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Title:

Gradient speech change during intervention for school-aged children and adults with cleft palate +/- lip

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Abstract

Gradient speech change, where speech sound production develops in a broadly step-wise fashion towards the standard adult form, is a well-recognised phenomenon in children developing typical speech, but is much less studied in speakers with developmental speech sound disorders. Instrumental techniques, such as electropalatography (EPG), may be useful for identifying gradient speech change and may supplement phonetic transcription in important ways. This study investigated whether gradient speech change occurred in six participants with cleft palate +/- lip undergoing intervention within a usage-based phonology framework (2/6 participants with speech distortions; 4/6 with pattern-based speech substitutions; combined total of 25 speech sounds targeted for intervention). Participants received weekly therapy in a hospital setting and were aged 10 – 27 years. Gradient speech change with target speech sounds was examined using EPG analysis which was undertaken after every fifth session of therapy. Presence of gradient change was determined by visually examining EPG palatograms and EPG indices for target speech sounds across successive EPG test points. This study found gradient speech change occurred in 22/25 target sounds over the course of intervention. This gradient change occurred for both speech distortions and pattern-based speech substitutions. The remaining 3/25 target sounds showed categorical change. Usage-based phonology was suggested as a theory with potential for explaining gradient speech change, with both typical and atypical speech, and with speech distortions and pattern-based speech substitutions. This finding adds to other research showing the objective data provided by instrumental techniques, such as EPG, may be a valuable complement to phonetic transcription.

Introduction

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Gradient speech change describes the gradual progression of an individual's pronunciation over time in the direction of the standard adult form (Bybee, 2001, 2010; Hewlett & Waters, 2004). Gradient speech change is a well-described phenomenon in young children developing typical speech (Smith & Kenney, 1999; Smith, 1973). For example, a young child's production of /s/ may progress, over time, from a [t̪͆], to [t], to [ts], then finally [s] (Smith, 1973). Along the way, variation in production is likely. For example, in successive attempts at a word, a child may realise /ʃ/ as [ç] or [s] interchangeably (Hewlett & Waters, 2004). Such variability may also include use of regressive and progressive phonological idioms (Ferguson & Farwell, 1975), that is, use of words that are consistently more or less advanced than what would be expected given a child's overall phonological system. Further, gradient speech change is likely to vary in its presentation from child to child (Hewlett & Waters, 2004; Smith & Kenney, 1999). While gradient speech change is well-identified in children developing typical speech, this phenomenon has received little attention in terms of assessment and treatment of individuals with speech sound disorder (SSD). We are aware of two previous studies considering gradient speech change in individuals with SSD. Glaspey and MacLeod (2010) demonstrated gradient speech change in a 3-year-old boy with "severe phonological disorder" over a course of intervention. Similarly, Cleland and Scobbie (2021) reported gradient speech change in five children with persistent velar fronting, aged 6 – 12 year, over a period of intervention.

Gradient speech change and dominant linguistic theory

A possible reason why gradient speech change has received less attention clinically is that dominant linguistic theory, as applied to speech and language therapy clinical practice, perhaps directs clinician's attention away from small phonetic variations in speech. Rather, attention is directed towards phonology and pattern-based speech errors. Since the 1970s and

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1980s, generative theory (Chomsky, 1968; Chomsky & Halle, 1968) has been influential in the understanding and treatment of SSD (McLeod & Baker, 2017; Williams et al., 2021). According to this linguistic theory, speakers are perceived to have abstract cognitive-linguistic knowledge that is, at least in part, innate and representative of the adult form (Chomsky, 1968; Prince & Smolensky, 1997). A series of fixed rules or constraints operate to convert this abstract knowledge to surface forms in an "all or none" manner, i.e. a rule is applied to all productions, or to none (Hewlett & Waters, 2004). Applying generative theory, children with SSDs are typically assigned to one of two broad groupings: those with difficulty with the physical production of speech/articulation impairment, and those with phonological impairment. The latter group is seen to make up the majority of individuals with SSD (McLeod & Baker, 2017). This group's speech is characterised by pattern-based errors, and their problems are attributed to difficulties with accessing and processing speech at a cognitive-linguistic level (McLeod & Baker, 2017). Such classification of SSDs has important implications for intervention. Those with articulation impairment are typically treated with articulatory and motor speech intervention approaches, such as traditional articulation therapy (Preston & Leece, 2021), while those with phonological impairment are commonly treated with phonological intervention approaches, such as minimal pair therapy (Baker, 2010).

For those children experiencing difficulty with articulation of speech sounds, one may predict gradient speech change as motor control for speech improves over time, or with practice. Recently, motor learning theory has been applied to the understanding of SSDs involving the motor production of speech (Maas et al., 2008). Schema theory (Schmidt, 1975) is the most commonly used motor learning theory applied to SSDs (Maas et al., 2008). Schema theory suggests that motor movement arises from generalised motor programmes (GMPs). GMPs are abstract structures, stored in memory, that identify the invariant parts of a set of motor

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movements. GMPs are adapted to meet specific task demands, including novel movements, through recall and recognition schemas. The schemas may be conceived as "rules" which operate to provide detailed instructions to the musculature. These schemas are refined by a positive and negative feedback system whereby errors in particular are used to develop and improve the schemas (Schmidt, 1975). This theory would therefore predict a progressive refinement of motor speech movements over time, and thus provides an explanation for gradient speech change in young children developing typical speech, or children with articulation impairment. However, as it exists, a limitation of Schema theory is that variability in speech is more difficult to account for given the all or none action of schemas.

For those children whose SSDs are attributed solely to difficulties at a cognitive-linguistic level, categorical change in speech sound production may be a prediction, given the systematic operation of rules and constraints theorised to underlie pattern-based errors. Cleland and Scobbie (2021) examined this prediction in an intervention study with five children with phonological impairment involving velar fronting, as cited above. Using ultrasound imaging, these researchers found that all five children with persistent velar fronting, aged 6;1 – 12;2 years, acquired /k/ in an articulatory gradient manner, rather than one-step categorical change. Consequently, in this study, participant's SSD difficulties were attributed to a combination of articulatory and cognitive-linguistic difficulties. More recently, generative theory has been expanded to account for cognitive-linguistic gradience (Bernhardt & Stemberger, 1998; Fanselow et al., 2006). For example, Bernhardt and Stemberger (1998) suggest phonological operations are subject to psychological processing, and that this psychological processing can lead to variance in production.

Speech sound disorders associated with cleft palate+/- lip

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Speech production difficulties associated with cleft palate +/- lip (CP+/-L) have traditionally been attributed to problems with the physical production of speech sounds due to the cleft condition, i.e. articulation impairment. Recently, motor learning theory has been used as the theoretical underpin for intervention with this client group (Hanley et al., 2023). Speech difficulties associated with CP+/-L have also been considered within phonological frameworks (Harding-Bell & Howard, 2011). Research and clinical experience shows that much atypical speech associated with CP+/-L involves groups of speech sounds which are seemingly produced in error in similar ways. Such atypical speech can be described using phonological patterns and include, for example, "backing" patterns, where sounds with anterior placement are substituted with sounds with more posterior placement, "non-oral substitution" patterns, where groups of oral pressure sounds are replaced by glottal and/or pharyngeal sounds, and where typical phonological patterns, such as stopping of sibilants, persist for longer (Chapman, 1993; Harding & Grunwell, 1996; Russell & Grunwell, 1993). It is suggested that such phonological patterns in cleft palate speech arise from the impact of structural anomalies on the young child's developing speech sound system, so that obligatory phonetic speech errors become integrated at a cognitive-linguistic level (Chapman, 1993; Harding & Grunwell, 1996). Further, successful treatment of structural deficiencies, for example, surgery to repair a cleft palate, or surgery to close an oro-nasal fistula, would not necessarily bring about typical speech. Rather, reorganisation at a cognitive-linguistic level may be needed (Hewlett, 1990). It is also suggested that some phonological patterns seen in children with CP+/-L may be akin to those children with phonological impairment of unknown aetiology (Chapman, 1993). Consequently, phonological approaches to treatment have been advocated and used with people with CP+/-L by some clinicians and researchers (e.g. Alighieri, Bettens, Bruneel, D'haeseleer, et al., 2020; Alighieri, Bettens, Bruneel, Sseremba, et al., 2020; Williams et al., 2021). If, as theorised by original generative theory,

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such phonological patterns are related to the operation of rules or constraints, once the child is stimulable for target speech sounds, categorical speech change may be a prediction with these pattern-based errors. To date, we are not aware of any research that has considered gradient speech change in individuals born with CP+/-L, either those with speech that can be described in terms of pattern-based speech substitutions, or those with speech distortions.

Phonetic transcription and instrumental analysis

Aside from theoretical considerations, another possible reason why gradient speech change has received less attention in the management of SSDs is that SLTs typically transcribe speech using broad phonetic transcription, rather than using narrow phonetic transcription (Knight et al., 2018). Consequently, SLTs may not identify small phonetic changes towards the adult form. Furthermore, even with narrow phonetic transcription, the precise nature of an articulation may be difficult for the SLT to detect. A number of instrumental studies report instances where SLTs phonetically transcribe a child's production of two phonemes as the same, but where instrumental analysis identifies differences in the articulation of each phoneme (see Gibbon & Lee, 2017 for a summary). Such occurrences are known as covert contrasts (Hewlett, 1988). As an example of this phenomenon, Gibbon & Lee (2016) describe the case of a 9-year old child with SSD where /s/ and /ʃ/ were both phonetically transcribed as [ɬ], but where instrumental analysis showed clear differences with tongue-palate contact for each phoneme. The assumption is that the child was attempting to signal differences in /s/ and /ʃ/, but these differences were not identified by the SLT through phonetic transcription. Given the apparent limitation of phonetic transcription, Lee (2021) advocates use of instrumental analysis to supplement phonetic transcription. However, in a recent study examining the speech of 39 children with cleft lip and palate, Cleland et al

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(2019) found similar error-detection rates in ultrasound-aided and traditional transcription, suggesting no significant advantage of instrumental assessment over phonetic transcription.

The current study used electropalatography (EPG) to examine changes with speech sound production in six individuals with SSD secondary to CP+/-L (including submucous cleft palate) undergoing intervention. EPG is an instrumental technique that provides visual information on tongue-palate contact for lingual speech sounds (Lee, 2021). Tongue-palate contact is identified by way of a custom-made plate containing sensors that is manufactured to fit snuggly to the roof of the mouth. The resultant tongue-palate contact is shown dynamically on a screen via a series of pictures, known as palatograms. Figure 1 shows the midpoint palatogram for a typical speaker with typical anatomy producing /t/. The black squares represent tongue-palate contact. The top of the picture represents contact in the alveolar region of the palate. This contact extends back to the velar region along the sides of the palate in a horse-shoe shaped pattern. This horse-shoe shape is the characteristic midpoint palatogram for /t/ for most typical speakers (McLeod & Singh, 2009). EPG palatograms can be examined at different points in time and changes with tongue-palate contact can be identified through visual analysis and numerical measurement (Lee, 2021). In this way, EPG may capture gradient speech change.

Insert Figure 1 about here

Aims

The main aims of the study were to investigate:

(1) whether or not gradient speech change occurred in six speakers with CP +/- L undergoing intervention using EPG analysis;

(2) whether or not speech change shown on EPG analysis varied with those speakers classified as having speech sound distortions compared to those classified as having pattern-based speech substitutions.

A secondary aim of the study was to examine:

(3) whether or not EPG assessment results would identify atypical lingual gestures not perceived by phonetic transcription alone.

Method

Participants

Six participants with persistent SSD related to CP+/-L undergoing weekly intervention at a regional cleft unit participated in this study. Participants' demographic information, main cleft speech characteristics, and target sounds for therapy is shown in Table 1. All participants had normal velopharyngeal function or mild signs of velopharyngeal incompetence on entry into the study. Individuals with sensori-neural hearing loss were excluded from this study. All participants had a history of mild to moderate conductive hearing loss. At the time of intervention, all participants' hearing was assessed as normal, apart from participant 2 who had bilateral moderate conductive hearing loss. For participant two, normal hearing was achieved with bilateral hearing aids, and aids were worn during intervention. All participants' SSD had been unchanged for at least 6-months prior to intervention. Participants were assigned as having either speech distortions or pattern-based speech substitutions using McLeod and Baker's (2017) definition of articulation impairment and phonological impairment (i.e. articulation = distorted sibilants and/or rhotics; phonological = pattern-based substitutions) (See Table 1). Participant one was classified as having pattern-based speech substitutions since the lingual sibilants /z, ʃ, ʒ, tʃ, dʒ/ were all

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realised with alveolar placement with lateral fricative airflow [ɬ, ɮ], resulting in loss of phonemic contrast, while /s/ was produced accurately.

Insert Table 1 about here

Intervention and assessment

Participants underwent weekly EPG therapy within a usage-based phonology framework. The usage-based EPG intervention technique involved high-volume, drill-based, speech production tasks, with a focus on single-word production. EPG visual feedback was used to facilitate articulatory production within single words. (Patrick et al., 2023). Participants' intervention involved three stages: 1). acquisition of speech targets in treated words, 2). lexical generalisation and, 3). functional generalisation, where speech was used in connected speech in all speaking settings. Participants were treated until all target speech sounds were produced typically, or very close to typical production, and until all target sounds achieved functional generalisation. EPG assessment occurred immediately prior to commencement of intervention, at the end of every fifth session of therapy, at completion of therapy and then 3-months following completion of therapy. In addition to EPG assessment, blinded phonetic transcription was carried out by two independent cleft-specialist SLTs prior to intervention, at completion of therapy, and on maintenance assessment, 3-months following completion of therapy.

EPG assessment

This study used the WinEPG system, Articulate Assistant software (Articulate Instruments Ltd., 2010), and Reading-style EPG palate (Wrench, 2007). EPG assessment involved reading speech stimuli. This speech stimuli included consonant-vowel (CV) sequences (pseudo-words) involving the English consonants /m, p, b, f, v, θ, ð, t, d, n, l, s, z, ʃ, tʃ, dʒ, k,

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g/. Each consonant was repeated 20 times, 10 times with the closed vowel /i/ (e.g. /ti/, /ti/…x10), and 10 times with the open vowel /a/ (e.g., /ta/, /ta/…x10). Simultaneous EPG and acoustic recordings were taken. One hundred palatograms per second were recorded. Participants' production of pseudo-words was later annotated by the first author from EPG and acoustic information using the "analyse" function of Articulate Assistant. Annotation differed depending on the manner of the consonant as shown in Table 2.

<u>*Insert Table 2 about here*</u>

Following this annotation, visual analysis of EPG palatograms and calculation of EPG indices was completed.

Visual Analysis

Cumulative EPG frames for target sounds were compared to EPG reference frames shown in McLeod and Singh (2009) and reference frames from the first author's own speech (i.e. frames from speakers with typical speech). Cumulative EPG frames were derived as follows: each frame of maximum contact for each CV repetition (up to 20 in total) was combined to produce one cumulative picture. The resultant cumulative pictures show percentage of contact for each EPG sensor by way of colour grading (see Figure 2). White squares show that tongue-palate contact never occurred during CV repetitions for the target sound (i.e. 0% tongue-palate contact), black squares show tongue-palate contact occurred with every repetition (i.e. 100% tongue-palate contact), while gradations of grey show percentages of contact between 0 - 100%. Cumulative pictures provide a display of variability in speech production at a particular point in time.

<u>*Insert Figure 2 about here*</u>

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Participants' cumulative EPG frames on initial assessment were described using the classification system developed by Gibbon (2004). EPG tongue-palate error patterns contained in this classification system include: increased contact; retracted to palatal or velar placement; fronted placement; open pattern; double articulation; increased variability; abnormal timing; and complete closure. The complete closure pattern affects lingual sibilants which are produced with an anterior tongue groove in typical speech. In the complete-closure pattern, no groove is seen; air is either directed around the lateral margins of the tongue (resulting in lateral production) or alternatively, no air is released from the mouth but rather air is directed through the nose (resulting in active/obligatory nasal fricative production).

In the visual inspection:

- If change is categorical, during intervention, we expected to see the patterns changing from one canonical palatogram shape at one point in intervention, i.e. typical velar shape to typical horseshoe shape, and then for this second canonical shape to remain stable.
- If change is gradient, we expected to see increased variability in the palatograms across intervention with gradual visual change in palatograms throughout intervention.

EPG indices

EPG indices reduce EPG data to single numerical values and selection of indices depends on the specific speech sound error (Lee, 2021). Table 3 outlines the speech sound errors evidenced by participants and the EPG indices used in this study (see Lee 2021 for a detailed description of EPG indices). The frame of maximal contact was used to compute all EPG indices.

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In examining the EPG indices:

- If change is categorical, during intervention, we expected the indices to increase/decrease (depending on the index) substantially at one point in intervention, and then to remain stable. "Stable" is defined as index values not increasing/decreasing by more than .05 points across subsequent testing points.
- If change is gradient, we expected variability with indices over the course of intervention with gradual increase/decrease in indices (depending on the index used), i.e. all variation not meeting the "categorical" criteria, as identified above.

<u>*Insert Table 3 about here*</u>

Phonetic transcription

Two independent cleft-specialist SLTs phonetically transcribed participants speech (single words) from video recordings prior to, at completion of therapy and 3-months following completion of therapy. The therapists were blind to assessment time-point. Speech was transcribed using narrow phonetic transcription using symbols of the International Phonetic Association (IPA) chart and its extensions (International Phonetic Association, 2015). Good levels of inter- and intra-rater agreement between listeners were shown (91.09%, 92.08 and 96.96% respectively).

Ethical approval

This study received ethical approval from the North-West-Greater Manchester East Research Ethics Committee (17/NW/0235).

Result

Speech change over the course of intervention

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Figure 3 shows cumulative EPG frames for target speech sounds in pseudo-words for each of the six consecutively treated participants, at each EPG assessment point during intervention. Likewise, Figure 4 shows EPG indices for each target sound in pseudo-words at each assessment time point. Number of EPG assessments differs for each participant as participants received varying amounts of therapy to achieve functional generalisation of target speech sounds. Participants 1, 3 and 5 outgrew their EPG plates during therapy. Consequently, EPG assessment was only possible for these participants while their EPG plates fitted. Intervention involved a total of 25 speech targets (participant 1 - 4 targets; participant 2 - 3 targets; participant 3 - 9 targets; participant 4 - 2 targets; participant 6 - 2 targets).

Insert Figure 3 and 4 about here

On visual EPG analysis (see Figure 3), gradient speech change was identified with 22/25 target sounds during intervention. For the two participants classified as having speech distortions (participants 2 and 5), 4/5 target sounds showed gradient speech change. Categorical change was shown with participant two's /tʃ/. For the remaining four participants classified as having pattern-based substitutions, 18/20 target sounds showed gradient speech change. Categorical change was shown with participant 4's /ʃ/ and participant 6's /n/.

Calculation of EPG indices (see Figure 4) over the course of therapy identified gradient speech change with 22/25 target sounds. For the two participants classified as having speech distortions, gradient speech change was seen for 4/5 target sounds. Categorical change was shown for participant 2's /tʃ/. In addition, it should be noted that participant 2's /z/ showed gradient change on the alveolar total (AT) index, while calculation of the centre of gravity (CoG) index for this target showed categorical change. Similarly, participant 5's /s/ showed gradient change on AT scores, while the CoG score for this speech target showed categorical

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change. While both these indices show change from posterior to anterior tongue-palate contact, these two indices are calculated differently. For the four participants classified as having pattern-based speech substitutions, 18/20 target sounds showed gradient speech change.   Categorical change occurred for participant 3's /d/ (AT scores) and categorical change was shown with participant 6's /n/ (AT scores). Categorical change was shown for participant 3's /s/ alveolar total (AT) scores, but not on the alveolar closure (AC) scores. These two indices measure different aspects of /s/ production, i.e. AT measures placement while AC indicates manner.

Comparison of EPG palatograms with phonetic transcription

Figure 3 shows EPG palatograms for all target sounds on assessment immediately prior to therapy, together with phonetic transcriptions for these sounds at the same time point, as blindly transcribed by two SLTs. Phonetic transcriptions did not match EPG palatograms for 14/24 target sounds, including 9/9 of participant three's target sounds, 3/5 of participant four's target sounds, and 2/2 of participant six's target sounds. Table 4 outlines the discrepancies between phonetic transcription and EPG palatograms.

Insert Table 4 about here

EPG palatograms broadly matched phonetic transcription at completion of therapy (P) and at maintenance (M) assessment. Following intervention, all target sounds were produced typically, or had moved in the direction of more typical production, as measured by phonetic transcription and comparison of EPG palatograms with reference frames of typical speakers.

In summary, study findings indicated gradient speech change over the course of therapy for most target speech sounds (Aim 1). Gradient speech change occurred for speech errors

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classified as speech distortions and with pattern-based speech substitutions (Aim 2). In this study, phonetic transcriptions did not always match EPG palatograms (Aim 3).

Discussion

The primary aim of this study was to examine whether or not gradient speech change occurred with six speakers with cleft palate speech undergoing intervention. Speech change was examined in two ways: 1). visual analysis of EPG palatograms, and 2). examination of change with EPG indices. In this study, a combined total of 25 speech sounds were targeted for intervention. According to our criteria for assessing gradient change (see methods section), gradient speech change was shown with 22/25 target sounds on EPG analysis. For the remaining 3/25 speech change was assessed as categorical. It should be noted that for 3/25 target sounds, EPG indices were at odds. All three target sounds were examined using two different indices (2/25 = alveolar total and centre of gravity; 1/25 = alveolar closure and alveolar total). For all three targets, one index showed gradient change, while the other showed categorical change. Since one index showed gradient change, and all were assessed as gradient on visual analysis, all three targets were classified as gradient in the overall reporting of results. Discordance with EPG indices can be explained by the fact that different EPG indices measure different aspects of tongue-palate contact (Lee, 2021). In addition, indices reduce data to single numerical values (Hardcastle et al., 1989). In this way, individual variability is potentially removed through such calculation, thus possibly explaining small differences in visual and EPG analysis. For this reason, visual analysis arguably provides a more sensitive measurement of type of speech change (i.e. gradient versus categorical), albeit this measure is more subjective.

Gradient speech change and dominant linguistic theory

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This study also examined if speech change shown during intervention varied with classification of SSD, i.e. speech distortions versus pattern-based speech substitutions. As discussed previously, dominant linguistic theory (generative theory), as applied in speech and language therapy intervention, may predict categorical, as opposed to gradient, change for those individuals classified with pattern-based speech substitutions (Cleland & Scobbie, 2021). This is because pattern-based speech substitutions are theorised as rule-based (McLeod & Baker, 2017). In the case of cleft palate speech, these rule-based patterns are seen to arise from the impact of an incomplete phonetic mechanism on a child's speech sound system at a cognitive-linguistic level (Chapman, 1993; Harding & Grunwell, 1996). In this study, 2/6 of our participants were classified with speech distortions, while 4/6 were classified with pattern-based speech substitutions. For the two participants classified as having speech distortions, 4/5 target sounds showed gradient change on EPG analysis. For the four participants classified as having pattern-based speech substitutions, 18/20 target sounds showed gradient speech change. Thus, the overall pattern was for gradient speech change across the course of intervention, regardless of error type. Categorical change did occur, but this was infrequent and occurred with both pattern-based speech substitutions and speech distortion. Thus, pattern-based speech substitutions did not respond to intervention in the way conceived by basic generative theory, i.e. categorical change in an "all or none" manner, once the participant was stimulable for a speech sound (though see further discussion below).

In this study, the overall pattern was for gradual change in palatograms and EPG indices over the course of intervention in the direction of more typical EPG patterns and indices. For some target sounds, gradual progressive refinement of targets was shown. For example, smooth trajectories for increases/decreases in EPG indices over time can be seen for all of participant one's target sounds and participant two's target sound /s/ (see Figure 4).

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However, for a number of other speech targets, although change was broadly in the direction of improvement over intervention, uneven trajectories are observed, for example, participant three's /z/ and /tʃ/ (see Figure 4). Such variability is perhaps more difficult to account for using schema motor learning theory. As discussed above, schema theory would suggest gradual progressive refinement of targets with progressive fine-tuning of schemas with practice over time (Schmidt, 1975).

As previously discussed, more recently generative theory has been expanded to account for cognitive-linguistic gradience (Bernhardt & Stemberger, 1998; Fanselow et al., 2006), such as the operation of psychological processing of phonological processes (Bernhardt & Stemberger, 1998). Such expansions of theory provide an account for gradience with pattern-based errors. However, it may be argued such extensions in theory lead to intricacies that make clinical application complex and make such expanded theories more difficult to test (Hewlett & Waters, 2004).

Usage-based phonology as an alternative theory to consider gradient speech change

Usage-based phonology theory (Bybee, 2001, 2010; Menn et al., 2013) is an alternative linguistic theory which may be useful for considering gradient speech change, in general, and in relation to the findings of this study. A particular strength of this theory lies with its elegant explanation of variance in speech sound development. Usage-based linguistic theory first emerged in the 1980's (Langacker, 1987) and describes an emergent model of phonology where an individual's speech sound system is seen to arise in a bottom-up way from listening and speaking events. To date, this theory has had relatively little clinical application (Patrick et al., 2023). According to usage-based phonology, at birth the mind is a blank slate. Listening and speaking events produce memories in the brain, and it is these memories that lead to first phonology (Vihman & Croft, 2007). Phonology is seen to develop progressively

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towards the standard adult form with subsequent listening and speaking events (and resultant memories), and the neurological associations made between these memories (Bybee, 2001).

Central to usage-based phonology is exemplar theory (Bybee, 2001). Exemplar theory proposes that individuals make category judgements by comparing new experiences with experiences already stored in memory (Nosofsky, 2011). Similar memory traces are grouped together, and a memory trace is more central or more marginal depending on the number and nature of shared features. Frequency of use will impact on the core of a category. The more frequent a memory trace, the more central that trace will become. However, the core of a category can shift, depending on the experience of the individual (Bybee, 2001). For example, a "word" will consist of all the motor/phonetic memories associated with the word. The core memory trace, i.e. the most frequently produced articulatory gesture, is the "exemplar". These phonetic memories will be associated with all the auditory memories of the word. In addition, these phonetic and auditory memories will be associated with the meanings of the word and the contexts in which the word has been used. Together all these related memories form an exemplar cluster (Bybee, 2001). The core exemplar for a spoken word will shift given the individual's motor control and speech experience. This flexibility of categorisation is used to explain how speech sound production can gradually change over time towards the standard adult model, as phonetic memories are grouped together to increasingly match the standard adult model (Bybee, 2001, 2010). Flexibility of categorisation also provides for explanations of variability and atypical instances within categories. For example, an articulatory gesture in a frequently used word may be more resistant to updating because the memory for the word is so entrenched with usage (Menn et al., 2013). Likewise, atypical speech may be strongly associated with a particular context, for example, speaking at home.

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Menn et al. (2013) considers phonological patterns observed in children developing typical speech from a usage-based phonology stance. The authors suggest patterns involving groups of speech sounds (e.g. velar fronting) may arise from neurological cross-representations. These authors suggest that each time a young child produces a word or hears a word, memories of other words with similar sounds or articulatory gestures are aroused to an extent. This neural arousal leads to neurological sub-networks. Such sub-networks become increasingly entrenched with usage and can subsequently lead to pattern-based realisations of similar sounds, e.g. where, in production, /k/ in new words is fronted to [t] in line with prevailing motoric patterns for /k/ in existing /k/ words. In the typically developing child, such pattern-based productions reduce and disappear with increasing motoric control of the speech articulators and with further exposure to listening and speaking events.

With usage-based theory, the mechanisms for speech change in adults are the same as for those in children, i.e. speech and listening events, and the cognitive association made following these events (Bybee, 2001, 2010; Menn, 2013). For example, Bybee (2001; 2010) uses usage-based phonology theory, as described above, to explain socio-phonetic speech change in typical adults over time. In this way, usage-based theory assumes continuity between adult and child phonology. The caveat to this adult-child continuity is that adults will have a greater number of memory traces onto which new speech experiences are compared and associated. Thus, speech change is predicted to be slower with increasing age (Patrick et al., 2023).

The findings of this study are consistent with usage-based phonology and exemplar theory, in so far as gradient speech change occurred for most speech targets for both school-aged children and adult participants. The presence of pattern-based speech substitutions is consistent with Menn et al's (2013) theorisation of speech patterns using usage-based phonological theory and may perhaps explain the finding of categorical change with some

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target sounds in pseudo-words in this study. Further research is needed to examine if the findings of this study can be replicated with larger numbers of individuals with cleft palate speech. Usage-based phonology and exemplar theory is also consistent with the general view regarding of the phonological features observed in cleft palate speech, as discussed above. That is, atypical and prolonged pattern-based speech substitutions arise from the impact of an incomplete phonetic mechanism on the child's developing speech sound system (Chapman, 1993; Harding and Grunwell, 1996). Moreover, usage-based theory provides a detailed psycholinguistic explanation of the nature of this bottom-up impact on the speech sound system, and provides an alternative to generative theory and motor learning theory. Application of usage-based theory in the treatment of cleft palate speech would suggest a focus on motor-phonetic production for both speech distortion and pattern-based speech substitutions.

Phonetic transcription and instrumental analysis

This study's secondary aim was to compare EPG assessment results with phonetic transcription with the prediction that that EPG assessment would identify atypical lingual gestures not perceived by phonetic transcription alone. Independent SLTs' phonetic transcription did not match EPG palatograms on assessment prior to intervention for 12/25 speech sound targets. The most striking disagreements occurred with participant 3 and 6. On assessment prior to intervention, one independent SLTs transcribed participant 3 's /s/, /z/, /ʃ/, /tʃ/ and /dʒ/ as palatal ([ç], [ʝ]), while the second independent SLT transcribed these speech sounds as lateral fricatives ([ɬ], [ɮ]). Similar listener differences in phonetic transcription of these lingual fricatives are described by Sell et al. (2009) and Chapman et al. (2016). Thus, these lingual sibilants appear more difficulty to assess in terms of placement and manner using phonetic transcription. Participant 3's EPG assessment prior to intervention provided an answer to this listener disagreement. EPG assessment showed a consistent retracted

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pattern to velar with lateral airflow. Lateral airflow was determined given EPG patterns of complete closure and accompanying fricative noise heard and seen on the spectrogram. Aside from potential for inappropriate phonetic cueing in non-instrumental therapy, such discrepancies have implications for reporting speech outcomes. In the UK, backing of anterior speech sounds to velar placement are categorised as “posterior cleft characteristics” while lateral and palatal production of lingual sibilants are categorised as “anterior cleft characteristics” (Sell et al., 1999). Posterior cleft characteristics involving three or more consonants represent an unsatisfactory outcome, while anterior cleft characteristics are viewed as more minor speech errors (John et al., 2006). In the UK, the Cleft Audit Protocol – Augmented (CAPS-A) uses a traffic light system to report national cleft speech outcomes. Green is used when speech is typical, light green is given to very minor distortions with speech production, yellow is given to cleft speech characteristics requiring speech therapy intervention or monitoring, and red represents an unsatisfactory speech outcome with need for intervention (John et al. 2006). With phonetic transcription only, participant 3 would be assigned a yellow outcome for errors with lingual sibilants. In contrast, EPG assessment would assign a red outcome for this participant’s lingual sibilant productions.

On assessment prior to intervention, independent SLTs’ phonetic transcription of participant 3’s /t/, /d/, /n/ and /l/ also did not consistently match EPG analysis. These speech sounds were at times transcribed as correct, while EPG assessment showed these sounds were never produced correctly. In a similar manner, the independent SLTs phonetic transcription of participant 6’s /n/ and /l/ showed that these listeners transcribed these phonemes as correct. However EPG analysis pre-therapy showed all productions of /l/ and /n/ in pseudo-words were retracted to velar placement for this participant. This suggests these phonemes with alveolar placement were more difficult to transcribe accurately with phonetic transcription, in terms of placement, given the listening conditions of this study. For participant 6, double

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articulation of /n/ (/n/ → [n͡ŋ]) was evident at times on EPG analysis, and this may have made phonetic transcription more difficult in terms of identifying phonetic placement. With regard to /l/, phonetic transcription may be more difficult due to reported variability in typical production of this phoneme. Magnetic resonance imaging and EPG data shows production of /l/ can vary dependent on word position and on the speaker (McLeod & Singh, 2009; Narayanan et al., 1997).

In this study, the transcribing SLTs used narrow phonetic transcription. Despite this, small changes with articulatory placement, as identified by visual analysis of EPG palatograms, were often not identified with phonetic transcription (see Figure 3). This finding is in contrast to a study by Cleland et al. (2019), as cited previously. These researchers examined the speech of 39 children with cleft lip and palate using ultrasound and traditional phonetic transcription (Cleland et al., 2019). In this study, ultrasound aided and traditional transcriptions showed similar error-detection rates, suggesting no significant advantage of this instrumental assessment over phonetic transcription. However, in the ultrasound study, errors identified by the transcribers were collapsed and classified into eight different sub-categories, potentially removing any small differences between ultrasound and phonetic transcription.

In the present study, small differences with phonetic transcription and EPG analysis may have been because the SLTs were insufficiently trained in narrow phonetic transcription to identify small differences with speech production. Alternatively, or in addition, it may be identification of small differences with production, as identified by EPG, were beyond the SLTs' capacity for perception. Limitations with human speech perception are suggested by instrumental studies identifying covert contrasts, as discussed above. However, research by a number of authors suggests SLTs do, in fact, have capacity to detect small sub-phonemic differences (Munson et al., 2010; Munson et al., 2012; Strombergsson et al., 2015). These

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researchers used visual analogue scales (VAS) to measure "target likeness" or "prototypicality" of children's' speech productions. Using VAS, these researchers found experienced and student SLT were able to identify small phonetic differences in the speech of children, and these differences were of the sort found in convert contrasts. These researchers pointed out that a shortcoming of phonetic transcription in that listeners are restricted to making a categorical choice when selecting transcription symbols. In comparison, VAS involve continuous measurement and thus appear better suited to identifying very subtle phonetic differences. However, a limitation with VAS is that they do not provide information of the source of a phonetic difference, for example, difference in place of articulation (Gibbon & Lee, 2017). Consequently, as they currently exist, VAS may be of less use clinically in the treatment of SSDs. Instrumental techniques, such as EPG, therefore appear important methods for providing information on the articulatory features underling small differences with speech sound production, and for the measurement of gradient speech change.

Limitations

Usage-based phonology was used as the theoretical rationale for the intervention received by participants in this study. As described above, gradient phonetic speech change is a key component of usage-based theory. Consequently, as with some other motor-based therapies (Bernthal et al., 2013; McLeod & Baker, 2017), during this intervention, gradient speech change was encouraged. However, in this study such encouragement involved large, phonemic, changes with speech sound production, rather than the small phonetic changes typically seen with participants' production on EPG (e.g. in the case of participant three, instruction was for anterior as opposed to posterior tongue-palate contact during this participant's remediation of /t/, /d/, /l/ and /n/). In addition, even when therapy produced speech sound productions that were judged by the treating SLT as accurate perceptually,

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subtle gradient change continued to occur during the functional generalisation phase of therapy for some participants (e.g. participant two's /s/ and /z/, and participant three's /t/ and/d/). However, it is possible that more categorical change may have occurred had intervention included phonological intervention tasks, such as minimal pair therapy tasks (Baker, 2010). In this intervention, at no time were generative-type phonological interventions used. Rather, all teaching episodes involved drill-based speech production.

In this study participants' palatograms for speech sound targets were compared to palatograms from typical speakers. However, caution is needed when comparing tongue-palate contact with that shown by speakers without CP +/- L. This is because the structure of the palate will be affected in individuals with the CP+/- L. At present little normative EPG data exists for individuals born with the cleft condition, though some preliminary work has been done by Yamamoto (2020). Yamamoto found tongue-palate contact patterns for Japanese speakers with unilateral cleft lip and palate matched those of typical speakers, and the matching occurred for a range of speech sounds. Nevertheless, caution with comparing speakers with the cleft condition with typical speakers is highlighted by participant five in this study. On assessment at the end of 15 sessions, this participant's EPG palatograms for /s/ and /z/ did not match the reference frame of the typical speaker. Examination of these palatograms alone would suggest a degree of palatalization with participant five's production of these sounds. However, at the same assessment point, narrow phonetic transcription judged these sounds as [s̪] and [z̪]. Thus, for this speaker, this less typical tongue-palate placement produced a broadly typical /s/ and /z/. This participant had a posterior crossbite which may explain her less typical tongue-palate placement. A further limitation of this study was participants' cumulative EPG pictures were compared to reference frames involving single EPG palatograms, rather than cumulative EPG frames. This occurred in the absence of any available cumulative EPG pictures for typical speakers. For this reason, again

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caution is needed in comparing participants' EPG frames with that of the reference frames of typical speakers in this study.

In this study, EPG assessment occurred after every fifth session. More frequent EPG assessment may have identified gradient change for those speech sound targets classified as showing "categorical" change in the current study.

It is important to note that this was a small scale study involving six participants with a wide age-range. As such, study findings need to be considered cautiously. Further research is needed to examine gradient speech change in larger numbers of individuals with SSDs associated with CP+/- L and to examine gradient change in studies stratified for age. Examination of gradient speech change with different intervention approaches is also indicated.

Conclusion and clinical implications

Gradient speech change was identified for all six participants with cleft palate speech undergoing intervention using EPG visual and indices analysis. A total of 25 speech sounds were targeted for intervention. Gradient speech change was shown for 22/25 target sounds on EPG analysis. The remaining 3/25 showed categorical change using our criteria for assessment. In this study, 4/6 participants were classified with pattern-based speech substitutions, while 2/6 participants presented with speech distortions. Pattern-based speech substitutions were typically acquired in an articulatory gradient manner. However, is should be noted that all study participants received drill-based speech production intervention. Different findings may have occurred with intervention which included generative-type phonological tasks. Usage-based phonology was discussed as a theory which shows some promise in elegantly explaining gradient speech change and also explaining speech distortions and pattern-based speech errors. Usage-based theory would suggest production

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practice is needed for the treatment of both speech distortions and pattern-based speech substitutions. This study supports Lee (2021) who suggests the objective data provided by EPG is a valuable complement to phonetic transcription in identifying lingual gestures not perceived by phonetic transcription and by adjudicating on differences in listeners' judgements. Finally, EPG and other instrumental techniques, such as ultrasound, may be particularly useful for directing our attention to, and providing information on, the articulatory features underling small differences with speech sound production.

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Disclosure statement

The authors report there are no competing interests to declare.

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Figure 1

A midpoint palatogram for a typical contact pattern for /t/

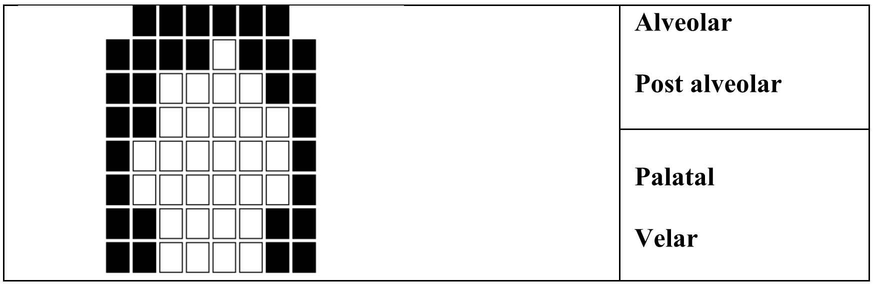

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Figure 2

Cumulative EPG frame

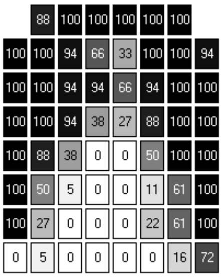

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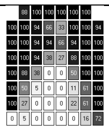
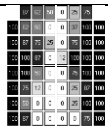
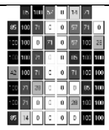
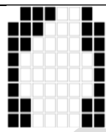
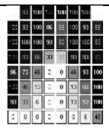
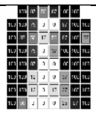
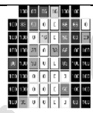
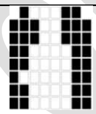
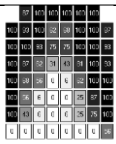
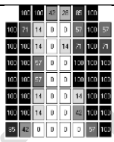
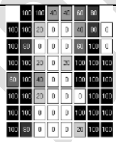
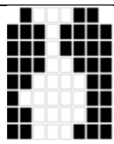
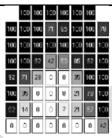
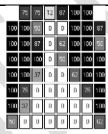
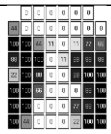
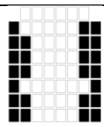
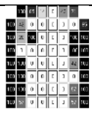
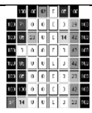
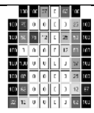
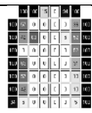
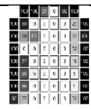
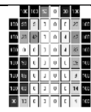
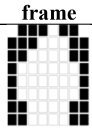
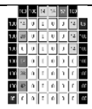
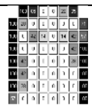
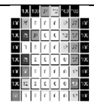
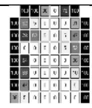
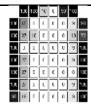
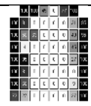
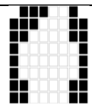
Figure 3

Cumulative EPG frames (pseudo-words) of maximal contact for participants' target speech sounds at EPG assessment points (plus reference EPG frame of typical adult speaker for comparison), phonetic transcriptions at each assessment point, and classification of speech change seen (gradient or categorical)

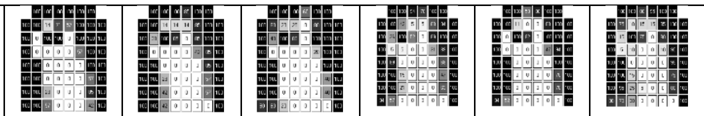
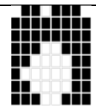
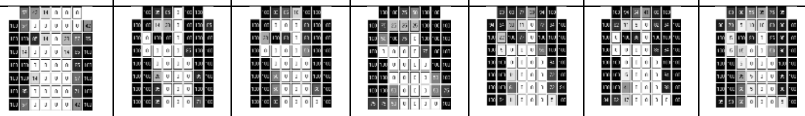
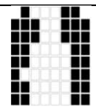
a. Participant 1 (speech substitutions)

Speech target	APT	A5	A10	Reference frame	Speech change
/z/	 Complete closure			 Typical	Gradient
Phonetic transcription	[ɮ]	[z]	[z]	[z]	
/tʃ/ fricative element	 Complete closure			 Typical	Gradient
Phonetic transcription	[ɬ]	[s]	[s]	[ʃ]	
/dʒ/ fricative element	 Complete closure			 Typical	Gradient
Phonetic transcription	[ɮ]	[z]	[z]	[ʒ]	
/ʃ/	 Complete closure			 Typical	Gradient
Phonetic transcription	[ɬ]	[s]	[ʃ]	[ʃ]	

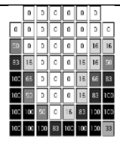
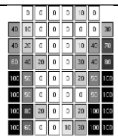
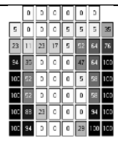
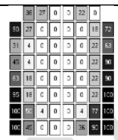
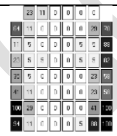
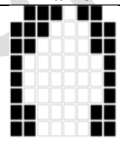
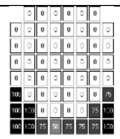
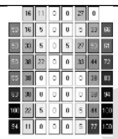
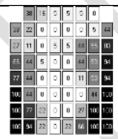
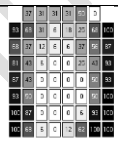
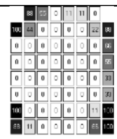
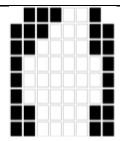
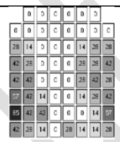
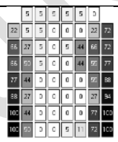
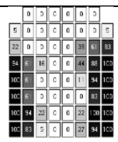
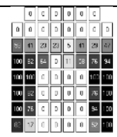
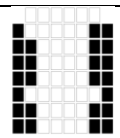
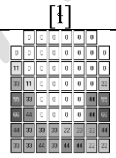
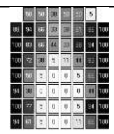
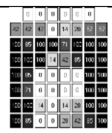
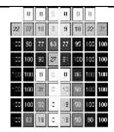
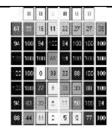
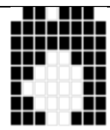
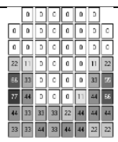
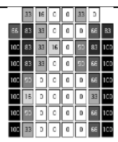
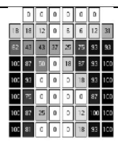
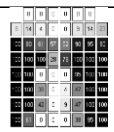
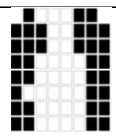
b. Participant 2 (speech distortions)

Speech target	APT	A5	A10	A15	A20	P	M	Reference frame	Speech change
/s/	 Retracted							 Typical	Gradient
Phonetic transcript.	[ʃ] or [ç]	[s]	[s]	[s]	[s]	[s]	[s]	[s]	
/z/	 Retracted						 1	 Typical	Gradient
Phonetic transcrip.	[ʒ] or [j]	[z]	[z]	[z]	[z]	[z]	[z]	[z]	

Article accepted for publication (10 May 2024): Patrick, K., Cleland, J., Rutter, B., & Fricke, S. (Accepted/In press). Gradient speech change during intervention for school-aged children and adults with cleft palate +/- lip. Clinical Linguistics & Phonetics.

/tʃ/ stop element	No stop element							 Typical	Categ.
Phonetic transcrip.		[t]	[t]	[t]	[t]	[t]	[t]	[t]	
/tʃ/ - fricative element								 Typical	
Phonetic transcrip.	[ʃ]	[ʃ]	[ʃ]	[ʃ]	[ʃ]	[ʃ]	[ʃ]		

c. *Participant 3 (speech substitutions)*

Speech target	**APT**	**A5**	**A10**	**A15**	**A20**	**Reference frame**	**Speech change**
/s/	 Retracted to velar; complete closure					 Typical	Gradient
Phonetic transcrip.	[ç] or [ɬ]	[s̪]	[s̪]	[s]	[s]	[s]	
/z/	 Retracted to velar; complete closure					 Typical	Gradient
Phonetic transcrip.	[ʝ] or [ɮ]	[z̪]	[z̪]	[z]	[z]	[z]	
/ʃ/	 Retracted to posterior					 Typical	Gradient
Phonetic transcrip.	[ç], [ʃʲ] or [ɬ]	[s̪] or [t̪]	[ʃ]	[ʃ]	[ʃ]	[ʃ]	
/tʃ/ stop element	 Retracted to posterior					 Typical	Gradient
Phonetic transcript.		[t] or [s]	[t]	[t]	[t]	[t]	
/tʃ/ fricative element					No fricative element	 Typical	Gradient
Phonetic	[ç] or [ɬ]	Prolonged	Prolonged	Prolonged		[ʃ]	

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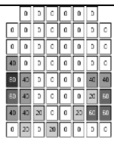
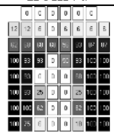
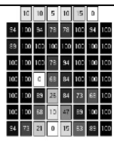
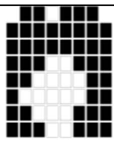
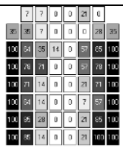
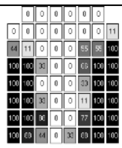
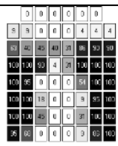
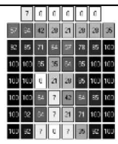
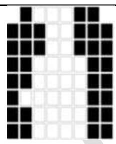
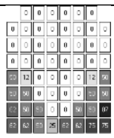
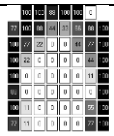
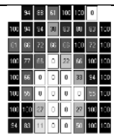
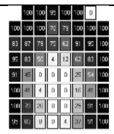
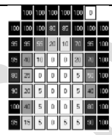
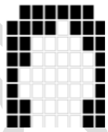
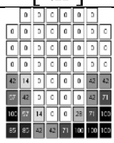
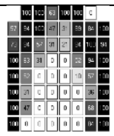
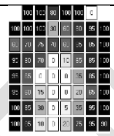
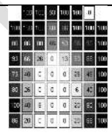
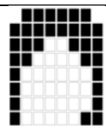
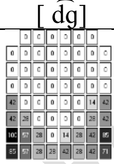
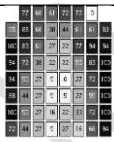
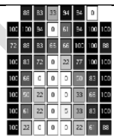
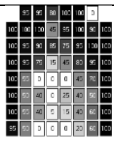
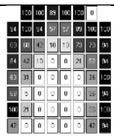
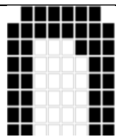
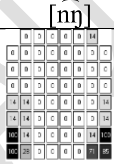
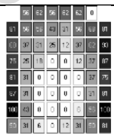
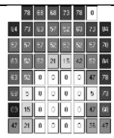
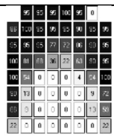
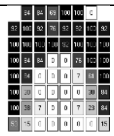
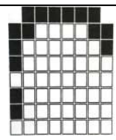
transcription		aspiration from /t/	aspiration from /t/	aspiration from /t/			
/dʒ/ stop element	 Retracted to posterior	No stop element	No stop element			 Typical	Gradient
Phonetic transcription				[d]	[d]		
/dʒ/ fricative element	No fricative element					 Typical	Gradient
Phonetic transcription	[j] or [ʓ]	[s]	[ʃ]	[ʒ]	[ʒ]	[ʒ]	
/t/	 Retracted to posterior placement					 Typical	Gradient
Phonetic transcription	[k], [t̠], or [t͡k]	[t̪]	[t̪]	[t]	[t]	[t]	
/d/	 Retracted to posterior placement					 Typical	Gradient
Phonetic transcription	[g], [d̠], or [d͡g]	[d̪]	[d]	[d]	[d]	[d]	
/n/	 Retracted to posterior					 Typical	Gradient
Phonetic transcription	[ŋ], [n̠], or [n͡ŋ]	[n]	[n]	[n]	[n]	[n]	
/l/	 Retracted to posterior					 Typical	Gradient
Phonetic transcription	[l] or [j]	[n] or [l]	[l]	[l]	[l]	[l]	

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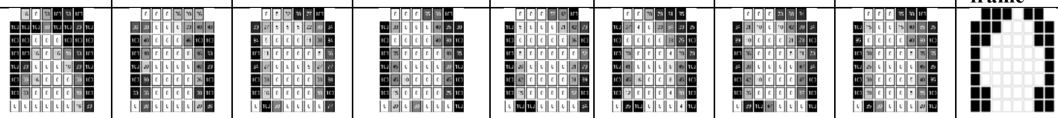
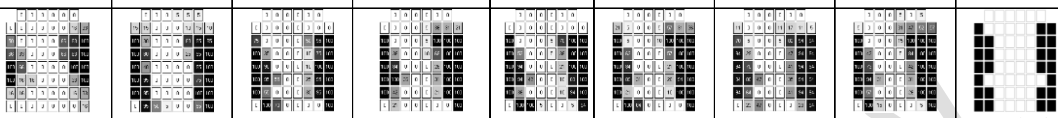
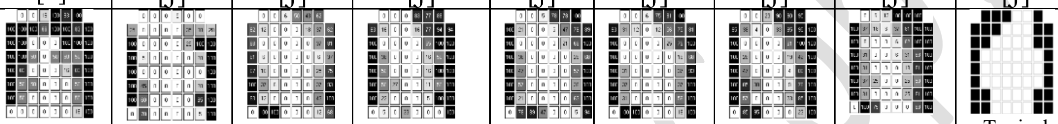
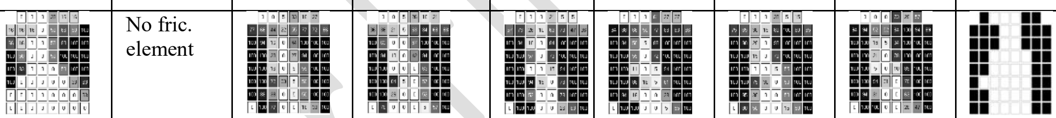
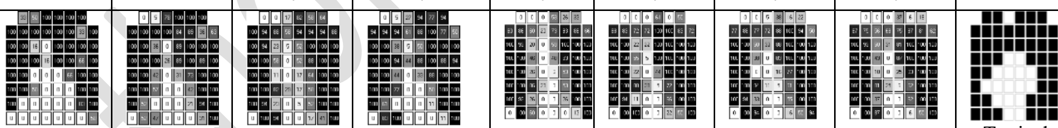
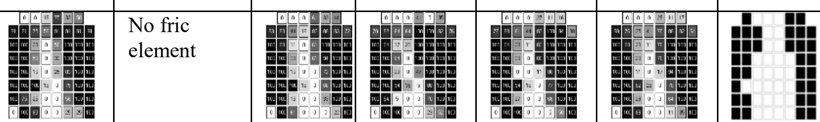
d. Participant 4 (speech substitutions)

Speech target	APT	A5	A10	A15	A20	A25	P	M	Ref. frame	Speech change
/s/ 	Complete closure								Typical	Gradient
Phonetic transcript.	[n̪̟̊] or [ħ]	[ʃ̪̇]	[s̪̟]	[s̪̟]	[s̪̟]	[s̪̟]	[s̪̟]	[s̪̟]	[s]	
/ʃ/ 	Double artic.								Typical	Categ.
	[ħ]	[ʃ̪̇]	[ʃ̪̇]	[ʃ̪̇]	[ʃ̪̇]	[ʃ̪̇]	[ʃ̪̇]	[ʃ̪̇]	[ʃ]	
/z/ 	Complete contact								Typical	Gradient
Phonetic transcrip.	[n]	[ʃ̪̇]	[s̪̟]	[s̪̟]	[s̪̟]	[s̪̟]	[s̪̟]/[z̪̟]	[s̪̟]/ [z̪̟]	[z]	
/tʃ/ stop elem. 	No stop element								Typical	Gradient
Phonetic transcrip.		[t̪]	[t̪]	[t̪]	[t̪]	[t̪]	[t̪]	[t̪]	[t]	
/tʃ/ fricative element 		No fric. element							Typical	Gradeint
Phonetic transcrip.	[ħ]		[ʃ̪̇]	[ʃ̪̇]	[ʃ̪̇]	[ʃ̪̇]	[ʃ̪̇]	[ʃ̪̇]	[ʃ]	
/dʒ/ stop element 									Typical	Gradient
Phonetic transcrip.	[nj]	[t̪]	[t̪]	[t̪]	[t̪]	[t̪]	[t̪]/ [d̪]	[t̪]/ [d̪]	[d]	
/dʒ/ fricative element 	No fric element	No fric element		No fric element					Typical	Gradient
Phonetic transcrip.			[ʃ̪̇]		[ʃ̪̇]	[ʃ̪̇]	[ʃ̪̇]/[ʒ̪̟]	[ʃ̪̇]/[ʒ̪̟]	[ʒ]	

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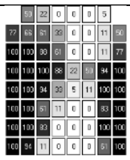
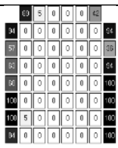
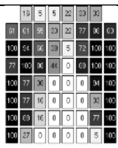
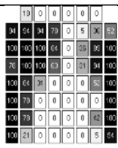
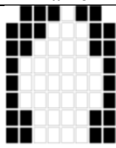
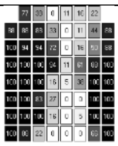
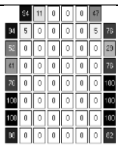
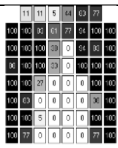
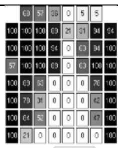
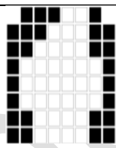
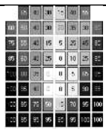
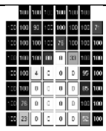
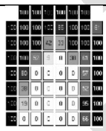
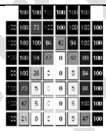
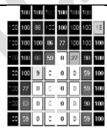
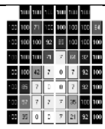
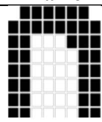
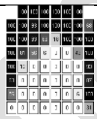
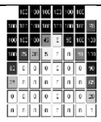
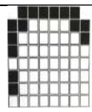
e. Participant 5(speech distortions)

Speech target	APT	A5	A10	A15	Reference frame	Speech change
s	 Retracted to palatal				 Typical	Gradient
Phonetic transcription	[ç]	[s̪̄]	[ts̪]	[s̪]	[s]	
z	 Retracted to palatal				 Typical	Gradient
Phonetic transcription	[j]	[z̪̄]	[dz̪]	[z̪]	[z]	

f. Participant 6(speech substitutions)

Speech target	APT	A5	A10	A15	P	M	Reference frame	Speech change
n	 Retracted to velar						 Typical	Categ.
Phonetic transcription	[n] or [ŋ]	[n]	[n]	[n]	[n]	[n]	[n]	
l	 Retracted to velar						 Typical	Gradient
Phonetic transcription	[l] or [j]	[l]	[l]	[l]	[l]	[l]	[l]	

Note: APT = Assessment prior to therapy; A5 = Assessment end of 5 treatment sessions; A10 = Assessment end of 10 treatment sessions; A15 = Assessment end of 15 sessions; A20 = end of 20 sessions; P = Assessment end of therapy; M = Assessment 3-months post therapy; Reference frame is from first author's productions of target sounds (frame of maximum contact); Categ. = Categorical; transcrip. = transcription; elem. = Element.

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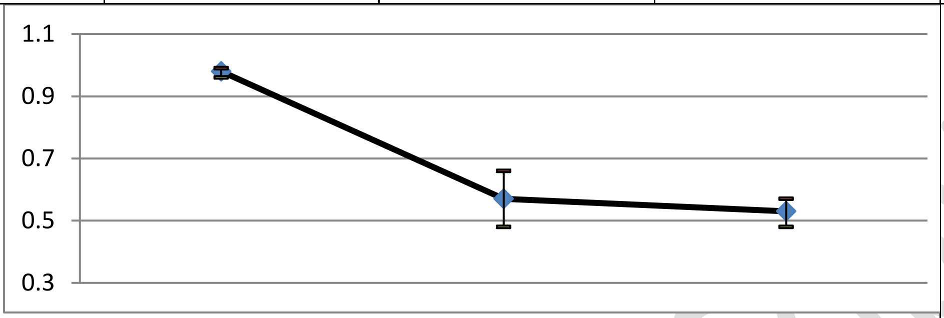
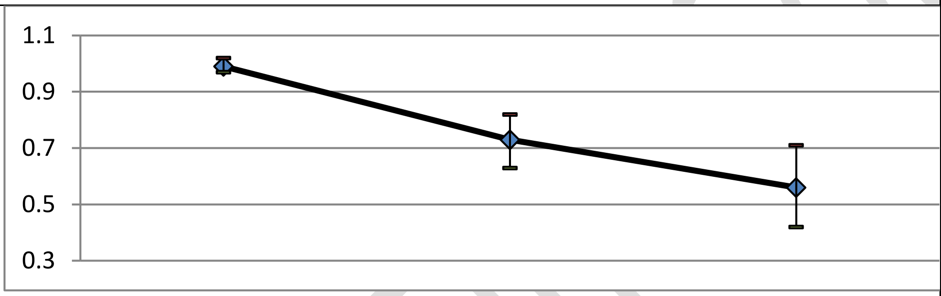
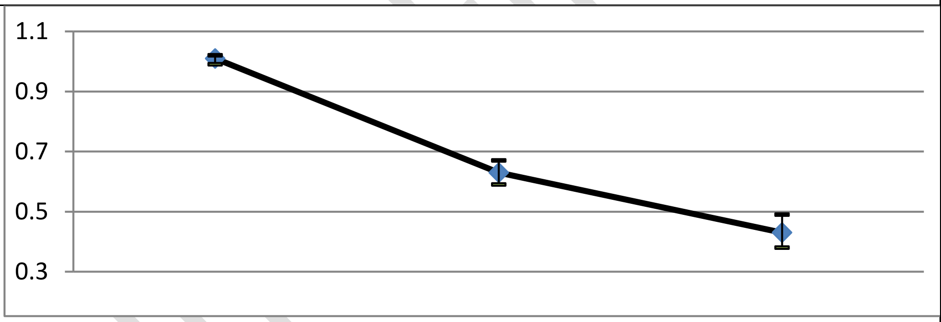
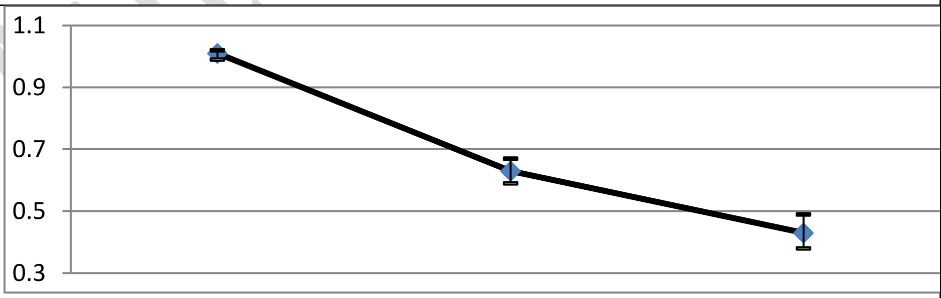
Figure 4

Average EPG indices scores for target sounds in pseudo-words at EPG assessment points with 95% confidence intervals and classification of speech change seen (gradient or categorical)

a. *Participant 1 (speech substitutions)*

Speech target	AC score	B3	A5	A10	Speech change
/z/					Gradient
/tʃ/ fric. elem.					Gradient
/dʒ/ fric. elem.					Gradient
/ʃ/					Gradient

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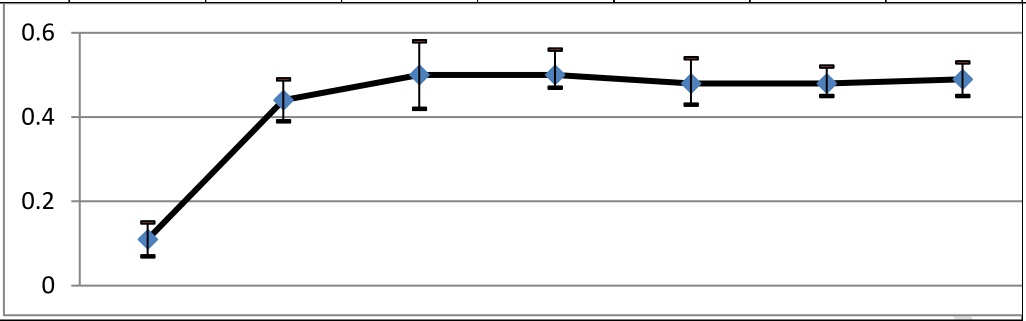
b). Participant 2 (speech distortions)

<table>
<tr><th>Speech target</th><th>AT score</th><th>B3</th><th>A5</th><th>A10</th><th>A15</th><th>A20</th><th>P</th><th>M</th><th>Speech change</th></tr>
<tr><td rowspan="4">/s/</td><td colspan="8">
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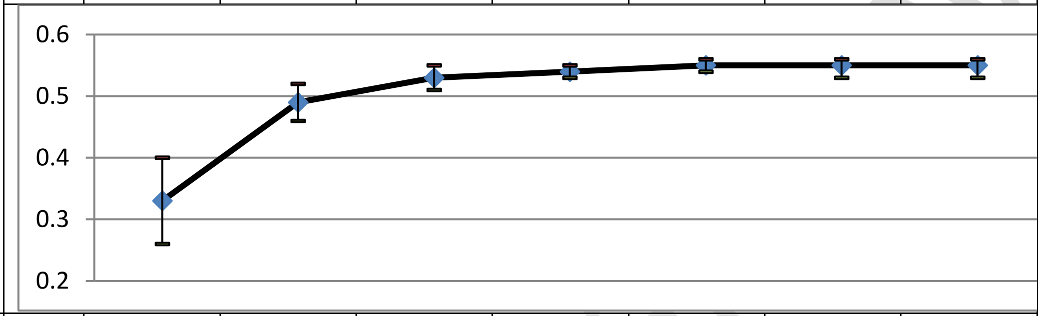
<tr><td>CoG score</td><td>B3</td><td>A5</td><td>A10</td><td>A15</td><td>A20</td><td>P</td><td>M</td><td></td></tr>
<tr><td colspan="8">
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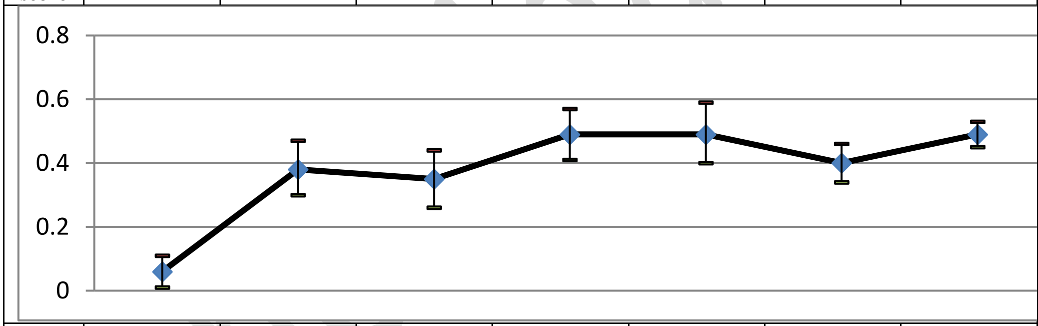
<tr><td colspan="8">
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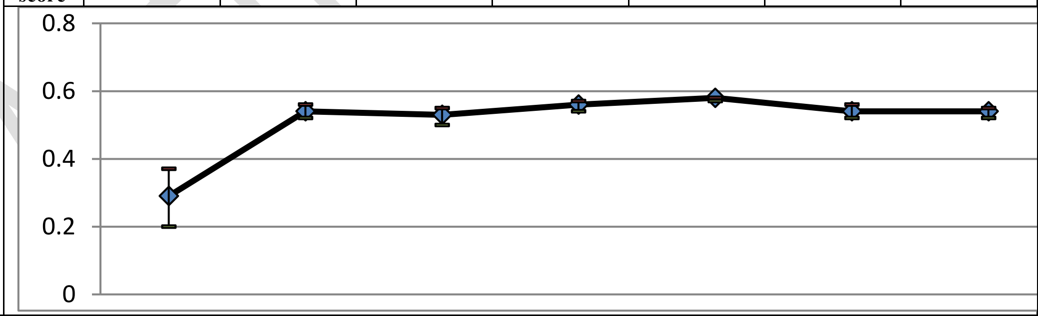
<tr><td>CoG score</td><td>B3</td><td>A5</td><td>A10</td><td>A15</td><td>A20</td><td>P</td><td>M</td><td></td></tr>
<tr><td colspan="8">
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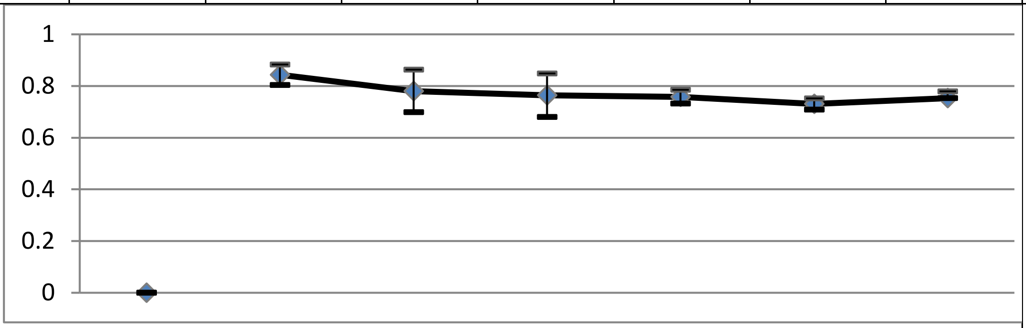
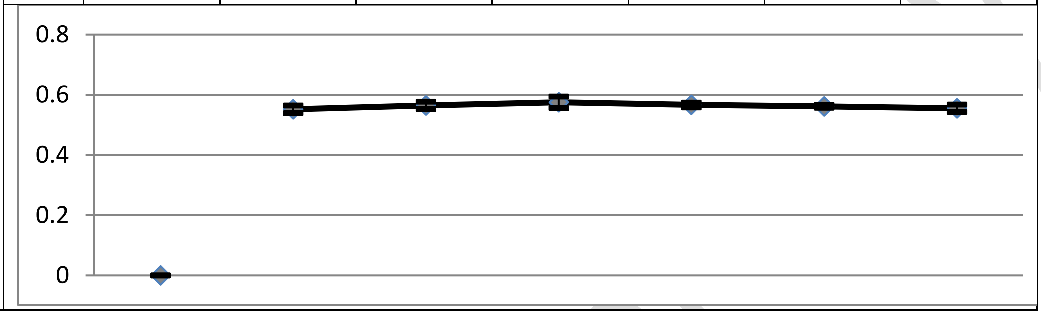
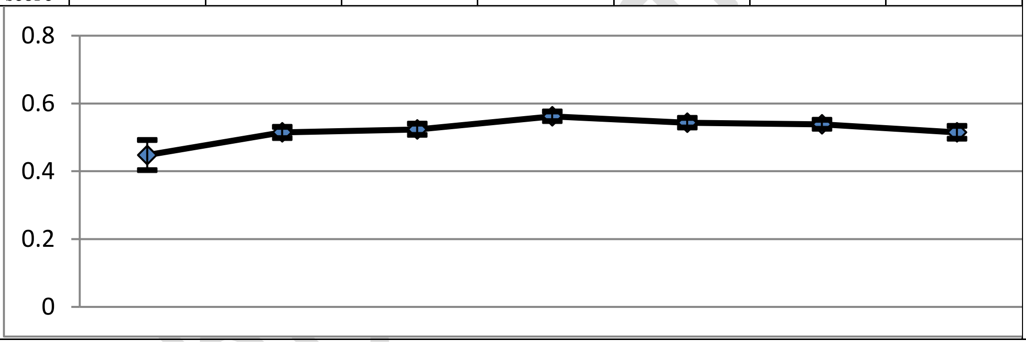
Speech target	AT score	B3	A5	A10	A15	A20	P	M	Speech change
/tʃ/ - stop elem.									Categ.
	COG score	B3	A5	A10	A15	A20	P	M	
									
Speech target	COG score	B3	A5	A10	A15	A20	P	M	
/tʃ/ - fric. elem.									

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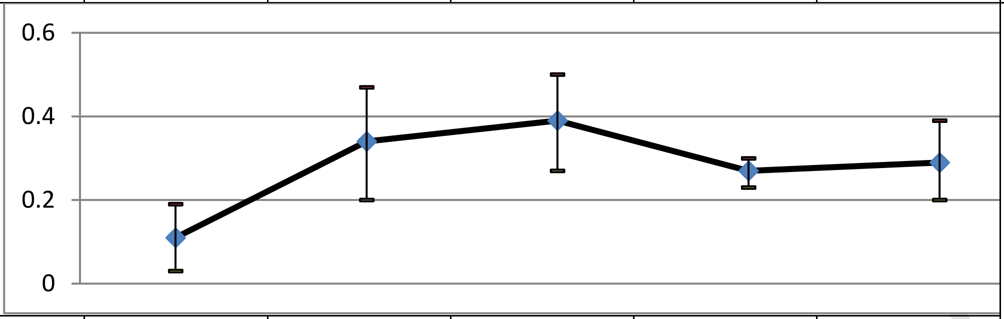
c). Participant 3 (substitutions)

<table>
<tr><th>Speech target</th><th>AC score</th><th>B3</th><th>A5</th><th>A10</th><th>A15</th><th>A20</th><th>Speech change</th></tr>
<tr><td>/s/</td><td colspan="6">
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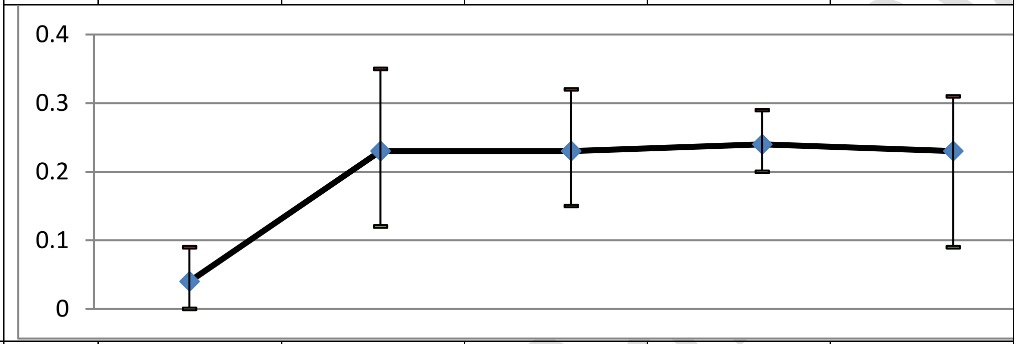
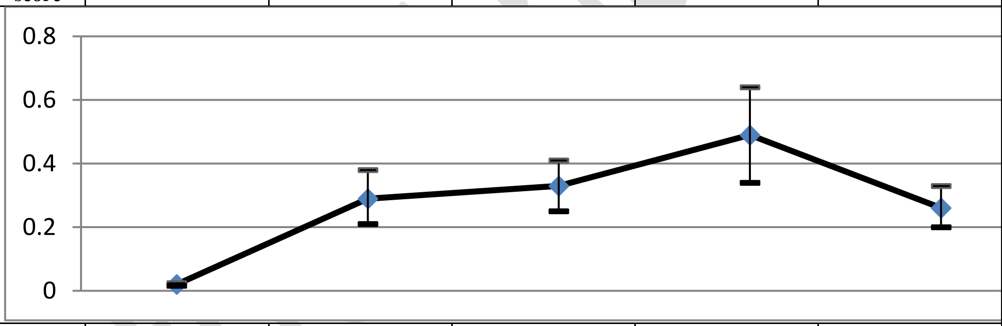
<tr><td></td><td>AT score</td><td>B3</td><td>A5</td><td>A10</td><td>A15</td><td>A20</td><td></td></tr>
<tr><td></td><td colspan="6">
</td><td>Categ.</td></tr>
<tr><th>Speech target</th><th>AC score</th><th>B3</th><th>A5</th><th>A10</th><th>A15</th><th>A20</th><th>Speech change</th></tr>
<tr><td>/z/</td><td colspan="6">
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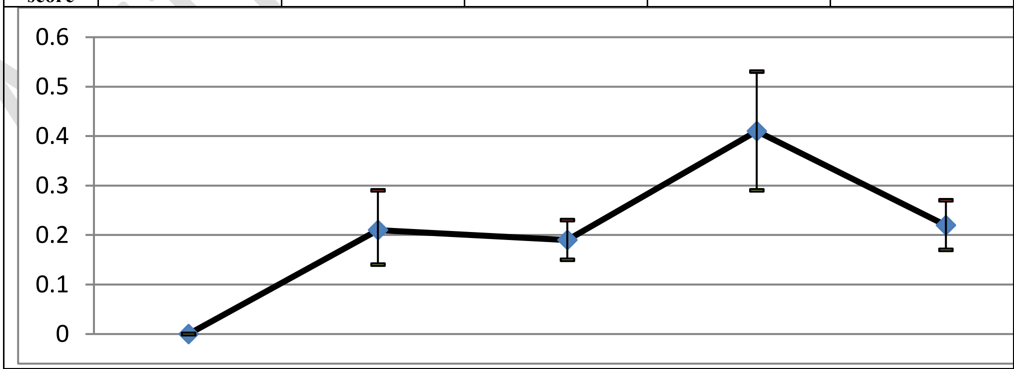
<tr><td></td><td>AT score</td><td>B3</td><td>A5</td><td>A10</td><td>A15</td><td>A20</td><td></td></tr>
<tr><td></td><td colspan="6">
</td><td>Gradient</td></tr>
</table>

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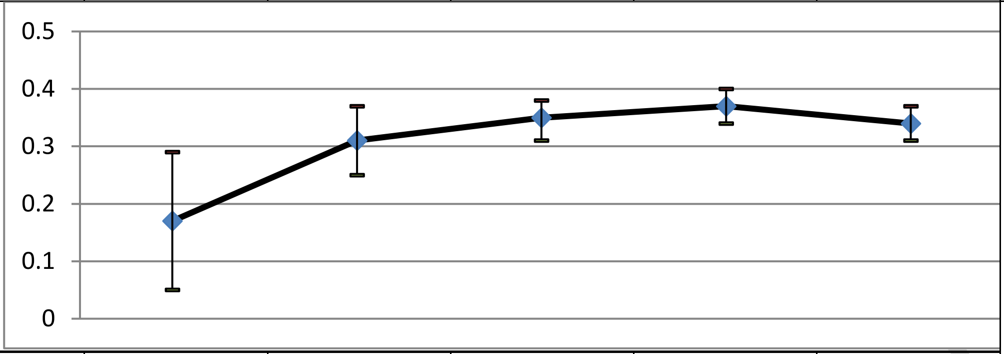
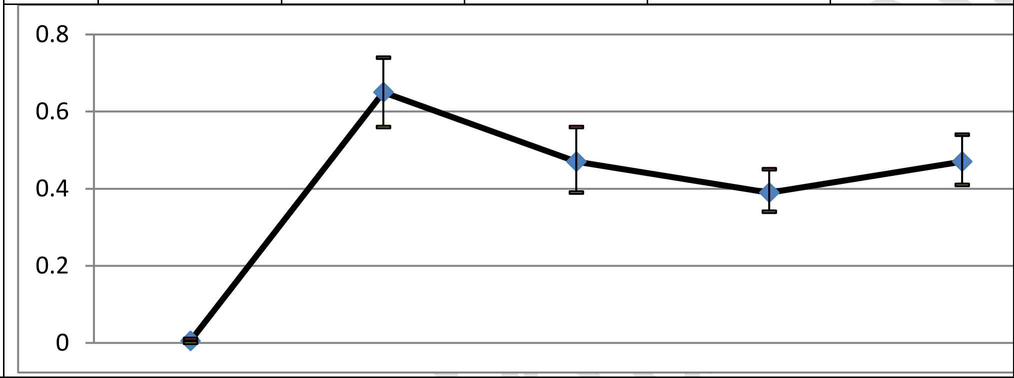
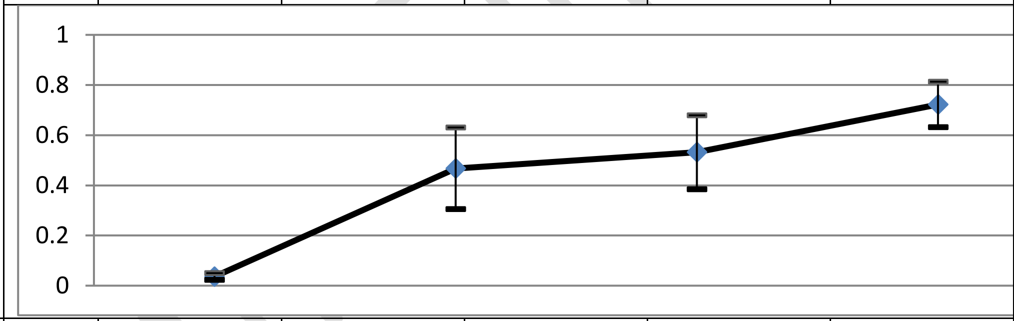
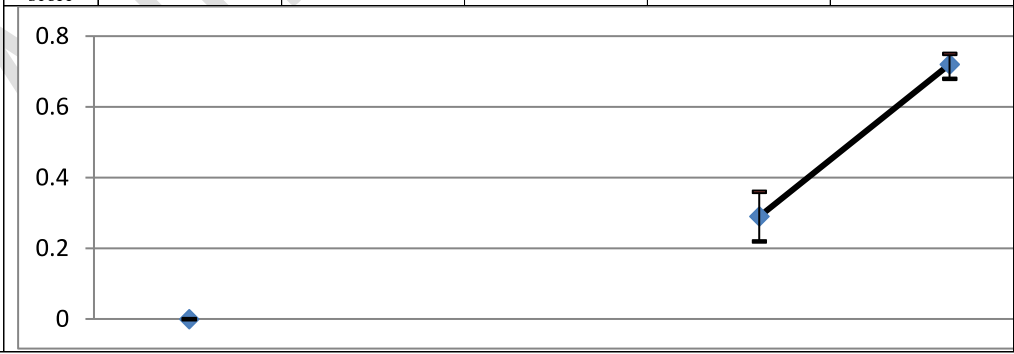
Speech sound target	WT score	B3	A5	A10	A15	A20	Speech change
/ʃ/							Gradient
	AT score	B3	A5	A10	A15	A20	
/tʃ/ stop elem.							Gradient
	AC score	B3	A5	A15	A15	A20	
/tʃ/ fric. elem.							Gradient
	AT score	B3	A5	A10	A15	A20	
/dʒ/ stop elem							Gradient

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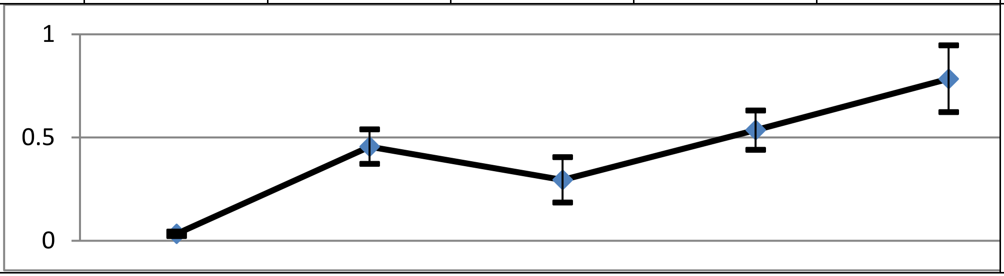
<table>
<tr><td></td><td>AT score</td><td>B3</td><td>A5</td><td>A10</td><td>A15</td><td>A20</td><td></td></tr>
<tr><td>/dʒ/ fric. elem.</td><td colspan="6">
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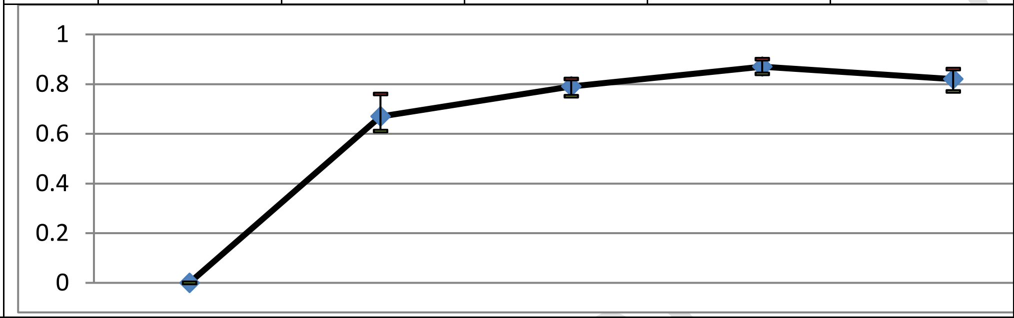
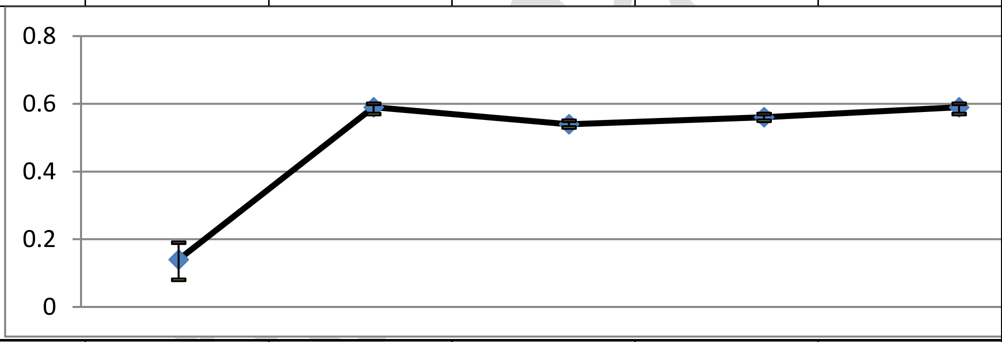
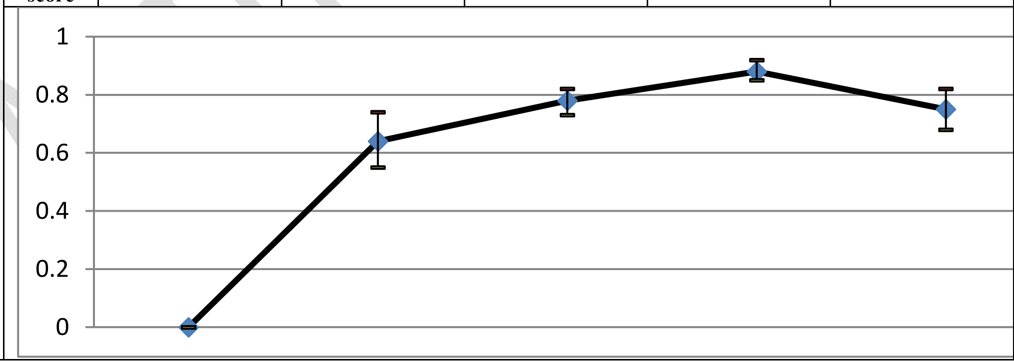
<table>
<tr><td>Speech target
/t/</td><td>AT score</td><td>B3</td><td>A5</td><td>A10</td><td>A15</td><td>A20</td><td>Speech change</td></tr>
<tr><td></td><td colspan="6">
</td><td>Gradient</td></tr>
<tr><td>Speech sound target</td><td>AT score</td><td>B3</td><td>A5</td><td>A10</td><td>A15</td><td>A20</td><td>Speech change</td></tr>
<tr><td>/d/</td><td colspan="6">
</td><td>Categ.</td></tr>
<tr><td></td><td>AT score</td><td>B3</td><td>A5</td><td>A10</td><td>A15</td><td>A20</td><td>Speech change</td></tr>
<tr><td>/n/</td><td colspan="6">
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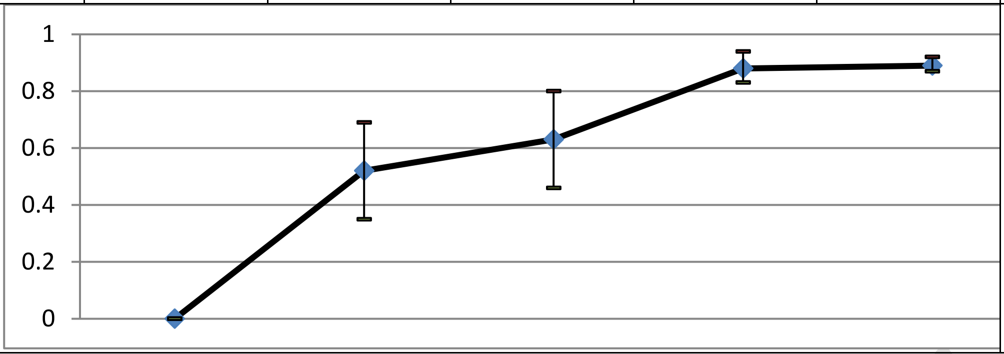
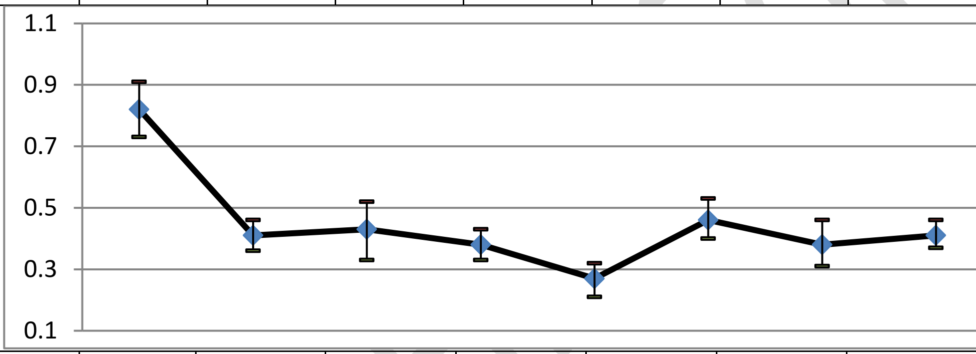
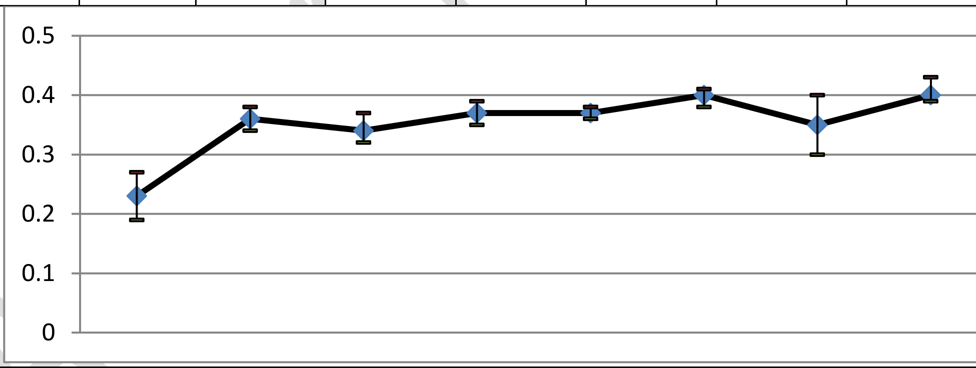
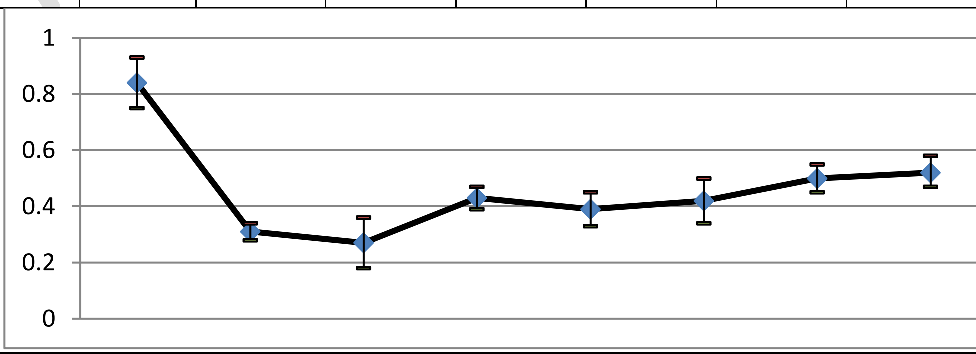
	AT score	B3	A5	A10	A15	A20	Speech change
/l/							Gradient

Participant 4 (substitutions)

Speech sound target	**AC score**	**B3**	**A5**	**A10**	**A15**	**A20**	**P**	**M**	**Speech change**
/s/									Gradient
Speech sound target	**WT score**	**B3**	**A5**	**A10**	**A15**	**A20**	**P**	**M**	
/ʃ/									Gradient
Speech sound target	**AC score**	**B3**	**A5**	**A10**	**A15**	**A20**	**P**	**M**	
/z/									Gradient

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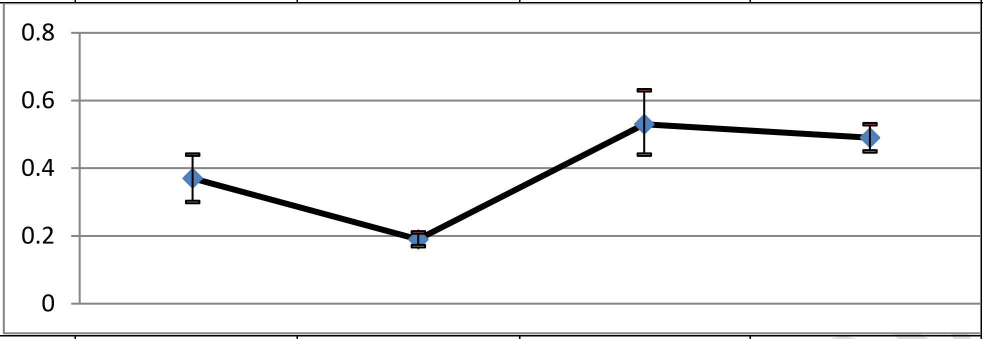
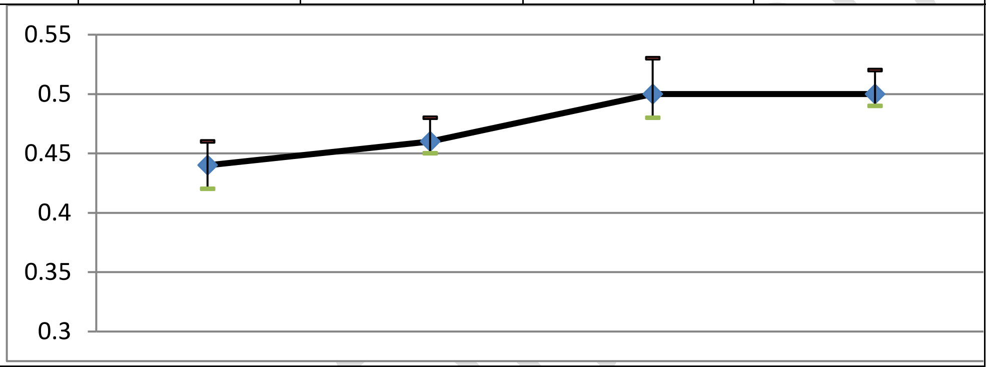
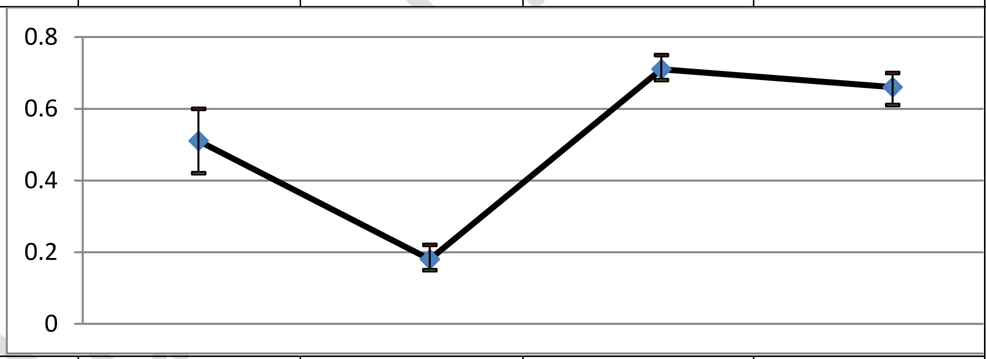
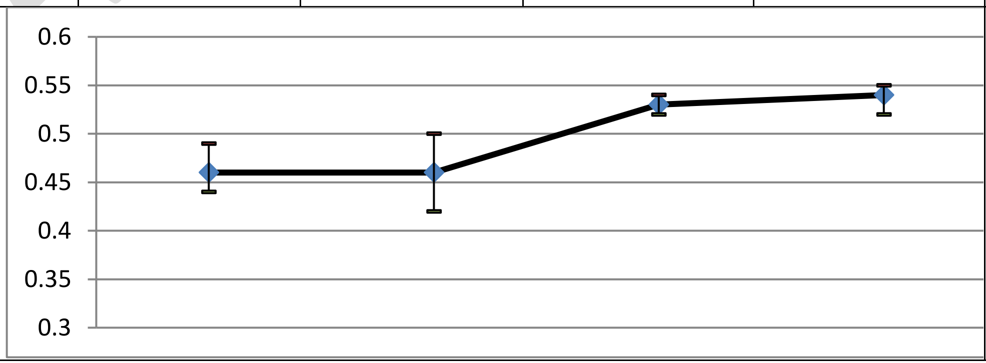
Participant 5 (distortions)

Speech sound target	AT score	B3	A5	A10	A15	Speech change
/s/						Gradient
Speech sound target	**COG score**	**B3**	**A5**	**A10**	**A15**	
/s/						Categ.
Speech sound target	AT score	B3	A5	A10	A15	
/z/						Gradient
Speech sound target	CoG score	B3	A5	A10	A15	
/z/						Gradient

f). Participant 6 (substitutions)

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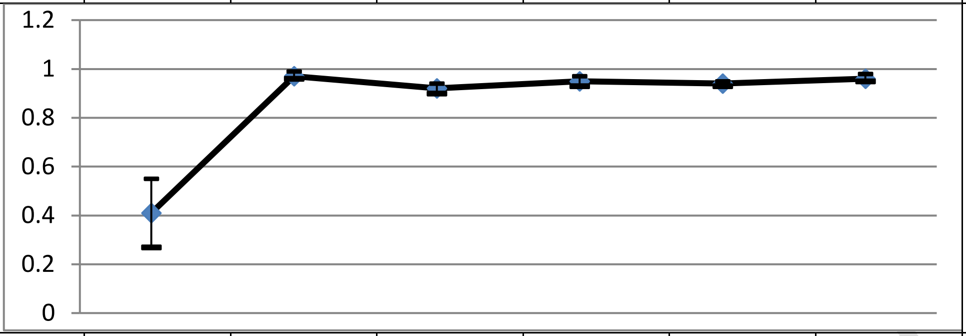
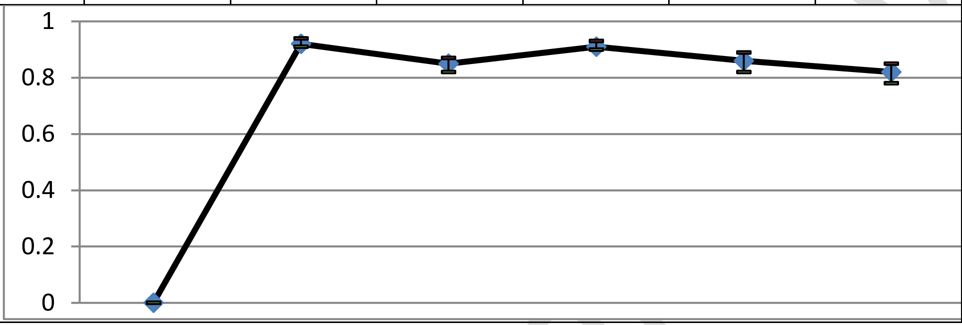
Speech sound target	AT score	B1	A5	A10	A15	P	M	Speech change
/n/								Categ.
	AT score	B1	A5	A10	A15	P	M	
/l/								Gradient

Note: AC = Alveolar closure; AT = Alveolar Total; CoG = Centre of gravity; WT= Whole total; B3 = Baseline 3; A5= Assessment session five; A10 = Assessment session 10; A15 = Assessment session 15; A20 = Assessment session20; P = Assessment following completion of therapy; M = Maintenance assessment 3-months post therapy; partic. = Participant; fric. = Fricative; elem. = Element; Categ. = Categorical. Increases in AT and CoG represents improvement with tongue-palate contact moving from posterior to more anterior. Decrease in AC score represents improvement with a change from no central oral airflow to central tongue flow for anterior lateral speech sound errors. Increase in WT represents improvement with a change from little tongue-palate contact, to increased tongue-palate contact.

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Table 1

Participants' demographic information, main cleft speech characteristics and therapy speech targets

Participant no.	Sex	Age	Diagnosis	Co-occurring diagnosis	Dental occlusion	Main cleft speech characteristics at word level	Type of SSD	Speech targets
1	M	10	Cleft palate		Class I (normal)	Lateral production of lingual sibilants	Substitutions	z, ʃ, tʃ, dʒ
2	F	20	Submucous cleft palate		Class II div I (mild)	Palatal production of /s/ and /z/; /tʃ/ → [ʃ]	Distortions.	tʃ, s, z
3	F	11	Submucous cleft palate	22q1.1 deletion syndrome	Class I	Backing and lateral production of lingual speech sounds	Substitutions	n, l, t, d, s, z, ʃ, tʃ, dʒ
4	F	27	Unilateral cleft lip and palate		Class I	Non-oral production of lingual sibilants	Substitutions	s, z, ʃ, tʃ, dʒ
5	F	7	Cleft palate		Left-sided crossbite primary molars	Palatal production of /s/ and/z/	Distortions	s, z
6	F	17	Unilateral cleft lip and palate		Class I	Backing of /n/ and /l/	Substitutions	n, l

M = male; F = female

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Table 2

System for annotating EPG data

Speech sound	Analysis (rationale)
Fricatives	Acoustic signal - onset to offset of friction (in order to capture the whole duration of the fricative).
Oral and nasal stops	First EPG frame of closure to release of closure using the acoustic signal (in order to capture the entire closure phase).
Affricatives	Analysed in two parts: 1. First EPG frame of closure to the release of closure using the acoustic signal (capturing the entire closure phase); 2. Acoustic signal - onset to offset of frication (capturing the entire duration of the fricative).
Glides	First EPG frame of lingual contact to release of contact (capturing the whole duration of contact).
Glottal stops and velar stops (not shown on EPG frames)	Acoustic signal – onset to offset (capturing the entire closure phase).

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Table 3

Study EPG indices and speech sound errors

EPG indices	Speech sound errors	Explanation of EPG indices and rationale for use	Expected change in scores with categorical change	Expected change in scores with gradient change
Alveolar Closure	/s/ → [ɬ] /z/ → [ɮ] /ʃ/ → [ɬ] /tʃ/ → [ɬ] /dʒ/ → [ɮ] /z/ →[n]	AC relates to the connectivity between the two sides of the palate. The higher the AC score the more contact between the two sides of the palate. A decrease in scores across test points shows a change from lateral airflow to central tongue airflow.	Substantial decrease in scores at one test point in intervention, and then stable scores with subsequent test points.	Gradual decrease in scores across test points.
Alveolar Closure	/s/ → [ɫ] /z/ → [ɫ̬] /ʃ/ → [ɫ] /tʃ/ → [kɫ] /dʒ/ → [g]	AC was also used for participant 3 who showed a pattern of backing and lateral production of lingual sibilants on EPG. An increase in scores across test points showed a change from no anterior central airflow to anterior central airflow.	Substantial increase in scores at one test point in intervention, and then stable scores with subsequent test points.	Gradual increase in scores across test points.
Alveloar Total and Center of Gravity	/s/ → [ʃ], [ç] /z/ → [ʒ], [ʝ] /t/ → [k] /d/ → [g] /n/ → [ŋ] /l/ → [ɰ]	AT is the number of electrodes contacted in the first three rows of the EPG palate (possible total of 22) per EPG frame. An increase in scores across test points shows a change from posterior to anterior tongue - palate contact. CoG shows the position of the main concentration of electrodes across the palate per EPG frame. Small CoG values relate to posterior tongue-palate contact. CoG values rise with increases in anterior tongue-palate contact. AT and CoG therefore can show any changes from posterior to anterior tongue-palate contact.	Substantial increase in scores at one test point in intervention, and then stable scores with subsequent test points.	Gradual increase in scores across test points.
Whole Total	/ʃ/ → [ħ]	WT represents the total number of electrodes contacted per EPG frame. WT was used to show a change from no tongue-palate to tongue palate contact, and also an increase	Substantial increase in scores at one test point in intervention, and then stable scores with subsequent test points.	Gradual increase in scores across test points.

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	in tongue-palate contact.

Note. AC = Alveolar Closure; AT = Alveolar Total; CoG = Centre of Gravity; WT = Whole Total

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Table 4

Discrepancies in phonetic transcription and tongue-palate placement on EPG

Participant	Speech sounds	SLTs phonetic transcription	Tongue-palate placement on EPG and sound and spectral data
3	s z ʃ tʃ dʒ	[ç] or [ɬ] [j] or [ɮ] [ç] or [ɬ] [ç] or [ɬ] [j] or [ɮ]	Consistent complete posterior tongue–palate contact in velar region with lateral airflow
	t d n l	[t], [k], or [t͡k] [d], [g], or [d͡g] [n], [ŋ], or [n͡ŋ], [l] or [j]	Consistent posterior tongue-palate closure in velar region
4	s	[n̥͋] or [ħ]	Consistent alveolar tongue-palate contact with accompanying pharyngeal frication
6	n	[n] or [ŋ]	Tongue palate contact in velar region, or double articulation with simultaneous alveolar and velar tongue-palate contact
	l	[l] or [j]	Consistent tongue-palate contact in velar region

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