiting a similar M1 for /f/ at the 45-minute condition compared to the no palate condition; however, a significant increase in M1 occurred

following 3 h of use. Finally, data for P3 revealed a significant decrease in M1 following 45 min, but similar spectral characteristics for /f/ following 3 h of adaptation. These results indicated that between the 45-minute and 3-hour conditions, some form of compensation occurred resulting in similar spectral distribution both with and without the palate in situ.

Conclusions

This study is 1 of only 2 to investigate the influence of a standard EPG artificial palate upon speech articulation. The findings of the study revealed that 2 of the 3 participants were perceived to have adapted to the presence of the palate. Corresponding acoustic analysis of the speech signal revealed changes to consonant articulation in the presence of the palate across all participants. In general, the majority of acoustic changes occurred at some point between the insertion of the palate and following the 45-minute sampling period.

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