Comparing acoustic analyses of speech data collected remotely

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Face-to-face speech data collection has been next to impossible globally due to COVID-19 restrictions. To address this problem, simultaneous recordings of three repetitions of the cardinal vowels were made using a Zoom H6 Handy Recorder with external microphone (henceforth *H6*) and compared with two alternatives accessible to potential participants at home: the Zoom meeting application (henceforth *Zoom*) and two lossless mobile phone applications (Awesome Voice Recorder, and Recorder; henceforth *Phone*). F0 was tracked accurately by all devices; however, for formant analysis (F1, F2, F3) Phone performed better than Zoom, i.e. more similarly to H6. Zoom recordings also exhibited unexpected drops in intensity. The results suggest that lossless format phone recordings present a viable option for at least some phonetic studies.

1. INTRODUCTION

Speech production studies have been significantly impacted by restrictions related to COVID-19, as both access to laboratories and face-to-face interaction with study participants have been restricted. In order to adapt to the situation, we set out to test whether alternatives easily accessible to participants recorded remotely can produce recordings suitable for acoustic analysis. Findings are of interest to all researchers with limited access to speech communities, for instance because of ethical, political, or financial restrictions.

Research has already examined the performance of several devices that can be used for recordings, such as iPads (De Decker, 2016; Maryn et al., 2017), computers (De Decker and Nycz, 2011; Kojima et al., 2019; Vogel et al., 2014), and smart phones (Grillo et al., 2016; Kojima et al., 2019; Manfredi et al., 2017; Uloza et al., 2015; Vogel et al., 2014; see Jannetts et al., 2019, for a review). Other studies have examined the effects of different file formats, such as lossless Apple .m4a files (De Decker and Nycz, 2011), lossy compressed .mp3 files (Bulgin et al., 2010), and audio extracted from compressed video files (De Decker and Nycz, 2011).

Two key findings emerge from these studies. First, F0 is often unaffected by recording device and file format (Bulgin et al., 2010; Fuchs and Maxwell, 2016; Jannetts et al., 2019; Maryn et al., 2017), though it is unclear whether this applies equally well to F0 that exhibits significant dynamic changes. Second, lossy formats distort the F1-F2 vowel space in unpredictable ways; both expansion and compression (i.e., changes in both F1 and F2 simultaneously) are observed inconsistently across speakers (Bulgin et al., 2010), with women's speech showing greater distortion in lossy files recorded in quiet conditions (De Decker and Nycz, 2011). Noise, on the other hand, can lead to greater vowel space distortion in male voices instead (De Decker, 2016). We add to this line of research, by comparing recordings made with a high-quality digital recorder, Zoom H6 Handy Recorder (henceforth *H6*) with recordings made using the Zoom cloud meeting application (henceforth *Zoom*), and mobile phone applications that produce sound files in lossless formats (henceforth *Phone*). We investigated these options because they are convenient and readily available. Other options are browser-based or require fast, stable internet connection. These features pose two problems: use requires suitable infrastructure in the locations where the data are collected, and this may not always be available; further, data saved in proprietary applications could create issues with data storage and personal data protection regulations.

2. METHODS

A. Participants

Four females (PF1-4) and three males (PM1-3), aged 30-52 (mean 37) took part in the study. PF1, PF2, PF4, and PM3 had specialised phonetics training, while PF3, PM1, and PM2 had broad training in linguistics. PF2, PF4, and PM2 were monolingual speakers of Australian English; the other four were multilingual with Mandarin (PF1), Bengali (PF3), Kurdish (PM1), and German (PM3) as L1s. The variable linguistic backgrounds of the participants are not a problem for the present study which focuses on differences between devices and thus on within-speaker comparisons. All participants were aware of the purpose of the study.

B. Materials

The materials consisted of pure tones and elicitation of the primary cardinal vowels, [i, e, ε , a, a, o, o, u]. Here we report only on the results from the vowel recordings.

C. Recording devices and applications

Participants made simultaneous recordings of the vowels using an H6 with an external microphone, a Phone running a recording application, and a laptop running Zoom; see Table I for

details. The range of mobile phones and computers used simulates real-world scenarios where participants in a remote speech production study would use different devices.

| Participant ID | Mobile phone | Арр | Zoom | Recorder | Microphone |
|----------------|---------------------|-----------------------|----------------------|----------|-----------------------|
| PF1 | Samsung Note10 | AVR ^a | MS Surface Pro 6 | Zoom H6 | Sennheiser HSP2 |
| PF2 | Samsung Galaxy S10e | AVR | Dell Precision 5520 | Zoom H6 | Rode NT3 cardioid mic |
| | | | | | (on stand) |
| PF3 | Samsung Note10 | AVR | MS Surface Pro 6 | Zoom H6 | Sennheiser HSP2 |
| PF4 | Google Pixel 3a | AVR | Lenovo Thinkpad T495 | Zoom H6 | Sennheiser HSP2 |
| PM1 | Samsung Note9 | AVR | MS Surface Pro 6 | Zoom H6 | Sennheiser HSP2 |
| PM2 | Apple iPhone 5s | AVR | Lenovo Thinkpad T495 | Zoom H6 | Sennheiser HSP2 |
| PM3 | bq AQUARIS E4.5 | Recorder ^b | Lenovo Thinkpad T495 | Zoom H6 | Sennheiser ME64 & K6P |
| | Ubuntu Edition | | | | |

TABLE I. Recording equipment and application information for each participant.

^a Awesome Voice Recorder (Newkline, 2020)

^bRecorder (DawnDIY, 2016) is an app available on Linux phones; see section 2.D. for details.

D. Recording procedure

All recordings were made in quiet home locations, using H6, Phone and Zoom simultaneously. The H6 recorded mono .wav files, at 44.1 kHz, 24 bits. Phone was used with two applications: Awesome Voice Recorder (henceforth *AVR*; Newkline, 2020) available on Android and iOS phones, and Recorder (DawnDIY, 2016) available on Linux phones. Both recorded mono-channel files, at 44.1 kHz, 256 bps, in lossless formats (.wav for AVR and .ogg for Recorder). Zoom v. 5.1.2 (28642.0705) with default settings was used to record stereo-channel .m4a files, a lossy format; files were saved locally.¹ The .ogg and.m4a files were converted to mono-channel .wav files at 44.1 kHz and 256 bps using VLC (VideoLan, 2019).

For the recordings of the vowels, we followed previous studies (e.g., Grillo et al., 2016; Manfredi et al., 2017; Maryn et al., 2017; Uloza et al., 2015; Vogel et al., 2014), and instructed participants to produce and sustain each vowel for 3-5 s. and repeat them three times. The devices were placed as follows: the Zoom computer was placed on a table directly in front of the participant, approximately 40-50 cm away, resembling a Zoom meeting set up; the participant held the Phone approximately 10-20 cm from their mouth; the digital recorder was used with either a head-mounted microphone or a microphone with pop filter on a stand 15 cm in front of the participant.

E. Measurements and Statistical Analysis

Vowels were manually segmented in Praat (Boersma and Weenink, 2019). Features were extracted using VoiceSauce (Shue, 2010). Mean F0, F1, F2, and F3 of all 3 tokens per vowel were calculated, for a corpus of 504 tokens [7 participants \times 8 vowels \times 3 repetitions \times 3 devices]. The range for extraction was 40-500 Hz for F0 and 0-6000 Hz for formants. Token means were calculated from values extracted every 1 ms throughout each token with a moving window length of 25 ms.

Linear mixed effect models (Bates et al., 2015) were built in R (R Core Team, 2020) to investigate how much variation in the dependent variables (frequency for tones, and F0, F1, F2, and F3 for vowels) can be ascribed to the recording devices. Due to the small size of the study, vowels were grouped by backness, so as to investigate separately front vowels [i, e, ε , a], in which F1, F2 and F3 are further apart, from back vowels [a, o, o, u], in which formants are largely closer together.

For each dependent variable, full models were constructed with two fixed effects and their interaction: DEVICE (H6, Phone, Zoom) and VOWEL_BACKNESS (front, back). Speaker was treated

as a random intercept, accounting for inter-speaker differences with respect to speech and the use of different phone and computer models (see Table 1). Random slopes for DEVICE were also included except when the full models failed to converge or resulted in singular fit. Linear models were used when including only one random intercept still led to singular fit.

Illustrative boxplots can be found in Fig. 1. The boxplots show *differences* between devices, calculated by subtracting H6 values from the Phone values and the Zoom values for the same token across the three devices. In other words, each value plotted represents the difference between matching paired tokens from the devices.

3. **RESULTS**

Statistical models and results are shown in Tables II-V; Fig. 1a-d illustrates the differences between devices for F0, F1, F2 and F3.

Regarding F0, there were no statistically significant differences among devices and no interaction between DEVICE and VOWEL_BACKNESS (see Table II). Nevertheless, the data contain some outliers. For instane, the positive outliers for the F0 of /e/ (circled in Fig. 1a) were both from the same repetition simultaneously recorded by the three devices. Such outliers suggest that on occasion both devices failed to capture F0 accurately.

For F1 and F2 there was no significant effect of DEVICE and of the DEVICE by VOWEL_BACKNESS interaction (see Tables III and IV respectively). For F3, however, there was a significant interaction between DEVICE and VOWEL_BACKNESS (see Table V): specifically, for back vowels, the F3 of Zoom recordings was higher than that of H6 by an average of 83.4 Hz, while for front vowels, it was *lower* by an average of 136.6 Hz. This is reflected in Fig. 1d, which also shows that the largest differences between Zoom and H6 were for the front vowels [ε] and [a].



FIG. 1. Boxplots of differences in frequency between H6 and Phone and H6 and Zoom for F0 (panel a), F1 (panel b), F2 (panel c) and F3 (panel d). The middle line represents the median, upper and lower edges of the box represent the first and third quartiles, and the whiskers indicate the range, up to 1.5 times the inter-quartile range away from the median.

TABLE II. Results from the final statistical model for F0 (intercept: H6, back);

| formula: f0 ~ | device + | backness | +(1) | speaker). |
|---------------|----------|----------|------|-----------|
|---------------|----------|----------|------|-----------|

| | Estimate | SE | df | t | Pr(> t) | sig. |
|---------------|-----------|---------|----------|--------|----------|-----------|
| (Intercept) | 170.85668 | 19.791 | 6.0325 | 8.633 | 0.000129 | p < 0.001 |
| devicePhone | 0.59543 | 1.44798 | 494 | 0.411 | 0.681095 | |
| deviceZoom | -0.03854 | 1.44798 | 494 | -0.027 | 0.978778 | |
| backnessfront | -1.8299 | 1.18234 | 494.0001 | -1.548 | 0.122336 | |

TABLE III. Results from the final statistical model for F1(intercept: H6, back);

| | Estimate | SE | df | t | Pr(> t) | sig. |
|---------------|----------|--------|---------|--------|----------|-----------|
| (Intercept) | 500.311 | 27.411 | 11.718 | 18.252 | 5.74E-10 | p < 0.005 |
| devicePhone | -8.164 | 20.617 | 494 | -0.396 | 0.692 | |
| deviceZoom | -37.435 | 20.617 | 494 | -1.816 | 0.07 | |
| backnessfront | 37.597 | 16.835 | 494.012 | 2.233 | 0.026 | p < 0.05 |

formula: $f1 \sim device + backness + (1 | speaker)$.

TABLE IV. Results from the final statistical model for F2 (intercept: H6, back);

formula: $f2 \sim device + backness + (1 | speaker)$.

| | Estimate | SE | df | t | Pr(> t) | sig. |
|---------------|----------|-------|--------|--------|-----------|-----------|
| (Intercept) | 941.39 | 56.12 | 12.96 | 16.774 | 3.59E-10 | p < 0.001 |
| devicePhone | -86.31 | 44.76 | 494 | -1.928 | 0.0544 | |
| deviceZoom | -86.32 | 44.76 | 494 | -1.929 | 0.0544 | |
| backnessfront | 1049.99 | 36.55 | 494.01 | 28.728 | <2.00E-16 | p < 0.001 |

TABLE V. Results from the final statistical model for F3 (intercept: H6, back);

formula: $f3 \sim device * backness + (1 | speaker).$

| | Estimate | SE | df | t | Pr(> t) | sig. |
|-------------------------------|----------|-------|--------|--------|----------|-----------|
| (Intercept) | 2821.31 | 64.96 | 9.28 | 43.429 | 4.88E-12 | p < 0.001 |
| devicePhone | 43.2 | 44.39 | 492 | 0.973 | 0.33096 | |
| deviceZoom | 83.42 | 44.39 | 492 | 1.879 | 0.0608 | |
| backnessfront | 142.76 | 44.26 | 492.01 | 3.225 | 0.00134 | p < 0.01 |
| devicePhone: backnessfront | -53.48 | 62.59 | 492.01 | -0.854 | 0.39333 | |
| deviceZoom: backnessfront | -220.04 | 62.59 | 492.01 | -3.515 | 0.00048 | p < 0.001 |

4. Additional issues

A. AVR missing samples

Audio files recorded by the AVR application using Android devices produced a warning when opened in Praat: "File too small (1-channel 16-bit). Missing samples were set to zero." However, there were no audible glitches and files could be opened. Sample dropping in these files was investigated to understand its possible effects on measurement extraction.

A small number of zero sequences were found in the recordings, confirming AVR was dropping samples. Analysis showed that the vast majority of zero sequences found within the recordings consisted of only 2 samples, while none exceeded 20 samples. Sequences of more than 20 zero samples were found only at the very beginning of recordings and had a maximum of 150 zeros (= 4.7 ms). Considering that the sampling rate was 44.1 kHz, these dropped samples formed a minute fraction of the duration of each recording and thus are unlikely to pose problems for analysis.

In order to completely rule out the possibility that these inconsistencies can negatively affect acoustic measurements, a simulation was run. Audio files containing artificial vowels with a duration of over 1 s were created using Praat's VowelEditor. These were compared to artificially corrupted versions of the same files, such that the latter included sequences of up to 20 zero samples. Over 4,800 such pairs were generated in Praat using ten different vowels with a variety of F0 slopes. Measurements of intensity, F0, F1 and F2 in both versions showed correlations above 0.99. This suggests that the missing samples in recordings from the AVR application do not present an issue in extracting these acoustic measures.

B. Zoom intensity drop

In Zoom recordings, intensity was not reliably tracked. Periods of extremely reduced intensity occurred at random, as shown in Fig. 2. In our view, such random, extreme errors make Zoom unsuitable for phonetic research, at least in relation to any intensity-related measurements.



FIG. 2. One repetition of vowel [0] from PF3's Zoom recording; spectrogram with intensity curve at top, waveform, below.

5. DISCUSSION AND CONCLUSIONS

In summary, Phone and Zoom recordings produced similar F0 values to the H6, a result consistent with previous studies which also showed that F0 is robust to lossy compression and unaffected by device choice (cf. Grillo et al., 2016; Uloza et al., 2015; Vogel et al., 2014).

Formant tracking did not reveal statistically significant differences between devices except for F3, which is difficult to track independently of device. Clearly, however, lossy compression such as that used by default in Zoom can aggravate F3 tracking problems (cf. Bulgin et al., 2010). Similarly, the intensity drops observed in the Zoom recordings, while not statistically modelled in this paper, could pose serious issues for analysis.

Close inspection of the data illustrated in Fig. 1 strongly indicates that there are inconsistencies in formant tracking for individual vowels, though a clear pattern for these did not emerge. Discrepancies affected both Zoom and Phone, but for the former there were more problems and they were of greater magnitude; consider, e.g., the F1 of [a] and [a], F2 of [i] and [ϵ], and F3 of [ϵ] and [a]. These large discrepancies failed to reach statistical significance most likely due to lack of power. Nevertheless, their effects on measurements can be considerable, as illustrated in Fig. 3, which depicts the vowel space of each participant by DEVICE. Fig. 3 illustrates the unpredictable nature of the tracking errors and the distortions they can bring. Based on these finding, we concur with De Decker and Nycz (2011) that researchers should not use different devices (e.g., Zoom and Phone) to record data for the same study, nor should they compare data obtained using different devices. Finally, we note that overall, more tracking errors occurred with the female data (PF1-4) than the male data (PM1-3), across all devices. This is in line with previous reports, such as De Decker and Nycz (2011). However, we also note that not all patterns can be explained by speaker sex. For example, the vowel spaces of PF3 are similar across devices while those of PM1 show substantial differences.



FIG. 3: Vowel space by device separately for each speaker.

In conclusion, our findings indicate that lossless recordings from phones can be a viable method for recording vowel data for acoustic analysis, at least with respect to F0, F1 and F2. On the other hand, caution is needed if conditions limit a researcher's choice to the use of lossy Zoom recordings, as these can lead to erratic outcomes.

ACKNOWLEDGEMENTS

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¹ The "enable original sound" option, available from v. 5.2.2 (45108.0831) in September 2020, had not been released at the time of data collection.

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| Participant ID | Mobile phone | Арр | Zoom | Recorder | Microphone |
|----------------|---------------------|-----------------------|----------------------|----------|-----------------------|
| PF1 | Samsung Note10 | AVR ^a | MS Surface Pro 6 | Zoom H6 | Sennheiser HSP2 |
| PF2 | Samsung Galaxy S10e | AVR | Dell Precision 5520 | Zoom H6 | Rode NT3 cardioid mic |
| | | | | | (on stand) |
| PF3 | Samsung Note10 | AVR | MS Surface Pro 6 | Zoom H6 | Sennheiser HSP2 |
| PF4 | Google Pixel 3a | AVR | Lenovo Thinkpad T495 | Zoom H6 | Sennheiser HSP2 |
| PM1 | Samsung Note9 | AVR | MS Surface Pro 6 | Zoom H6 | Sennheiser HSP2 |
| PM2 | Apple iPhone 5s | AVR | Lenovo Thinkpad T495 | Zoom H6 | Sennheiser HSP2 |
| PM3 | bq AQUARIS E4.5 | Recorder ^b | Lenovo Thinkpad T495 | Zoom H6 | Sennheiser ME64 & K6P |
| | Ubuntu Edition | | | | |

TABLE I. Recording equipment and application information for each participant.

^a Awesome Voice Recorder (Newkline, 2020)

^b Recorder (DawnDIY, 2016) is an app available on Linux phones; see section 2.D. for details.

TABLE II. Results from the final statistical model for F0 (intercept: H6, back);

| $10111101a$. $10 \sim uevice + 0ackness + (1 speaker$ | formula: f0 | ~ device + | backness + | (1 | speaker). |
|--|-------------|------------|------------|----|-----------|
|--|-------------|------------|------------|----|-----------|

| | Estimate | SE | df | t | Pr(> t) | sig. |
|---------------|-----------|---------|---------|--------|----------|-----------|
| (Intercept) | 170.85668 | 19.791 | 6.0325 | 8.633 | 0.000129 | p < 0.001 |
| devicePhone | 0.59543 | 1.44798 | 494 | 0.411 | 0.681095 | |
| deviceZoom | -0.03854 | 1.44798 | 494 | -0.027 | 0.978778 | |
| backnessfront | -1.8299 | 1.18234 | 494.000 | -1.548 | 0.122336 | |
| | | | 1 | | | |

TABLE III. Results from the final statistical model for F1(intercept: H6, back);

| | Estimate | SE | df | t | Pr(> t) | sig. |
|---------------|----------|--------|---------|--------|----------|-----------|
| (Intercept) | 500.311 | 27.411 | 11.718 | 18.252 | 5.74E-10 | p < 0.005 |
| devicePhone | -8.164 | 20.617 | 494 | -0.396 | 0.692 | |
| deviceZoom | -37.435 | 20.617 | 494 | -1.816 | 0.07 | |
| backnessfront | 37.597 | 16.835 | 494.012 | 2.233 | 0.026 | p < 0.05 |

formula: $f1 \sim device + backness + (1 | speaker).$

TABLE IV. Results from the final statistical model for F2 (intercept: H6, back);

| | Estimate | SE | df | t | Pr(> t) | sig. |
|---------------|----------|-------|--------|--------|-----------|-----------|
| (Intercept) | 941.39 | 56.12 | 12.96 | 16.774 | 3.59E-10 | p < 0.001 |
| devicePhone | -86.31 | 44.76 | 494 | -1.928 | 0.0544 | |
| deviceZoom | -86.32 | 44.76 | 494 | -1.929 | 0.0544 | |
| backnessfront | 1049.99 | 36.55 | 494.01 | 28.728 | <2.00E-16 | p < 0.001 |

formula: $f2 \sim device + backness + (1 | speaker)$.

TABLE V. Results from the final statistical model for F3 (intercept: H6, back);

| formula: f3 ~ device * backness + (1 speaker). | |
|--|--|
|--|--|

| | Estimate | SE | df | t | Pr(> t) | sig. |
|---------------|----------|-------|--------|--------|----------|-----------|
| (Intercept) | 2821.31 | 64.96 | 9.28 | 43.429 | 4.88E-12 | p < 0.001 |
| devicePhone | 43.2 | 44.39 | 492 | 0.973 | 0.33096 | |
| deviceZoom | 83.42 | 44.39 | 492 | 1.879 | 0.0608 | |
| backnessfront | 142.76 | 44.26 | 492.01 | 3.225 | 0.00134 | p < 0.01 |
| devicePhone: | -53.48 | 62.59 | 492.01 | -0.854 | 0.39333 | |
| backnessfront | | | | | | |
| deviceZoom: | -220.04 | 62.59 | 492.01 | -3.515 | 0.00048 | p < 0.001 |
| backnessfront | | | | | | |

Collected figure captions:

FIG. 1. Boxplots of differences in frequency between H6 and Phone and H6 and Zoom for F0 (panel a), F1 (panel b), F2 (panel c) and F3 (panel d). The middle line represents the median, upper and lower edges of the box represent the first and third quartiles, and the whiskers indicate the range, up to 1.5 times the inter-quartile range away from the median.

FIG. 2. One repetition of vowel [0] from PF3's Zoom recording; spectrogram with intensity curve at top, waveform, below.

FIG. 3: Vowel space by device separately for each speaker.