Experimental approaches in electromagnetic articulography

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Abstract

This short paper provides an overview of a study on experimental approaches in electromagnetic articulography (EMA) by Rebernik *et al.* (forthcoming, 2021). It consists of three parts: in the first part, we provide an overview of existing data collection practices, with a focus on sensor placement. This overview is based on a literature review of 905 publications from a large variety of journals and conferences, identified through a systematic keyword search in Google Scholar. In the second part of this paper, we briefly describe the steps of an EMA data collection procedure, including our method of placing EMA sensors. Finally, in the third part of this paper, we evaluate three approaches for preparing (NDI WAVE) EMA sensors reported in the literature by testing how long the sensors remain attached to the tongue. Specifically, we test: 1) out-of-the-box sensors, 2) sensors coated in latex, and 3) sensors coated in latex with an additional latex flap. Results indicate no clear general effect of sensor preparation type on adhesion duration.

Keywords: speech kinematics, EMA, articulation, electromagnetic articulography, NDI WAVE

1. Introduction

Electromagnetic articulography (EMA) is a point-tracking method for the study of speech kinematics, whereby sensors placed on the articulators (e.g., tongue, lips and jaw) track the articulators' 3D movement in real time (Schönle *et al.*, 1987; Mennen *et al.*, 2010; Hoole & Nguyen, 1999). The advantages of EMA include high spatial accuracy and temporal resolution, and the ability to measure multiple articulators at once and directly. Furthermore, it is safe to use and minimally invasive. The sensors are well-tolerated by the participants, while changes in speech acoustics are minor (e.g., Dromey *et al.*, 2018).

Some disadvantages of EMA include the fact that sensor placement is limited to the anterior vocal tract and it is not possible to examine the full shape of the tongue (as EMA is a *point*-tracking method). There are significant limitations to how many sensors can be placed and where they can be placed (e.g., it is more difficult to place sensors more posteriorly on the tongue and not too many sensors can be placed next to each other). Consequently, the success of EMA greatly depends on accurate and durable sensor placement.

The goal of this study was threefold. First, we reviewed how researchers have previously described EMA data collection procedures, with a focus on sensor placement. Second, we described our own data collection procedure. Third, we carried out an experiment to compare three approaches for attaching sensors to the tongue.

2. Literature review

2.1. Search criteria

We used Google scholar to collect journal papers and conference proceedings papers by using the search terms *articulography*, *articulograph*, *articulometry*, and *articulometer*. We excluded papers that were less than four pages long, papers that did not describe studies with participants, and papers that were not written in English. These search criteria, limited to the time period between 1987-2019, led to 905 identified publications, which included 412 journal papers, 413 conference papers, and 80 other writings (most frequently doctoral dissertations). We identified the following parameters in these publications: type of EMA device in use, number of participants, population (healthy versus pathological), total number of sensors, number of tongue sensors, placement and preparation of sensors, and adhesive used for sensor placement. Not all publications included all parameters. Our analysis of this literature review focused on journal publications only, to avoid duplication of studies.

2.2. Findings

2.2.1. Participants

Around 75% of studies tested 10 participants or fewer, and nearly 50% of the studies included five participants or fewer. This is also in line with Kochetov (2020) who reported that the median number of participants in an EMA study is five. Furthermore, the participants are predominantly healthy adults (80% of the studies), although some studies have tested children (e.g., Schötz *et al.*, 2013) and individuals with various speech disorders, such as stuttering (e.g., Didirková & Hirsch, 2019) or hypokinetic dysarthria (e.g., Kearney *et al*., 2018).

Due to the time-consuming nature of the method, a limited number of participants is to be expected, which is why articulatory-driven sensor placement across participants is essential.

2.2.2. General sensor placement

The most common sensor setup includes three or four reference sensors (on the nasion, upper incisor, and mastoid processes) and six movement sensors (i.e., upper and lower lip, jaw, and three sensors on the tongue). There is some variability in the placement of reference sensors, as some researchers place them directly on the bony structures (which do not move during speech) while others use, for example, a pair of goggles to which reference sensors are already attached before the arrival of the participant.

Lip movement sensors are placed on the vermillion border of the upper and lower lips. Relatively few researchers place sensors on the lip corners. The jaw movement sensor is most frequently placed on the gingiva above the lower incisor, but some researchers also place it on the chin.

2.2.3. Tongue sensors placement

The most frequent procedure is to place three sensors on the tongue (49% of studies), ranging from the tongue apex to the root along the median sulcus. The exact placement strategies differ, however. Some researchers choose to place sensors equidistantly, for example with 1 or 2 cm between the sensors. Others prefer placing the tongue tip sensor 1 cm behind the tongue apex, the tongue back sensor "as far back as comfortable", and the remaining sensor midway between the two.

However, it is often unclear how the placement for the tongue tip sensor is measured exactly (e.g., with a ruler versus "eyeballing", with the tongue stretched out or inside the mouth) nor is it specified how the degree of participant's comfort is assessed for the placement of the tongue back sensor.

Our literature review demonstrates that experimental designs greatly vary across empirical studies. This discrepancy is likely to impact how speech sounds are examined and hence limits researchers' ability to compare results across studies.

3. Data collection procedure

The following section briefly describes the steps involved in our EMA data collection procedure.

3.1. Sensor preparation

We prepare three types of sensors before the experiment. First, we prepare sensors by dipping them into mask-making latex. These "latexed" sensors are to be placed on the nasion, both mastoids, lips, and tongue (except the most posterior tongue sensor). Second, we prepare a latex flap sensor by placing the sensor head on a flat surface, after which we apply latex to it using a paintbrush. This sensor is to be placed most posteriorly on the tongue. Third, we prepare sensors with a Stomahesive wafer (**Figure 1**), which are to be placed on the gingiva above and below the upper and lower incisors. Stomahesive adheres very well to the gingival tissue, which makes it highly suitable for reference and jaw movement sensors. Before use, we check all sensors for any defects and we disinfect them using SporeClear (Hu-Friedy, LLC).

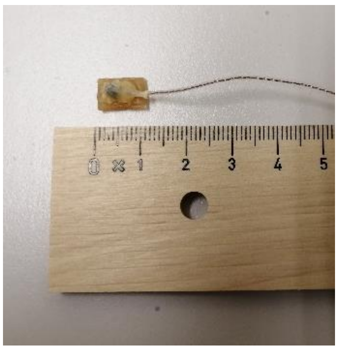

Figure 1: *Example of an incisor sensor prepared with Stomahesive wafer.*

3.2. Participant preparation

When a participant arrives, we check that they are not pregnant and do not have any metal inside or around their head (including a pacemaker). Otherwise, they cannot participate in the experiment. We further check that they are not allergic to latex, due to our sensor preparation methods. If possible, we ask the participant to remove their jewelry, glasses and hearing aids; we also note the presence of dentures, as they can introduce micromovements that will be detected by EMA (Hoke *et al.*, 2017).

Before sensor placement, we describe the procedure to the participants using a dental dummy mouth that has sensors attached (**Figure 2**). We also ask the participants to scrub their tongue with a toothbrush in front of a mirror – this removes some of the coating on the tongue and helps with adhesiveness.

Figure 2: *Dummy mouth with sensors.*

3.3. Attachment of reference sensors

All sensors are being held in reverse-action tweezers before application. For application, we add a drop of adhesive (PeriAcryl®90 HV) and press the sensor down on the body part using a wooden tongue depressor. After placement, we secure the sensor wires using medical tape.

Starting with the reference sensors, we first place the sensors on the left and right mastoids. If the participant is wearing glasses, we place the sensors right underneath the frame. Mastoid sensors are followed by the nasion sensor, placed to not disturb the participant's vision. Finally, we place the sensor (prepared with Stomahesive) on the gingiva above the upper incisor.

While in theory three sensors are sufficient to correct for head movements, we (along with a large number of other researchers) use four in case one sensor malfunctions.

3.4. Palate trace and biteplate recording

After placing the reference sensors, we perform the palate trace and do the biteplate recording. For the palate trace, we tape a spare sensor to the participant's thumb. We subsequently instruct the participant (with help of the dummy mouth; **Figure 2**) to trace their thumb from the back of the hard palate to their front teeth. This data allows us to superimpose the palate shape on data points recorded from other sensors.

Afterwards, we conduct the biteplate recording. The participant is instructed to hold a protractor (which has three sensors on it; **Figure 3**) firmly between their teeth. We check the recording on the spot, to confirm that the reference sensors are attached well.

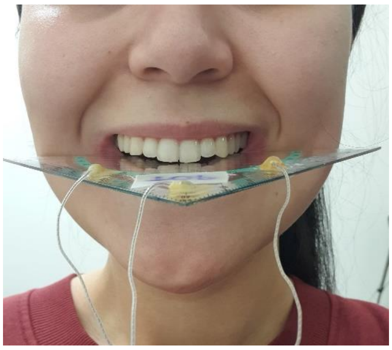

Figure 3: *Biteplate protractor held between front teeth, in contact with the molars.*

3.5. Attachment of movement sensors

3.5.1. Attachment of tongue sensors

We most frequently place three tongue sensors along the median sulcus in the following order: tongue back (TB), tongue mid (TM) and tongue tip (TT).

For the TB sensor, we give the participant a color transfer applicator stick and ask them to trace the stick along the midline of their hard palate (similar to what they did before during the palate trace with the spare sensor). They are subsequently instructed to say the sound /k/ and stick out their tongue immediately afterwards. We then draw a coronal line through the point of the /k/ constriction. This allows us to have an indication of where the participant is pronouncing their posterior sounds and can measure velar tongue movement without making the participant uncomfortable by placing the sensor too far back.

We additionally place a ruler on the participant's outstretched tongue and mark a point at 1 cm posterior to the tongue apex, through which we also draw a coronal line. **Figure 4** shows the tongue marked for the placement of the TT and TB sensors.

Before placing the sensors, we dry the participant's tongue using barber tape. We place the TB sensor on the point of the /k/ constriction, the TM sensor equidistantly between the TT and TB sensor, and the TT sensor at the 1 cm point.

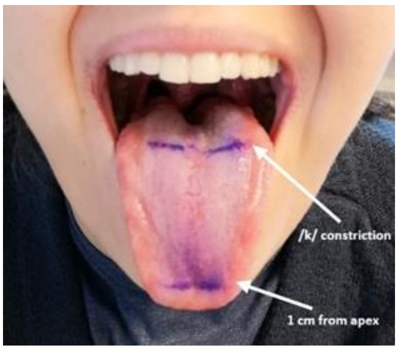

Figure 4: *Indicatory markings for tongue sensor placement.*

3.5.2. Attachment of other movement sensors

Finally, we attach the remaining sensors. Specifically, this includes the jaw movement sensor and the lip sensors. We place the jaw movement sensor (prepared with Stomahesive) on the gingiva below the lower incisor. If that is not possible – for example, because the participant is already struggling with the number of intraoral sensors or because there is not enough space, which can especially happen in the case of children – then we place the jaw movement sensor on the chin, where there is least skin movement. Lip sensors are subsequently placed on the vermillion border of the upper and lower lips with a drop of adhesive. Depending on the participant, lip sensor removal can be slightly uncomfortable (e.g., in the case of facial hair).

4. Sensor adhesion experiment

4.1. Method and goal

We evaluated three approaches for attaching (NDI Wave) EMA sensors with respect to the duration the sensors remain attached to the tongue. Specifically, we adhered out of the box sensors (**Figure 5**, left above), sensors coated in latex (**Figure 5**, right above) and sensors coated in latex with an additional latex flap (**Figure 5**, below).

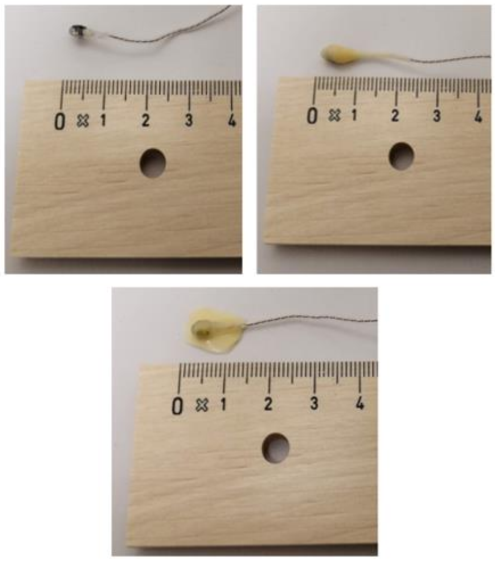

Figure 5: *Sensor types next to a metric ruler (above: out-of-the-box sensor on the left, latexed sensor on the right; below: latex flap sensor).*

While the first two types of sensors are frequently used, the additional latex flap, which increases the adhesion surface, is not often included. Notable exceptions, which also increased the sensor surface but using a different approach, include Ji *et al.* (2013) and Goozée *et al.* (2000) who placed pads of silk cloth between the sensors and lingual surfaces; and Wieling *et al.* (2015) who glued a transparent layer of plastic to the bottom of the sensors.

We tested ten female participants, aged between 20 and 30, across three separate sessions. We adhered five sensors to the tongue, with the tongue tip (TT) sensor placed 1 cm from the tongue apex (measured with an outstretched tongue, using a ruler), the tongue back (TB) sensor positioned at the marked place of the /k/ constriction, and the tongue middle (TM) sensor positioned halfway between the two (see also **Figure 4** above for tongue markings). The tongue lateral sensors (TLL and TLR, respectively) were positioned laterally to the TM sensor.

The participants read aloud a text for sensor habituation, then proceeded with reading aloud a wordlist, and finally performed a syllable repetition task. The experimental procedure was terminated when all sensors had fallen off or when the tasks had been repeated twice (approximately after 45 minutes).

4.2. Results

Using linear mixed-effects regression modelling with the optimal random-effects structure, we evaluated whether sensor preparation type (**Figure 6**) and sensor position (**Figure 7**) affected sensor adhesiveness. We determined the best model for our data via model comparison, and found that it only warrants the inclusion of the distinction between the TB sensor and other sensors (TT, TM, TLL, TLR), in addition to a by-subject random intercept and a by-subject random slope for the contrast between the TB sensor and other sensors. This model showed that the TB sensor adhered approximately 14 minutes less than the other sensors ($\beta = -14.0$, $t = -5.0$, $p < 0.001$).

When testing for the effect of sensor preparation on the TB versus other sensors, we found that the latex flap improved the adhesion time of the TB sensor by 9 minutes compared to the bare (out-of-the-box) sensor.

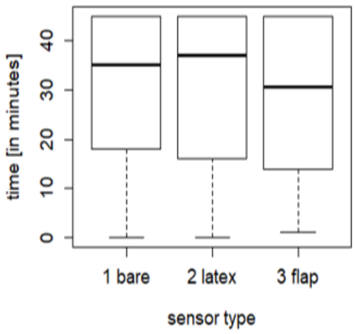

Figure 6: *Effect of sensor preparation type on adhesiveness.*

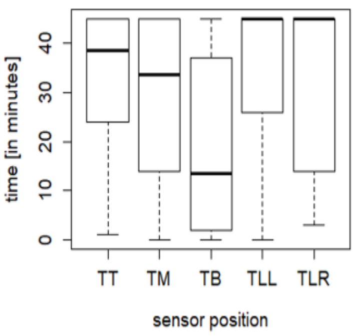

Figure 7: *Effect of sensor position on adhesiveness.*

5. Discussion and conclusion

To conclude, our findings drawn from our literature review and empirical investigation offer possible strategies for sensor placement and emphasize the importance of ensuring cross-study comparability. As EMA data collection and analysis are time-consuming and technically demanding, it is difficult to include a large number of participants (but see, e.g., Wieling *et al.*, 2015). Five participants seem to be the norm in EMA research, but 50 or more participants would be needed for a study to have 80% power (Brysbaert 2019). If it is not feasible to test large numbers of participants using EMA, then the procedure used for testing should be carefully devised in order to facilitate between- and within-speaker comparability. One of the ways to do this, is to ensure reliable, accurate and replicable sensor placement. Our findings may serve as a starting point for further debate on the topic.

6. Acknowledgements

This paper is a short version of Rebernik *et al.* (forthcoming, 2021), which will appear in *Laboratory Phonology*. For more details, please consult the full version. The authors would like to thank the anonymous reviewers and the ISSP conference attendees, who helped us further clarify the paper.

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