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Reviewing 30 years of electromagnetic articulography: some suggestions for improved experimental approaches

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Abstract

This paper reviews data collection practices in electromagnetic articulography (EMA) studies with a focus on sensor placement. Our overview is based on a literature review of 165 EMA papers published in *Journal of Laboratory Phonology*, *The Journal of the Acoustical Society of America*, *Journal of Phonetics*, *Journal of Speech, Language, and Hearing Research*, and *Clinical Linguistics and Phonetics*, in addition to 83 papers published in the proceedings of the past five ICPhS conferences (i.e. since 2003). This review shows that experimental designs greatly vary, which in turn may limit researchers' ability to compare results across studies. Consequently, we suggest an articulatory-driven strategy for determining where to position sensors on the tongue without causing discomfort to the participant. We also evaluate three approaches for attaching (NDI Wave) EMA sensors with respect to the duration the sensors remain attached to the tongue: 1) attaching out-of-the-box sensors, 2) attaching sensors coated in latex, and 3) attaching sensors coated in latex with an additional latex flap. Results indicate that sensors with a latex flap in general adhere better than out-of-the-box and latex-coated sensors, but the success of this method also varies as a consequence of participant's tongue anatomy.

Keywords: electromagnetic articulography; articulation; methodology; EMA; NDI Wave

1. Introduction

Electromagnetic articulography (EMA)[1] is a point-tracking method frequently used in the study of speech production. Sensors placed on the articulators (including tongue, lips and jaw) are used to track movement in real time in 3D. On the one hand, the advantages of EMA include high spatial and temporal resolution of data collected within the oral cavity, it is biologically safe and minimally invasive, the participants tolerate it well and it does not interfere (too much) with their speech. On the other hand, there are several disadvantages: the attachment of EMA sensors is more difficult on more posterior parts of the tongue, it is not possible to place too many sensors at once, and (as EMA is a point-tracking technique) sensor coordinates only provide partial information that does not capture the movement of the entire tongue surface or vocal tract (Mennen et al., 2010). Consequently, ensuring accurate and durable sensor placement is crucial for EMA experiments, and is therefore the focus of this paper.

Several articulographs are currently available on the market, with two main manufacturers, namely Carstens Medizinelektronik (Bovenden, Germany) and Northern Digital Inc. (Waterloo, Canada). Carstens Medizinelektronik has manufactured several articulography devices spanning from the late 1990s, including models AG100, AG200, AG500 and AG501, with the latter being the most recent. Northern Digital Inc. has manufactured the Wave articulograph, which came to the market in 2009 and has now been discontinued as their new articulograph, Vox-EMA, is soon to be released. In the past, the MIT system articulograph (Perkell et al., 1992) and the Movetrack system (Branderud, 1985) were also used as some of the first articulographs available.[2] As articulographs are costly, it is not uncommon for a lab to keep using an older device (see methodological overview below). However, improvements have been made and with the development of newer EMA devices, it became possible to collect more information, going from 2D EMMA (midsagittal) systems to 3D systems with 3 Cartesian coordinates and two angular coordinates (Hoole and Zierdt, 2010).

The tracking accuracy of articulographs is likewise consistently improving. The Wave system has $<$ 0.5 mm tracking error for 95% of position samples for human jaw movement (Berry, 2011). The Carstens AG500 has a median error of $<$ 0.5 mm across different types of recordings, including manual movements and various speech tasks (Yunusova, Green and Mefferd, 2009) and shows some numerical instabilities and anomalies (Stella et al., 2013). The AG500 articulograph is dependent on calibration and on the location of the sensors in the electromagnetic field as well as on the proximity between sensors (Yunusova, Green and Mefferd, 2009). Finally, a comparison of the Wave system and several Carstens systems (namely the AG200, AG500 and AG501) revealed that all four devices show local precision of around 1 mm but a large range of global precision, spanning from 3 mm to 2.18 cm (Savariaux et al., 2017), with the AG501 as the most accurate device with precision of 0.3 mm (RMS; Electromagnetic Articulograph, 2019). Comparisons of the AG500 and AG501 additionally revealed that the AG501 is not only more accurate but also more user-friendly (Stella et al., 2013).

Beyond collecting acoustic data, there has always been interest in combining articulography data collection with other methods measuring speech. Some of the methods that have been co-registered with electromagnetic articulography include: ultrasound tongue imaging (UTI; e.g. Aron et al., 2016; Benuš and Gafos, 2007), electropalatography (EPG; e.g. West, 1999; Simonsen, Moen and Cowen, 2008; Harper, Lee, Goldstein and Byrd, 2018), electromyography (EMG; e.g. Rong, Loucks, Kim and Hasegawa-Johnson, 2012), real-time magnetic resonance imaging (rtMRI; e.g. Kim, Lammert, Ghosh and Narayanan, 2014) and motion capture (e.g. Kroos, Bundgaard-Nielsen & Best, 2012; Krivokapić, Tiede and Tyrone, 2017).

In this paper, we first briefly discuss certain methodological considerations to be made when studying speech production with EMA. Second, we overview current practices and trends in EMA data collection, based on our review of 247 papers from five peer-reviewed journals and the last five editions of the ICPhS conference. Specifically, while we do include general information about the devices in use, the number of participants and frequently studied (clinical) populations, we mostly focus on the sensors' configuration, including the number, placement and types of sensors. Third, we describe our data collection procedure in detail and present an experiment with which we tested the sensor adhesion duration using three different approaches. Finally, we discuss our results and provide some recommendations for future practice.

2. Methodological considerations

There are several factors to be considered when conducting an EMA study. On the one hand, it is important to correctly place the sensors depending on the experimental design and to optimize sensor adhesion time to ensure cross-trial comparability (after re-attachment, a sensor might not be in the exact same position). On the other hand, it is necessary to consider the participants, making their experimental experience as comfortable as possible while not sacrificing scientific accuracy. This includes keeping in mind individual differences in facial and intraoral anatomy but also taking precautions for sensitive populations, such as those suffering from various types of disorders or the youngest or eldest among us.

2.1. Articulograph safety and participant exclusion criteria

Electromagnetic articulographs are safe to use (Hasegawa-Johnson, 1998). Both the AG500 and Wave articulographs fulfil the safety requirements for electrical equipment (Wave User Guide, 2009; Carstens AG500 Manual, 2006). Unfortunately, however, little research has been targeted specifically at the electromagnetic frequency ranges of EMA systems (Hoole and Nguyen, 1999), meaning that a lot of information about safety is inferred as opposed to systematically tested.

Due to the moderate-strength magnetic field[3] there are certain exclusion criteria that are specific to EMA and do not apply to acoustic speech production experiments. Common exclusion criteria for participant recruitment include (as in the Wave User Guide, 2009 and Carstens AG500 manual, 2006):

- pacemakers (the magnetic field of the EMA may interfere with the pacemaker operation);
- large metal objects in or around the head (e.g. hearing aid);
- insulin pumps.

Some studies have tested the exclusion criteria that concern large metal objects in or around the head. Katz et al. (2003) tested compatibility of the Clarion 1.2 S-Series cochlear implant with the Carstens AG100 articulograph in order to determine whether EMA affects the functioning of the implant, the accuracy of the measurements or the participants' speech perception. They determined that this particular brand and type of cochlear implant was compatible with this particular articulograph, and did not show adverse effects. Joglar, Nguyen, Garst and Katz (2009) tested potential interference between pacemakers/implantable cardioverter-defibrillators with the Carstens AG100. They determined that devices from Medtronic (type D154VRC), St. Jude (types 5172 and V-193) and Guidant (types 1860, T180, 1852 and 1853) were compatible with the Carstens AG100. Finally, Mücke et al. (2018; 2019) tested Essential Tremor patients who had undergone thalamic deep brain stimulation (DBS) surgery. Participants were tested using the Carstens AG501 while the implant was active and inactive, with no reported adverse effects. However, as new articulographs and medical devices come on the market, it is necessary to verify their field strength and electromagnetic frequency before doing any testing on participants. Additionally, some researchers advise against including pregnant women in empirical studies using EMA (Hoole and Nguyen, 1999) as the effect of the magnetic field is not entirely clear and it is better to err on the side of caution.

Despite these restrictions however, compared to some other methods that can visualize speech (including for example rtMRI), articulographs are less restrictive regarding the movement of the participant and, at least in the case of the Wave EMA system, more portable as well.

2.2. Placement of EMA sensors

Articulographs can be used to study the behaviour of both extraoral (i.e. the lips and the jaw) and intraoral (i.e. the tongue) articulators. However, the exact measurement of particular sounds and comparability across participants significantly depends on accurate sensor placement. Figure 1 shows typical sensor placement for EMA studies, which includes movement sensors, used to track the movement of articulators (red dots), and reference sensors, which are placed on orofacial structures that do not move during speech production (green dots).

The main goal of reference sensors is to correct for head movements subsequent to participants' recording, i.e. they correct for apparent movement of the tongue, lips or jaw that in fact only occurs in the data due to head movement. They are usually placed on bony structures, including the nasion (N), mastoids (behind both ears; ML and MR) and the gumline of upper central or lateral incisors (UI). In addition to reference sensors, a biteplate[4] recording is additionally made with a biteplate object that has 3 sensors attached to it (see Figure 7 in Section 4.1 for a picture of our biteplate). The object is placed between the participant's teeth in order to rotate the acquired data to a comparable occlusal plane between participants (Westbury, 1994).

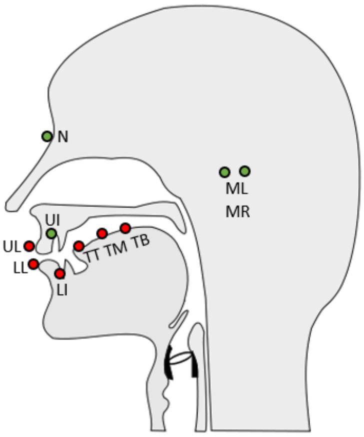

Figure 1: EMA sensors (original image by Tavin, distributed under the CC Attribution 3.0 Unported license; sensor points were added by the authors)

Movement sensors are placed on the lips, jaw and tongue in order to track articulator movements. Lip sensors are placed on the vermillion border of the upper and lower lip (UL and LL in the schematic above). They are used for tracking the movement of the lips (e.g. labial protrusion, spreading). Based on this data, it is possible, for example, to estimate variations in lip aperture or between lip area that are phonetically relevant (e.g. production of bilabial stops as compared to fricatives, or between rounded and unrounded vowels). The lower incisor sensor (LI in the schematic depiction) is used for tracking the movement of the jaw and placed on central or lateral lower incisors. Placement on the gums beneath the lower incisors as opposed to the chin is preferred, as there is no added skin movement. However, even without skin movement, jaw movement is still often difficult to decouple from tongue and lower lip movement (e.g. Henriques and van Lieshout, 2013).

Finally, several sensors are placed on the tongue surface. While the general placement of tongue sensors is visible on the schematic above, the exact positions are in fact highly variable. The relevant tongue anatomy is as follows: the tongue apex or tongue tip (marked with 1 in Figure 2 below) is the most anterior part of the tongue. The median sulcus (marked with 2) is the midline of the tongue, which “splits” the tongue body into two parts. The tongue body or corpus (marked with 3) includes the tongue dorsum used during speech, going from the tongue apex to the tongue root (marked with 4). EMA sensors are usually placed midsagitally on the median sulcus, however the exact placement varies depending on the study and researcher. Presuming three sensors, one sensor is placed on or near the tongue apex, one sensor close to the tongue root and one sensor in between (see a detailed discussion in Section 3.4). For consistency sake, we will refer to these sensors as tongue tip (TT), tongue middle (TM) and tongue back (TB), but note that researchers use a variety of denotations.

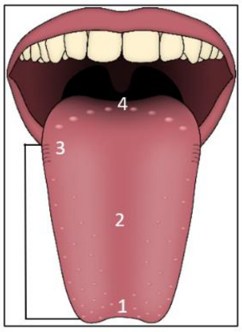

Figure 2: Tongue anatomy: 1 is tongue tip, 2 is the median sulcus, 3 is the tongue body or corpus, 4 is tongue root (original image by Jonas Töle, distributed under the CC CC0 1.0 Universal Public Domain Dedication license).

This sensor configuration with three or four sensors on the tongue allows researchers to investigate the production of a wide variety of sounds, from alveolar stops (tongue tip sensor, 1) to velars (tongue back sensor, 4). Lateral articulatory movements of the tongue are minimal (Perkell et al., 1992), thus sensors placed midsagittally suffice. However, one or two sensors may be added on the lateral parts of the tongue for the study of lateral sounds.

2.3. Speaker’s tongue anatomy and oral cavity

Differences in tongue anatomy (as described above) and shape of oral cavity across individuals are far from negligible. Tongue shapes vary vastly from one individual to the next (King and Parent, 2001). Some individuals may have a more fissured tongue with more grooving than others, which makes sensor adhesion to the median sulcus more difficult. On the one hand, tongue length depends on age, with adults having a longer tongue than children (Vorperian et al., 2005). On the other hand, gender effects on tongue length are less evident.

Some studies showed that men have significantly larger tongue breadth and volume (Oliver and Evans, 1986) while others did not even though men do usually have larger bony structure (Hopkin, 1967).

Tongue movement – and consequently sensor placement – also depends on the restrictions posed by the rest of the oral cavity, which shows large anatomical differences across individuals. Some people have plenty of gingival tissue above and below their incisors, making it easy to place reference sensors and sensors for tracking jaw movements. Yet others have little space and a very prominent labial frenulum, which complicates the placement of sensors to central upper and lower incisors. Likewise, there are differences between speakers in the height, length, slope, width and curvature of the hard palate (e.g. Brunner, Fuchs and Perrier, 2009; Rudy and Yunusova, 2013). Furthermore, salivary flow rates (i.e. the quantity of saliva) differ greatly across healthy individuals (Whelton, 2012). This may substantially influence how well sensors adhere to the tongue, as the usual cyanoacrylate adhesives (see description of adhesives below) polymerize after coming into contact with saliva. Moreover, the production of saliva is heavily influenced by external factors, such as degree of hydration or circadian rhythm, but also by minor factors including gender, age (children salivate more than adults) and body weight (Whelton, 2012).

In order to draw valid conclusions about speech kinematics and speech motor control based on EMA data, it is necessary to ensure between-subjects comparability. However, human anatomy makes this difficult. Researchers employing this technique have used various approaches to tackle this issue, most notably by introducing palate trace recordings, whereby a sensor is traced over the palate across the occlusal plane, providing an estimate of the shape of participants' oral cavity (please consult Neufeld and van Lieshout, 2014, for a description on how EMA sensors can be used to construct a 3D model of the hard palate). Most important, however, is to ensure that sensors are adhered to anatomically comparable places on the articulators. In the sections below, we discuss the placement of tongue sensors in more detail.

3. Practices and trends in EMA data collection

In order to determine current practices and trends in EMA data collection, we collected papers from the following journals: *Journal of Laboratory Phonology*, *The Journal of the Acoustical Society of America*, *Journal of Phonetics*, *Journal of Speech, Language, and Hearing Research*, and *Clinical Linguistics and Phonetics*. We employed the search terms "electromagnetic articulography", "articulograph", "EMA", "EMMA", "Carstens" and "NDI Wave" at the journals' websites, which led to 165 identified papers. We excluded abstracts, and papers that did not describe studies with participants (e.g. because the researchers focused on a new analysis procedure or device accuracy). Additionally, we examined the last 5 conference proceedings of the International Congress of the Phonetic Sciences (ICPhS). As ICPhS is organized once every 4 years, with the latest one having been organized in August 2019 (Melbourne, Australia), the 82 identified EMA papers from this conference represent about 15 years of articulography research as well as the latest studies carried out in the field. We thus found and studied altogether 247 papers. While this by no means encompasses the entirety of published works utilizing articulographs, we do believe it will provide a representative overview of EMA data collection procedures.

While reviewing the papers, we identified and registered the following parameters: type of EMA device in use, number of participants, population (healthy versus pathological), total number of sensors, number of tongue sensors, placement of sensors, sensor preparation, and adhesive used for sensor placement. Not all papers included all information. For example, while most papers mention the device type and number of sensors, few of them mention the adhesive in use.

In Appendix A, we have provided a table with all included studies from the journals (part 1 of the appendix) and the ICPhS conference (part 2 of the appendix). In the remainder of this section, we will discuss the number of studies using a certain procedure and provide example studies. Further details are available in the appendix.

3.1. General information

In the complete set of 247 papers, Carstens AG100 and Carstens AG100 are most frequently used. Table 1 lists commonly used articulographs in five time periods, namely the years 1990-1999, 2000-2005; 2006-2010, 2011-2015, and 2016-2019.

Table 1: Articulographs in use since the 1990s.

Time	Number of studies	Articulographs (number of studies)
1990-1999	15	Perkell-system EMMA (9) Carstens AG100 (5) Unspecified (1)
2000-2005	49	Carstens AG100 (31) Perkell-system EMMA (7) Carstens AG200 (2)

		Unspecified (9)
2006-2010	27 (one study used AG100 + AG500; both are counted)	Carstens AG100 (13) Carstens AG500 (4) Carstens AG200 (4) Perkell-system EMMA (2) Unspecified (6)
2011-2015	94 (studies used combinations EMMA + AG500, AG500 + Wave, AG500 + AG200	Carstens AG500 (45) NDI Wave (16) Carstens AG100 (12) Carstens AG200 (8), AG501 (4), Perkell-system EMMA (3) Unspecified (9)
2016-2019	62 (studies used combinations AG500+AG501; AG500 + Wave)	NDI Wave (32) Carstens AG501 (18) Carstens AG500 (12) AG200 (1), AG100 (1)

Several brands of adhesive are used to adhere the sensors, but only 48 out of 247 studies mention the exact type of adhesive. In the case of studies employing Carstens articulographs, this might also be due to the fact that researchers presumably use the adhesive the adhesive recommended on the Carstens website, namely Epiglu (Meyer-Haake GmbH). To our knowledge, NDI does not give any adhesive recommendations. The most popular (mentioned) adhesive is PeriAcryl®90 by Glustitch (20 out of 49 studies), followed by Isodent cyanoacrylate adhesive by Ellman International (7 studies) and Cyano Veneer Fast by Scheu Dental Technology (6 studies), Cyanodent by Ellman International (2 studies), Histoacryl by B. Braun (2 studies) and Aron Alpha by Toagosei (1 study). Note that IsoDent and Cyano-Dent adhesives appear to be discontinued[5], while the use of Histoacryl intra-orally may be problematic due to potential cytotoxic effects on cell cultures (Schneider and Otto, 2012).

What these adhesives (except for Histoacryl; Schneider and Otto, 2012) have in common is that they are intended for oral tissue (e.g. for use in dental or oral surgery), are biologically safe and highly viscous. Dental cements, including Ketac™ (7 studies), Fuji (2 studies) and Durelon (1 study), have also been used by several labs to attach tongue sensors (e.g. Mooshammer, Hoole and Geumann, 2006; Tabain, 2003; Steele and van Leishout, 2004), but are more invasive, as they involve covering the tongue dorsum with a hard substance.

3.2. Participants

Due to high time demands of the method, EMA studies frequently limit their number of participants. Out of 251 studies, more than 80% had 10 participants or fewer; around 50%

had 5 participants or fewer. Amongst those with the largest participant samples are Wieling, Veenstra, Adank, Weber and Tiede (2015) who tested 43 healthy participants, Lee, Dickey and Simmons who tested (2019) who tested 45 participants, including healthy speakers and those with dysarthria secondary to amyothropic lateral sclerosis (ALS), Cheng, Murdoch, Goozée and Scott (2007; the same sample also reported in Murdoch, Cheng and Goozée, 2012) who tested 48 adults and children, Wieling et al. (2016) who tested 48 adults, Schötz, Frid and Löfqvist (2013) who tested 50 adults and children, and McClean, Tasko and Runyan (2004) who tested 80 adults, including 37 stutterers.

The majority of tested participants are healthy adults (90% of the studies). Several studies have tested children from five years of age onwards, for example Katz and Bharadwaj (2001); Cheng, Murdoch, Goozée and Scott (2007); Schötz, Frid and Löfqvist (2013). Most frequently, such studies compare adult speech versus child speech in order to determine how the movements of individual articulators develop.

Articulographs have also been used to study disordered speech in individuals suffering from: Parkinson's disease (e.g. Kearney et al., 2018; Mefferd and Dietrich, 2019), Friedrich's ataxia (e.g. Folker et al., 2011), stuttering (e.g. Didirkova and Hirsch, 2019; McClean, Tusko and Runyan, 2004), cerebral palsy (e.g. Rong, Loucks, Kim and Hasegawa-Johnson, 2012), hearing impairments (e.g. Xue, Zhang, Bain and Wang, 2018), amyotrophic lateral sclerosis (e.g. Lee and Bell, 2018; Shellikeri et al., 2016), and apraxia of speech (e.g. Bartle-Meyer, Goozée and Murdoch, 2009; Nijland, Maassen, Hulstijn and Peters, 2004).

3.3. Number of sensors

The number of sensors largely depends on the study design. There seem to be two general strategies in choosing how many sensors will be adhered. Some prefer to have the minimum number of sensors needed, in order to decrease the time necessary for participant preparation. Usually these are studies with a very narrow focus, for example a targeted study of lip movement or jaw movement. Others prefer to adhere more sensors and collect additional data, in order to eliminate the need for several testing sessions. Frequently, studies describe how many sensors were adhered and then specify that the focus of the current analysis is on a particular sensor (e.g. data for lips, jaw and several tongue points was collected, yet the analysis concerns only the tongue tip sensor). As EMA data analysis is time-consuming, such a strategy focusing only on part of the data is not surprising.

In total, the reviewed studies show that a participant can have anywhere from 2 to 9 movement sensors attached, including:

- tongue (between 2 and 6 sensors, see details below);
- lips (between 2 and 4 sensors – upper lip and lower lip are frequent; lip corners are used occasionally);
- jaw (usually 1 sensor on the lower incisor to track jaw movement).

In addition to movement sensors, there are also between two and four reference sensors attached to the nasion, behind the left and right mastoid, and above the upper incisors. In our review, the highest number of sensors (reference and movement) adhered to a participant is 12, but most frequently around 8 sensors are used.

Concerning tongue sensors, 228 studies explicitly mention tongue sensors and their placement. 19 out of 231 studies use one tongue sensor; 55 studies use two tongue sensors; 107 studies use three tongue sensors; 41 studies use four tongue sensors; and 6 studies use five tongue sensors. Either 2 or 3 sensors on the tongue are the most popular option. If 4 tongue sensors are used, this brings the total of intraoral sensors to 6 (including the reference sensor on upper incisor and jaw movement sensor on lower incisors).

3.4. Positioning of tongue sensors

Of special interest to us is the placement of tongue sensors. As stated above, researchers most frequently use two or three tongue sensors, namely on the tongue tip (TT), tongue back (TB) and tongue middle (TM), placed along the tongue median sulcus. When three sensors are used, there are two main approaches to dividing the tongue dorsum: either by placing TT and TB according to a pre-determined measurement strategy or by spacing the sensors equidistantly. Several measurement possibilities and strategies of placement are described in Table 2.

In their placement of the TT sensor, most researchers provide a measurement, with "approximately 1 cm" from apex (i.e. the anatomical tongue tip) as the most popular choice. The exact method of measurement (i.e. by ruler, calliper or simply "eyeballing") is most often not specified. Furthermore, with few exceptions, it is not often specified whether the measurements were performed with the tongue extended versus the tongue resting inside the mouth. It should be noted that this can make a big difference: based on our experience, a point that is 1 cm from the apex with the tongue in rest can be nearly 1.5 cm from the apex when the tongue is stretched out.

For the placement of the TB and TM sensors, strategies are more varied. Some decide on a specific measurement, e.g. by placing TB and TM sensors with 2 cm of space in between each sensor or by placing the TB sensor 4-5 cm from tongue tip and with TM sensor in between the two. Others decide to place the TB sensor "as far back as possible" and the TM sensor in between.

Table 2: Tongue sensor placement strategies.

Sensor	**Methods of placement**	**Example studies**
Tongue Tip	From apex	
	5 mm	Byrd et al., 2005
	10 mm	Kearney et al., 2018; Kochetov et al., 2014; Dromey, Hunter and Nissen, 2018; Folker et al., 2011
	15 mm	Tilsen, Das and McKee, 2014
	Just behind the most anterior part of the tongue	Koos et al., 2013; Tomaschek et al., 2018
	If equidistantly	
	10 mm between each sensor	Tomaschek and Leemann, 2018
	20 mm between each sensor	Xue et al., 2018; Steele, van Lieshout and Pelletier, 2012
	Measure not defined	Simonsen and Moen, 2004; Marin, 2013
Tongue Back	Opposite the end of hard palate	Brunner, Hoole and Perrier, 2011
	15 mm from TT sensor	Lee and Bell, 2018
	20-30 mm from TT sensor	Dromey, Hunter and Nissen, 2018; Ji, Berry and Johnson, 2013
	40-50 mm from TT sensor	Mefferd, 2019; Matthies et al. (1996)
	As far back as feasible	Cler et al., 2017; Wieling et al., 2015; Steele and van Lieshout, 2004; Carignan, 2014; Brunner et al., 2014
Tongue Middle	If without TB	
	60-70 mm from tongue tip	Tilsen, 2017

	40-55 mm from tongue tip	Choo, Yoon and Kim, 2014; Murdoch, Cheng and Goozée, 2012
	If 1 TM sensor: equal distance from tongue tip and tongue back sensors	Brunner, Fuchs and Perrier, 2011; Carignan, 2014; Kuhnert and Hoole, 2004; Wieling et al., 2016
	If 2 TM sensors: equal-spaced between front and back extremes	Lucero and Löfqvist, 2005; Benuš, 2011

Beyond our literature review, it is necessary to mention a recent paper, wherein Patem, Illa, Afshan and Ghosh (2018) used dynamic programming in order to determine optimal sensor placement for the sounds of American English based on rtMRI video frames of the vocal tract. Based on four participants' data, they determined that the optimal placement for three tongue sensors is at 19.93 ± 11.45 mm from tongue base[6] (tongue tip sensor), 38.2 ± 11.52 mm from tongue tip (tongue middle sensor) and 80.51 ± 13.51 mm from tongue tip (tongue back sensor). While these measurements are exact and very useful to know, it would in practice be difficult to measure a participant's tongue in such detail. Furthermore, the confidence intervals are rather large.

3.5. Preparing and placing sensors

In this subsection, we will discuss how the various sensors are placed and prepared. We will first discuss the placement of the reference sensors, then the sensors on the lips, the sensors on the upper and lower incisor, and finally the tongue sensors.

3.5.1. Reference sensors

There are between two and four reference sensors placed intra- and extraorally. Reference sensors placed on extraoral structures (i.e. the nasion and mastoid sensors) are taped using medical or dental adhesive tape. They need to be taped firmly to prevent movement; a small drop of adhesive can additionally be added. They can also be coated in latex to make disinfection easier. The intraoral sensor is placed on the gingiva above upper central or lateral incisors (Section 3.5.3 discusses the placement of incisor sensors specifically). Alternatively, the reference sensors can be placed on a pair of goggles or a plastic glasses frame (as in, e.g. Ji, Berry and Johnson, 2013; Mefferd, 2019; Thompson and Kim, 2019). Columns regarding reference sensors in Appendix A can be consulted for more information.

3.5.2. Lip sensors

Lip sensors are placed on the vermillion border of the upper and lower lip. They can be bare or latexed (to increase hygiene, as these sensors are likely to come in contact with saliva). Most often they are adhered with a piece of tape. To increase adhesiveness, a small drop of adhesive can also be added, which ensures that the sensors are firmly adhered for the duration of the experiment and is especially important if the medical tape does not stick well (e.g. because of participant's sweat or large labial movements).

3.5.3. Incisor sensors

Incisor sensors are placed on the gingiva above the upper central or lateral incisor (i.e. the reference sensor) and on the gingiva below the lower central or lateral incisor (i.e. the jaw movement sensor). The majority of studies adhere the incisor sensors using the same dental adhesive as on the tongue. However, a different method is also possible, namely by adhering sensors to a piece of Stomahesive wafer (ConvaTec PLC). This is the method used by our lab as well as in some other studies (e.g. Mefferd, 2017; 2019). Adhesion of the sensor to the Stomahesive wafer both increases the surface of the sensor as well as, due to the nature of the material, increases adhesion to the participant's gingival tissue.

3.5.4. Tongue sensors

Most studies do not mention any special preparation of sensors prior to placement. One option for sensor placement is to adhere them to the tongue without any preparation, in their original state. Another approach is to coat the sensors in latex before adhesion. This is also suggested on the website of the Carstens articulograph (Electromagnetic Articulograph, 2019), where they indicate that Plasty-late latex milk (Glorex GmbH) is a suitable product for preparing the sensors this way. The latex coating, they report, keeps the sensors clean and without glue residue. In their Carstens AG500 Manual (2006) they additionally state, under the "Cleaning and disinfection of sensors" section, that it is recommended to coat the sensors as the latex can simply be peeled off after testing. Sensors can (and, if possible, should) according to Carstens be coated in latex for use on other facial surfaces, not just lingual, as this increases sterility and sensor longevity.

In this paper, we suggest a third, further developed, way of preparing tongue sensors, which combines the beneficial sterility of latex sensors with an increase in adhesion time. Namely, we cover the top of the sensors with a small, thin flap of latex (see Figure 5 in section 4.2 below). We are not the first lab trying to increase the adhesion surface, as Ji, Berry and Johnson (2013) placed small squares of silk between the sensor and lingual surfaces, Wieling et al. (2015) glued a small transparent layer of plastic to the bottom of the sensors, and Goozée et al. (2000) added small circular pads of silk cloth beneath the sensors. However, our approach is relatively fast and easy to apply, and may considerably increase the time sensors remain adhered to the tongue surface during EMA experiments. To demonstrate this, we also carried out an experiment, comparing the adhesion times of out-of-the-box sensors, latex-coated sensors and sensors with a latex flap.

4. Methods

4.1. Data collection procedure

4.1.1. Preparation and reference sensors

Our data collection procedure is as follows. First, we ask the participant to take a toothbrush and scrub their tongue – we tell them to do it front of a mirror, so that they are aware of how far back they are reaching and do not trigger their gag reflex. By scrubbing their tongue, they remove the coating that covers the tongue (the amount of coating differs per participant[7]). We ask the participant to remove jewellery and their hearing aid, if possible, as both make sensor placement more difficult and may interfere with the signal. We also ask participants whether they are wearing dentures, as they may introduce slight movement to an otherwise stable area (e.g. sensors attached to dentures move if the dentures move relative to the head or jaw). Since dentures cannot be removed without impeding articulation, we cannot do anything about them, except to note their presence.

Subsequently, the participant is asked to sit down next to the EMA field generator (we use the NDI Wave system). We first place 4 reference sensors:[8]

- mastoid right,
- mastoid left,
- nasion, and
- upper incisor.

All sensors (reference and others) are first held in reverse tweezers (Hobbycraft), as that makes the application of sensors to the participant easier. The first three reference sensors are applied after the researcher has sterilized their hands using Sterilium® (Medline). Before placing any intraoral sensors, the researcher puts on (latex) dental gloves and a dental mask.[9]

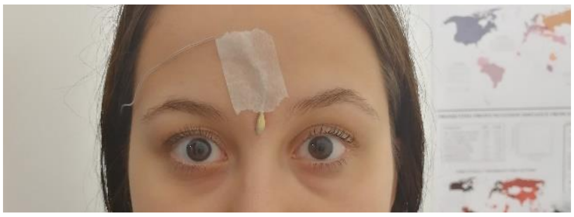

Figure 3: Nasion sensor.

The mastoid sensors are placed behind the participant's ears on the skin covering the mastoid part of the temporal bone, where there is least skin movement (Figure 4). The nasion sensor (Figure 3) is placed on the part where there is least skin creasing. If the participant is wearing glasses, the sensor is placed right above or below the glasses, depending on the frame. The first three sensors are secured with a drop of glue. We use PeriAcryl®90 HV adhesive (GluStitch Inc.), which is a dental surgery cyanoacrylate adhesive dressing, biologically safe for intraoral use. The wires are adhered to the participant using Leukopor tape (BSN medical GmbH).

Figure 4: Mastoid sensor.

The final sensor is placed on the maxilla, namely on the upper incisor (UI), as the upper jaw does not move during speech and can also be used as an intraoral reference point. A day before testing we prepare the UI sensor with a Stomahesive wafer (ConvaTec PLC) by cutting a small rectangular piece of about 10 mm × 6 mm. The sensor is placed on top of this piece and a drop of latex is applied to it in order to make it adhere (Figure 5, left and center).

Once the latex has dried, the UI sensor is ready to be applied. We place the UI reference sensor on the gingiva above the left upper incisor – we avoid placing any incisor sensors to the midsagittal line, directly above the central incisors, due to the labial frenulum, which connects the upper lip to the gingival tissue and is quite sensitive. UI sensor placement relative to the labial frenulum are also seen in Figure 5 (right).

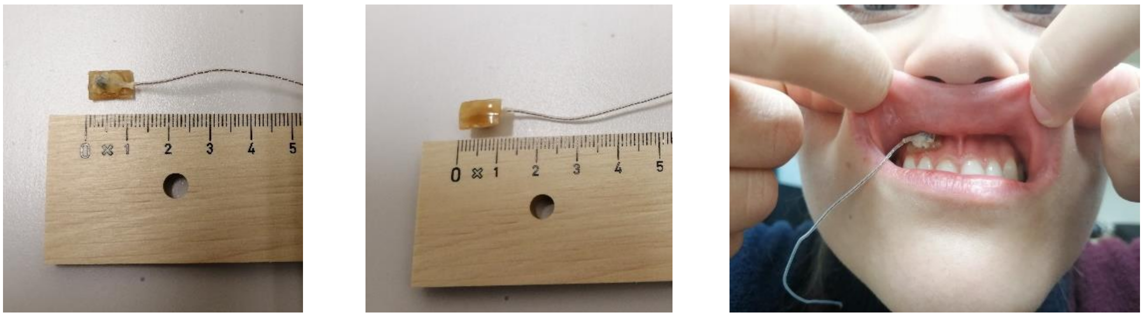

Figure 5: Upper incisor sensor latex side (left), gingival side (center) and placement (right).

After the reference sensors have been placed, the palate trace and biteplate recordings follow. For the former, we tape one spare sensor on the edge of the participant's dominant thumb and tell them to trace it from the edge of the hard palate to their front teeth. The exact trace and the purpose behind it is explained with the help of a mouth puppet (Super Duper® Publications; Figure 6), which is also useful in decreasing participants' eventual anxiety. The palate trace is performed twice.

Figure 6: Mouth puppet with attached sensors is very useful in explaining EMA.

For the biteplate recording, we have a triangular protractor with three sensors glued to it (Figure 7). The participant is asked to hold this triangle between their teeth and remain silent for a few seconds. We check the biteplate recording on the spot by calculating the Euclidean distances between all the reference sensors and the 3 sensors on the biteplate, using MATLAB (MathWorks Inc.). If these distances remain relatively constant over time, this indicates that the position of the reference sensors and the bite plate sensors are correctly tracked.

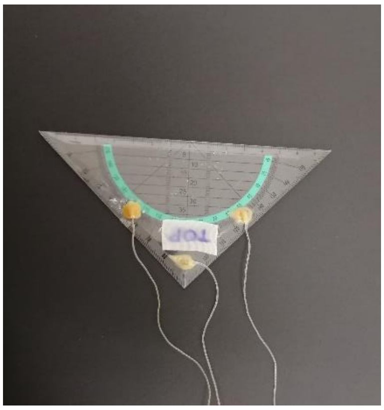

Figure 7: Biteplate protractor.

4.1.2. Attaching movement sensors

After the palate trace and biteplate recordings, we proceed with attaching sensors to the articulators that we wish to capture. Most frequently, these sensors are the following (listed in the order of placement):

- tongue back,
- tongue tip,
- lower incisor,
- upper lip, and
- lower lip.

In order to determine where to place the tongue back sensor, we use a colour transfer applicator stick (Dr. Thompson's, GUNZdental). We ask the participant to drag the stick midsagitally across the midline of their hard palate (as they had done before with the palate trace sensor) and then pronounce the sound /k/, followed by sticking out their tongue.[10] The colour from the applicator is transferred from the hard palate to the part of the tongue where the back-most (velar) sound is made. We use the same stick to draw a coronal line through this spot. Additionally, we use measuring tape to measure 1 cm from the tongue apex (when the tongue is stretched) and drag a coronal line through that point as well. The coronal line enables us to always re-adhere the sensor to the approximate same position if it starts getting lose. Figure 8 below shows the coronal lines on the tongue left by the colour transfer applicator stick, with the median sulcus still clearly visible.

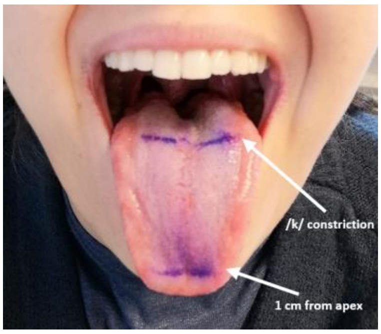

Figure 8: Indicatory markings for sensor placement.

The participant can now swallow as the coronal lines will remain clear, even when they come in contact with saliva. The tongue tip (TT) and tongue back (TB) sensors are pre-prepared to have a latex flap cover, which increases the surface of the sensor. The benefits and drawbacks of preparing the sensors this way are discussed under the results of our experiment. The participant is asked to stick out their tongue as far as possible. We place barber tape (folded 3 times to contain at least 4 layers) on the back line marking on participant's tongue, dab the tape on the tongue for about 5-10 seconds and finally drag the tape across the tongue. This procedure dries the tongue dorsum and is crucial in ensuring that sensors do not fall off easily.

The TB sensor is placed on the crossing between the marked back line and the median sulcus, so that the wire of the sensor is pointing to the side of the lip. A wooden tongue depressor is used to press the sensor to the tongue for 10-20 seconds. The wire is then secured to the cheek using Leukopor tape. Here it is essential that the wires have enough slack, since otherwise large speech gestures may lead to tension. The process is repeated for the TT sensor, whereby the wire of the sensor is placed to the side, as a wire running over the tongue tip may feel uncomfortable for the participant (Hoole and Nguyen, 1999). The final intra-oral sensor is the lower incisor (LI), which tracks jaw movements. This sensor is prepared beforehand with the Stomahesive wafer (see UI sensor above) and attached to the right lower incisor.

Finally, two sensors are attached to the middle of the vermillion border of the upper and lower lip using a drop of dental adhesive. Depending on the participant, the removal of lip sensors can lead to mild discomfort (e.g. for participants with a beard).

All extraoral sensors are pre-prepared, namely dipped in latex. This is done because it is easier to remove glue from the sensors afterwards (one simply peels off the latex) and to disinfect the sensors in order to re-use them for another participant. In case of re-use, we disinfect sensors first using SPORECLEAR Medical Device Disinfectant (Hu-Friedy Mfg. Co., LLC) and then wipe them with an alcohol wipe before storing them.

4.2. *Experiment: Sensor adhesion times*

The present experiment was designed in order to test how well different types of sensors adhere to the tongue. As discussed in Section 3.2, the most common way to collect data is with sensors that have not been pre-prepared in any way. However, in this paper we wish to investigate if using sensors covered in latex is beneficial. Please note that using latex on the sensors means that before any sensor placement takes place, the researcher needs to verify that the participant has no latex allergies (this is already essential when using latex gloves).

We tested three types of sensors, namely: out-of-the-box ("bare") sensors, latex-coated ("latexed") sensors and sensors with a latex flap. All sensors are wiped with an alcohol wipe and placed on a sterilized tray a short time before the participant's arrival, which increases sterility and hygiene. Out-of-the-box sensors (Figure 9, left) are the sensors provided by NDI, screwed into the miniature terminal blocks without any pre-preparation. Latexed sensors (Figure 9, center) are dipped in mask-making latex (RD-407 Mask Making Latex, Monster Makers), which makes them rounder and smoothens the edges. Finally, sensors with a latex flap (Figure 9, right) are covered in latex using a brush, which creates a circular surface surrounding the sensor (approximate surface: 70 mm^2).

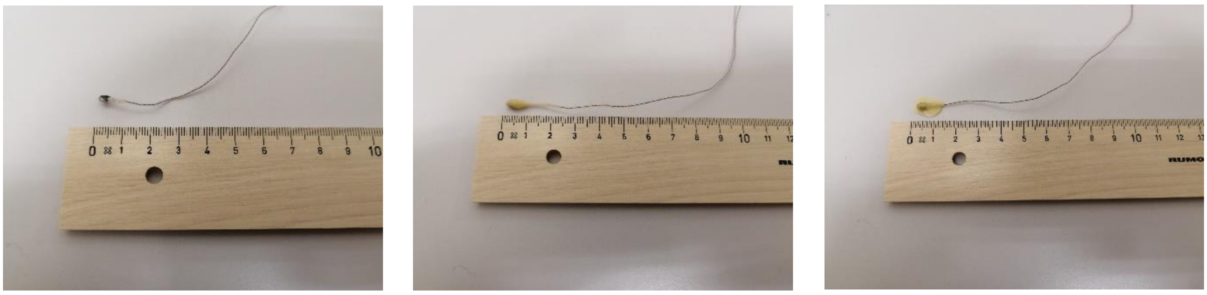

Figure 9: Sensor types (from left to right: out of the box, latexed, latex flap)

In order to test these three types, we recruited 5 participants whom we tested across three sessions. All 5 participants were women, between 20 and 30 years of age. In each of the sessions, we used one type of sensor and followed the same application procedure for each type (description in Section 4.1 above). By testing the sensors across three different sessions, which took place on three different days, we avoided the risk of glue residue and tongue fatigue, both of which would influence the resulting adhesion times. During the first session, we adhered out-of-the-box sensors, during the second session the latexed sensors, and during the final session the sensors with the latex flap.

During every session, we placed five sensors on the tongue, as this is towards the upper end of the number of tongue sensors used by researchers (see appendix). The sensors in question were placed on the tongue tip (TT; 1 cm from apex), tongue back (TB; place of /k/ constriction), tongue middle (TM; between TT and TB), and tongue lateral right and left (LatR and LatL, placed to the left and right of the TM sensor). While few studies use lateral sounds, we wished to assess whether different types of sensors are also suitable for studying lateral parts of the tongue, which move differently and are more prone to interference from the participants' molars.

The sensor placement process took approximately 10 minutes. After we placed the five sensors on the tongue, we immediately started to display the stimuli to the participants using PowerPoint on a desktop computer in front of them. The Wave was not turned on for this experiment, as we were not collecting kinematic data and merely wished to determine how long it took for each individual sensor to fall off. Figure 10 below displays an example of sensor placement for latexed sensors.

Figure 10: Sensor placement

The experimental procedure consisted of the following tasks and stimuli. First, the participants read the short text *Please Call Stella* from the *Speech Accent Archive* (Weinberger, 2015). This allowed them to get used to speaking with sensors in their mouth (i.e. the sensor habituation stage) and took approximately 1 minute. Following the text was a wordlist. It contained 300 words of varying lengths and from various thematic fields (e.g. vegetables, fruit, school, vocations). Each word appeared on the screen for 4 seconds, during which the participant had to read it out loud. This took 20 minutes. Finally, at the end of the first wordlist, the participants performed the diadochokinesis task at a comfortable speaking rate without a metronome. The DDK task involved the repetition of syllables 'pa', 'ta', 'ka' and 'pataka', and was included because, in our experience, repetitive movements often cause sensors to fall off. The three tasks were repeated twice or stopped earlier, if all the sensors had fallen off. When a sensor fell off, we removed it and noted the time it fell off. We did not re-attach any sensors.

The experimental procedure, including participant preparation (5 minutes) and sensor placement (10 minutes), took altogether at most 60 minutes. At that point, we stopped the experiment and removed the remaining sensors, meaning that the maximum time a sensor was adhered to a person was 45 minutes. The procedure is schematically presented in Figure 11.

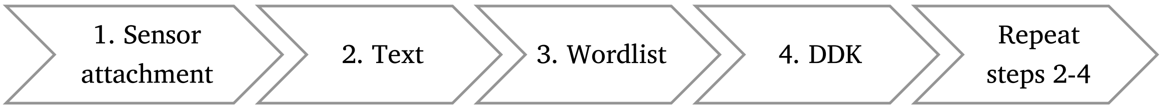

Figure 11: Experimental procedure

Additionally, we also took several anatomical measurements of the tongue for all five participants. First, we measured the tongue length, here defined as the distance between the tongue apex and the /k/ constriction. Second, we measured the tongue width, defined as the widest part of the tongue (usually parallel to the molar teeth). Finally, we asked the participants to extend their tongue and open their mouth as wide as they could. We measured the vertical length between the tongue and lowest part of their upper central incisors. We defined this as “mouth opening”, which in effect represents the workable oral space that the researcher has while doing sensor placement.

5. Results and discussion

The overview of average adhesion times per sensor type and placement shows that for all sensors it is better to use the latex flap as opposed to just the out-of-the-box sensor provided by NDI, or covering the sensor in latex without adding the flap. As can be seen in Figure 12 and Table 3 below, some sensors, namely the tongue middle (TM) and tongue back (TB), adhere noticeably better when they have a latex flap. This is especially important in the case of the TB sensor, where the out-of-the-box sensor adheres on average for 12 minutes while the latex flap sensor adheres for 27 minutes in our experimental procedure. With lateral sensors, the difference is less pronounced, as the out-of-the-box sensors adhere for 29 minutes and 31 minutes (left and right, respectively) while the latex flap sensors adhere for 36 minutes (both). Similarly, for tongue tip (TT) sensors, the difference is not as obvious as both types of sensors adhere on average 30 minutes. For all sensor positions, except TB, choosing the latexed version of the sensor fares worst.

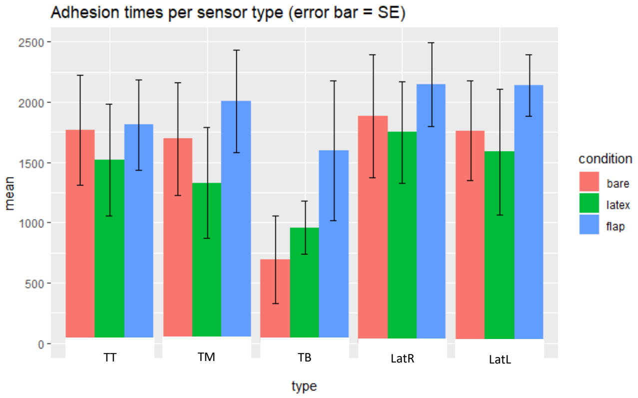

Figure 12: Sensor adhesion times, with standard error bars.

Table 3: Average adhesion times per sensor.

Sensor type	**Average adhesion times [in seconds]**				
	TT	TM	TB	LatL	LatR
Out-of-the-box	1770	1698	693	1764	1885
Latex	1522	1331	961	1588	1751
Latex flap	1811	2007	1598	2137	2146

Unfortunately, the picture does not remain as clear when we compare adhesion times of sensors across participants, as there is substantial individual variability (see Table 4 and Table 5 below). For the TT sensor, the latex flap was the best option for 2 out of 5 participants (P02 and P03); the latexed sensor adhered best for 1 participant (P05); the out-of-the-box sensor adhered best for 1 participant (P01); and the type did not matter for 1 participant (P04). For the TM sensor, the latex flap sensor adhered best for two participants (P01 and P03); the latexed sensor adhered best for 1 participant (P02); the out-of-the-box sensor adhered best for 1 participant (P05); and the type did not matter for 1 participant (P04).

Table 4: Adhesion times per participant (TT, TM, TB)

Placement →	**TT**					**TM**					**TB**				
Type ↓	P01	P02	P03	P04	P05	P01	P02	P03	P04	P05	P01	P02	P03	P04	P05
Out-of-the-box	2082	52	1750	2700	2265	1695	15	1650	2700	2430	1072	60	185	196	1953
Latex	1420	980	143	2700	2369	1741	1580	143	2700	490	1380	977	580	369	1498
Latex flap	1327	1450	2700	2700	1080	2700	855	2700	2700	1080	190	2700	2700	2200	200

Table 5: Adhesion times per participant (LatL, LatR)

Placement →	**LatL**					**LatR**				
Type ↓	P01	P02	P03	P04	P05	P01	P02	P03	P04	P05
Out-of-the-box	1531	590	1297	2700	2700	322	2700	1005	2700	2700
Latex	2700	15	908	2700	1616	1650	644	1060	2700	2700
Latex flap	2700	1975	1948	2700	1360	2700	1550	2700	2700	1080

For the TB sensor, the latex flap sensor adhered best for 3 participants (P02, P03 and P04); the latexed sensor adhered best for 1 participant (P01); and the out-of-the-box sensor adhered best for 1 participant (P05). For the left lateral sensor, the latex flap adhered best for 2 participants (P02 and P03); the out-of-the-box sensor adhered best for 1 participant (P05); for 1 participant (P01), both latexed and latex flap sensors adhered until the end. Finally, for the right lateral sensor, the latex flap adhered best for 2 participants (P01 and P03); the out-of-the-box sensor adhered best for 1 participant (P02); for 1 participant (P05) both out-of-the-box and latexed sensors adhered until the end. For both lateral sensors, the sensor type did not matter for 1 participant (P04).

In general, the latex-flap approach was most successful. However, the individual differences are, at least partially, explainable through individual tongue anatomies of the five participants. Table 6 shows the length and width of each participant's tongue as well as information on the mouth opening height when the tongue is extended.

Table 6: Tongue anatomy measures.

Participant	Length	Width	Opening
P01	67 mm	55 mm	25 mm
P02	58 mm	45 mm	35 mm
P03	50 mm	44 mm	16 mm
P04	63 mm	45 mm	32 mm
P05	65 mm	35 mm	23 mm

Especially insightful are the participants who clearly show a preference for one sensor attachment type. Participant P02 is one such individual. She has a reasonably large tongue (length: 58 mm; width: 45 mm; opening: 25 mm) but a heavy salivary flow rate.[11] For her, the latex flap sensors or latexed sensors were the better choice for all midsagittally-placed sensors. On the other hand, participant P05 had a narrow and long tongue (length: 65 mm; width: 35 mm; opening: 23 mm) and did not produce as much saliva. For her, out-of-the-box sensors (smaller in size) were more suitable. For participant P03, who had a small but wide tongue (length: 50 mm; width: 44 mm; opening: 16 mm) that did not extend much, the latex flap sensors worked better. Partially, that was because she also produced a bigger flow of saliva; and partially because she was not capable of opening her mouth wide enough. In this case, the placement is easier when a wider sensor surface is available. Finally, participant P04 stands out, as all types of sensors, excepting TB, remained adhered for the full duration of the experiment. Her tongue was fairly long (length: 63 mm; width: 45 mm; width: 32 mm) and quite dry. She was able to open her mouth wide but not keep it that way for long;

consequently, the latex flap worked best for the TB sensor even though it did not matter as much for the other sensors.

Further, we would like to mention perceptual impressions of different types of sensors, both by the participants as well as by ourselves. We noticed that when participants had all five sensors with latex flaps attached, this seemed to impact their speaking experience in two ways. First, it seemingly took them longer to get used to speaking with the sensors in their mouth (the habituation text was not enough; instead their speech returned to pre-sensor levels during the start of the wordlist). Specifically, regarding the tongue tip sensor, the pronunciation of sounds /t/ and /s/ was made harder. Second, five sensors seemed to cause a heavier salivary flow rate (please note, however, that this is not usually the case when fewer sensors are used). On the side of participants, they noted that while they felt the presence of five latex flap sensors more than the five out-of-the-box sensors, they also thought that loose flap sensors were more comfortable than loose out-of-the-box sensors (i.e. with the out-of-the-box sensors, the edges are sharper and therefore slightly uncomfortable).

Finally, there is a clear practical advantage of latex flap sensors: they do not easily fall off in their entirety. Instead, they simply detach partly (as part of the flap remains attached) and, with frequent checking of the participant's tongue between experimental trials, it is easy to re-attach the sensors. Instead of having to find the exact same spot again, one can simply add a drop of adhesive to the still-attached sensor.

6. Conclusion

The goal of this paper was to review approaches in collecting speech production data using electromagnetic articulography (EMA), and to inform on several approaches we use in our lab. The focus of the paper was threefold: first, sensor preparation is important; second, there are anatomical and physiological differences between talkers that influence adhesiveness of different sensor types; and third, accurate sensor placement matters in ensuring comparability between participants and across trials.

First, regarding sensor preparation: according to our systematic literature review, researchers most frequently use out-of-the-box sensors or latexed sensors to place on the tongue. Our proposed approach, which consists of increasing the surface of the sensor, thus making it adhere better, is rarely used. In order to determine which type of sensor – out-of-the-box, latexed or with latex flap – adheres best, we ran an experiment, wherein we tested five participants across three sessions. The results show that using the latex flap sensors was the best approach, nearly doubling the adhesion time in the tongue back position as well as increasing the adhesion time for the other sensor positions. However, for the tongue tip sensor, adhering the latex flap seems to influence the speaking experience, namely by increasing the time it took the participants to get used to speaking with sensors in their mouth. Consequently, it may be better to experiment with using a reduced flap surface in that position or increased habituation time provided before the start of an experimental procedure.

When attaching intraoral sensors, it is crucial to preserve a sterile environment. In general, latexed sensors (both with or without latex flaps) are more hygienic, easier to clean, and preserve the longevity of sensors if one wishes to re-use them. However, our experiment showed that sensors merely coated in latex – the method suggested on the Carstens website – generally show the lowest adhesion times in our experimental approach. Latex flap sensors therefore seem the better option. An additional advantage is that they do not fall off easily in their entirety, as it is easy to add a drop of adhesive to a slightly detached sensor.

However, and this brings us to the second goal of this paper: the difference between talkers should not be ignored. This refers to both talker anatomy and the adhesiveness of sensors as well as to the difference in healthy adult populations versus sensitive populations, such as children, the elderly or those suffering from various types of diseases and speech disorders. While our experiment in general showed that latex flap sensors fare better, especially in the tongue back position, this result was very much speaker-dependent. Latex flap sensors were very well suited for the two speakers who had heavier salivary flow rates and were not able to open their mouths as wide. For another speaker, with a long and narrow dry tongue, out-of-the-box sensors were more suitable.

Partially, sensor adhesion is also affected by the wires leading from the mouth. In our case, we adhered five sensors on the tongue in order to study the maximum number of sensors used, although our review showed that the average number of sensors is two to three. With fewer intraoral sensors, there are fewer wires that can become tangled and the sensors are likely to adhere longer. The importance of wire placement was also shown in the adhesiveness of lateral sensors. One reason that the right lateral sensor tended to adhere slightly longer than the left lateral sensor was likely because there were no other wires in the way.

On the one hand, the more sensors there are on the tongue, the more points we are able to track and the better picture of the articulators' movement we obtain. On the other hand, with the lower and upper incisor sensors (jaw movement and reference sensors, respectively) attached, speakers frequently have 5 wires in their mouth, which makes speech less comfortable and fluent. More tongue sensors are especially problematic where sensitive populations are concerned, as they are more prone to fatigue, find it more difficult to stick out their tongue and open their mouth wide, their speech is more likely to be impeded by a foreign object in their oral cavity, and, in the case of children, they also salivate more and need more frequent toilet visits (which necessitates shorter preparation times and experimental procedures). When testing children and patients (e.g. those suffering from Parkinson's disease), we therefore opt for two tongue sensors (tongue tip and tongue back).

Finally, our third goal was to highlight the importance of adhering sensors to anatomically comparable articulatory places in order to ensure between-speaker and within-speaker comparability across trials. For this reason, we place the tongue tip sensor 1 cm from the tip and the tongue back sensor on the place of the /k/ constriction. This ensures that we are placing the sensors to a larger extent based on the speakers' articulatory strategies and anatomy as opposed to general (rather arbitrary) measurements.[12]

Going forward, as point-tracking technology continues developing and becomes more advanced, it is also necessary to strive to find improved and more consistent methods of sensor adhesion and placement. This paper represented our attempt at presenting the best practices and suggestions for EMA data collection, but it is our hope to further encourage debate on the topic.

Acknowledgments

We would like to acknowledge that many parts of the EMA approach used in our lab are also based on borrowing successful approaches from other labs. We would particularly like to thank Mark Tiede for demonstrating his procedure at Haskins Laboratories. Furthermore, we would like to thank all other researchers with whom we have discussed issues and exchanged experiences regarding EMA studies, including June Sun, Fabian Tomaschek, Marianne Pouplier, Michael Proctor, Stefanie Keulen, etc. We would further like to acknowledge funding from the Dutch Research Organisation (NWO) to Martijn Wieling (grants no. 019.2011.3.110.016, 016.144.049 and PGW.19.034). At present, the Speech Lab Groningen is a seed testing site for Northern Digital Inc. However, this has not affected the present paper in any way. We are not affiliated nor received benefits from the other product manufacturers that were mentioned in our data collection procedure specifically, nor with any that were mentioned in this paper in general.

Notes

[1] Electromagnetic Articulography (EMA) used to be known as Electromagnetic Midsagittal Articulography (EMMA). While the “midsagittal” part is not applicable anymore as the sensors are tracked in 3D, both spellings remain in use in the literature.

[2] The predecessor to the articulographs was the X-ray microbeam, which tracked 6 pellets on the tongue and teeth (Kiritani, 1985).

[3] Please note that the term “moderate-strength” is used here as the field is strong enough to cause interference with various devices (to the extent of corrupting the data, not harming the participant), but not nearly as strong as, for example, the field in an MRI chamber.

[4] Researchers refer to both “biteplate” and “biteplane” recordings.

[5] The company Ellman International, Inc., seems to have been acquired by Cynosure, Inc., in 2004 (Cynosure, Inc., 2014, para. 1) and some products discontinued.

[6] Unfortunately, Patem et al. (2018) do not specify how their manual annotators defined “tongue base”, but it is presumed that it refers to the point where the tongue meets the floor of the mouth.

[7] Coffee, especially, leaves a brown coating on the tongue, which is not optimal for sensor placement.

[8] In principle, three (or even two) reference sensors are enough to correct head movement, however, we use one additional sensor as a backup in case one of the reference sensors malfunctions. We do not use the NDI 6DOF sensor (containing two sensors with a specific distance and orientation towards each other) which may be used to automatically correct for head movement, as it is beneficial to maximize the difference between the reference sensors to minimize the influence of noise from the reference sensors on the rotation.

[9] We use the dental mask for adults but often avoid it for children, as they do not yet have such a strong “germ reflex” and we noticed it makes them feel uncomfortable.

[10] This procedure is similar to the procedure used by Brunner, Hoole and Perrier (2011). However, we use the colour transfer applicator to mark the spot where the participant produces their /k/. Brunner, Hoole and Perrier (2011) used an oral disinfectant with a strong purple colouring agent and asked the participant to close their mouth and push their tongue (neutral position) against the hard palate. The colour mark was thus transferred to the tongue dorsum.

[11] We did not measure the salivary flow rate, so this is an impression based on the experience we have with the five participants in this experiment as well as participants in other studies.

[12] 1 cm behind the tongue tip is also somewhat arbitrary, however it seems to be a good compromise between seeing (and measuring) tongue tip movements and not impeding participants' speech.

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