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ELECTROMAGNETIC ARTICULOGRAPHY IN COARTICULATION RESEARCH[1]

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ABSTRACT

This paper gives an overview of the basic methodological issues relevant to the use of electromagnetic articulography in experimental phonetics. The following topics are covered: measurement principle, sources of error, environmental conditions, combination with other equipment, disturbances to the subjects' speech, safety. Finally, an example is given of how this technique can provide new information on lingual articulation even within the framework of a very simple coarticulation paradigm.

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INTRODUCTION

Electromagnetic articulography (EMMA[2]) belongs to the category of transduction device that provides data on the trajectories of articulator fleshpoints in a two-dimensional Cartesian space. It thus provides data comparable to that available from the well-established x-ray microbeam system (cf. Westbury, 1994). This contribution reviews some of the methodological issues involved in employing EMMA for phonetic investigations, particularly for studies of coarticulation. On the face of it, EMMA is extremely well suited to the study of coarticulation since it allows a wide range of utterances to be recorded in a single session (sessions of 30 minutes or more being feasible). Moreover, since it provides kinematic data in readily analyzable form it should help to remedy one of the most serious failings of instrumental studies of coarticulation to date, namely the small number of subjects per experiment. EMMA is able to monitor the movements on the mid-sagittal plane of most of the articulatory structures that have been the focus of coarticulatory studies, i.e lips, jaw, tongue, velum[3], but it is probably of most interest for the tongue, since for the lips and jaw other well-established techniques are readily available. Currently three main systems are available to individual laboratories: the MIT system (cf. Perkell, Cohen, Svirsky, Matthies, Garabieta & Jackson, 1992), the AG100 system (Carstens Medizinelektronik, Göttingen, Germany), and the Movetrack system (Botronic, Hägersten, Sweden; cf. Branderud, 1985). Various other implementations of the electromagnetic measurement principle have also been reported in the literature (e.g Hixon, 1971; Panagos & Strube, 1987; Sonoda & Ogata, 1992; Ogata & Sonoda, 1994). For more detailed discussion of the issues raised here the reader is referred in particular to Perkell et al. (1992) as well as to Gracco (1995) and to the proceedings of a workshop on EMMA collected in FIPKM 31 (=Forschungsberichte des Instituts für Phonetik und Sprachliche Kommunikation, Munich).

The following topics will be covered: measurement principle and sources of error; environmental conditions and combination with other equipment; disturbances to the subjects' speech; safety. A number of issues that are not specific to EMMA, but rather are common to fleshpoint tracking systems in general, will not be covered here. These include issues that can in fact be crucial to the interpretability of the data, such as correction for head movement and definition of anatomically-based coordinate systems. In addition to the above sources an extremely valuable discussion of these issues is to be found in Westbury (1994). Examples of the analysis of issues relevant to various ramifications of the topic of coarticulation can be found in Hoole et al., (1990), Katz et al. (1990), Perkell (1990), Keating et al. (1994), Hoole et al. (1993), Kühnert (1993), Harrington et al. (1995), Hoole & Kühnert (1995), Löfqvist & Gracco (1995), Mooshammer et al. (1995), Ní Chasaide & Fitzpatrick (1995), Recasens (1995), Romero (1996).

MEASUREMENT PRINCIPLE AND SOURCES OF ERROR

When an alternating magnetic field is generated by a transmitter coil the strength of the signal induced in a transducer (receiver coil) is approximately inversely proportional to the cube of the distance between transmitter and receiver. This basic configuration of a transmitter-receiver pair formed the foundation for the use of magnetometer systems in studies of respiratory kinematics (Hixon, Goldman & Mead, 1973), in which the variable of interest is simply the distance between the transmitter and receiver. For studies of tongue movement more information is required, namely the coordinates of the fleshpoints in two-dimensional space. Under ideal conditions, two transmitters would suffice to determine these coordinates by triangulation. Particularly when monitoring tongue movements it is unfortunately the case that ideal conditions do not apply: specifically, the fleshpoint locations are only transduced accurately when the main axes of transmitter and receiver coils are parallel to each other. Misalignment of transmitter and receiver can result from rotation of the receiver coils about either of the two axes shown in Fig.1 (following Perkell & Cohen, 1986, these rotational movements will be referred to as "twist" and "tilt", or together as "rotational misalignment"). When rotational misalignment occurs the effective surface area presented by the receiver coils to the magnetic field is reduced, and the induced signal declines proportional to the cosine of the angle of misalignment; the apparent distance between transmitter and receiver thus increases. Clearly rotational shifts (especially tilt) are to be expected with an organ such as the tongue which is highly deformable and which may be pressed against the vaulted shape of the hard palate.

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[2] We will use the abbreviation introduced by Perkell et al. (1992) for the MIT system. The second m stands for "midsaggital".

[3] Application of the transducers to the velum may require sutures (see Engelke & Schönle, 1991) rather than surgical glue.

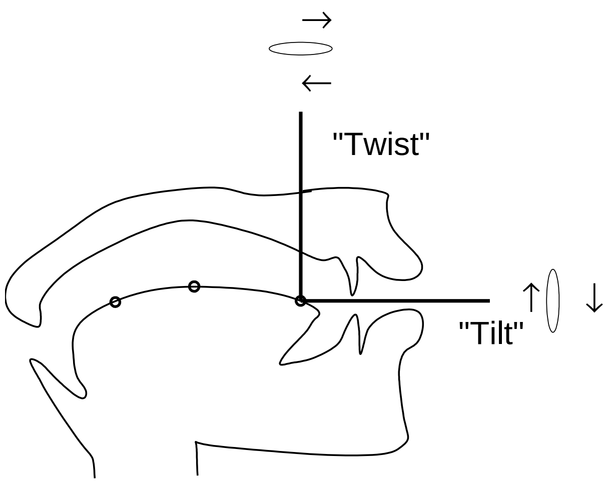

Fig. 1: *Rotational axes of magnetometer sensors that lead to a reduction in the induced signal for typical sensor locations on the tongue.*

Since van der Giet (1977) pointed out this problem various solutions have been tried. In this contribution we will concentrate on the approach followed in the current MIT system[4] (Perkell et al., 1992) and in the commercially available AG100, both systems being based on a solution developed by a group in Göttingen (Höhne et al., 1987; Schönle et al., 1987; Schönle, 1988; Schönle et al., 1989). The idea is essentially that the use of a third transmitter provides the additional information needed to determine and correct for the rotational misalignment. For the amount of misalignment likely to be encountered in speech, the problem can be considered resolved (see e.g Perkell et al., 1992). There remains, however, the less tractable problem of errors caused by displacement of the transducers out of the plane on which the transmitters are located (usually the midline). Due to the curvature of the lines of magnetic flux, this will have an effect somewhat similar to rotational misalignment since the axis of the transducer is no longer parallel to the lines of flux (see fig. 5 in Perkell et al., 1992. cf. also Gracco & Nye, 1993). Published tests of both the MIT and the AG100 system agree in showing a sharp rise in measurement error when off-midline placement is combined with rotational misalignment (see e.g. Perkell et al., 1992; Honda & Kaburagi, 1993; Schönle, Müller & Wenig, 1989). For example, Honda & Kaburagi found for the AG100 system about 1.5 to 2 mm of error with 5 mm displacement from the midline and 20 deg. of twist, increasing to 4 mm of error with 10 mm of displacement, and a further increase to 10 mm of error for 20 mm of displacement and 20 deg of both twist and tilt. Perkell et al. (1992) summarized the results for the MIT system (which appears slightly less sensitive to this source of error than the AG100) as showing that the error should remain below 1mm as long as displacement is less than 5mm and misalignment less than 20 deg.

Thus great care must be taken to place the transducers on the midline and measurements with large amounts of rotational misalignment may well need to be discarded[5]. (An additional consideration, compounding the off-midline problem, is that monitoring the angle of rotational misalignment to detect unreliable data is itself less reliable when the sensors are not mounted on the midline). One must further be able to assume that the tongue does not show substantial lateral deviations during articulation, which may not be justified for some pathological populations. Complete resolution of these problems will only be achieved if a full 3-D system proves feasible (cf. Zierdt, 1993; Branderud et al., 1993). On condition, however, that appropriate precautions in experimental technique are taken (e.g Perkell et al., 1992; Hoole, 1993; Alfonso, Neely, van Lieshout, Hulstijn & Peters, 1993) then the problems are clearly not an insuperable obstacle to acquiring valid data of the kind typically required in coarticulation experiments.

Having discussed the main problems we now summarize the accuracy to be expected from such systems. For the MIT system, which is the one most extensively tested to date, the accuracy approaches 0.5 mm over a range of measurement positions sufficient to capture the main speech articulators (Perkell et al., 1992). It was initially not possible to demonstrate this level of accuracy so convincingly for the AG100 (cf. Schönle et al., 1989; Tuller, Shao & Kelso, 1990; Honda & Kaburagi, 1993), but work by Hoole (1993, 1996) suggests that this may be largely due to the fact that calibration hardware and software was originally much less sophisticated for the AG100 than for the MIT system. Finally, Nguyen & Marchal (1993) report a clearly acceptable level of accuracy for the Movetrack system, at least for non-misaligned conditions. Two further points must be made here, however.

Firstly, it is important to be clear about the kind of accuracy required in any given experiment (cf. Perkell et al.,

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[4] An alternative approach followed in an earlier MIT system was to use two transmitters and a more complicated bi-axial receiver (Perkell & Cohen, 1986; Perkell et al., 1992).

[5] We have been assuming here that correction for rotational misalignment is essential for transducing tongue movements accurately. In fact, not much information is actually available on how much a transducer on the tongue changes its alignment during actual speech utterances. Hoole (1993) has found a typical standard deviation of about 3 deg. in the course of an utterance for transducers on the tongue. Assuming a corresponding range of about +/- 2.5 standard deviations (i.e 15 deg.) this agrees well with Branderud et al. (1993) who have estimated that the tilt angle for a set of Swedish vowels covers a range of about 15 deg. in both static and dynamic conditions. Branderud et al. discuss the conditions under which it might be possible to assume that the two-transmitter Movetrack system (i.e without compensation for rotational misalignment) also gives an accurate picture of lingual articulation.

1992, p3085-6). The accuracy referred to above can be designated "absolute accuracy". This kind of accuracy is relevant if one is interested in measuring the distance between, say the tongue and the hard palate. In coarticulatory studies one will often be more concerned with relative accuracy, in other words the accuracy in transducing *differences* in the position of a point on the tongue as a function of context. Relative accuracy will generally be better than absolute accuracy, if, as will often be the case, error vectors do not change much within the small portion of the measurement field to which a single fleshpoint is restricted (typically an area of no more than 2 by 2 cm). Relative accuracy may also still be quite good at large angles of rotational misalignment, as long as the misalignment stays fairly constant. If one is simply interested in timing as opposed to spatial measurements then the demands on accuracy are probably even less stringent (for example, the transillumination technique is known to give valid information on laryngeal timing, even though the signal cannot be calibrated, cf. chapter on techniques for investigating laryngeal articulation).

The second point to make is that while there has been fairly extensive bench testing of magnetometer systems, there have been few direct attempts to validate performance during actual speech utterances (see Hoole, 1993, for an indirect assessment of the plausibility of EMMA data, based on comparison with EPG data). For monitoring the tongue, the most direct approach to date is to be found in work by Honda & Kaburagi (1993) comparing simultaneous ultrasound and EMMA (AG100) transduction of tongue configuration. The difference between the position of the tongue measured magnetically and ultrasonically averaged out at slightly over 1mm. This is of the order of the estimated measurement error for the ultrasound and EMMA system and may be regarded as fairly satisfactory, particularly as Honda & Kaburagi used only a simple technique for calibrating the EMMA system. In addition, reconstruction of complete tongue contours from the 4 EMMA transducers on the tongue also gave satisfactory results. Recently, Hertrich & Ackermann (1997) found very close agreement between the results from a passive optical system and simultaneously acquired data from the AG100 when monitoring movement of upper and lower lip.

ENVIRONMENTAL CONDITIONS AND COMBINATIONS WITH OTHER EQUIPMENT

As discussed by Gracco & Nye (1993) the user needs to pay careful attention to any sources of electromagnetic interference (e.g computer screens) whenever a new installation of a magnetometer system is carried out. Our own experience suggests that a stable ambient temperature and generous warm-up time are advisable.

The question of environmental conditions leads on to the issue of what other instrumental procedures can be combined with EMMA without resulting in unacceptable levels of mutual electromagnetic interference. Both Schönle (1988, p. 23, using a forerunner of the AG100) and Perkell et al. (1992, using the older MIT two-transmitter system) report no problems in combining EMMA and EMG. The AG100 has been successfully combined with ultrasound (Honda & Kaburagi, see above) and with EPG (Hoole, 1993; Rouco & Recasens, 1996), though the latter authors do note that EMMA sensors can cause some (probably) recoverable "excavation" of EPG patterns on the midline. Informal tests in our lab suggest no major interference between the optoelectronic SELSPOT system and the AG100; however, Kaburagi (personal communication) has noted interference between the AG100 and a different optoelectronic device (Hamamatsu Photonics); similarly the OPTOTRAK system is reported to cause interference in the MIT EMMA system (Vatikiotis-Bateson, personal communication). The AG100 interferes massively with the laryngograph signal at the transmitter frequencies, but appropriate filtering of the laryngograph signal would probably eliminate this problem.

This indicates that many useful combinations are feasible. However, since the different EMMA systems operate at different frequencies and power levels, unproblematic combinations with one EMMA system may not prove so with another one.

INTERFERENCE WITH SUBJECTS' ARTICULATION

The situation here can be considered comparable to the x-ray microbeam system since the EMMA sensors are roughly the same size (i.e about 3 to 4 mm square and 2 to 3 mm high) as the microbeam pellets. The latter have not generally been considered an undue source of disturbance. Our own experience (see also Perkell et al., 1992, p.3081) suggests that subjects feel irritated if a transducer on the tongue is placed closer than about 1cm to the tongue tip (it is also important to run lead wires out of the side of the mouth, rather than over the tongue tip). Thus for details of tongue-tip articulation EMMA may need supplementing by techniques such as EPG (cf. Hoole, 1993). A simultaneous combination of EMMA and EPG did, however, result in distortion of fricative articulation in one subject reported on in Hoole, Nguyen-Trong & Hardcastle (1993). There remains a need for comparative acoustic analysis of speech sounds produced with and without EMMA transducers in place, especially for sounds such as fricatives.

SAFETY

The possibility of harmful effects from long-term exposure to electromagnetic radiation is matter of ongoing public concern. The International Radiation Protection Association has published (1990; see also Bernhardt, 1988) a set of guidelines on exposure to magnetic fields. However, it is important to note that in the absence of conclusive evidence of long-term effects, the exposure limits set out therein were related to magnetic field strengths known to cause *immediate* biological effects. The basic criterion used was the current density occurring naturally in the human body. This is of the order of 10mA/m^2. Magnetic fields inducing current densities of this order correspond to the exposure level at which demonstrable biological effects start occurring. At current densities of the order of 100 above this criterion level acute danger to health can be expected (e.g cardiac malfunction). The magnetic flux density expected to induce the criterion current density of 10 mA/m^2 is 5 mT (milliTeslar). The IRPA recommendation (for 50/60Hz fields) is that occupational exposure at this level is permissible for up to 2 hours per day. The limit for continuous occupational exposure is set at 0.5 mT and the limit for continuous exposure of the general public is set at 0.1 mT. By way of comparison, average household levels have been estimated to be in the range up to 1 µT, though some household appliances (e.g hair-dryers) can generate substantially stronger fields (up to 1 mT). It should be reiterated that the above limits refer to immediate biological effects. If adverse effects of longterm exposure to weak magnetic fields are demonstrated, then a substantial downward revision of these limits may be called for.

For users of EMMA systems one problem is that there is little research targeted specifically at the frequency ranges at which these devices operate. As discussed by Perkell et al. (1992) the most relevant source of epidemiological information is probably from studies of long-term exposure to computer terminals, since one of the main frequency components in the latter, namely the horizontal line frequency, is comparable to the frequencies found in EMMA systems. Perkell et al. give the field strength to which the subject is exposed in the three-transmitter MIT system as 0.163 µT (1.63 milliGauss) and have found this to be comparable to a typical computer terminal. Field strengths of this order have also been reported for Movetrack. No measurements of field strengths in the AG100 have been published but they are clearly higher than in the MIT system and have been estimated (A. Zierdt, personal communication) to be of the order of 10 µT. Recent measurements recently made by M. Hasegawa-Johnson at UCLA indicate that a slightly higher figure may be more realistic. These findings are available as an internet document (http://pc241.icsl.ucla.edu/emma/report-nomu.html) which includes an excellent discussion of the relevant biophysical background. Currently, there are no grounds for disquiet, but it is probably advisable to avoid pregnant subjects and wearers of pace-makers (Bernhardt, 1988, p.23), and to remain alert to further epidemiological findings in this area.

ILLUSTRATION OF COARTICULATORY EFFECTS

Finally, an illustration of the kind of coarticulatory effects that can be observed with a typical magnetometer experimental setup is given in Fig. 2. This shows the influence of symmetric flanking consonants on tongue configuration for the two vowels /e:/ and /ɛ/[6]. Note, for example, that the areas of the ellipses enclosing all data points for a given fleshpoint are generally larger for the short vowel /ɛ/ (Fig. 2, bottom) than for the long vowel /e:/ (Fig. 2, top). This is probably a straightforward effect of the shorter vowel overlapping more with the flanking consonants, and thus showing stronger contextual influences. A more interesting contextual effect which is common to both vowels (and which to our knowledge has not previously been pointed out in the literature) is that fleshpoints on the anterior part of the tongue (refer especially to the front three sensors in Fig. 2) may well be located more *posteriorily* in /t/-context than in /k/-context, even though we customarily think of /t/ as being articulated further forward than /k/. The explanation may be that the tongue body has to retract somewhat to give the tongue-tip room to elevate for the alveolar articulation of /t/.

Thus, use of the magnetometer helps to make it clear that there can still be much to learn about the organization of even very simple sound sequences recorded, as here, within what is undoubtedly one of the commonest paradigms for examining coarticulatory effects.

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[6] See Hoole & Kühnert (1995) for further discussion of patterns of contextual (coarticulatory) and token-to-token variability in the realization of the German vowel system.

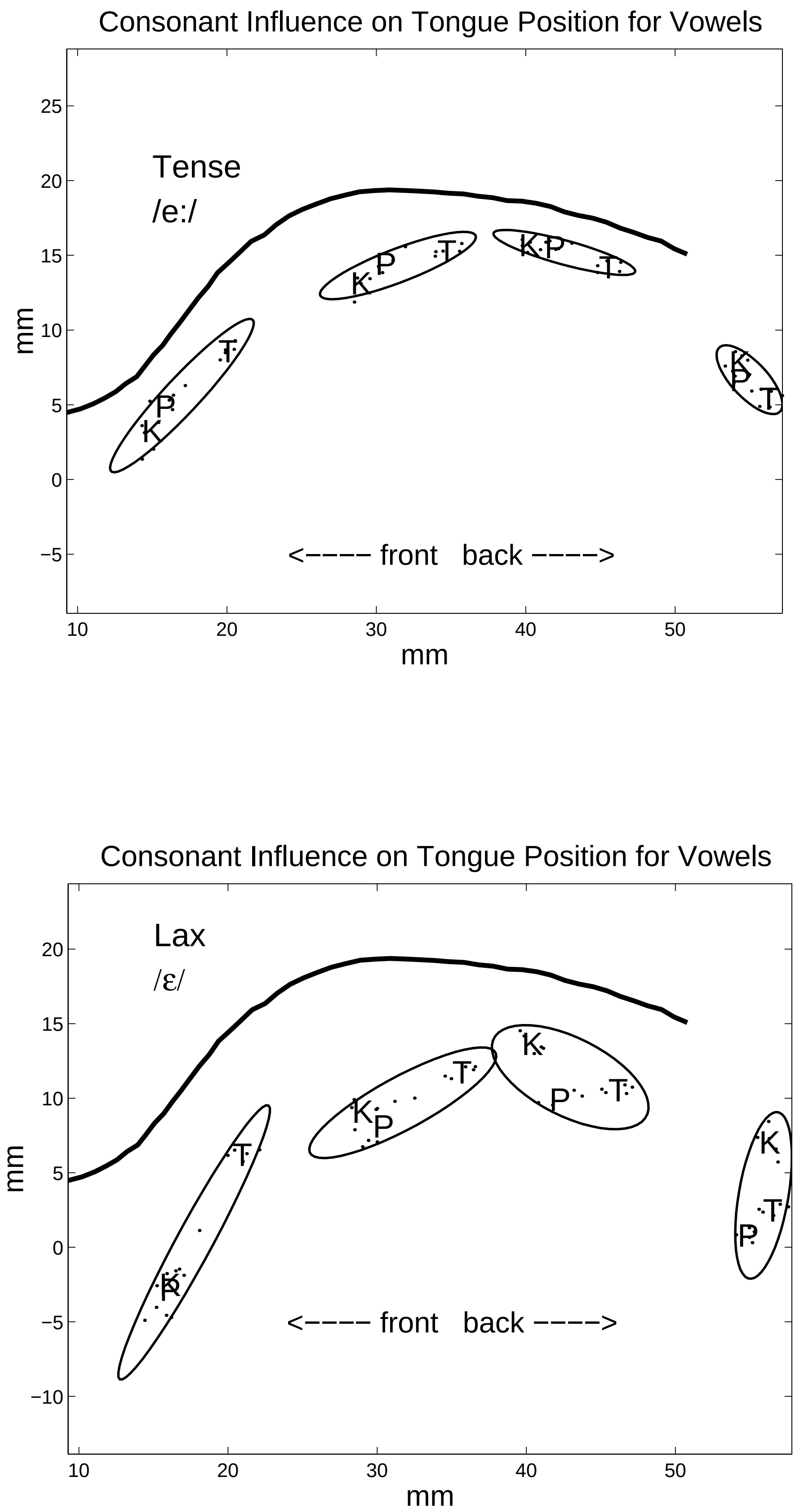

Fig.2: *Positions of four fleshpoints on the tongue for the German tense-lax vowel pair /e:/ (top) and /ɛ/ (bottom) in the three consonantal contexts /p/, /t/ and /k/ (averaged over approximately 5 tokens per consonant). Ellipses enclose two-sigma areas of variation over all tokens and contexts at each fleshpoint. The contour of the hard palate is also shown.*

REFERENCES

(FIPKM = Forschungsberichte des Instituts für Phonetik und Sprachliche Kommunikation, München)

Alfonso, P., Neely, J.R., van Lieshout, P.H.H.M., Hulstijn, W. & Peters, H.F.M. (1993). "*Calibration, Validation, and Hardware-Software Modifications to the Carstens EMMA System"*. FIPKM, 31, 105-120.

Bernhardt, J. (1988). "*The establishment of frequency-dependent limits for electric and magnetic fields and evaluation of indirect effects"*. Radiation and Environmental Biophysics, 27, 1-27.

Branderud, P. (1985). "*Movetrack - A movement tracking system*". Perilus IV, Stockholm University, 20-29.

Branderud, P., McAllister, A. & Kassling. B (1993). "*Methodological studies of Movetrack coil placement procedures and their consequences for accuracy"*. FIPKM, 31, 65-81.

Engelke, W.D. & Schönle, P.W. (1991). "*Elektromagnetische Artikulographie: Eine neue Methode zur Untersuchung von Bewegungsfunktionen des Gaumensegels"*. Folia Phoniatrica, 43, 147-152.

Giet van der, G. (1977). "*Computer-controlled method for measuring articulatory activities*". J. Acoust. Soc. Am., 61, 1072-1076.

Gracco, V.L & Nye, P.W. (1993). "*Magnetometry in speech articulation research: some misadventures on the road to enlightenment"*. FIPKM, 31,

Gracco, V.L. (1995). "*Electromagnetic articulography: A brief overivew"*. Proceedings XIIIth Int. Conf. Phon. Sci., Stockholm, 4:58-61.

Harrington, J., Fletcher, J. & Roberts, C. (1995). "*Coarticulation and the accented/unaccented distinction: evidence from jaw movement data"*. J. Phonetics, 305-322.

Hertrich, I. & Ackermann, H. (1997). "*Accuracy of lip movement analysis. Comparison between electromagnetic articulography and an optical two-camera device*". FIPKM, 35 (in press).

Hixon, T., (1971). "*An electromagnetic method for transducing jaw movements during speech"*. J. Acoust. Soc. Am., 49, 603-606.

Hixon, T., Goldman, M. & Mead, J. (1973). "*Kinematics of the chest wall during speech production: volume displacements of the rib cage, abdomen and lung*". J. Speech and Hearing Res., 16, 78-115.

Höhne, J., Schönle, P., Conrad, B., Veldscholten, H., Wenig, P., Fakhouri, H., Sandner, N. & Hong, G. (1987). "*Direct measurement of vocal tract shape - Articulography*". In: J. Laver & M. Jack (eds.), Proc. European Conf. on Speech Technology, 2, 230-232, Edinburgh.

Honda, M. & Kaburagi, T. (1993). "*Comparison of electromagnetic and ultrasonic techniques for monitoring tongue motion"*. FIPKM, 31,

Hoole, P., Gfroerer, S. & Tillmann, H.G. (1990). "*Electromagnetic articulography as a tool in the study of lingual coarticulation*". FIPKM, 28, 107-122.

Hoole, P., Nguyen-Trong, N. & Hardcastle, W. (1993). "*A comparative investigation of coarticulation in fricatives: electropalatographic, elctromagnetic and acoustic data*". Language and Speech, 36, 263-288.

Hoole, P. (1993). "*Methodological considerations in the use of electromagnetic articulography in phonetic research"*. FIPKM, 31, 43-64.

Hoole, P. & Kühnert, B. (1995) "*Patterns of lingual variability in German vowel production*". Proceedings XIIIth Int. Conf. Phon. Sci., Stockholm, 2:442-445.

Hoole, P. (1996). "*Issues in the acquisition, processing, reduction and parameterization of articulographic data"*. FIPKM, 34, 158-173.

International Radiation Protection Association (1990). "*Interim guidelines on limits of exposure to 50/60Hz electric and magnetic fields"*. Health Physics, 58, 113-122.

Katz, W., Machetanz, J., Orth, U. & Schönle, P. (1990). "*A kinematic analysis of anticipatory coarticulation in the speech of anterior aphasic subjects using electromagnetic articulography"*. Brain and Language, 3, 555-575.

Keating, P., Lindblom, B., Lubker, J. & Kreiman, J. (1994). "*Variability in jaw height for segments in English and Swedish VCVs"*. J. Phonetics, 22, 407-422.

Kühnert, B. (1993). "*Some kinematic aspects of alveolar-velar assimilations*". FIPKM 31, 263-272.

Löfqvist, A. & Gracco, V. (1995). "*Articulatory kinematics in stop consonants"*. Proc. XIIIth Int. Cong. Phon. Sci. Stockholm, 3, 572-575.

Mooshammer, C., Hoole, P. & Kühnert, B. (1995). "*On loops*". J. Phonetics, 23: 3-21.

Ní Chasaide, A. & Fitzpatrick, L. (1995). "*Assimilation of Irish palatalized and velarized stops"*. Proc. XIIIth Int. Cong. Phon. Sci. Stockholm, 2, 334-337.

Nguyen, N. & Marchal, A. (1993). "*Assessment of an electromagnetic system for the investigation of articulatory movements in speech production."* J. Acoustical Soc. America, 94, 1152-1155.

Ogata, K. & Sonoda, Y. (1994). "*A study of sensor arrangements for detecting movements and inclinations of tongue point during speech"*. Proc. 1994 Int. Conf. Spoken Lang. Processing, 2, 659-662.

Panagos, G. & Strube, H.W. (1987). "*Two Magnetic Methods for Articulatory Measurements"*. Phonetica, 44, 197-209.

Perkell, J.S. & Cohen, M.S. (1986). "*An alternating magnetic field system for tracking multiple speech articulatory movements in the mid-saggital plane*". MIT Technical Report 512.

Perkell, J. (1990). "*Testing theories of speech production: Implications of some detailed analyses of variable articulatory data"*. In W.J. Hardcastle & A. Marchal (eds.), Speech production and speech modelling, pp. 263-288. Dordrecht, Kluwer.

Perkell, J., Cohen, M., Svirsky, M., Matthies, M., Garabieta, I. & Jackson, M. (1992). "*Electro-magnetic midsagittal articulometer (EMMA) systems for transducing speech articulatory movements*". J. Acoustical Soc. America, 92, 3078-3096.

Recasens, D. (1995). "*An EMMA investigation of lingual assimilation and coarticulation in a selected set of Catalan consonant clusters"*. Proc. XIIIth Int. Cong. Phon. Sci. Stockholm, 2, 582-585.

Romero, J. (1996). "*Articulatory blending of lingual gestures"*. J. Phonetics, 24, 99-111.

Rouco, A. & Recasens, D. (1996). "Reliability of electromagnetic midsagittal articulometry and electropalatography data acquired simultaneously". J. Acoust. Soc. Am, 100, 3384-3390.

Schönle, P., Grabe, K., Wenig, P., Höhne, J., Schrader, J. & Conrad, B. (1987). "*Electromagnetic articulography: use of alternating magnetic fields for tracking movements of multiple points inside and outside the vocal tract"*. Brain and Language, 31, 26-35.

Schönle, P. (1988). "*Elektromagnetische Artikulographie*". Berlin, Springer

Schönle, P., Müller, C., Wenig, P. (1989). "*Echtzeitanalyse von orofacialen Bewegungen mit Hilfe der electromagnetischen Artikulographie*". Biomedizinische Technik. 34, 126-130.

Sonoda, Y. & Ogata, K. (1992). "*Improvements of magnetometer sensing system for monitoring tongue point movements during speech"*. Proc. 1992 Int. Conf. Spoken Lang. Processing, 2, 843-846.

Tuller, B., Shao, S., Kelso, J.A.S. (1990), "*An evaluation of an alternating magnetic field device for monitoring tongue movements*". J. Acoust. Soc. Am. 88(2), 674-679.

Westbury, J. (1994). "*X-ray microbeam speech production database user's handbook"*. Waisman Center on Mental Retardation and Human Development, University of Wisconsin, Madison.

Zierdt, A. (1993). "*Problems of electromagnetic position transduction for a three-dimensional articulographic measurement system"*. FIPKM, 31, 137-141.