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VOWEL IMAGING

Alice Lee, Natalia Zharkova, and Fiona E. Gibbon

Various imaging techniques have been used for directly viewing or tracing articulatory movements during vowel production. Some of the instruments were developed to investigate normal speech and were subsequently used for disordered speech. Others were developed to investigate different body parts and were later applied to the articulators for examining the cause of vowel misarticulation. The techniques described in this chapter include electropalatography (EPG), ultrasound, X-ray, magnetic resonance imaging, and motion tracking – electromagnetic articulography and optoelectronic. They are presented in the order of how commonly they have been used in research and clinical settings and this starts with EPG.

ELECTROPALATOGRAPHY

Electropalatography (EPG) is a technique that detects and displays visually the tongue's contact against the hard palate during speech. A few different EPG systems have been developed and three have dominated over the past 40 years. A British system, developed originally at the University of Reading, was used in the majority of studies conducted in Europe and Hong Kong (Gibbon and Wood 2010; Hardcastle and Gibbon 1997; Hardcastle, Gibbon and Jones 1991). A new Windows® version of the Reading EPG – WinEPG™, has been developed more recently (Articulate Instruments Ltd). The Kay Palatometer was used most widely in the United States (Fletcher 1983) although there is now a new EPG system manufactured by CompleteSpeech™, which was formerly known as LogoMetrix® (Schmidt 2007). The Rion EPG was most widely used in Japan (Fujimura, Tatsumi and Kagaya 1973) but this system has not been available commercially since 1996 (Fujiwara 2007). All EPG systems differ in details such as the construction of the dental plates, number and configuration of sensors, and the hardware and software specifications but they share some common general features.

A component of all EPG systems is an artificial plate, which is custom-made from an accurate dental impression to fit against a speaker's hard palate (Hardcastle and Gibbon 1997). Embedded in the artificial plate are sensors exposed to the lingual surface that detect tongue contact. The traditional Reading plates are still manufactured; they are made from a relatively rigid acrylic and are held in place by metal clasps that fit over the upper teeth. There are 62 sensors placed according to identifiable anatomical landmarks (Hardcastle et al. 1991; see Figure 1). A newer version, the Articulate EPG plate, has a similar design to the Reading plate and is compatible with the Reading EPG systems. It is made using thermoforming and flexible circuits sealed between layers of acrylic plastic (Wrench 2007).

Insert Figure 1 about here

Typical contact pattern for vowels

EPG records characteristic tongue palate contact patterns in normal speakers for all English lingual phonemes. For vowels, varying amounts of contact are registered during relatively close vowels /i/, /ɪ/, /e/, /u/, and /ʊ/ and rising diphthongs /eɪ/, /ɑɪ/, /oɪ/, /aʊ/, and /əʊ/. There is usually minimal contact during open vowels, such as /ɑ/ and /ɒ/. Normative data from adults and children are available from a recent reference by McLeod and Singh (2009) and a number of in-depth studies of normal articulatory patterns for various consonants (for a review, see Gibbon and Lee, 2011; Gibbon, Lee and Yuen 2010). These data are important for the identification of abnormal EPG patterns in individuals with articulation disorders and are useful when devising appropriate target patterns when EPG is used for visual feedback therapy.

A recent study by Gibbon et al. (2010) described the contact pattern of English monophthongs /i, u, a/ and diphthongs /ai, oi, au/ produced by 10 typical adult speakers. They found that there was no instance of complete contact across the palate during any of the six vowels investigated (see Figures 1b and 3). The free of contact along the sagittal midline of the tongue indicates a groove configuration, allowing air to flow out of the mouth during vowel production. The six vowels showed different contact profiles – both /ai/ and /oi/ had minimal contact in the first quarter of the vowel segment, followed by a slight increase in contact in the second quarter, a rapid rise at the temporal midpoint and reaching a peak at the end of the vowel; /au/ had a similar profile although the increase in contact was less rapid (see Figure 2b). For the monophthongs, /a/ registered minimal amount of contact throughout, whereas /i/ and /u/ started out with a higher amount of contact, indicating a relatively high tongue position, followed by a gradual upward movement until the target position was reached; the amount of contact was higher for /i/ than /u/ throughout the segment (see Figure 2a). Although /oi/ and /ai/ have high off-glides, the EPG data showed that tongue height for the diphthong off-glides is lower compared with monophthong /i/; the same was observed for /au/ compared with /u/. Finally, the amount of contact varied between speakers (see Figure 3) but the overall contact shape was similar – for example, all speakers showed posterior lateral contact for vowel /i/.

Insert Figures 2 and 3 about here

EPG is also useful for studying different accents of a language. Figure 4 shows the average contact profiles of the vowels for the words "pay" and "bow", which were produced as [ei] and [ou] respectively by five adult speakers of Southern British Standard (SBS) and [e] and [o] respectively by five adult speakers of Scottish English (SE). The productions [ei] and [ou] by the SBS speakers showed a contact profile that is similar to that of the diphthongs described above. While the productions [e] and [o] by the SE speakers had a contact profile resembling that of a monophthong – [e] started at a higher tongue position than [o] but both productions showed a gradual, small increase in mean percent content over time. The findings are consistent with the observation reported in previous literature that, generally speaking, speakers of SE realise the diphthongs /ei/ and /ou/ as monophthongs /e/ and /o/ (Wells 1982).

Insert Figure 4 about here

Tongue palate contact patterns for misarticulated vowels

Only a few previous EPG studies described atypical contact pattern for vowel productions (e.g., Gibbon 2004; Howard 2001; Yamashita and Michi 1991; Yamashita et al. 1992). Yamashita and colleagues found that productions that were perceived as "nasopharyngeal misarticulation" (i.e., articulation errors resulting in sounds similar to /n/ or /ŋ/ perceptually) were associated with an EPG pattern of complete contact across the palate (Yamashita et al. 1992, p. 202). As an example, they showed the dynamic EPG frames of the syllable /aʃi/ produced by a 4-year-old child with repaired cleft palate – no contact was registered in the first 12 EPG frames of the /a/ segment, followed by gradual increase of lateral contact in the subsequent 12 frames; complete contact occurred in the fifth last frame of the /a/ segment and this complete oral constriction was maintained throughout the /ʃ/ and /i/ segments. Because of the occluded oral cavity, air was being directed through the nose and this was confirmed by a mirror test – a cold dental mirror placed under the nostrils fogs up when there is nasal airflow. Gibbon, Smeaton-Ewins and Crampin (2005) conducted a more detailed study on the EPG pattern of five selected vowels produced by 18 Scottish English-speaking children with repaired cleft palate. Seven children showed complete contact across the palate for more than one vowel, with four of them produced complete contact frequently during the production of high vowels /i/, /ɪ/, and /ʉ/. Complete contact was observed most often in /i/ (40%), /ʉ/ (16%), and /ɪ/ (6%) but not in lower vowels /o/ and /ɔ/.

IMAGING TECHNIQUES

Ultrasound, X-ray, and magnetic resonance imaging (MRI) are direct instrumental measures that allow recording visual images of the human body primarily for medical diagnosis and have subsequently been used to record the movement and position of the articulators, in particular the tongue. Collectively, these techniques have the advantage of creating the most realistic images of the vocal tract, or parts of it. They also involve minimum disruption to natural speech and some are capable of providing an extensive view of the vocal tract.

Ultrasound

Ultrasound imaging is a technique that can visualise in real time the internal soft tissues of the articulators involved in speaking. The procedure of ultrasound scanning is based on the ability of sound waves of very high frequencies to pass through body tissues and to be reflected back to the source, upon reaching an interface between substances of different density (for the technical details, see Stone 2005; 2010). Early ultrasound speech studies used a single pulse echo transducer, which tracked the articulator movements along one line (e.g., Parush et al. 1983). Array transducers are used to obtain two-dimensional (2D) images.

In speech research, ultrasound has mostly been used to image tongue movements. In order to obtain a 2D tongue image, the transducer is placed below the chin, enabling the waves to go upwards. Depending on how the transducer is rotated, the images can be midsagittal or coronal. Figure 5 shows midsagittal and coronal images of the vowels /i/ and /a/. The bright white line is the result of the air interface at the tongue surface. The dark area below the white line is the tongue body, and the lower edge of the white line corresponds to the tongue surface. Using tongue reconstruction in three dimensions from multiple 2D images has been reported in speech studies (e.g. Stone and Lundberg 1996; Bressmann et al. 2005).

Insert Figure 5 about here

Because ultrasound waves are reflected upon meeting a tongue-air interface, the palate and the pharyngeal walls are not normally imaged. The hyoid bone and the mandible refract the waves, creating acoustic shadows, which can obscure parts of the tongue root and/or tip. The tip can also be missing from an image because the waves may not reach it, being reflected at the interface between the floor of the mouth and the air above it. Several techniques have been suggested for imaging the hard palate and the tongue tip with ultrasound (Stone 2005). The frame rate used in most ultrasound studies to date is around 30 Hz, and is limited by the video output rate for non-digital ultrasound scanners. Digital ultrasound systems adapted for speech research can achieve the frame rate of 100 Hz and higher (Wrench and Scobbie 2008; Miller and Finch, 2011). Stabilising the transducer relative to the head is necessary for statistical analyses based on multiple repetitions of speech sounds. Various systems controlling for transducer position are used in research laboratories (for a review, see Stone 2005).

Ultrasound is useful in studying vowels, where the whole tongue shape matters for producing a required perceptual effect. In Figure 6a, outlines of the midsagittal tongue position are displayed for ten repetitions of the vowels /i/ and /a/. Figure 6b displays the tongue movement over the diphthong /ai/.

Insert Figure 6 about here

A number of studies have reported ultrasound data on vowel production in typical adult speech – MacKay (1977); Morrish et al. (1985); Stone et al. (1987, 1988); Stone and Lundberg (1996); Chiang et al. (2003); Pouplier et al. (2004); Gick et al. (2006); Wilson (2007); Noiray et al. (2008); McLeod and Singh (2009); Zharkova and Hewlett (2009). Vowel-on-consonant coarticulatory effects in typically developing children were studied in Zharkova et al. (2011).

Being noninvasive and safe, ultrasound imaging can be used extensively, making it possible to get large amounts of data for speech research. The technique is suitable for use with very young children or in people with physical disabilities or learning difficulties. In disordered speech, Shawker and Sonies (1984) found significant differences in articulation of the vowels /a/ and /i/ between three speakers with neurological disease and dysarthria and ten control participants. Keller (1987) observed irregularities in tongue movement over repetitions of the syllable /ka/ in two speakers with Parkinson's disease, a speaker with senile dementia, and a speaker with mild stuttering. Bressmann et al. (2007) found decreased midsagittal grooving and increased lingual asymmetry in 12 people who had undergone partial glossectomy (for tongue surface plots, see Bressmann et al. 2005). Gibbon and Wolters (2005) reported backing of tongue placement during the production of vowels /i, a, u/ (e.g., /i/ was abnormally close to /u/) in an adult male with a repaired cleft lip and palate. Speech errors in adults without speech disorders have also been analysed with ultrasound (e.g. Pouplier 2004).

Ultrasound images of the tongue are easy to interpret, making the technique very attractive for providing biofeedback (Bernhardt, Stemberger and Bacsfalvi 2010). Bernhardt et al. (2003) and Bacsfalvi et al. (2007) reported the results of a speech therapy programme for adolescents with hearing loss, which involved the use of ultrasound as biofeedback for vowel production. All participants showed some improvements in tense-lax vowel contrast for high vowels. No quantitative ultrasound measurements were made. In therapy, the requirement for stabilising the transducer position relative to the head is a particular complication. Without the stabilisation, visual comparison of ultrasound images can be made before and after therapy, but quantitative comparison of multiple repetitions is only possible if post-recording processing is applied, which is cumbersome and not always realistic in the clinical setting. Designing measures that could produce quantitative results without postprocessing the data would greatly enhance the perspectives of ultrasound as a diagnostic tool.

Ultrasound has been used in second language acquisition research (Gick et al. 2008) and in sociophonetic analysis (Lawson, Stuart-Smith and Scobbie 2008). Portable ultrasound scanners have been employed in fieldwork (Gick, Bird and Wilson 2005). Ultrasound can also be used for imaging the pharyngeal wall (Skolnick, Zagzebski and Watkin 1975) and assessing changes in larynx height (Hamlet 1980; Esling and Moisik 2010).

X-ray

X-ray uses ionizing radiation to obtain photographic images of internal body structures. The X-ray beam is projected from one side of the body, through all the tissues, to a photographic film or a fluoroscopic screen on the other side. The image obtained is a result of differential attenuation of radiation photon particles by the tissues (Kummer 2008). The denser the tissue, the greater the degree of attenuation, and the fewer the radiation particles that reach the film. This results in less exposure of the film and the image obtained is near the white end of the spectrum (Fischbach 2004; Kummer 2008). Hence, dense structures such as bones (e.g., hard palate) appear white, whereas soft tissues such as the tongue and lips are darker. Because X-ray presents a 2D, summation image of a three-dimensional (3D) structure, it can be difficult to measure soft tissues such as the tongue, as the bony structures of the jaw and teeth may obscure the view (Stone 2010). It can also be difficult to identify which part of the tongue (lateral or midline) is being imaged unless a contrast medium is used to mark the midline (Stone 2010).

Various X-ray techniques have been developed over the past century (see Ball and Lowry 2001; Stone 2010, for a review) and some of them have been applied to speech studies. X-ray images may be still (e.g., Fant 1970) or cine. Serial or cineradiography can record dynamic events and was widely used for investigating articulator motion up until the early 1970s (Hiimae and Palmer 2003; Perkell 1969). A few Phonetics Laboratories have digitized the data and compiled X-ray databases of speech; and some recent studies have used advanced data analysis procedures to quantify these data (e.g., Iskarous 2005; Jallon and Berthommier 2009). Videofluorography, which consists of an X-ray image intensifier linked to a video camera, became widely used in the late 80s for diagnostic radiological purposes and had the advantage of having lower radiation levels.

Nowadays, due to radiation exposure, X-ray techniques are used only for essential medical purposes (e.g., videofluoroscopic examination of dysphagia), and not for routine investigation of articulation. In spite of this, some studies have used X-ray techniques to investigate vowel misarticulations (e.g., Morrish 1984; Tye-Murray 1991). For example, Morrish (1984) used videofluoroscopy and acoustic analysis to study the compensatory strategies for vowel articulation in a 66-year-old men who received total glossectomy and re-lining of the oral cavity with a flap of tissue containing the frontalis muscle. The first formant (F1) values for the different vowels (/i, e, a, o, u/) were within normal limits but the second formant (F2) values did not distinguish the front vowel /i/ and back vowel /u/. The videofluoroscopic exam showed that the speaker had reduced mobility of the flap and exaggerated vertical displacement of the mandible. It was suggested that the speaker used wide mandibular excursion to compensate for tongue height, resulting in adequate F1 values; but there was difficulty to increase anterior-posterior displacement of the mandible to compensate for tongue advancement, hence, the F2 values between front and back vowels were not distinctive (Morrish 1984).

Magnetic resonance imaging (MRI)

MRI is another biologically safe, noninvasive technique that gives high quality images of the hard and soft tissues of the full length of the vocal tract, from lips to larynx (Stone 1991; Baer et al. 1991). MRI uses radiofrequency waves with scanners consisting of electromagnets that surround the body to create a magnetic field. MRI scanning detects the presence of hydrogen atoms with the images highlighting differences in the water content and distribution in body tissues. The result is that tissue with fewer hydrogen atoms, such as bones and air, is dark, whereas tissue with many hydrogen atoms, such as muscle, is lighter. Like ultrasound, MRI scans generate 2D images, which can be combined to produce 3D images. Although MRI is now used increasingly to investigate tongue movement in speech, it was used primarily to identify abnormal mass (Cha and Patten 1989; Wein et al. 1991). In the past, the technique's slow temporal resolution made it unsuitable for investigating dynamic aspects of speech. However, recent advances mean that it is now possible to record the dynamics of speech, including segment durations, articulator positions, vocal tract constrictions, and interarticulator timing (Narayanan et al. 2004).

MRI has been used to study articulation problems as a result of structural deficits or neurological impairment and most of the studies focus on consonant production (e.g., Sato-Wakabayashi et al. 2008; Shinagawa, et al. 2005). A Japanese study by Watanabe et al. (1994) used MRI and acoustic analysis to investigate the production of five Japanese vowels (/a, i, u, e, o/) in five male adults with amyotrophic lateral sclerosis (ALS) and five typical healthy males. The normal individuals showed clear, differentiable tongue shapes for the different vowels, while the differences in tongue shapes were unclear for the speakers with ALS (Watanabe et al. 1994). The results of F1 and F2 measurements were in congruence with the MRI findings, which showed that speakers with ALS had reduced tongue movement for high vowels /i, u, e/.

Although undoubtedly a research tool for the future, carious features of MRI restrict its routine clinical application for imaging the articulators. The scanners are costly and require specialists to operate and maintain them. There is also the procedural limitation that requires a person to lie inside a large cylinder, making it unsuitable for children or those with claustrophobia. On a practical level, MRI imaging is accompanied by a continuous loud noise, making it difficult to obtain satisfactory sound recordings to accompany the images. It is also possible that the supine position alters articulator relationships during speech. These limitations mean that, for the foreseeable future, MRI is likely to be a research tool used with speakers who are able to comply with the experimental set up.

MOTION TRACKING

Two varieties of instruments – magnetic and optoelectronic systems – are discussed in this section. They are biologically safe but collectively more invasive and therefore more disruptive potentially to natural speech compared to the techniques described in the previous section. The so-called ‘point tracking’ systems can measure movement of discrete fleshpoints at high sampling rates. Their capability to measure articulatory kinematics, such as displacement, velocity, acceleration, duration and amplitude, makes them instruments of choice for measuring speech motor control in normal and disordered speech. There is a growing literature on their use with adults and typical children. The data recorded by these instruments is displayed in the form of traces that are less immediately intuitive, and more difficult to interpret, than the images produced by the techniques already discussed in previous sections. This may be a reason why these techniques have not been used to provide biofeedback of articulation yet.

Magnetic systems

The most frequently used magnetic motion capture system used in speech research is electromagnetic articulography (EMA) or electromagnetic midsagittal articulography (EMMA). The two most widely used systems have been developed in Europe (Schönle et al. 1987) and the North America (Perkell et al. 1992). The transmitter coils are mounted on a specially constructed helmet, forming an equilateral triangle in front of the chin, in front of the forehead, and behind the neck. The receiver coils are glued to various locations on the vocal tract at midline – typically on the bridge of the nose, the maxillary gum ridge (to monitor head movement) on the upper and lower lips, the mandibular gum ridge and three or four points on the tongue (see Figure 7). Each transducer coil is excited by a sinusoidal signal at a different frequency and this generates an alternating magnetic field, which induces an alternating signal in the receiver coils (Barlow et al. 2009; Stone 2010). The voltage of this signal is inversely proportional to the cube of the distance between the transmitter and the receiver coil. The voltage is sampled at a high frequency, for calculating the actual location of the receiver coils as they move in a 2D plane over time (Barlow et al. 2009; Stone 2010). A recently developed EMA system, AG500 (Carstens Medizinelectronik, Lenglern, Germany), is able to record 3D data. The new system is judged as adequate for registering articulatory movement as long as specific steps are taken before, during, and after data acquisition – for example, calibrate the system before each experiment (see Yunusova, Green and Mefferd 2009). There is another new system that can also acquire 3D data using a wireless sensor (Dromey et al. 2006). However, it does not allow simultaneous tracking of multiple fleshpoints and the head of the speaker has to remain still during the recording.

Insert Figure 7 about here

Not many studies report EMA data for articulation disorders and most of them focus on consonant production (for a review, see Katz, Bharadwaj and Stettler 2006). One disadvantage of EMA is that it is invasive insofar as it involves gluing small coils directly onto the articulators, which can interfere with normal speech (Katz et al. 2006). Moreover, in many systems (except the recent 3D EMA system – AG500, which does not require a helmet), the experimental set up restricts speaker movement because of the large, cumbersome helmet. The procedural restrictions of the technique have meant that it has not been used with young children or infants.

Optoelectronic systems

An ordinary cine or video camera can be used to investigate the coordinated actions of visually accessible articulators, namely the lips and jaw (Baken 1987). More sophisticated optical motion systems, such as Optotrak (Guiard-Marigny and Ostry 1997), Selspot (Kelso et al. 1985) and VICON (Gibert et al. 2005), can record movement at discrete points located on the lips and jaw in 3Ds. These systems collect movement data with a video camera by attaching small infrared, light emitting diodes or reflective markers to the articulators. The camera tracks the markers attached to the jaw and lips and using several cameras together makes it possible to measure the movements of each marker. These techniques can therefore be used to record important features of vowel production, such as lip spreading, rounding and protrusion.

Optical devices have been used to investigate lip and/or jaw movement during speech in typical children and adults (e.g., Green, Moore and Reilly 2002) and individuals with impaired speech motor control, such as stuttering (e.g., Jäncke et al. 1997) and dysarthrias (e.g., Ackermann et al. 1997; Svensson, Henningson and Karlsson 1993). A study by Ackermann, Hertrich and Scharf (1995) investigated lower lip excursions during the production of /paːp/ and /pap/ in four German-speaking patients with ataxic dysarthria and six typical healthy adults. They found that the normal speakers showed clearly faster lower lip movement in closing gesture than opening gesture and the lip movements were slightly faster when /p/ is adjacent to short vowel /a/ as compared to long vowel /aː/. However, the distinction was less obvious in the speakers with ataxic dysarthria and they showed an overall reduced speed of lower lip movements.

Although the markers used in systems such as VICON may interfere with natural speech to some extent, an important advantage of this technique is that it is one of the few that can record orofacial movements in young children, infants and even new born babies. An obvious limitation of this technique, however, is that it records externally visible structures only and cannot investigate the major articulators situated within the vocal tract.

CONCLUSION

The past decade has seen an increase in the variety of instruments available, as well as their technical sophistication and user friendliness. While some instruments are underused for measuring articulation, in particular vowel productions, other instruments, such as EPG and ultrasound, have received increasing interest, partly because of their facility to provide visual feedback that can be used in speech therapy to modify abnormal articulations, such as vowel disorders (Bernhardt et al. 2010). The development of new technologies that offer the prospect of more effective diagnosis and treatments is highly desirable in order to improve healthcare provision and quality of life for individuals with articulation disorders.

Although the technology of instrumental analysis of articulation has advanced substantially, there are still many challenges to overcome to obtain the data. Many instruments are expensive and have high maintenance and operational costs. The procedural demands of using many techniques make them unsuitable for use with some populations, such as young children or those in poor health. The analysis of instrumental data can be a technically complex and time consuming task and often involves processing large quantities of data. Some techniques are invasive or uncomfortable for the speaker and so are not well suited for gathering naturalistic speech samples or large data sets. Taken together, these factors restrict the use of many instruments to research conducted in specialized laboratories or medical facilities. Overcoming these challenges and translating the results into routine practice requires strong collaborative links between researchers in the academic setting, clinical professionals in the health services, and people who experience articulation disorders in their everyday lives. These links ensure that research is relevant, practical and effectively disseminated.

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Captions for Figures

Figure 1. (a) Photograph of a Reading EPG plate, placed on top of the plaster model made from the Alginate impression of the palate and upper teeth of an adult with normal craniofacial structure; and (b) a single EPG frame for a high vowel /i/, where tongue palate contact is indicated by filled boxes and no contact by empty boxes, along with EPG frame row numbers 1 through 8 indicated, as are the phonetic regions of the palate and the part of the tongue assumed to make contact with these regions.

Figure 2. Average percent contact profiles for (a) monophthongs /i/, /u/, and /a/ and (b) diphthongs /ai/, /oi/, and /au/ produced by 10 adult native English speakers. The measurements were taken at five annotation points – the onset (point 1) and offset (point 5) of the vowel and three evenly spaced time points (points 2, 3, and 4).

Figure 3. Dynamic sequences of EPG frames from (a) a speaker who showed the highest amount of percent tongue palate contact and (b) a speaker who had the lowest amount of contact for vowels /i/, /u/, and /a/ (Gibbon et al. 2010).

Figure 4. Average percent contact profiles for diphthongs (a) /ei/ and (b) /ou/ produced by the five adult speakers of Southern British Standard and five adult speakers of Scottish English, who took part in Gibbon et al.'s (2010) study.

Figure 5. Ultrasound images of the vowels /a/ (on the left) and /i/ (on the right). The images are taken from the middle of the underlined vowel in the sentences "a pah papa"

and “a pea papa”. Midsagittal images are in the first row, coronal images are in the second row. In midsagittal images, the anterior part of the tongue is on the right; the shadow of the hyoid bone can be seen on the left, and the shadow of the mandible on the right. The images in this and the next figure are based on productions by the second author of this chapter.

Figure 6. Tracings of ultrasound tongue curves, the anterior part of the tongue is on the right: (a) ten repetitions of the vowel /a/, solid lines; ten repetitions of the vowel /i/, dotted lines; the data are taken from the sentences described in the caption for Figure 5; (b) ten successive tongue curves over the diphthong /ai/ from the sentence “a pie papa”; the first five tongue contours are in solid lines, the last five tongue contours are in dotted lines.

Figure 7. Photograph of a typical EMA setup.

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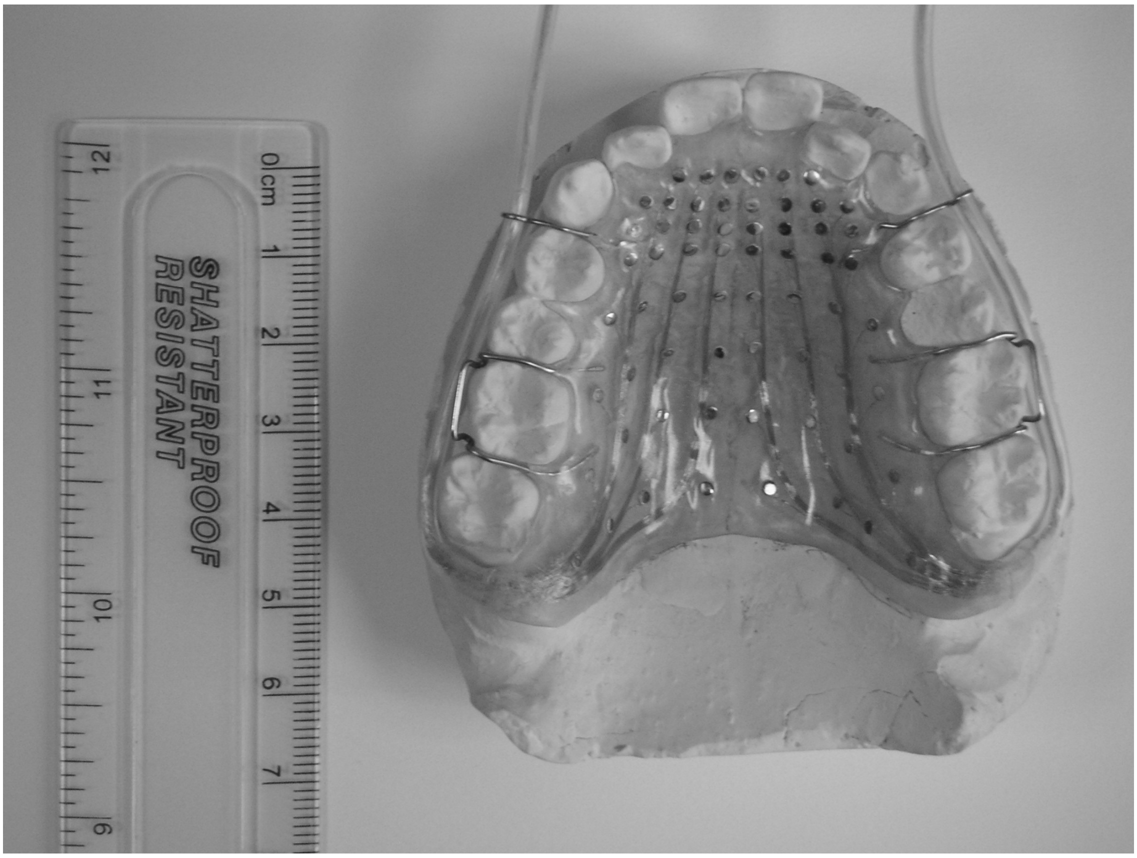
Figure 1.

(a)



(b)

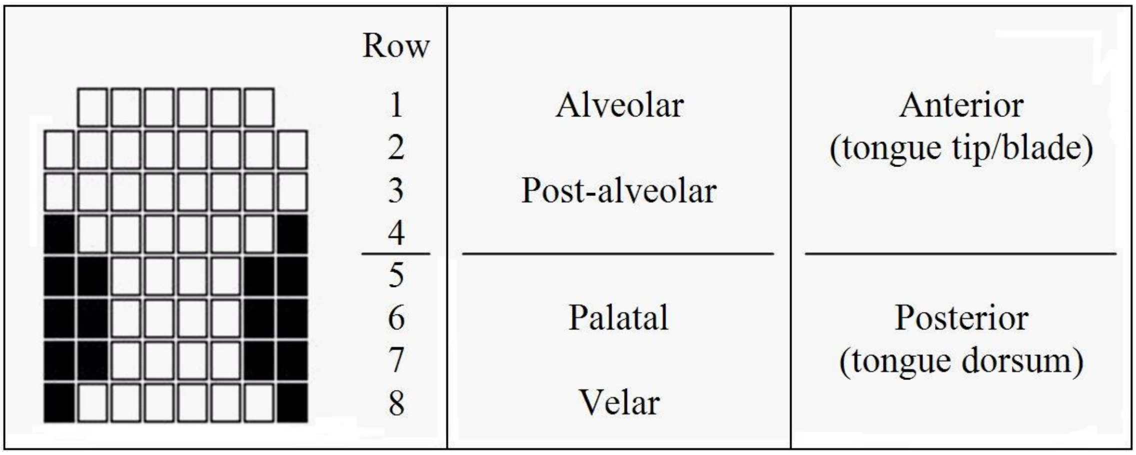


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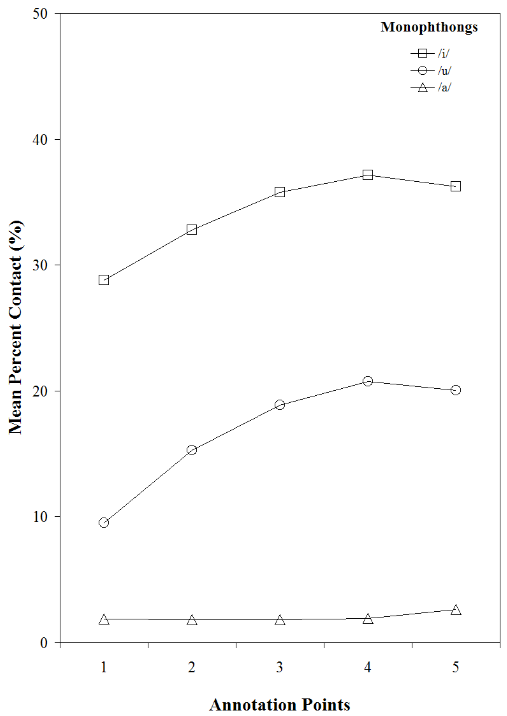
Figure 2.

(a)



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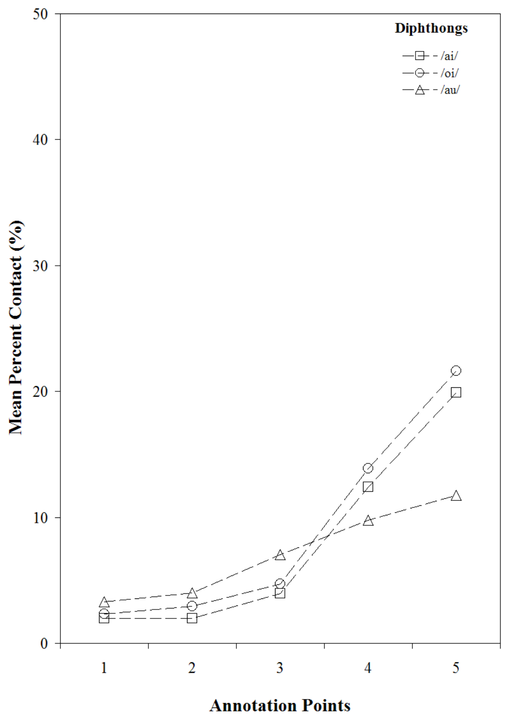

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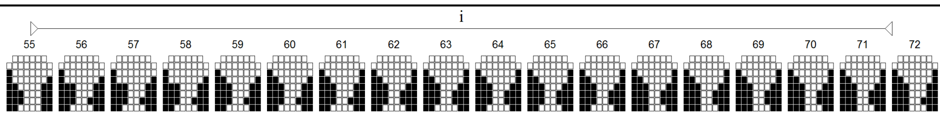
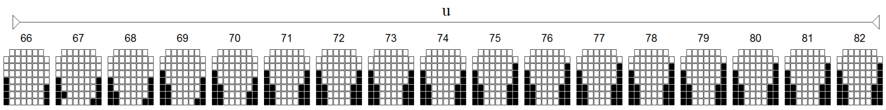
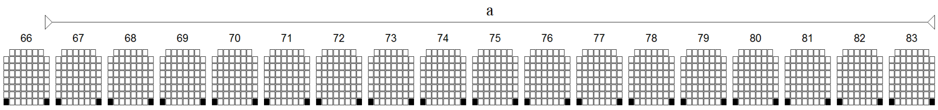
Figure 3.

(a)

Vowel	EPG frames
/i/	
/u/	
/a/	

(b)

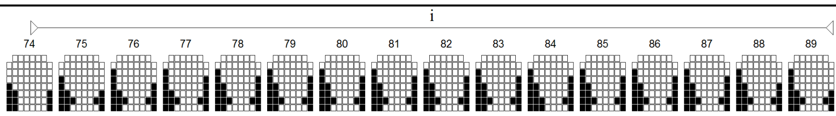
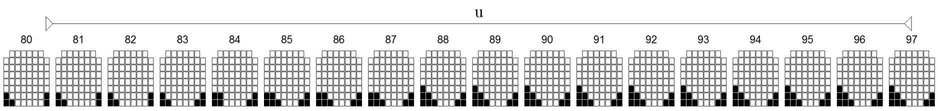
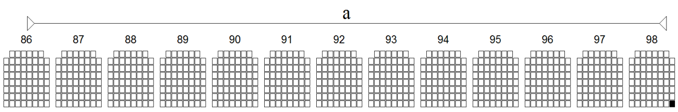
Vowel	EPG frames
/i/	
/u/	
/a/	

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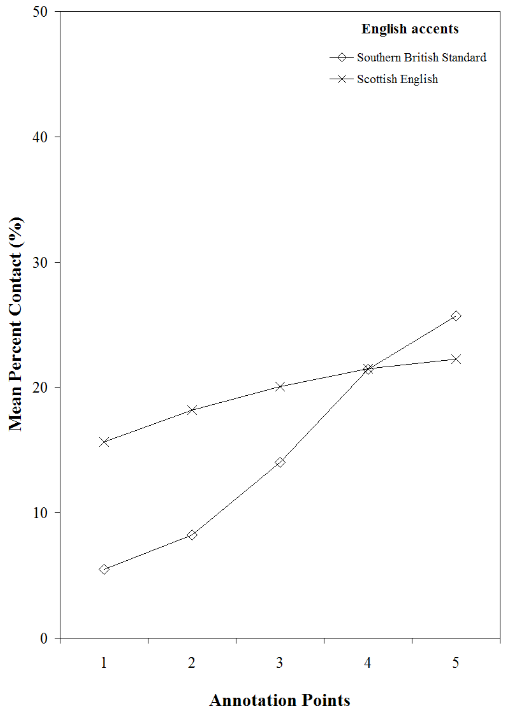
Figure 4.

(a)



(b)

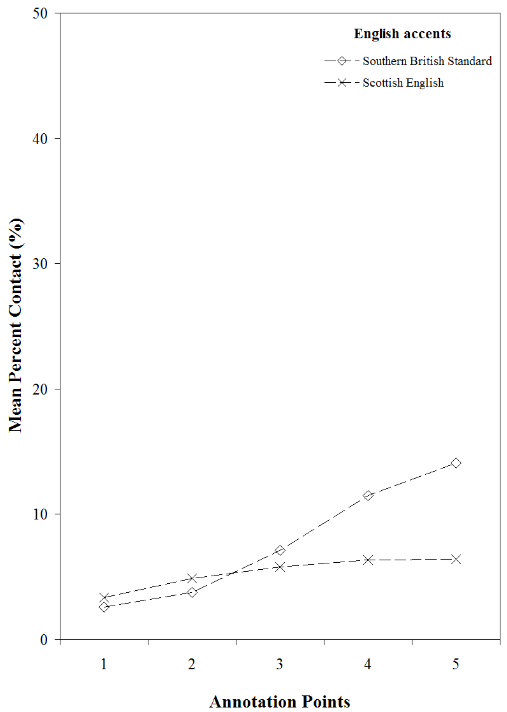


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Figure 5.

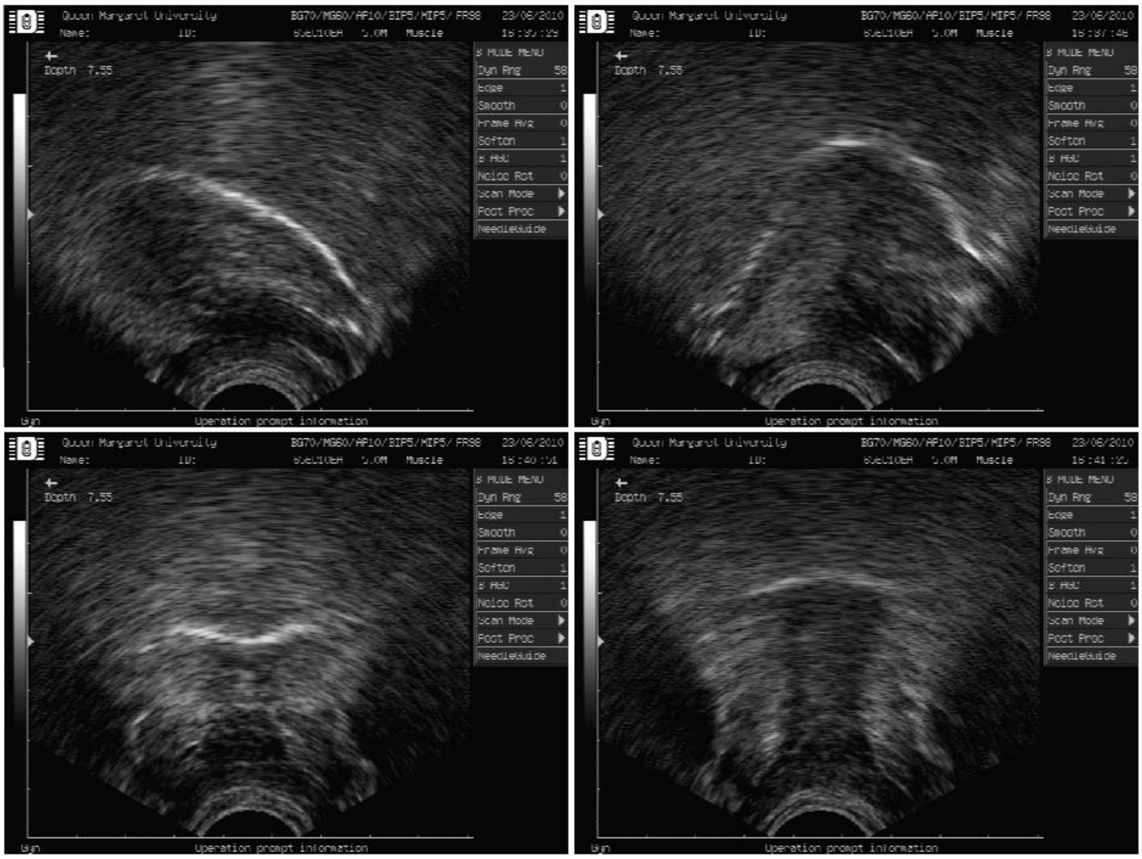

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Figure 6.

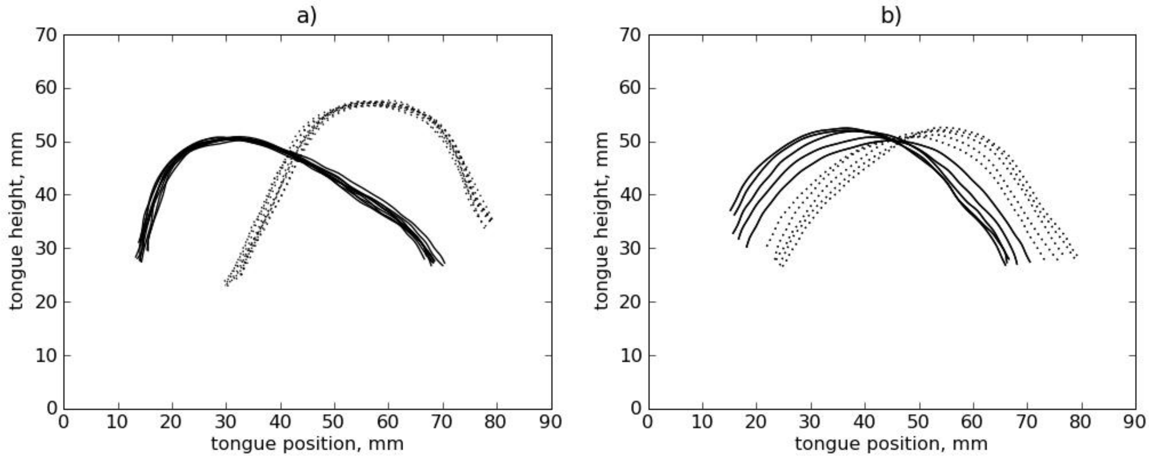

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Figure 7.