Biofeedback Interventions

22

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ABSTRACT

Biofeedback interventions use instrumentation to allow speakers to visualize and modify their own speech production in real time. This chapter focuses on three types of biofeedback used for treating children with speech sound disorders (SSD): electropalatography (EPG), ultrasound, and acoustic biofeedback. EPG and ultrasound show real-time articulatory movements, and acoustic biofeedback uses either a spectrogram or linear predictive coding spectrum to distinguish speech sounds. All of the techniques can be incorporated into a motor-learning paradigm whereby the visual display provides specific information about the nature of the articulatory or acoustic parameters required to produce accurate speech. Biofeedback is normally used to help school-age children as well as adults with a wide variety of SSDs acquire lingual speech sounds that they have not acquired in the course of normal development. An emerging evidence base, currently consisting primarily of a large number of case studies and single case experimental designs, points toward the effectiveness of biofeedback.

ABOUT THE VIDEO

The video for this chapter, Biofeedback Interventions, can be streamed from the Brookes Publishing Download Hub. The accompanying video demonstrates some of the technologies that are used for biofeedback interventions for children with SSD. Included in this video is a simultaneous recording of a typical speaker, showing ultrasound images of the tongue alongside electropalatography images, which show tongue-palate contact. Segments of ultrasound biofeedback therapy sessions are shown of a 17-year-old female with distortion of American English /ɹ/,[1] followed by a 5-year-old girl with cleft palate who is backing alveolar stops. For a video of visual acoustic biofeedback on /ɹ/, see https://figshare.com/articles/Video_Demonstration_of_the_staRt_app_McAllister_Byun_et_al_2017_/5116318.

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[1] The consonant /ɹ/ is often written as /r/ in English texts. In this book, we use /ɹ/ to indicate the alveolar approximant "r" found in English to align with International Phonetic Alphabet usage.

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INTRODUCTION

In the context of treating children and adults with SSD, **biofeedback** involves technologically enhanced visualization of articulatory movements or acoustic information. Many articulatory movements are hidden within the vocal tract, and acoustic properties of speech can be abstract, leading to challenges in describing to clients the desired movements or sounds. Additionally, articulatory and acoustic information is temporary and fleeting. Visualization enables speech processes to become more concrete and accessible, thereby enabling more explicit cues by the clinician and more awareness by the client. However, because visual biofeedback often requires access to and training in specific technologies, it is usually not the first treatment that is considered for individuals with SSD.

There are a number of examples of biofeedback in the literature. One of the simplest forms of biofeedback is a mirror, which allows clients to visualize articulatory movements of the lips, jaw, and tongue tip. However, many articulatory movements (e.g., dorsal elevation for /k, ɡ/) can be difficult to visualize with just a mirror, necessitating alternative strategies. The biofeedback strategies that are the most commonly described in the literature for SSD are **electropalatography**, ultrasound, and visual acoustic.

EPG is a technology that uses instrumentation to display tongue-palate contact. Each client must wear an individualized pseudopalate, with sensors that detect lingual contact from either the dental or alveolar region to the boundary of the hard and soft palate. The pseudopalate is created from a dental impression so that it fits along the upper dental arch. Figure 22.1 displays a pseudopalate, along with an example of the contact patterns for the /t/ sound for a typical production.

Ultrasound is a technology that converts reflected high-frequency sound waves (higher than the ear can hear) to images. By holding a transducer against the skin beneath the chin, the contour of the tongue can be displayed, revealing important information about tongue shape during speech. Sagittal views can be used to image the tongue from front to back to display movements of the tongue blade, dorsum, and root, and coronal views can be used to visualize the tongue from side to side to display information such as tongue grooving during production of sibilants. Figure 22.2 shows a midsagittal (left, tongue tip to the right) and coronal ultrasound image for /s/.

Visual **acoustic biofeedback** involves display of spectral information, usually in the form of either a spectrogram or linear predictive coding (LPC) spectrum. Frequency information such as the location of the first two or three formants can be used to distinguish

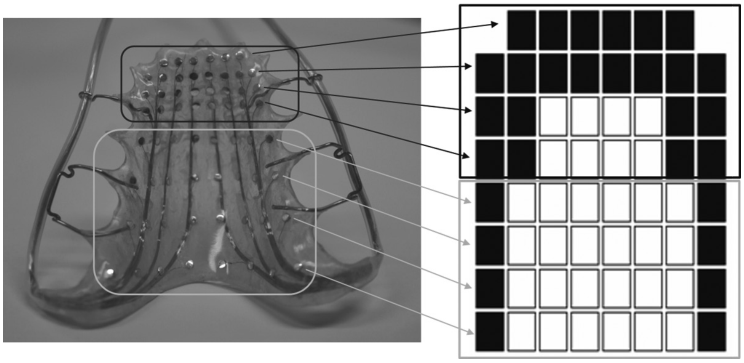

Figure 22.1. Electropalatography image of /t/ during stop closure.

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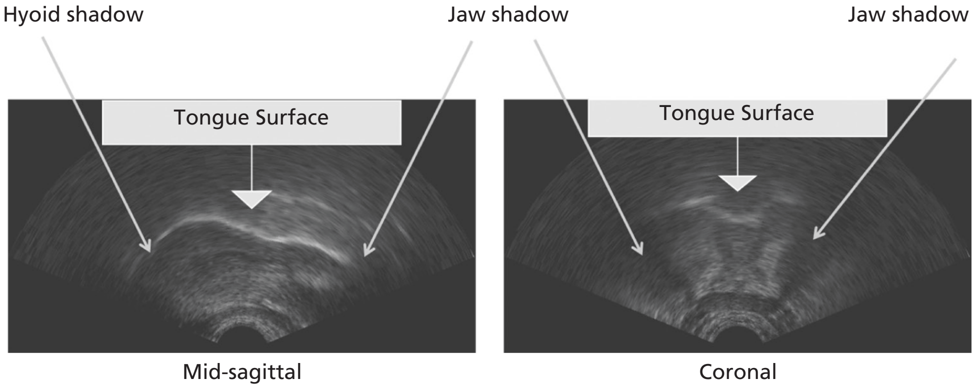

Figure 22.2. Midsagittal and coronal view of /s/ with ultrasound imaging.

sonorant sounds such as vowels and semivowels. Figure 22.3 shows an example of visual acoustic biofeedback display contrasting the spectrum for correct and distorted /ɹ/ which differ by location of the third formant.

All of these techniques can be used for assessment or progress monitoring in addition to providing biofeedback (e.g., Gibbon et al., 2001). **Acoustic analysis** is well described in the literature and therefore can dovetail with visual acoustic biofeedback to measure changes

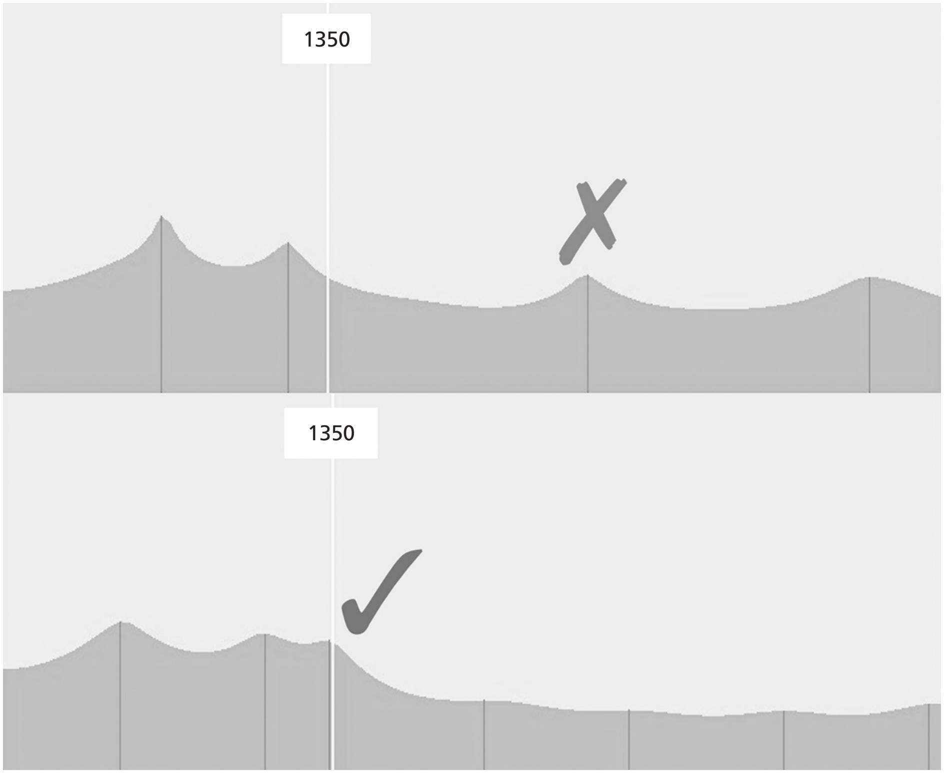

Figure 22.3. Correct and distorted productions of /ɹ/ with visual acoustic imaging.

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in formant frequencies after intervention. Likewise, EPG has been used extensively to measure tongue–palate contact before and after intervention as a method of quantifying change (e.g., Nordberg, Carlsson, & Lohmander, 2011). In contrast, fewer studies (exceptions include Bressman, Harper, Zhylich, & Kulkarni, 2016; Cleland, Scobbie, & Wrench, 2015) have used ultrasound images for assessment, as tongue contours may be difficult to quantify.

TARGET POPULATIONS

Biofeedback approaches are appropriate for a wide range of clients with SSD. Because biofeedback is a visually oriented approach, clients must have adequate visual acuity and visual processing to be able to take advantage of the information presented on the screen, and they should possess the ability to sustain attention to the display during speech practice. Motivation to improve speech is also important, as biofeedback approaches typically are drill oriented and require repeated practice. Biofeedback is most commonly applied with school-age children and with adults, primarily because clients must possess adequate cognitive skills to be able to integrate the visual feedback with their feedforward speech production systems. Thus, toddlers and preschoolers generally are not appropriate candidates, and the one study that explored the use of ultrasound biofeedback with preschoolers reported relatively limited gains in production of velar sounds (Heng, McCabe, Clarke, & Preston, 2016). Even for school-age children and adults, biofeedback is not usually the first intervention that is considered because cost and access to the technologies may prevent immediate implementation. Thus, biofeedback options are often considered after other interventions have been tried and have failed.

To date, ultrasound biofeedback has been applied most frequently to individuals with residual speech errors (e.g., Preston et al., 2014), childhood apraxia of speech (e.g., Preston, Brick, & Landi, 2013), and hearing impairment (e.g., Bacsfalvi, Bernhardt, & Gick, 2007). Visual acoustic biofeedback has been studied with clients with hearing loss (Ertmer, Stark, & Karlan, 1996) and with residual /ɹ/ errors (e.g., McAllister Byun, 2017; Shuster, Ruscello, & Smith, 1992). EPG has been applied to a wider range of clients, including those with residual sound errors (e.g., Carter & Edwards, 2004; Dagenais, Critz-Crosby, & Adams, 1994; Hitchcock, McAlister Byun, Swartz, & Lazarus, 2017), cleft palate (e.g., Gibbon & Hardcastle, 1989; Lohmander, Henriksson, & Havstam, 2010), hearing loss (Crawford, 1995 Dagenais, 1992), and Down syndrome (Cleland, Timmins, Wood, Hardcastle, & Wishart, 2009; Gibbon, McNeill, Wood, & Watson, 2003; Wood, Timmins, Wishart, Hardcastle, & Cleland, 2018), most commonly addressing errors on /t, d, k, ɡ, s, z, ʧ, ʤ/ and high versus low vowels. In addition to SSD, biofeedback approaches may be appropriate for teaching phonetic aspects of speech sounds for individuals learning a new language (Gick et al., 2008), for adults with acquired apraxia of speech (Preston & Leaman, 2014), and for adults with speech impairments following glossectomy (Blyth, McCabe, Madill, & Ballard, 2016). In general, we advocate that selection of biofeedback as an intervention approach should be based on the nature of the client's errors rather than the SSD subtype or presumed etiology.

The specific sounds that can be targeted vary among the available biofeedback technologies (Table 22.1). For example, EPG is appropriate for clients who produce errors on lingual sounds that require tongue–palate contact, which may include alveolar, palato-alveolar, and velar consonants, as well as high vowels (but not mid or low vowels). Similarly, because ultrasound provides only a visual display of the tongue, it is appropriate for clients with errors on most lingual phonemes (except for interdentals because they are too anterior to successfully image). However, neither EPG nor ultrasound is appropriate to teach labial,

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Table 22.1. Likely English sound targets for three biofeedback interventions

Electropalatography	Ultrasound	Visual acoustic
t, d, n, s, z, j, ʃ, ʧ, ʤ, k, g, ŋ, ɹ, l	t, d, n, s, z, j, ʃ, ʧ, ʤ, k, g, ŋ, ɹ, l	ɹ, l, w, j
i	All vowels	All vowels

dental, and glottal sounds or nonlingual errors such as voicing and nasalization. Finally, acoustic biofeedback has been most commonly applied to vowels or semivowels because of their clear steady-state formant structure, although real-time spectrograms may be appropriate to contrast acoustic information associated with manner of articulation (e.g., stops vs. fricatives) and place of articulation (e.g., palato-alveolar vs. alveolar fricatives).

Tolerance of the technology may also play a role in identifying appropriate candidates. For example, EPG requires obtaining a dental impression and insertion of a pseudopalate, which some clients may find uncomfortable or distracting, and which require time to adapt (McLeod & Searl, 2006). In addition, EPG may not be appropriate for children whose dentition is still changing due to the loss of deciduous teeth, the emergence of permanent teeth, or the rearranging of teeth due to orthodontic treatment. With respect to ultrasound, some children find the positioning of the transducer to be annoying or distracting, and others may find the gel to be uncomfortable or “gooey” (Preston, Holliman-Lopez, & Leece, 2018), although most children learn to tolerate these minor annoyances. One exception may include children with autism spectrum disorders or others with significant tactile hypersensitivities that impede tolerance of ultrasound gel or the transducer against the skin. Also, children with a very small mandible may have too little visible tongue surface due to the acoustic shadows caused by bone in the ultrasound image, making them unsuitable candidates. In general, acoustic biofeedback is likely to be tolerated most readily because it requires only a microphone and related software.

Biofeedback has been applied primarily to children and young people with persistent or residual SSD. This is for two main reasons. First, these types of disorders may be caused by motor-based or articulatory impairments, and biofeedback is a motor-based approach. Second, these disorders often prove resistant to traditional types of intervention, making these more specialist interventions a second-line approach. In addition to idiopathic SSD, biofeedback is used for clients with articulatory or motor disorders of known cause. EPG in particular is used for treating compensatory articulations in cleft lip and palate (see Lee, Law, & Gibbon, 2009, for a review). Likewise, as a motor-based disorder, childhood apraxia of speech has been treated with both ultrasound (Preston et al., 2013; Preston, Leece, McNamara, & Maas, 2017) and EPG (Lundeborg & McAllister, 2007). Children with developmental dysarthria due to cerebral palsy have also been treated with EPG, although further research is required with this group of children (Morgan, Liegeois, & Occomore, 2007; Nordberg, Berg, Carlsson, & Lohmander, 2008; Nordberg, Carlsson, & Lohmander, 2011).

Somewhat counterintuitively, children with phonological impairments have also been treated with both ultrasound (Cleland et al., 2015; Heng et al., 2016) and EPG (e.g., Dagenais, 1995; Dent, Gibbon, & Hardcastle, 1995; Friel, 1998). In these cases, the visual display may be used as a source of new feedback, and the intervention normally incorporates aspects of phonological intervention, such as minimal pairs therapy (Chapter 3). That is, instead of children practicing only a new articulation, they would explicitly contrast the target articulation with their error. Biofeedback might also be used for children with SSD whose surface-level error results in homophony but whose underlying articulatory patterns reflect

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undifferentiated lingual gestures, whereby the child is unable to differentiate the movement of the front and back of the tongue (Cleland, Scobbie, Heyde, Roxburgh, & Wrench, 2017; Gibbon, 1999) or covert contrast (Gibbon, 1990; McAllister Byun, Buchwald, & Mizoguchi, 2016). Biofeedback has therefore been used in the literature for children with almost all subtypes of SSD.

ASSESSMENT AND ANALYSIS METHODS

Biofeedback is often used to treat children with SSD who have been unresponsive to previous types of intervention. There is no standard assessment to determine whether or not the approach is suitable for an individual. Rather, the decision to trial a course of biofeedback is typically based on the surface form of the error (see Table 22.1 for suitable targets) and a lack of progress with either more traditional articulatory approaches (for children with distortion types of errors) or phonological approaches (for children whose errors are perceived as substitutions or omissions). When included as part of the assessment process, articulatory (EPG or ultrasound) and acoustic analyses are always used in tandem with auditory-impressionistic transcriptions and traditional speech assessments, such as single-word naming tasks.

All of the types of technology described here are also used extensively in the phonetics literature to measure aspects of speech that may be difficult to detect from auditory-impressionistic transcription. However, in the clinical literature, EPG is almost always used as both an intervention *and* an assessment tool because EPG provides normalized data that is easily quantified into indices. In contrast, quantification of ultrasound imaging data is in its infancy. In clinical practice, performing EPG, ultrasound, or acoustic analysis of data is a time-consuming process that requires specialized skills. However, several studies have shown that these types of analyses make it possible to identify speech patterns that suggest motor-based impairments. During assessment, instrumental techniques allow the clinician to circumvent problems with transcription that are influenced by categorical perception. That is, the clinician is more able to identify subtle phonetic errors and subphonemic contrasts (covert contrasts) when the data are objective. This is particularly important because children with abnormal anatomy, such as children with cleft palate, may make perceptually acceptable productions with unusual tongue–palate contact or tongue-shape patterns. Identifying subtle motor-based impairments changes the focus of intervention from a cognitive-linguistic approach to an articulatory and/or motor approach.

Assessment before and after biofeedback intervention usually follows the principles of any speech assessment. Traditionally, assessment has focused on the levels of body functions and structures (especially for children with cleft palate). Recent research has moved to also incorporating measures of activities and participation, since even mild distortions can cause social, emotional, and academic challenges (Hitchcock, Harel, & McAllister Byun, 2015). Any measures of activity and participation can be used alongside biofeedback assessment. In practice, assessment begins with a battery of standardized speech, language, and often cognitive measures to determine suitability for biofeedback. The speech assessment begins with assessment of the consonants and vowels of the target language in a variety of lexical and phonotactic contexts. Examples include the *Goldman-Fristoe Test of Articulation 3* (Goldman & Fristoe, 2015) and the *Diagnostic Evaluation of Articulation and Phonology* (Dodd, Zhu, Crosbie, Holm, & Ozanne, 2002, 2006) for children with articulation and phonological disorders, or the Cleftnet Protocol for children with cleft lip and

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palate (Gibbon & Wood, 2010). From these tasks, phonetic and phonological analyses reveal which consonants and vowels are in error in the child's system. Not all error patterns are suitable for remediation with biofeedback; the clinician therefore must select targets that are imageable with the technique of choice (Table 22.1). Typically, substitution or distortion errors are the focus of intervention rather than structural errors (such as cluster reduction), which might be better treated with other interventions. Moreover, the clinician should consider whether the error in question is likely to be visible on the biofeedback display. That is, errors that involve incorrect tongue placement would be suitable for EPG and ultrasound, whereas voicing and nasalization errors would not, although these could potentially be displayed acoustically. Which technique to choose also depends on the technology available to the clinician. For many clients, there may be only one potential error that can be treated. This is especially true of children with residual speech errors who present only with rhotic or sibilant errors. However, for other children with multiple errors, it can be more difficult to choose where to begin intervention. Cleland and colleagues (2015) suggest target selection should follow a developmental perspective, focused on imageable errors; however, more research in this area is required.

Once the intervention target has been selected, it is usual to audio-record (with ultrasound or EPG where applicable) a probe word list containing multiple exemplars of the target speech sound in a variety of lexical and phonotactic contexts, including different vowel environments, syllable positions, clusters, and multisyllabic words and sentences. Example lists can be found in the Ultrax2020 clinicians' manual (available at https://strathprints.strath.ac.uk/63372) and in Preston and Edwards (2007). Probe lists are important because single-word articulation tasks rarely provide sufficient opportunity to sample errors adequately (Macrae, 2017). Probes are not only useful for tracking intervention progress, they also give the clinician an opportunity to determine whether there are any contexts in which the target is produced correctly, which may provide a starting point for intervention. Likewise, stimulability testing is an important part of the assessment and may be an important prognostic factor (Preston, Leece, & Maas, 2017). Articulatory or acoustic analysis can determine whether children's productions during stimulability testing or imitation tasks are more accurate than spontaneous speech, or vice versa. Minimal pairs (in which the child's error results in homophony) are important to elicit for the purposes of identifying covert contrasts, and multiple repetitions of the same word gives indication of articulatory variability in children's speech.

Electropalatography

Researchers have used various classification systems to describe abnormal EPG patterns. Hardcastle and Gibbon (1997) subdivide errors into three main types: abnormal tongue–palate contact; abnormal timing; and spatial substitution errors, which are similar to those found in typical speech but in the wrong location (e.g., classic velar fronting where /k/ is produced as [t] with a realization similar to that of a typical child's /t/). These errors may concur with phonetic transcription of the child's speech, for example, in the case of spatial substitution errors, or they may reveal covert contrasts. The most frequent error is a spatial distortion, often occurring on sibilants. Figure 22.4 shows an example of an abnormal production of /s/ from a child with Down syndrome (right) alongside an example of /s/ from a typical child (left). Using specialized software, it is possible to average EPG patterns from multiple repetitions of the same word. In this example, the midpoint of the fricative /s/ from 10 repetitions of *sun* is selected and averaged. Darker squares represent electrodes that are

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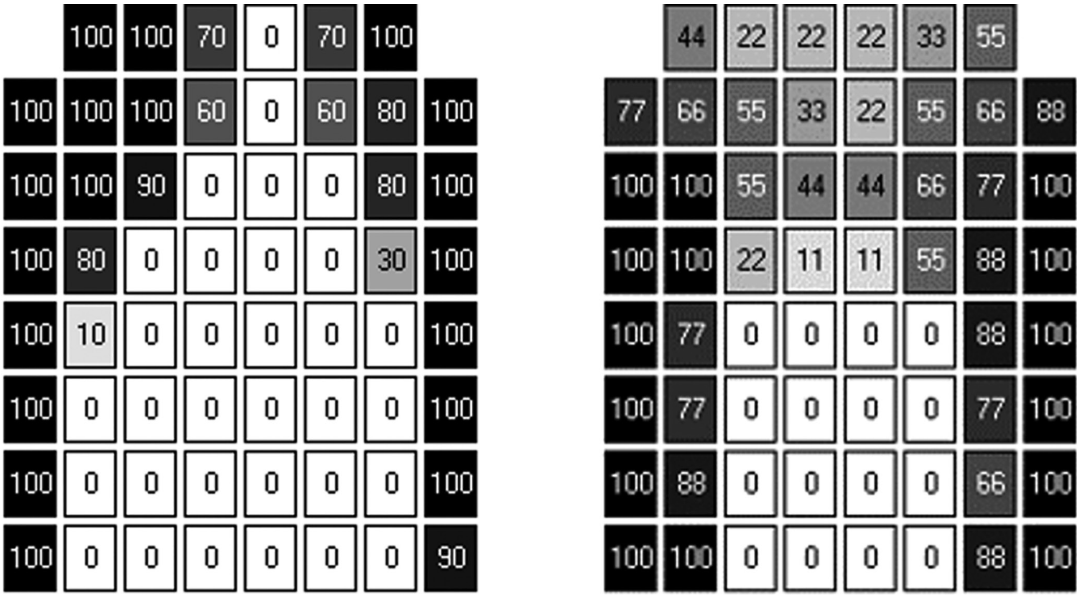

	100	100	70	0	70	100	
100	100	100	60	0	60	80	100
100	100	90	0	0	0	80	100
100	80	0	0	0	0	30	100
100	10	0	0	0	0	0	100
100	0	0	0	0	0	0	100
100	0	0	0	0	0	0	100
100	0	0	0	0	0	0	90

	44	22	22	22	33	55	
77	66	55	33	22	55	66	88
100	100	55	44	44	66	77	100
100	100	22	11	11	55	88	100
100	77	0	0	0	0	88	100
100	77	0	0	0	0	77	100
100	88	0	0	0	0	66	100
100	100	0	0	0	0	88	100

Figure 22.4. Typical tongue–palate contact for /s/ as seen with electropalatography.

activated more often. Electrodes in grey are therefore variably on or off, with a high degree of variability potentially indicative of speech motor control problems. In this example, the typical child consistently produces /s/ with a central groove, whereas the child with Down syndrome shows variable contact into the palatal region with no central groove, transcribed as [ɬ].

Ultrasound

Only a small number of studies have used ultrasound to identify errors in children with SSD. McAllister Byun and colleagues (2016) and Cleland and colleagues (2017) both used ultrasound to identify covert contrast in children who were fronting velars. Cleland's team (2017), in the same paper, additionally identified retroflex productions (for alveolar and velar targets) and undifferentiated lingual gestures in the speech of one child with a persistent SSD. In a study of children with cleft lip and palate, Cleland, Lloyd, et al. (2019) identify the same errors as those found with EPG, including abnormal tongue shapes, spatial substitutions, and timing errors. Figure 22.5 shows some examples of tongue shapes for distorted productions of rhotics in children with residual SSD.

Visual Acoustic

Visual-acoustic biofeedback can easily be used as both a treatment and a measurement tool. For example, in treatment of /ɹ/ distortions (e.g., McAllister Byun, 2017), LPC spectra can show the client a target low third formant (F3), which closely approximates the second formant (F2). This target can be contrasted with errors in rhotic production represented in the acoustic biofeedback as abnormally high F3 values. A posttreatment reduction in F3–F2 is therefore indicative of progress and potentially a quicker (if automated) and more reliable measure than a phonetic transcription (Campbell & McAllister Byun, 2018).

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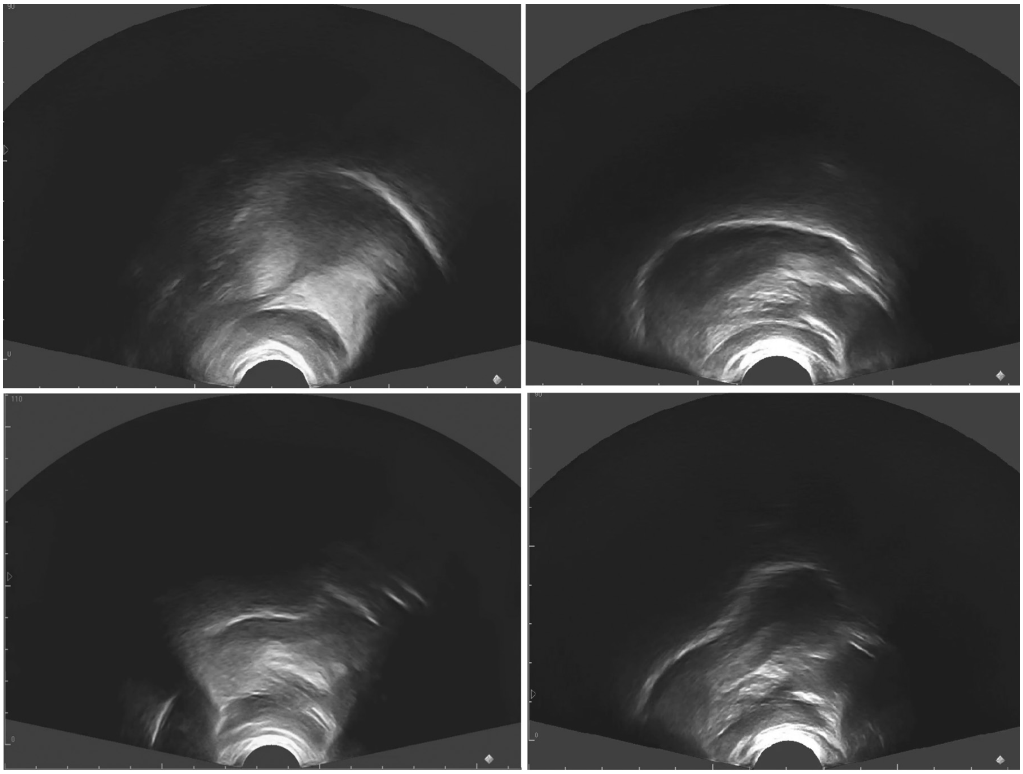

Figure 22.5. Distorted (top row) and correct (bottom row) tongue shapes for /ɹ/ with ultrasound imaging.

THEORETICAL BASIS

Speech sound learning can be described as a process of achieving appropriate articulatory movements to produce acoustic features that result in an acceptable form of a sound based on the speaker's language and dialect. Children with SSD have been found to differ from children with typical speech in their auditory perception of speech sounds, often resulting in poor recognition of errors (e.g., Shuster, 1998). Therefore, visual biofeedback is intended to add a new sensory modality to speech sound learning, presumably enabling clients to recognize correct and incorrect productions of sounds through the visual, in addition to the auditory, mode. Thus, during biofeedback interventions, aspects of cueing, feedback, and self-monitoring tend to emphasize what is seen and how it corresponds to what is heard.

Dominant Theoretical Rationale for the Intervention Approach

Biofeedback studies have often invoked Schema-Based Motor Learning Theory as a framework to conceptualize the role of visual feedback in learning new motor patterns (see Maas et al., 2008; Preston et al., 2014). Within this framework, feedback that is available to a learner can be broadly categorized as **knowledge of results** or **knowledge of performance**. Knowledge of results involves feedback only on accuracy (i.e., correct/incorrect, accurate/inaccurate). Knowledge of results feedback, therefore, requires that a client's production of a sound be broadly categorized as successfully matching the intended speech

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sound or not matching it (e.g., "Good /s/"or "That /k/ wasn't quite right"). However, knowledge of results feedback does not include specific information about why a production was correct or incorrect. Such detailed feedback about the specific nature of the client's production is provided in knowledge of performance feedback. Biofeedback provides the opportunity to offer specific knowledge of performance feedback, enabling the client to receive more exact information about the movements that were executed (with ultrasound or EPG) or the acoustic targets that were hit (with visual acoustic biofeedback). Biofeedback enables the clinician to provide feedback that is specific to the nature of the correct or incorrect production, such as "I saw you lift the front of your tongue, not the back of your tongue for the /k/" or "I didn't see you make a groove in the middle of the tongue for the /s/." The purpose of biofeedback is for the client to be able to interpret the visual display, judge the nature of their production, and begin to self-correct productions. This detailed feedback is likely to be most beneficial in the early stages of acquiring a speech sound, such as establishing a sound in isolation, syllables, or words (when individual sounds may be prolonged). Biofeedback is presumably less beneficial in the later stages of learning, such as practicing sounds in sentences or in conversational speech. Thus, clinically, it is important to determine whether the client is in the early stages of acquiring a speech sound (when biofeedback might be considered) or in the later stages of generalization (when biofeedback is less likely to be beneficial).

Level of Consequences Being Addressed

Biofeedback addresses speech intelligibility via improving speech movements. Within the framework of the *International Classification of Functioning, Disability and Health—Children and Youth Version* (ICF-CY; World Health Organization, 2007), the ultimate goal is to improve *d3 Communication,* and as a result, *d7 Interpersonal interactions and relationships*. Hitchcock, Harel, and McAllister Byun (2015) demonstrated that residual speech sound errors (which are often targeted in biofeedback therapy) cause Activity limitations and Participation restrictions. While reducing limitations and improving participation are clearly goals of the intervention, most of the empirical evidence focuses on measuring improvement only in *b320 Articulation functions*, and *b3 Voice and speech functions*, under the Body Functions component of the ICF-CY.

Target Areas of Intervention

Biofeedback primarily addresses speech motor learning, and therefore SSD is considered in the context of a difficulty with motor aspects of speech production. Biofeedback focuses almost exclusively on speech output, with the clinician working at the level of *b3 Voice and speech functions*. This is especially the case when the child presents with a residual speech sound error, such as a distorted /s/ or /ɹ/ or a compensatory articulation due to cleft palate. The goals of intervention tend to be very much impairment based, with further research required on expanding target selection to address aspects beyond this. However, since the intervention tends to be drill based, clinicians often ask for client input on target words (containing the target speech sound) to incorporate into the intervention. This allows the clinician to also incorporate highly functional goals, for example, accurate production of family member's names.

Speech perception is likely implicated in children with persistent or residual SSD, even when the distortions are relatively minor (McAllister Byun & Tiede, 2017). Many studies at least measure speech perception, even if they do not treat it. In two recent studies, perceptual training (in the form of correct/incorrect judgments of recorded words)

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was incorporated during treatment sessions along with ultrasound biofeedback in order to address the SSD at multiple levels of representation (Preston & Leece, 2017; Preston, Leece, et al., 2017). In studies of children with surface-level mergers (e.g., velar fronting [Cleland et al., 2015]), intervention may also incorporate elements of other interventions that include perception/input-level activities. For example, a child with velar fronting may be tested on perception of the contrast both auditorily and with the visual model, and biofeedback may be added to an approach such as minimal pairs intervention as a hybrid approach. More research is needed to determine the importance of speech perception training integrated into biofeedback.

EMPIRICAL BASIS

Studies investigating the effectiveness of biofeedback for treating children and adults with SSD began appearing in the literature in the 1980s. There are around 100 peer-reviewed articles, most of which report successful remediation of previously intractable SSD. Most of the intervention studies are single case reports or case series, with only a few small-group studies (see Table 22.2). Studies report on a wide variety of etiologies and subtypes of SSD (discussed earlier), but idiopathic SSD (including **articulation disorders** and residual speech sound errors [RSSEs]) and cleft lip and palate form the most substantial portion of the literature.

A 2009 Cochrane review of EPG for treating compensatory articulations in cleft lip and palate (Lee, Law, & Gibbon, 2009) concluded that there was a lack of high-quality evidence for EPG, with only one small randomized controlled trial (RCT) meeting inclusion criteria for the review. A recent systematic review of ultrasound biofeedback (Sugden, Lloyd, Lam, & Cleland, 2019) found that the majority of studies are single case experimental designs or case studies, with few group studies. A review of all three biofeedback techniques (Hitchcock, Swartz, & Lopez, 2019) focusing on treatment intensity found a small relationship between treatment intensity and efficacy but again concluded that further research is required. There are currently no meta-analyses on biofeedback for SSD. Therefore, despite the large number of published studies, there is a lack of high-quality, particularly group, studies for all three types of biofeedback.

Several recent studies of all three biofeedback techniques have employed various types of single case experimental designs (level 2; see Table 22.2). These more robust designs show that biofeedback can be clinically useful for establishing new articulations. However, unlike the case studies conducted in the 1980s and 1990s, they also show that some children do not respond or have difficulty with generalization (e.g., McAllister Byun & Campbell, 2016; Preston, Maas, Whittle, Leece, & McCabe, 2016). Effect sizes vary in the literature from no effect in specific children (nonresponders) to large effect sizes where children begin the intervention with 0% target correct and are discharged with 100% (e.g., Preston et al., 2013). In recent studies, outcomes are normally measured on the basis of speech sound accuracy on untreated word lists. This approach has the advantage of measuring generalization, but the disadvantage is that children who are not able to generalize at the end of the intervention period appear as nonresponders even if they were able to achieve the target articulation in limited contexts. This concurs with a UK survey of clinical practice with EPG where clinicians noted that 60 children treated between 1993 and 2003 made gains in improving their articulation, but many had difficulty generalizing their new skills to everyday situations (Gibbon & Paterson, 2006). It is therefore probable that earlier studies were subject to selection bias in publication.

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Table 22.2. Levels of evidence for biofeedback interventions

Level	Description	Biofeedback type	References supporting the intervention	References that do not support the intervention
1	**Meta-analysis, systematic review, randomized controlled trial** (RCT)	US	Bressman, Harper, Zhylich, & Kulkarni, 2016; Furniss & Wenger, 2018; Preston, Hitchcock, & Leece, 2020; Sugden, Lloyd, Lam, & Cleland, 2019	
		EPG	Dagenais, Critz-Crosby, Fletcher, & McCutcheon, 1994; Gibbon et al., 2001; Lee, Law, & Gibbon, 2009; Michi, Yamashita, Imai, Suzuki, & Yoshida, 1993	Wood, Timmins, Wishart, Hardcastle, & Cleland, 2019
		US/EPG/Ac	Hitchcock, Swartz, & Lopez, 2009	
2	**Controlled study without randomization** (single case experimental design [SCED], case control study, cohort study, quasi-experimental study)	US	Bacsfalvi, 2010; Heng, McCabe, Clarke, & Preston, 2016; Preston, Brick, & Landi, 2013; Preston, Holliman-Lopez, & Leece, 2018; Preston, Leece, & Maas, 2017; Preston, Leece, McNamara, & Maas, 2017; Preston et al., 2014; Preston et al. (2019); Sjolie, Leece, & Preston, 2016	Preston, Maas, Whittle, Leece, & McCabe, 2016
		Ac	Ertmer, Stark, & Karlan, 1996; McAllister Byun, 2017; McAllister Byun & Campbell, 2016; McAllister Byun & Hitchcock, 2012; McAllister Byun, Swartz, Halpin, Szeredi, & Maas, 2016	
		EPG	Lohmander, Henriksson, & Havstam, 2010; Hitchcock, McAllister Byun, Swartz, & Lazarus, 2017; Pratt, 2007	
3	**Nonexperimental/nonanalytic studies** (correlational study, case report, case study)	US	Adler-Bock, Bernhardt, Bacsfalvi, Gick, Radanov, & Williams, 2005; Bernhardt, Gick, & Bacsfalvi, 2007; Bernhardt et al., 2008; Cleland, Scobbie, & Wrench, 2015; Cleland, Scobbie, Roxburgh, Heyde, & Wrench, 2019; Fawcett, Bacsfalvi, & Bernhardt, 2008; Hitchcock & McAllister Byun, 2015; Lee, Wrench, & Sancibrian, 2015; Lipetz & Bernhardt, 2013; Modha, Bernhardt, Church, & Bacsfalvi, 2008; Preston & Leece, 2017; Preston, Leece, & Maas, 2016; Roxburgh, Cleland, & Scobbie, 2016; Shawker & Sonies, 1985	—
		US & EPG	Bacsfalvi & Bernhardt, 2011; Bacsfalvi, Bernhardt, & Gick, 2007; Bernhardt, Gick, Bacsfalvi, & Ashdown, 2003	
		Ac	McAllister Byun et al., 2017; Shuster, Ruscello, & Smith, 1992; Shuster, Ruscello, & Toth, 1995	
		Ac & Aero	Ruscello, Yanero, & Ghalichebaf, 1995	

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Table 22.2. *(continued)*

Level	Description	Biofeedback type	References supporting the intervention	References that do not support the intervention
		EPG	Bernhardt, Bacsfalvi, Gick, Radanov, & Williams, 2005; Carter & Edwards, 2004; Cleland, Timmins, Wood, Hardcastle, & Wishart, 2009; Crawford, 1995; Dagenais, Critx-Crosby, & Adams, 1994; Dent, Gibbon, & Hardcastle, 1992, Fletcher & Hasagawa, 1983; Friel, 1998; Gibbon & Hardcastle, 1987, 1989, 1999; Gibbon, Hardcastle, Dent, & Nixon, 1996; Gibbon, Dent, & Hardcastle, 1993; Gibbon, Hardcastle, & Moore, 1990; Gibbon & Lee, 2015; Gibbon & McKenzie Beck, 2002; Gibbon, McNeill, Wood, & Watson, 2003; Gibbon & Wood, 2003; Hickey, 1992; Lundeborg & McAllister, 2007; McAuliffe & Cornwell, 2008; Michi, Suzuki, Yamashita, & Imai, 1986; Morgan Barry, 1995; Morgan, Liegeois, & Occomore, 2007; Moses, 1939; Nordberg, Carlsson, & Lohmander, 2011; Pantelemidou, Herman, & Thomas, 2003; Öller Darelid, Hartelius, & Lohmander, 2016; Scobbie, Wood, & Wrench, 2004; Suzuki, 1989; Wood, Wishart, Hardcastle, Cleland, & Timmins, 2009	
4	**Expert opinion** (expert committee report, consensus conference, clinical experience of respected authorities)	US	Bernhardt, Gick, Bacsfalvi, Adler-Bock, & Adler-Bock, 2005; Preston, McAllister Byun, Boyce, et al., 2017	—
		Ac	Ruscello, 1995	
		EPG	Dagenais, 1995; Dent, Gibbon, & Hardcastle, 1995; Maine & Serry, 2012; Morgan Barry & St. Leger, 1995	

Levels of evidence are adapted from the Scottish Intercollegiate Guideline Network: https://www.sign.ac.uk/assets/sign_grading_system_1999_2012.pdf.

Key: Ac, acoustic biofeedback; Aero, aerodynamic biofeedback; EPG, electropalatography; US, ultrasound biofeedback.

There remains a pressing need for good-quality RCTs for all three biofeedback techniques both to determine whether they are more effective than traditional motor-based interventions and to determine which biofeedback technique is most useful for which children. To date, two small-scale RCTs (n = 6, n = 17) comparing ultrasound biofeedback and traditional non-biofeedback treatment showed roughly similar improvements between treatments in children with idiopathic SSD (Bressmann et al., 2016; Furniss & Wenger, 2018). One RCT for children with residual /ɹ/ errors (n = 36) showed that treatment that included ultrasound biofeedback did not differ from a treatment that included

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both ultrasound biofeedback and speech perception training (Preston, Hitchcock, & Leece, 2020). Additionally, one RCT used a cross-over design in which 12 children were randomized to receive either four sessions of EPG biofeedback followed by four sessions of non-EPG treatment, or the reverse (Gibbon et al., 2001). The researchers suggested that the EPG treatment resulted in more normalization of tongue–palate contact for /t/ and /s/ compared to non-EPG treatment, although some children failed to respond to both treatment conditions. An RCT with children with hearing loss (n = 18) suggested that EPG could result in improvements in speech sound production that were as good as or better than non-biofeedback treatment (Dagenais, Critz-Crosby, Fletcher, & McCutcheon, 1994). Larger-scale studies are needed to definitively determine if biofeedback treatment outperforms no-biofeedback as well as to determine predictors of response to intervention. Overall, the evidence points toward the use of biofeedback for acquiring new articulations in children with articulatory or motor-based disorders; however, further intervention may be required to cement new articulations and promote generalization to everyday situations. Table 22.2 summarizes the levels of evidence for the research reviewed in this section.

PRACTICAL REQUIREMENTS

Each of the three biofeedback approaches requires access to technology that may not be readily available. Acoustic biofeedback needs only a microphone and a computer/device and is potentially the cheapest and easiest technique to access; it is also most suitable for home practice. In fact, McAllister Byun and colleagues (2017) developed an iOS app, staRt, for treatment of rhotic distortions. Similar apps for treatment of other sonorants exist but are typically not supported by research evidence at present.

Both ultrasound and EPG are more expensive techniques that are primarily available in specialist clinics and universities. An exception is cleft palate clinics in the United Kingdom, which typically have access to EPG (Lee et al., 2009). EPG equipment typically consists of a pseudopalate, connector (to transfer the signal from the palate to the computer), and computer or home-practice unit. Because each pseudopalate is custom made, clients must visit the dentist to have an impression made of their upper teeth prior to manufacture of the palate. This necessitates a waiting period between initial assessment for suitability of EPG and commencement of treatment. It also means that the cost per patient is relatively high for this technique, with pseudopalates costing between about $200 (CompleteSpeech palate) and $600 (Reading palate) in 2019. EPG systems are available from CompleteSpeech (https://completespeech.com) and Rose Medical (http://rose-medical.com). Both systems have home-practice versions available, which may enable clients to practice with greater intensity.

Ultrasound systems comprise a transducer (probe) and a processor, which may be an independent (cart-style or laptop) system or a USB-compatible system, which connects to a standard PC/tablet. Ultrasound systems vary widely in price, from around $6,000 to more than $100,000 in 2019. (The more expensive devices often are designed for imaging areas of the body that require more advanced techniques, but the less expensive devices are typically suitable for speech therapy.) In order to use ultrasound for biofeedback, the clinician needs only a standard B-mode **medical ultrasound** system, normally with a convex (40–60 mm) or microconvex (20 mm) probe. This provides adequate real-time feedback of articulations. However, in order to perform a detailed articulatory assessment, a system that can synchronize and record ultrasound and acoustics is useful. Systems designed by

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Articulate Instruments Ltd. and Ultraspeech-tools have both been used in intervention studies, though other systems exist in research laboratories. At present, ultrasound is not available for home practice, though clinicians may still provide non-biofeedback homework tasks designed to support the in-clinic learning.

Nature of Sessions

Since biofeedback sessions incorporate principles of motor learning, intensive clinician-led individual practice is required. Sessions are normally individual and last between 30 minutes and an hour. The number of sessions required varies widely across the literature from 1 (Bernhardt et al., 2008) to more than 50 sessions (Hitchcock et al., 2017). At present, the optimal dosage of biofeedback intervention is unknown but is likely to vary, with children with residual distortions or cognitive impairments requiring a greater number of sessions. The number of trials achieved within each session is also likely to be an important dosage factor, with several hundred trials elicited in many sessions (e.g., Preston, Leece, & Maas, 2017).

Personnel

Biofeedback is a treatment that may, in some instances, require significant therapist time and significant commitment from clients. However, it should be noted that some studies report years of ineffective therapy followed by quick progress with biofeedback. Such reports suggest that biofeedback may be potentially more cost effective than other interventions. Typically, clients are also required to travel to clinics to be treated by specialist clinicians, which may be a practical limitation. However, Bernhardt and colleagues (2007) describe a model wherein local clinicians provided ultrasound treatment in conjunction with web-based consultation with specialist university-based clinicians. Likewise, the CLEFTNET UK project (Lee, Gibbon, Crampin, Yeun, & McLennan, 2007) was designed to link cleft centers using EPG to a central university-based laboratory for help analyzing EPG data and planning intervention. The ULTRAX2020 project (Cleland, Wrench, Lloyd, & Sugden, 2018) provides a similar system for clinicians using ultrasound in the UK. An alternative model is intensive delivery (Preston & Leece, 2017; Preston, Leece, & Maas, 2016) where clients travel to specialist clinics for a defined period of time for daily intervention. This may be both cost effective and theoretically motivated, as intensive practice may be beneficial in the early stages of acquiring new articulations (Sugden et al., 2019). Caregivers are often not mentioned explicitly in the literature as being a key part of the intervention team. The exception to this is EPG, where portable training units may be used for home practice, often supported by a parent or caregiver. EPG has also been used by educational support staff (learning assistants) in a study of children with Down syndrome where more intensive intervention was made possible using a consultation and training model (Wood, Grayson, & Timmins, 2016)

KEY COMPONENTS

The key components of biofeedback are a real-time visual display representing the client's speech production and drill-based practice to achieve more accurate articulatory movements. This practice is coupled with detailed verbal feedback from the treating clinician to help the client interpret the images. Thus, the most essential and unique component is the use of the visual display to discuss actions that were correct (e.g., "Good job pulling

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the tongue root back for /ɹ/") or incorrect (e.g., "I didn't see you make a groove for the /s/"). In addition, as children are familiarized with the visual display, self-monitoring and self-correction of errors become key elements to biofeedback intervention.

Target Selection

Specific sound targets are typically singletons or sequences of sounds, and the type of biofeedback limits the targets that may be suitable (see Table 22.1). Often, a single target sound is chosen, especially if there is only one error in the child's system, such as a distorted sibilant or rhotic. Where there are to be multiple targets chosen in the case of children with more complex SSD, these can be addressed sequentially (e.g., Preston et al., 2014) or by dividing sessions into practice on multiple targets (e.g., Preston et al., 2013).

Goals

The goal is to learn to produce a specific speech sound, or sequence of sounds, and then integrate this sound into continuous speech. Goal attack strategies are therefore typically vertical, targeting one or two speech sounds or sequences at a time. Typical biofeedback sessions begin by clients learning to associate the movements of their articulators with the images they see on the screen. Even though the image may be abstract, especially in the case of acoustic displays, when children can see the effect their own articulations have on the visual display, it helps them to bootstrap their proprioceptive and tactile feedback with the new visual modality. Understanding the visual display is thought to be relatively intuitive, even for children with cognitive impairments (Cleland et al., 2009).

Procedures

In biofeedback intervention, the clinician and client focus on a digital display (computer or ultrasound monitor). Normally, the clinician and client sit side by side facing the display, and caregivers may or may not be involved. The software used to display the biofeedback varies widely but has in common the fact that the display is in (near) real time. This is important because it allows the child to change his or her articulations in response to visual and verbal feedback from the clinician *while* in the act of articulating.

Clinicians may begin by asking the client to copy movements/tongue-shapes/contact patterns that were identified in the assessment as being present in the child's phonetic inventory. Initially, speech sounds tend to be practiced slowly in order to make the visual acoustic or articulatory processes last for a sufficient duration that the child can interpret the image. Once the child has learned to associate the movements of their articulators with the display, the clinician provides the client with a target to emulate. The target is described either by pointing out particular regions on the screen (e.g., "raise the back of your tongue to *here*") or by providing a visual model ("copy this movement" or "make this EPG pattern"). In the case of EPG, quasi-static contact patterns, which are based on the speech of typical adult speakers, are often used. Alternatively, the clinician may model an appropriate contact pattern, freezing the display at the point of maximum contact and discussing the salient features of the target pattern. For example, if a child has a lateral lisp, the clinician may model /s/ with central airflow and discuss the need to make contact between the sides of the tongue and the insides of the molars while making a "tunnel down the middle for the air to escape."

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Alternatively, the clinician may use shaping techniques, attempting to achieve /s/ from a rapid [t t t t t sː]. For ultrasound, many studies use live demonstration by the clinician of appropriate tongue movements (e.g., Bernhardt, Gick, Bacsfalvi, & Ashdown, 2003; Bressmann et al., 2016; Preston, Leece, & Maas, 2016), or static images of tongue shapes (e.g., McAllister Byun, Hitchcock, & Swartz, 2014), although Cleland and colleagues (2015) used videos of typical children producing the target. For visual acoustic treatment of rhotics, the child is instructed to match the third formant location to a visual target. Recent research aims to individualize the location of this formant target (Campbell & McAllister Byun, 2018). Individualization of targets is important across all three biofeedback techniques because the eventual perceptually acceptable articulation the child achieves may be realized in heterogeneous ways due to either motor equivalence (e.g., bunched versus retroflex /ɹ/) or abnormal anatomy (e.g., in cleft palate). It is therefore important that the clinician bears in mind that the aim of the intervention is to produce perceptually acceptable speech, not a particular tongue-shape or contact pattern (McAllister Byun et al., 2014). However, certain salient features of the target will be universal; for example, an acceptable /s/ requires a central groove, albeit the contact pattern may be asymmetrical.

Establishing a new articulation is both the key strength of biofeedback and the most difficult part of the intervention, particularly if the client is not stimulable for the target. While the live visual display is unique to biofeedback, the clinician uses the visual feedback along with many other articulatory intervention techniques (e.g., modeling, phonetic cueing, shaping) to elicit an acceptable production. Facilitative contexts can be used to elicit a new articulation; for example, a high back vowel may facilitate a velar. Biofeedback interventions therefore share much in common with traditional articulation therapy (see Chapter 17). Occasionally, clinicians will find it useful to begin with a silent articulation with EPG or ultrasound (Hardcastle, Gibbon, & Jones, 1991) to avoid evoking an old motor program.

List of General Therapy Steps

The general sequence of intervention is shown in Figure 22.6. Once the child is able to achieve the target, the aim is generally to move through increasingly complex articulatory contexts towards achieving acceptable conversational speech. The clinician should ensure that the difficulty of each speech performance task is neither too difficult nor too easy for the child. Some recent studies work within the “challenge point framework” (Hitchcock & McAllister Byun, 2015, p. 59) where the child is required to achieve 80% accuracy at a specific level of an articulatory hierarchy before moving onto a more difficult context. For example, a child working on prevocalic /ɹ/ might be required to produce 80% accurate /ɹ/ onsets in single syllable words before moving onto disyllabic words. It is not necessary for a child to achieve 100% accuracy within a session in order to begin working at a more difficult level; in fact, this may impede generalization (Hitchcock & McAllister Byun, 2015).

At all stages in the intervention, the child is encouraged to use the visual display to self-monitor and self-correct their errors. Frequency of feedback from the clinician should be faded. The amount of biofeedback should also be reduced as the intervention progresses to allow the child to self-monitor and self-correct based on the auditory feedback (Preston et al., 2018). Once the child has established the new articulation, sessions should incorporate some practice without the biofeedback, increasing the time without biofeedback as intervention progresses.

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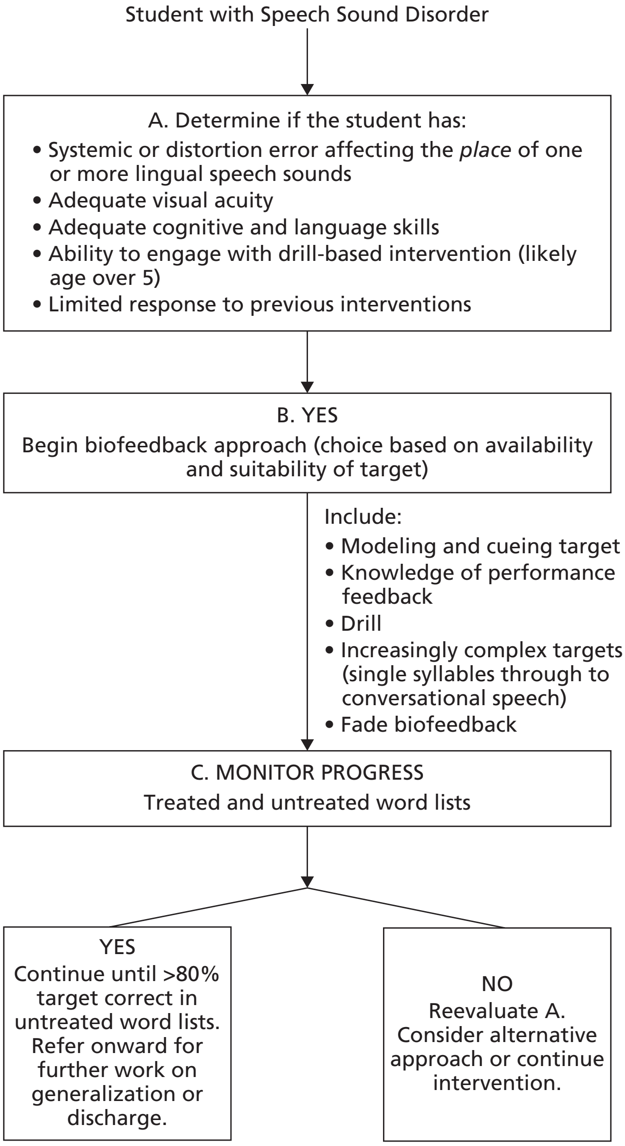

Figure 22.6. Flowchart of the general sequence of intervention steps for biofeedback.

Activities in Which Procedures Are Embedded

The activities in biofeedback are generally drill based, aiming to achieve a high number of trials in a session. Normally, a target-specific list of words is used in the intervention, and these may be presented to children as either written text or picture cards, depending on their age and the type of software being used. The activities can be embedded in various games for younger children; for example, games that involve dice throws can be useful in eliciting large numbers of trials. However, in the early stages of intervention, it is important that the clinician ensures that children are looking at the biofeedback screen and not concentrating their attention on any games that are being used as reinforcements.

MONITORING PROGRESS AND GENERALIZATION

Progress during intervention is principally measured perceptually, but it can also be measured using the biofeedback technique itself—for example, by monitoring changes in EPG contact patterns or acoustic parameters. As is standard practice for most motor-based speech interventions, acquisition is measured by tracking accuracy of target words that have been explicitly treated in the intervention sessions. It is useful to collect these word lists during each session—either at the end of the session to measure acquisition or at the beginning of the next session to measure retention from the previous intervention session (e.g., Sjolie, Leece, & Preston, 2016). Progress can be monitored quickly and easily by the clinician by transcribing the word lists and calculating the percentage of targets correct. This is especially important when following a challenge point framework approach wherein the child is required to produce a particular number of productions correctly (often 8 out of 10) before progressing to a different phase in intervention.

It is also important to monitor progress by measuring generalization. With respect to biofeedback, two types of generalization are important: accuracy of untreated words/sentences (and beyond) and accuracy of productions elicited without the biofeedback. It can be useful to record untreated word lists simultaneously with the imaging technique in order for the clinician to also monitor objective changes in articulation or acoustics; this can be achieved by covering the display during the recording. (For EPG it should be noted that the presence of the pseudopalate alters sensory feedback, and therefore it may be necessary to monitor progress without the palate in place.) The frequency with which generalization should be monitored varies in the literature from every session to approximately once per month. Clinicians are encouraged to follow the protocol in their particular working environment for frequency of assessment and review.

CONSIDERATIONS FOR CHILDREN FROM CULTURALLY AND LINGUISTICALLY DIVERSE POPULATIONS

Access to certain biofeedback technologies remains limited in some regions, particularly in Majority World countries and in rural communities. However, biofeedback approaches may be clinically appropriate for many clients, including those who are multilingual. Target selection for biofeedback intervention in children with SSD is of course guided by language and dialect. For example, allophones of /t/ vary by prosodic and phonetic context; clinicians should be mindful that training a lingual target for a voiceless alveolar stop [t] in word-initial position such as *tin* will differ significantly from the glottal stop [ʔ] found in within word positions such as *mitten*. Furthermore, biofeedback approaches may be particularly useful for learning the phonetic features of a new language. It is important to focus treatment on achieving productions that are acoustically appropriate for the dialect, not necessarily productions that conform to a specific visual pattern on a feedback display (which may vary somewhat across dialects).

Because most biofeedback approaches rely heavily on technology, it is worth considering whether clients may object to their use for cultural or religious reasons. For example, some members of Orthodox Judaism and other religions may refrain from using certain technologies, and they therefore may prefer interventions that are not technologically enhanced. Likewise, clients who observe Ramadan may wish to refrain from using EPG during this time, since it involves insertion of the pseudopalate. Thus, it is important to discuss with patients and their families how, when, and why biofeedback interventions may be implemented. Engaging in cooperative decision making will ensure that clients' values and beliefs are respected as part of the clinical process.

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Case Studies

The case studies that follow illustrate how ultrasound biofeedback may be used in intervention.

Scott

Scott, a 6-year-old boy with a long history of consistent phonological impairment, was referred for ultrasound biofeedback as part of a research project at a Scottish university. (Scott [pseudonym] is reported in Cleland et al., 2015, and Cleland et al., 2017, as "01M (Ultrax)"). He had received multiple different phonological interventions over the preceding 3 years but continued to present with velar fronting, which had been unresponsive to intervention. Scott was offered ultrasound biofeedback with the initial goal of establishing correct production for velar plosives and the ultimate goal of correct production in conversational speech.

Assessment with the Diagnostic Evaluation of Articulation and Phonology: Articulation (Dodd et al., 2002) assessment showed that Scott spontaneously produced all the consonants of English in words except /k/, /g/, /ŋ/, /ʃ/, /ʒ/, and /ɹ/. On imitation, Scott achieved /ʃ/, /ʒ/. Scott was not able to achieve an accurate velar (or /ɹ/); however, ultrasound assessment of stimulability during production of velars revealed that Scott produced a retroflex stop for /k/ when he produced it in isolation. While this was not used in spontaneous speech, it perhaps demonstrated effort on Scott's part to achieve contrastiveness or at least a more posterior articulation.

On a target-specific word list, Scott achieved 0% velars correct, with all velars fronted to alveolar stops in words and sentences. Ultrasound assessment revealed that /t, k/ minimal pairs were produced identically, indicating no covert contrast (see Cleland et al., 2017). Children who persistently do not differentiate coronal and dorsal articulations may have an underlying motoric deficit. Gibbon (1999) suggests that this may manifest as an "undifferentiated lingual gesture" (p. 382), where the tongue moves as a whole, rather than, as expected, by executing gestures using independent parts.

Scott received eleven 45-minute sessions of ultrasound biofeedback therapy. Working through an articulatory hierarchy, intervention began by using a video model of a typical child producing a velar to elicit a velar nasal /ŋ/ (the nasal was chosen because it could easily be sustained, whereas plosives are fleeting). He achieved a velar nasal in his first session, though the clinician identified incorrect retroflexes and undifferentiated lingual gestures on the ultrasound display. By session 5, Scott was able to produce a dorsal stop, but it was transcribed as uvular. By session 11, Scott had generalized his new production to conversational speech, but it remained more retracted than expected (see Figure 22.7). At this point, the intervention was successful in that Scott had achieved a contrast between velars and alveolars; however, his speech still sounded different from that of his peers.

Scott returned to the university clinic 6 weeks later. He had retained his contrast between alveolars and velars and had also refined his production to be more in line with typical children and clearly velar rather than uvular. His productions had also become more consistent, indicating better speech motor control during velar gestures. Figure 22.7 shows a clear difference between pretherapy, posttherapy, and 6 weeks posttherapy average tongue shapes for /k/. At 6-weeks postintervention, he scored

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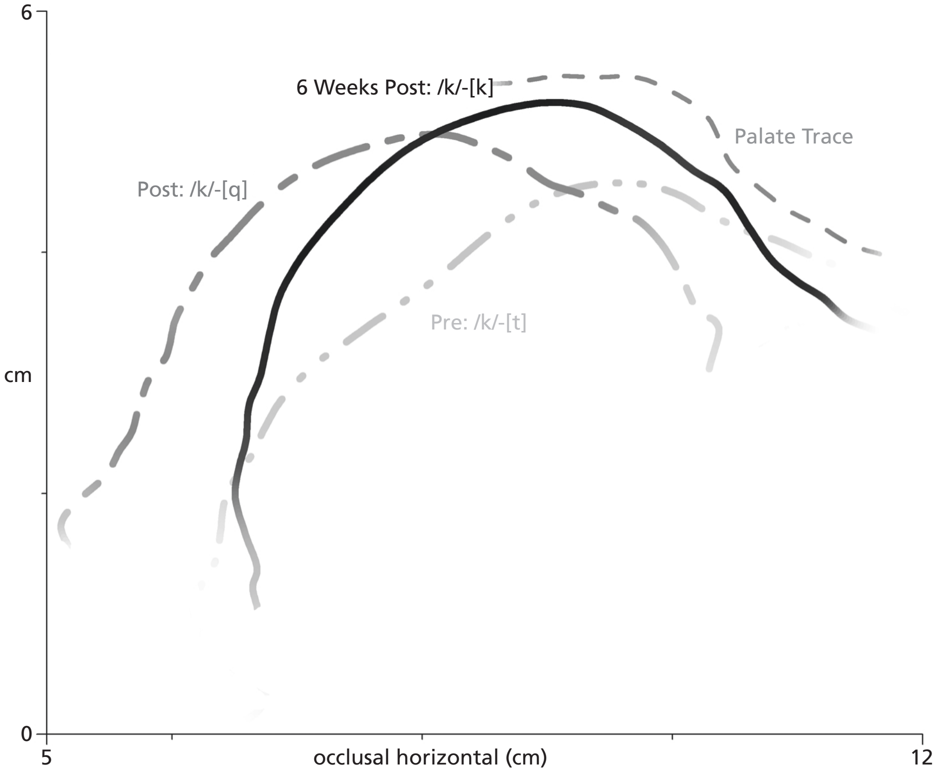

Figure 22.7. Tongue shapes for /k/ pre- and posttherapy.

100% velars correct in an untreated word list, and all productions were scored as phonetically accurate velars. Velars were correct in conversational speech. Scott's mother said, "Scott had speech therapy over an extensive time period, specifically focused on the *k* sound. Despite this, and their hard work, he was unable to make this sound. However, with ultrasound, he quickly grasped the correct positioning of the tongue and was able to generalize the sound. . . . His confidence has increased and he is now able to communicate clearly without anxiety."

Katia

Katia was a 17-year-old female with typical speech development with the exception of a persistent distortion of American English /ɹ/ (see Preston & Leece, 2017). She received traditional articulation therapy twice weekly from ages 13 to 15 years but was unsuccessful at improving her /ɹ/. She therefore attended an intensive treatment program at the age of 17. Therapy consisted of fourteen 1-hour treatment sessions over 5 days that included auditory perceptual training, speech practice with ultrasound biofeedback (24 minutes per session), and practice without biofeedback. Prior to treatment, she was not stimulable for correct /ɹ/ in any contexts. Before treatment, her distorted /ɹ/ was characterized by a high posterior tongue dorsum and low tongue blade (see Figure 22.5, left column) accompanied by occasional nasal emission.

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During treatment, Katia was cued to achieve a correct /ɹ/ by focusing on lowering the tongue dorsum, elevating the tongue blade and retracting the tongue root. She had particular difficulty maintaining a low tongue dorsum, and therefore practice included some phonetic contexts that were intended to be facilitative (e.g., low vowels such as /ɹæ/, /ɑɹ/). Speech motor chaining procedures were used to build core syllables to longer utterances, including monosyllabic words, multisyllabic words, phrases, and sentences. Self-evaluation was emphasized during treatment to encourage her to recognize correct and incorrect productions and to pair those judgments with the tongue shape on the display. She did not achieve any correct productions during the first 2 hours of therapy, but in the third hour, she produced over 50 correct syllables, and by the 14th hour, she exceeded 600 correct productions in an hour-long session (with stimuli ranging from syllables through sentences). Posttreatment, Katia's accuracy on untrained /ɹ/ words without biofeedback was 55%, and her accuracy in untrained sentences without biofeedback was 40%. Because of this level of accuracy, biofeedback was no longer required. However, she continued to work on generalization to complex speech tasks (phrases, sentences, and conversation) for more than a year in order to stabilize productions in connected speech. The intensive week with biofeedback therefore facilitated acquisition of /ɹ/, but additional practice was required for generalization.

LEARNING ACTIVITIES

The following learning activities will help readers consolidate their understanding of biofeedback intervention.

1. Describe a good candidate for biofeedback intervention. Focus on the child's likely age and speech errors.
2. Compare and contrast acoustic biofeedback, ultrasound biofeedback, and electropalatography. What are the main advantages and disadvantages of each technique?
3. Choose an appropriate biofeedback technique, initial target, and cueing strategy for Sarah, who is 10 years old. She has a history of moderate to severe SSD with resolution of all errors except residual rhotic and sibilant distortions. She is getting teased at school because she cannot say her own name properly. Previous speech therapy notes show that Sarah has a lateralized /s/ and /z/ (although other sibilants are accurate) and a uvular approximant realization of /ɹ/ in both prevocalic and postvocalic word positions.

FUTURE DIRECTIONS

As the cost of technologies decreases, access to technologies increases, and as training becomes available, biofeedback approaches will undoubtedly become more common. It is possible that, rather than biofeedback being considered after other treatments have failed, these approaches may soon represent an essential component of standard care. However, it will be important to identify characteristics of clients who are best suited to biofeedback interventions (i.e., likely responders or nonresponders to the intervention). Moreover, the visual information provided by these technologies may be diagnostically useful, and studies are needed on how to apply images of articulatory or acoustic features of speech to clinical diagnosis, prognosis, and treatment planning.

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The present levels of evidence are primarily case reports and single case experimental designs. Thus, there remains a pressing need for higher levels of evidence, including further randomized controlled trials, to support the evidence base for biofeedback interventions. Such studies could compare biofeedback approaches to more traditional (non-biofeedback) treatments, or could compare different types of biofeedback. Furthermore, translational studies will be needed to determine if the treatment effects that have been observed in clinical research can be replicated in more traditional settings such as schools and hospitals. Research on the optimal dosage and service delivery models would also be of clinical value.

New technologies beyond those described in this chapter are likely to emerge, including electromagnetic articulography (EMA; e.g., Katz, McNeil, & Garst, 2010), which has recently been implemented with adults with acquired speech impairments and young people with RSSEs (e.g., Mental, 2018). Finally, advances in technology will inevitably result in greater accessibility and implementation. Thus, we expect biofeedback to play a critical role in the future management of children and adults with SSD.

SUMMARY

Biofeedback interventions aid the therapeutic process by providing technologically enhanced visual displays of articulatory or acoustic information. Clients are taught to recognize salient aspects of their productions based on visual displays and they can eventually learn to self-monitor and self-correct. Ultrasound and EPG highlight the *articulatory* targets of speech sounds, whereas visual acoustic feedback highlights *acoustic* features of speech sounds. Biofeedback is particularly useful to help establish new speech patterns, but it should be gradually withdrawn to facilitate generalization.

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