THE EFFECTS OF AIRFLOW AND CONSTRICTION OF THE VOCAL TRACT IN THE PRODUCTION OF AEROSOLS FROM SPEECH

By

Jacqueline A. L. McCurdy

B.M., University of Iowa, 2001

M.M., New England Conservatory of Music, 2004

D.M.A., University of Iowa, 2015

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Committee Members:

Dr. Allison Hilger

Dr. Pui Fong Kan

Professor Jen Lewon

Abstract

McCurdy, Jacqueline A. L. (MA-SLP, Speech, Language, and Hearing Sciences)

The effects of airflow and constriction of the vocal tract in the production of aerosols from speech

Thesis directed by Associate Professor Dr. Allison Hilger

With the rise of infectious disease spread by airborne transmission such as SARS-CoV-2, there is a need to understand the role of speech aerosol in transmission. This study examined the role of the speech mechanism in the production of aerosols of five female participants. Particle counts were measured for sustained vowels /ɑ, i, ɛ, ə/ produced in modal register, falsetto register, vocal fry, whisper, loud, and with an h-onset. The presence of a super emitter altered results and necessitated analysis that included and excluded the super emitter. Our results consistently showed that amount of airflow through the speech mechanism contributes to the amount of particles released with whispering and loud voice producing the most, followed by modal register, falsetto register, h-onset, and lastly vocal fry. Tongue tension and vowel shape did not contribute to changes in particle generation as both tense, lax, open, and closed vowels produced high particle counts.

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Introduction

"Despite the evidence and strong hypothesis, the world appears to be locked in the old way of thinking that only direct contact matters in infection spread" (Morawska & Cao, 2020, p. 2-3).

Often viruses are opportunistic and dynamic in their ability to reproduce (Killingley & Nguyen-Van-Tam, 2013) such that transmission of diseases enters and exits through several routes in the body, whether it be through the mouth, eyes, or respiratory tract (Johnson & Morawska, 2009). When a person becomes infected with a virus, they will shed higher levels of aerosol particles through breathing, coughing, sneezing, or talking (Killingley & Nguyen-Van-Tam, 2013). Large clusters of infection are a result of viral spread (Morawska & Cao, 2020). Disease prevention measures, like hand washing, are effective in droplet transmission, but in aerosol transmission hand hygiene will do little to contain virus spread (Killingley & Nguygen-Van-Tram, 2013). To mitigate impact on human life in viral spread, virus detection must consider transmission type across a variety of settings from healthcare, schools, workplaces, to homes (Killingley & Nguyen-Van-Tam, 2013). Currently, there is little research on aerosol disease transmission and thus, understanding aerosol generation from speech is highly important for developing disease prevention measures.

The transmission type of a virus is determined by droplet or aerosol particle size. One factor that determines the size of a droplet or aerosol particle is the size of the pathogen's DNA (Gralton et al., 2010) such that the larger the size of the DNA the larger the size of the particle and vice versa. A second factor in particle size is due to the changes in viscosity of expelled material from infected individuals, which generally tend to be bigger compared to healthy individuals (Gralton et al., 2010). Transmission of viruses are spread through three accepted routes dependent on particle size: droplets (larger than 10 µm), droplet nuclei (smaller than 5 µm), or through direct contact transmission where the infected particles meet the mucous membrane of the upper respiratory tract (URT), or through spread by a contaminated surface (Killingley & Nguyen-Van-Tam, 2013). The World Health Organization defines 5µm as the cut-off between airborne and droplet transmission; thus, viral airborne transmission is infection by expelled particles of small size (Gralton et al., 2010).

The size of the particle can also determine how many people are infected and the severity of the infection. The distance the particles travel is proportional to the size of the droplet (Killingley & Nguyen-Van-Tam, 2013). The particles produced by coughing and sneezing are larger and are pulled down by gravity within a few feet of the person (Killingley & Nguyen-Van-Tam, 2013), and these droplets can land on surfaces to spread to other individuals (Gralton et al., 2010). Frequent hand washing and keeping a distance of one meter (m) is usually recommended in this type of disease transmission (Morawska & Cao, 2020). Small particles, on the other hand, remain suspended in the air for prolonged periods of time, can expose more individuals at a greater distance from the source (Gralton et al., 2010), and remain infective (Cowling et al., 2013). In airborne transmission, humidity may also play a role in the particle trajectory in that the transmission is slowed by the presence of moisture in the air (Gralton et al., 2010). Particle size also determines how far it travels in the respiratory tract: particles larger than 10 µm affect the URT and particles that are smaller than 5 µm have the ability to go further into the airway infecting the lower respiratory tract (LRT) (Gralton et al., 2010), and even into the alveolar region of the lungs (Lindsley et al., 2010). LRT infections are associated with increased severity, morbidity, and fatality (Gralton et al., 2010).

Currently, there are two theories about how particles form in the respiratory tract. Gralton et al. (2010) hypothesized that the gas in the alveolar region is warm and wet, and as it passes from the lungs into the upper airways, a cooling of the gas occurs that creates liquid droplets (condensation) that is carried by turbulent high-speed airflow that expels the liquid particles during exhalation. Particles can also snowball as they move through the respiratory tract (Gralton et al., 2010). Other sources of particle generation are liquid films on airway openings, like the vocal folds (Gralton et al., 2010). The vibration of the vocal folds during speech and coughing are suggested by Gralton et al. (2010) as the majority of particle generation. When there is infection along the respiratory tract, the site of infection should be the same or very close to a major site of particle generation (Gralton et al., 2010). The released particles from an afflicted individual during breathing or speech are a mixture of infected particles and non-infected particles (Gralton et al., 2010).

A second theory of particle formation by Johnson and Morawska (2009) is through fluid film bursts. Johnson and Morawska (2009) conjectured that as the air pressure in the respiratory tract overcomes the surface tension of an airway opening, the collection of fluid on these surfaces will bubble, burst, and create liquid fragments. As breathing becomes deeper and faster, like when a person is exercising, more blockages are opened creating more fluid film bursts (Johnson & Morawska, 2009). Johnson and Morawska (2009) also found evidence that the fluid film burst phenomenon happens on inhalation as the alveoli increase in size.

Current Aerosol Research

Currently, there is little research on the role of speech in airborne disease transmission. A study by Abkarian et al. (2020) focused on the laminar flow of speech aerosols and the production of saliva filaments (droplets). The participants were placed in front of a laser screen and performed different speech tasks into a fog with droplets that stay in the air for 10 minutes to look at turbulence (Abkarian et al., 2020). The outflow of air in exhalation is responsible for the dispersion of droplets and aerosols away from the speaker. One finding of this study is that there is increased propagation of particle disturbance after exercise, due to the increase of volumetric airflow (Abkarian et al., 2020). Plosive consonants /b, p, t, d, k, g/ and the nasal consonant /m/ resulted in increased droplet release (Abkarian et al., 2020). Additionally, Abkarian et al. (2020) studied the dilution of speech aerosols. Speech creates a continuous turbulent jet of air that spreads transversely, which then mixes with the air in the environment as seen in Figure 1 (Abkarian et al., 2020). Since plosive consonants drive more air, these speech sounds create more turbulence in the speech airstream (Abkarian et al., 2020), that can be seen in the irregularity of the speech plume in Figure 1. The researchers found dilution to be between 0.04 and 0.05 at 1.5 m away from the mouth of the speaker. The dilution levels when placed directly in front of the speaker are around 3% of the initial value at a distance of 2 meters and after 30 seconds. Dilution is also shown in Figure 1 with the spread of the speech plume as it mixes with air in the environment.

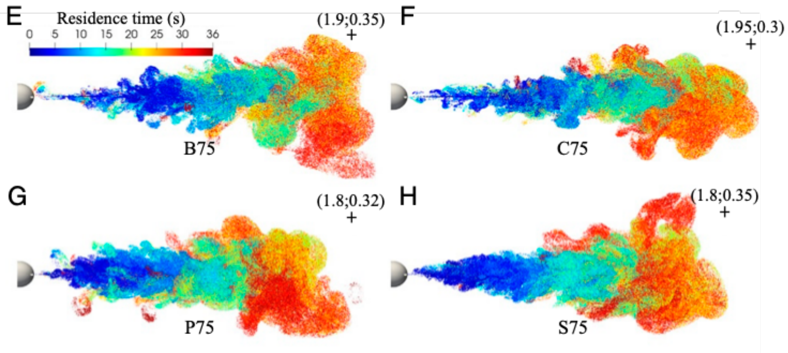

Figure 1. Schematic of turbulent airflow found in the study by Abkarian et al. (2020, p. 25242).

A study by Abkarian and Stone (2020) focused on the stretching and break-up of saliva. This study used fog machine mist and a laser screen to measure droplet size by pictures from a high-speed camera (Abkarian & Stone, 2020). The researchers found that bilabials /b/ and /p/ and alveolars /t/ and /d/ generate the largest number of droplets per unit time, and the number of droplets produced is greater than droplets produced with vowels (Abkarian & Stone, 2020). It was noted that the phoneme /k/ had a lower number of particles produced (Abkarian & Stone, 2020). They concluded that rapid movements in oral cavity (lips, tongue relative to palate or teeth) are a source of high droplet numbers (Abkarian & Stone, 2020). Additionally, this study found that lip balm mitigates the formation of small droplets (Abkarian & Stone, 2020). Abkarian and Stone (2020) hypothesized that wetting properties at the lips reduced the stability of the saliva filaments and thus prevents their formation. Furthermore, the participants included the presence of superspreaders, or superemitters, of aerosols producing an unusually large number of droplets during speech (Abkarian & Stone, 2020).

A study by Asadi et al. (2019) addressed the effects of loudness on speech particle generation. The participants in this study were seated in front of a laminar flow hood and spoke into a funnel that directed the aerosols into an aerodynamic particle sizer. One finding was a linear correlation of particle emission and amplitude (loudness) of speech (Asadi et al., 2019). The speech plumes were revealed to have a homogenous mixture of different sizes of particles that was independent of the loudness of speech, or the language spoken (English, Spanish, Mandarin, and Arabic were tested). Particles generated during speech were found to be only slightly larger than particles emitted while breathing (Asadi et al., 2019). Asadi et al. (2019) also found the presence of superemitters among their participants. Those that were not deemed superemitters were found to emit fewer than three particles per second in speech tasks and that superemitters produced more (Asadi et al., 2019). No trends in the data were found for the presence of superemitters across gender, age, or body mass index (Asadi et al., 2019). However, Asadi et al. (2019) found two types of superemitters: speech superemitters and breathing superemitters. The speech superemitters were not necessarily breathing superemitters, and vice versa (Asadi et al., 2019). The authors suggested that individual manners of articulation affect particle deposits before they escape the mouth (Asadi et al., 2019). Asadi et al. (2019) concluded that speech is more dangerous in aerosolized virus transmission than breathing alone.

Asadi et al. (2020) extended their 2019 study to examine the effects of voicing and articulation manner on particle generation. Similar to their 2019 study, the participants were placed in front of a laminar flow hood and performed speech tasks into a funnel directing the plumes of speech outflow into an aerodynamic particle sizer (Asadi et al., 2020). The researchers found that the /i/ vowel produced twice the number of particles when compared to other vowels, which is shown in Figure 2. In comparing voiced plosives /d, b, g/ to voiceless fricative sounds /f, h, s, ʃ/, voiced plosive sounds released more particles. More specifically, the voiceless plosive /t/ released more particles than the voiceless fricative /ʃ/, and that the resonant consonant /m/ released more particles than /ʃ/ (Asadi et al., 2020). The authors also found that phrases with higher vowel fractions (to consonants) yielded significantly larger particle numbers, and that phrases with higher voiceless fricative fractions yielded a smaller number of particles (Asadi et al., 2020). Asadi et al. (2020) hypothesized that the speech particle emission rate is correlated with voicing and manner of articulation.

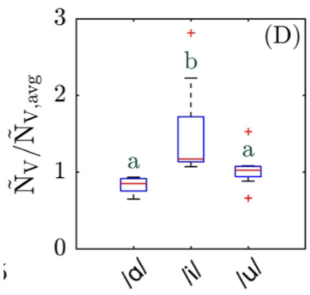

Figure 2. Graph showing particle emission averages on the vowels /ɑ, i, u/ from the study by Asadi et al. (2020, p. 6).

A related aerosol study by Mutsch et al. (2022) focused on particle emission during exercise and elucidates on the exhalatory element in non-speech release of aerosols. Participants in the study wore a two-way mask so that the exhalation was directed to a particle counter while the person was exercising on a stationary bicycle (Mutsch et al., 2022). Particle emission increased 132-fold during exercise (from 580 ± 489 particles/min at rest to 76,200 ± 48,000 particles/min) and the average particle size was 0.46 ± 0.05 µm (Mutsch et al., 2022). Additionally, the researchers found that dehydration caused an increase in aerosol particle emission (Mutsch et al., 2022).

As the world sees the rise of infectious diseases like SARS-CoV-2 there is importance of understanding the mechanisms of airborne disease transmission in order to mitigate the impact on human life. The study of speech aerosolization is in its infancy with many areas for discovery and growth. Up to this point, no voice researchers have been a part of this research and it has mostly been studied by engineering research. While they have focused on details like that of plosive consonants, none of this research shows understanding of the details of the speech mechanism. This study aims to explore the role the speech mechanism plays in particle generation.

A Brief Discussion of the Vocal Mechanism

A brief summary of the vocal mechanism including airflow, vocal fold movement, vocal registers, and deposits in the vocal tract will provide a background for understanding aerosol generation from vocal fold vibration.

Airflow

The speech mechanism is dependent on airflow for phonation. Air is pushed out of the lungs, converted to oscillatory flow in the larynx, and continues through the oral cavity to be released from the mouth (Titze, 2001, p. 75). If this airflow meets adducted vocal folds, the vocal folds become the first point of airflow resistance. As pressure across the adducted vocal folds increases, the amount of positive pressure determines the excursion of the vocal fold tissue when air pressure overcomes the surface tension of the vocal folds. If this is paired with low tissue viscosity, the airflow will become turbulent (Titze, 2001, p. 80). According to Titze, when the air comes out of the glottis it acts like a “jet emerging from a nozzle of a pressurized garden hose" (Titze, 2001, p. 320). More so, the velocity of the airflow combined with the configuration of the glottis can make this jet of air dynamic and unstable. (Titze, 2001, p. 320). See Figure 3 for a depiction of an unstable jet.

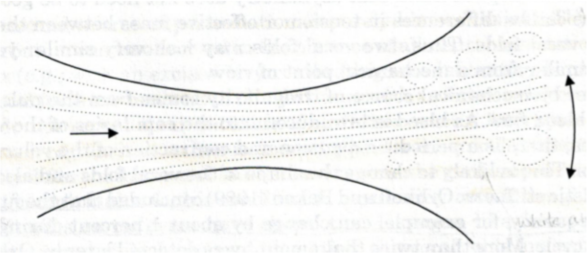

Figure 3. Schematic of an unstable jet of air (Titze, 2000, p. 320).

Resistance in the speech mechanism (flow resistance) is difficult to measure due to the nature of the variety of geometric forms that are shaped in the vocal tract during speech (Titze, 2000, p. 79, as cited by Scherer & Guo, 1991). To highlight these different geometric shapes, Figure 4 shows unilateral air flow over the true and false vocal folds. Female speakers are also noted to have larger glottal resistance due to the smaller size of their larynges (Titze, 2000, p. 79). Downstream from the glottis, a secondary point of flow resistance during speech is the tongue and teeth, which also affects the jet of air passing through the respiratory tract (Titze, 2000, p. 79).

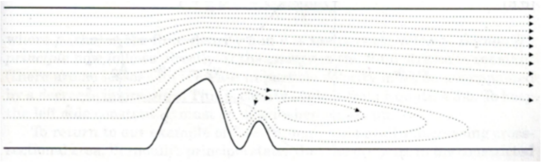

Figure 4. Computerized schematic of air particle flow over the vocal folds (Titze, 2000, p. 75).

There is a delicate interplay of forces between air pressure and tissue movement at the glottis. Because the Bernoulli forces create an oscillation of the opening and closing of the vocal folds during phonation, there is build up, delay, and collapse of the forward momentum of the airstream (Titze, 2000, p. 108). Peak airflow and peak displacement of the vocal folds do not happen simultaneously, but instead peak airflow happens at a later point than peak displacement of the vocal folds (Titze, 2000, p. 110). Figure 5 shows this phenomenon. Deceleration of airflow is also delayed, but the complete closure of the vocal folds causes a sudden drop in pressure in the system (Titze, 2000, p. 110). This combination of the changes in airflow at the glottis from this phenomenon suggests that airflow is asymmetric in the speech mechanism, which extends to the asymmetry of air particle velocity in the system (Titze, 2000, p. 110). The forces of resistance and the asymmetry of the speech mechanism may contribute to or affect particle generation above the glottis.

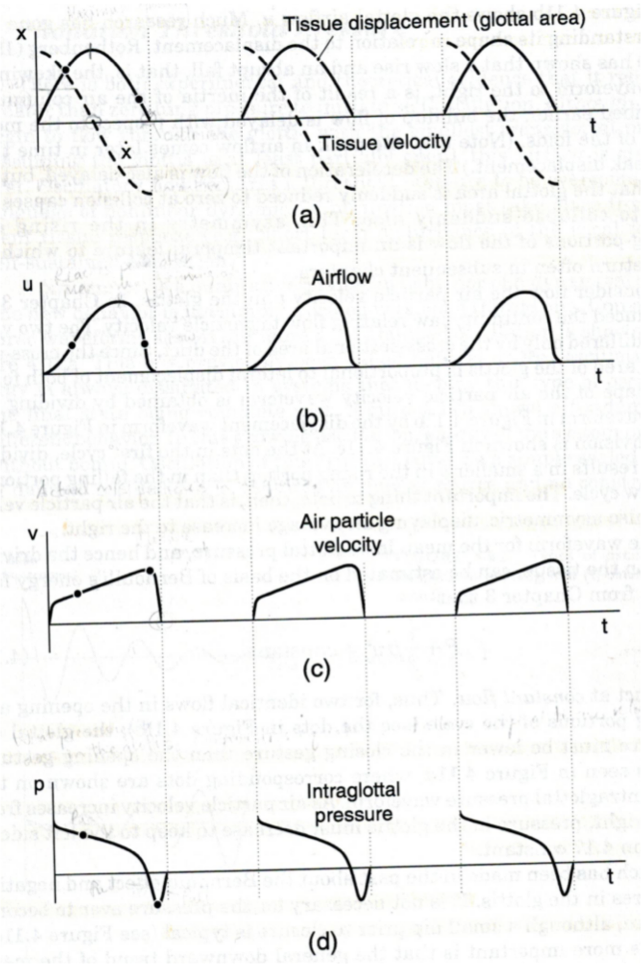

Figure 5. Schematic of the waveforms of tissue displacement, airflow, air particle velocity, and intraglottal pressure changes over time (Titze, 2000, p. 109).

Vocal Fold Motion

Vocal fold motion is nonuniform tissue movement (Titze, 2001, 102). The motion is determined by the coaction of the tissue layers of the vocal folds (see Figure 6), where the outmost layer (cover) can move relatively independently because it is loosely attached to the other layers (Titze, 2001, p. 62). The motion has been observed to be a wavelike motion of the cover, but considering the other layers, a ribbon model is suggested by Titze (2001, p. 62) to be more appropriate. Generally, the maximum amplitude occurs in the middle of the ribbon, gradually decreasing to the end points (Titze, 2001, p 105). The nonuniform tissue movement causes a delayed action between the upper and lower portions of the vocal folds and asymmetric driving pressure (Titze, 2001, p. 108). More so, the outgoing and return path of the tissue movement will be different, and is not identical (Titze, 2001, p. 104). The pattern of vocal fold vibration is also a consideration in particle generation in the respiratory tract.

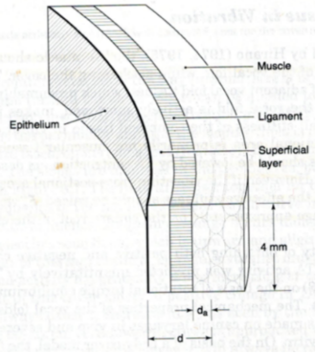

Figure 6. Schematic of the layers of the vocal folds (Titze, 2000, p. 228).

Vocal Registers

Vocal registers are defined as “perceptually distinct regions of vocal quality” (Titze, 2001, p. 282). In speech, there are three registers: modal, falsetto, and vocal fry. The modal register is generally the register for habitual speech. It has a “heavier quality” which is produced with reduced vocal fold length, a lax cover, and full involvement of the thyroyartenoid (TA) muscle in vibration (see Figure 6) (Titze, 2001, p. 285). The TA, which regulates the effective tension, bulges the vocal fold medially below the level of the vocal processes, creating a thicker and deeper vibratory structure (Titze, 2001, p. 291). More so, in this register, the bottom of the vocal fold is adducted more when compared to the falsetto register (Titze, 2001, p. 285). The falsetto register has a “lighter” quality and is produced by an elongated and stiffened cover at higher pitches (Titze, 2000, p. 285). The TA is dormant, so the ligament carries the tension and only the mucosa can be relatively lax in this register (Titze, 2000, p. 291). Additionally, the higher pitches of the falsetto register require more lung pressure to maintain the same amplitude of vibration (Titze, 2000, p. 70). Vocal fry (pulse register) is produced with minimal airflow through the glottis creating localized pulses and gaps (Titze, 2000, p. 285).

Breathiness, a perceptual correlate of turbulence, is a result of excessive average airflow and a widened glottis where the vocal folds do not make contact (Titze, 2000, p. 80). In whispered speech or breathy speech, there is increased flow resistance with turbulence and increased dissipated energy due to complex flow patterns in the vocal tract (see Figure 4) (Titze, 2000, p. 80). More so, the turbulence in the glottal airstream during whispering creates a “hissing” quality in the absence of vocal fold vibration (Titze, 2000, p. 127). When the vocal folds are vibrating and are paired with turbulent airflow, it is labeled as aspiration (Titze, 2000, p. 127). Aspiration is a perceptual component of breathy voice (Titze, 2000, p. 117). In speech, breathy voice is initiated by using an h-onset, which creates the initial turbulent airflow (Titze, 2000, p. 80).

The speech mechanism also changes based on the amount of energy (effort) put through the system. In loud speech production, there is increased lung effort driving more air and accompanying higher pitch (Titze, 2000, p. 248). When the vocal folds are adducted during loud phonation, there is greater resistance to flow, thus needing more lung pressure to expel air in a reasonable amount of time (Titze, 2000, p. 70). Amplitude of vibration increases and goes deep into the vocal fold tissue (Titze, 2000, p. 229).

Variation of the Speech Mechanism

The speech mechanism is defined by variation where internal “noises" of the body, like sporadic motion of electrical impulses and fluids, that are present in the vocal signal with consequent small fluctuations of frequency, amplitude and wave shape (Titze, 2001, p. 311). It happens that the larynx is particularly vulnerable to fluctuations in neural, vascular, lymphatic, and other transport systems (Titze, 2001, p. 311). Even lung pressure is variable and is not steady over longer periods of phonation (Titze, 2000, p. 320). As mentioned previously, the vocal folds have irregularities in tissue geometry and mechanical properties that cause changes in forces and motions for each opening and closing of the vocal folds’ vibratory cycle (Titze, 2001, p. 318). Additionally, differences of tension or effective mass can cause asymmetry between right and left vocal folds resulting in an uneven opening and closing at glottal midline (Titze, 2001, p. 318). Thus, an aperiodic waveform is produced for every attempt at a steady sound (Titze, 2001, p. 311).

Deposits in the Respiratory Tract

By the nature of the throat as part of the respiratory tract, there are different deposits from the laryngeal area and up through the oral cavity. Sticky deposits on the vocal folds and other respiratory linings can be a result of insufficient hydration and the body’s inability to dilute them and move them into the stomach (Titze, 2001, p. 349). Additionally, food particles can be accumulated in the piriform sinuses (Titze, 2001, p. 321). Since sound pressures are relatively high in these pockets due to their proximity to the source of sound, loose materials are easily moved in and around the piriform sinuses (Titze, 2001, p. 321). Moreover, a heavy coating from foods like milk or chocolate can form large, viscous globules above the larynx (Titze, 2001, p. 321).

The healthiness of the vocal fold tissue can contribute to particle generation. The tissue of the vocal folds change in their elastic properties and levels of viscosity with water intake, infectious disease, trauma, toxic materials, temperature, or other internal or external conditions (Titze, 2001, p. 114). These changes can be significant for phonation (Titze, 2001, p. 349). As healthy vocal fold tissue is expected to have the presence of a mucosal wave on the cover, the absence of the mucosal wave implies impedance of the vocal folds and requires considerably greater pulmonary effort during phonation (Titze, 2001, p. 114). When there is presence of infectious disease, increased blood flow and irrigation of the vocal folds are the body's first responses to invasion; they become red and thickened along with the swelling of the subglottal regions (Titze, 2001, p. 347). As the body heals, white blood cells are responsible for the removal of dead tissue cells and debris causing the vocal fold tissue to become more viscous and difficult to move (Titze, 2001, p. 347-8). This directly elevates phonation threshold pressure so that sounds may not be able to be produced in a normal way (Titze, 2001, p. 347).

Hypothesis

This study builds on the work by Asadi et al. (2020) to further explore changes in how airflow, the position of the tongue, and the tension of the tongue contribute to the release of speech particles. Titze and Verdolini Abbott (2012, p. 254) state that "there is no sound or speech without air movement." Potential particle generation at the glottis is affected by the rate of airstream which drives vocal registers, onset, and loudness. Since whispered speech uses increased airflow paired with low airway resistance, it would be expected that this vocal condition would produce high amounts of particles. The h-onset condition would be expected to produce high amounts of particles by the increased initial airflow. The loud vocal condition is produced with increased effort and airflow and would thus release high amounts of speech particles. On the opposite end of the particle spectrum is the vocal fry register, which is produced with minimal airflow, and would be expected to release the least amount of speech particles.

The second hypothesis is how the position of the tongue affects particle generation. The Continuity Law of Incompressible Flow (Titze, 2000, p. 76) states at the point of constriction the velocity increases to keep the flow at the same rate. In the speech mechanism, the first point of constriction is at the vocal folds (see Figure 7), and a second constriction is formed by the placement of the articulators (tongue, teeth, and lips).

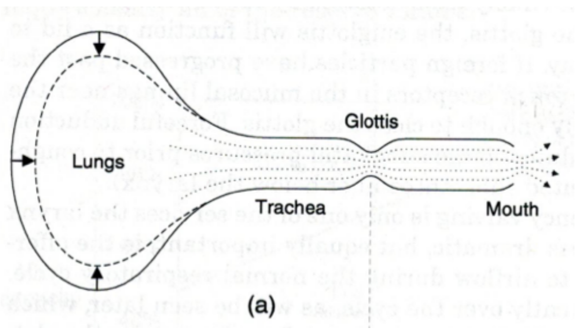

Figure 7. Schematic of airflow from the lungs and constriction at the glottis (Titze, 2000, p. 65).

The tongue becomes the second point of constriction when it is in the position of the /i/ vowel, which is produced by a high-front tongue position (see Figure 8).

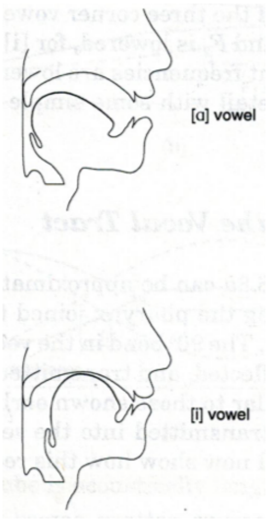

Figure 8. Schematic of the tongue position of the /i/ and /ɑ/ vowels (Titze, 2000, p. 163).

Applying the Law of Incompressible Flow, the airspeed should increase due to the narrowing of space between the tongue and the roof of the mouth contributing to the doubling of particles released in this vowel position.

Another factor in the production of speech aerosol may lie in the tension of the tongue. Watery saliva emerges from sublingual and salivary glands in oral movements (Groher & Crary, 2021, p. 210). Tense vowels /i, ɑ/ may also contribute to changes in particle amounts by the back of the tongue contracting to make these vowels, which in turn squeezes the salivary glands in the tongue resulting in an increase of particle generation.

Methods & Materials

This study was conducted at the Air Quality Lab Chamber at the University of Colorado Boulder. Five female participants participated in the study and ranged in age from 22-43 years. There were no exclusion factors of participants in the study. The plume aerosols of a participant’s speech production were sampled by an aerodynamic particle sizer (APS, 3321, TSI) to measure total particle size distributions. The participants were asked to perform speech tasks into a funnel to reduce any effects of airflow in the room. Participants wore an over-ear microphone (AKG C420 Condenser Microphone) connected to an audio interface (Motu Ultralite-mk3 Hybrid) and were presented with the loudness of their speech as a visual scale of speech loudness to keep it within the appropriate range for each test (i.e., 70-75 dB SPL). The speech tasks began in one vocal condition of a sustained vowel for five seconds. Following the task, the participant was given 35 seconds of rest with instructions to breathe through the nose. This allowed for each plume to be measured separately. This procedure was repeated two more times, for a total of three trials on each vowel and across vocal registers and conditions. The vowels measured included /ɑ, i, ɛ, ə/, and vocal registers tested included modal, glottal fry, falsetto, and vocal conditions of whisper, loud voice, and breathy onset (starting with /h/).

Statistical analyses were completed using R (version 3.6.1) (www.R-project.org). An ANOVA test was run using the aov() function from the stats package in R (R Core Team, 2013) to compare effects of aerosol generation among phonation and vowel tasks. Tukey's multiple comparison was used for post-hoc analyses using the TukeyHSD() function from the stats package in R (R Core Team, 2013). Analyses were completed for each subject, the group excluding the superemitter (4 individuals), and the entire group (5 individuals). An alpha level of $p < .05$ was set for all analyses.

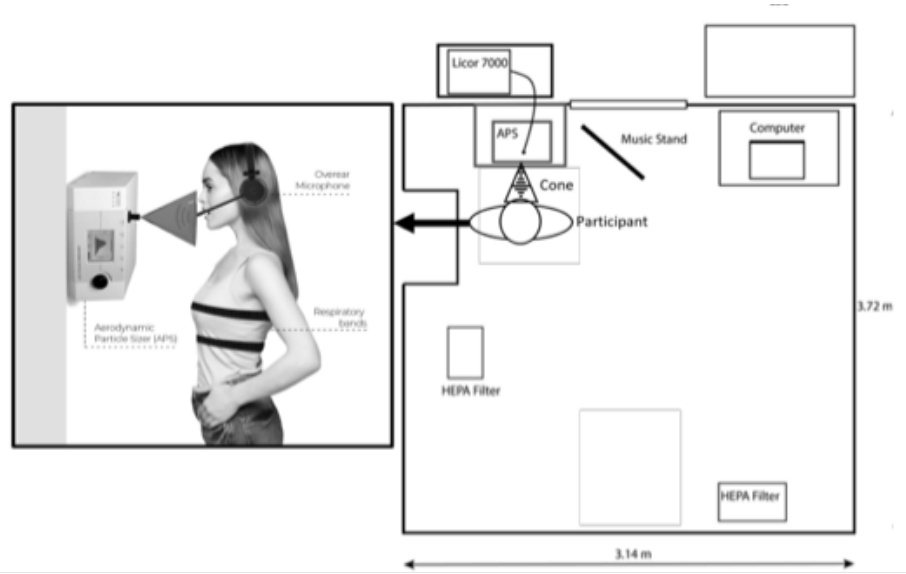

Figure 9. Graphical display of the Air Quality Lab Chamber (AQLC) (right) and the specific testing setup for speech production (left).

Results

For the purposes of data analysis, the first seven seconds (six readings) of data points were used for each task. The starting time point for each participant's task was adjusted within a 2-3 sec. span to capture accurate measurements from the aerosol plume. Particle counts measured during the silent periods were omitted for two reasons: 1) particles not cleared from the machine are not representative of the aerosol plume created by vocalization; and 2) ambient particle counts may have contributed to measurements during this phase. This was intended to capture accurate data from the aerosol plume and not any particles that were not cleared from the machine or ambient particles in the air. Figures 10-25 show the aerosol measurements collected for each individual in the form of violin plots, the mean measurements in bar charts, and peak values for particle emission in Table 1.

One of the participants in the study appeared to have particle emission patterns that are consistent with superemitter characteristics (Abkarian & Stone, 2020; Asadi et al., 2019; Asadi et al., 2020) in comparison to the other participants. This participant exhibited higher particle counts for all vowels for vocal conditions of whisper, loud, h-onset, and the falsetto register.

To determine an overview of particle emission for each task, analyses were completed based on the entire cohort (Figures 22 and 23) as well as the 4 participants that did not possess superemitter aerosol characteristics (Figures 24 and 25). The general approach was based on combining all measurements for each task for the different groups to calculate a one-way ANOVA followed by a Tukey HSD test to determine which pairwise comparisons were significant (see Table 2). For the group of 5 participants, only 1 comparison was determined to be significant, which was the vowel /i/ for the whisper and loud conditions (difference of the means = 0.043, $F_{5,105} = 21.07$, $p < .0005$). The overall results were different with exclusion of the superemitter: the loud condition released the most particles, followed by the whisper condition, modal, falsetto, h-onset, and lastly vocal fry ($F_{3,3.7} = 2.84$, $p = .04$). The vowels that released the most particles for the entire group included /ɑ, ɛ, ə/ but were dependent on the vocal task, and for the non-superemitter group the vowels that released the most were /ɑ, ɛ, i/ (see Table 1 and Figures 10-25).

The observation that one individual can influence the outcomes of this study prompted an assessment of statistically significant pairwise comparisons of vowels and tasks for each individual. One-way ANOVAs were calculated (see figures in the supplemental section) and the Tukey HSD test was used to determine which comparisons were significant (Table 2). For four of the five participants, the loud condition on the vowel /ɑ/ released more particles than all vowels (/ɑ, i, ɛ, ə/) compared to the h-onset condition, the falsetto register, and the vocal fry register (p < .0001). For the non-superemitter participants, the particle release loud /i/ task was significant compared to particle release on all vowels in the h-onset condition, the falsetto register, and the vocal fry register (p < .0001). For three of these participants, the data showed significance of particle release on loud /ɑ/ and loud /ɛ/ compared to all vowels in the falsetto register and vocal fry register, and h-onset condition on the vowels /ɑ, ɛ, ə/ (p < .0001). For the full list of post hoc comparisons see the supplemental section.

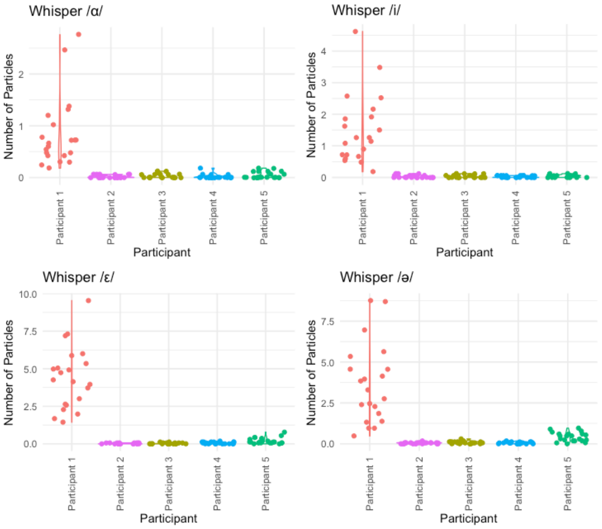

Figure 10. Four graphs are presented with number of particles as a function of the participants in the whisper condition. From left to right, the top two graphs show particle number for the /ɑ/ and the /i/ vowels, and the bottom two graphs show the /ɛ/ and the /ə/ vowels. Individual particles are represented as dots overlaid by a violin distribution.

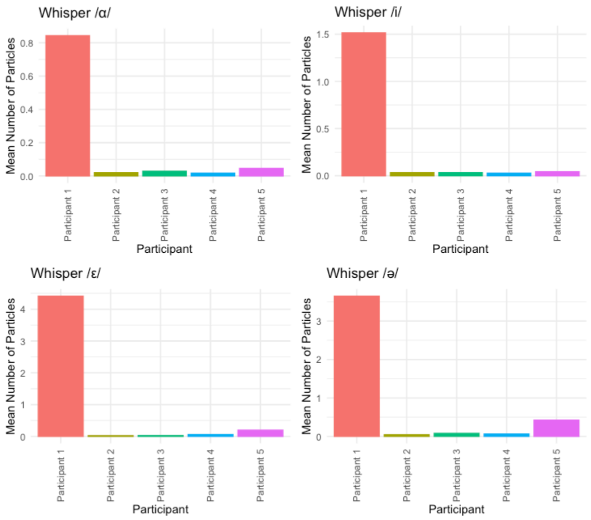

Figure 11. Four graphs are presented with mean number of particles as a function of the participants in the whisper condition. From left to right, the top two graphs show mean particle numbers for the /ɑ/ and the /i/ vowels, and the bottom two graphs the /ɛ/ and the /ə/ vowels.

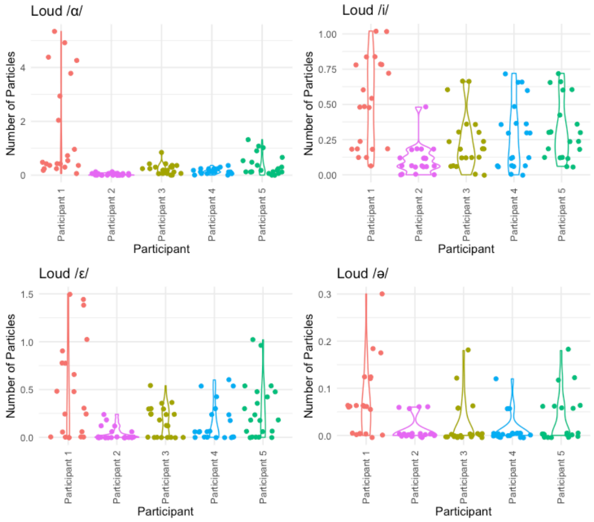

Figure 12. Four graphs are presented with number of particles as a function of the participants in the loud condition. From left to right, the top two graphs show particle number for the /ɑ/ and the /i/ vowels, and the bottom two graphs show the /ɛ/ and the /ə/ vowels. Individual particles are represented as dots overlaid by a violin distribution.

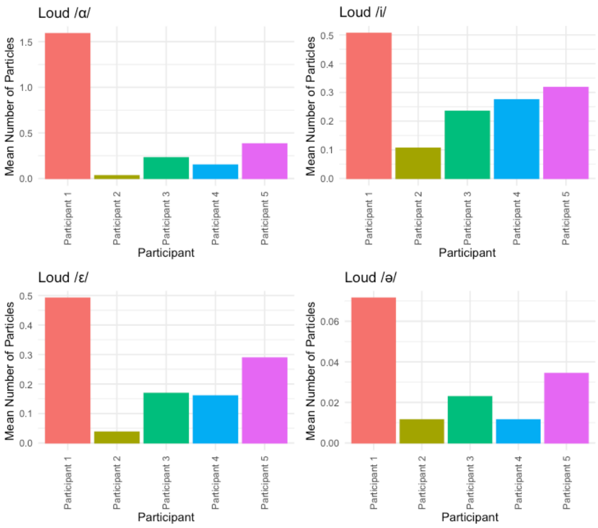

Figure 13. Four graphs are presented with mean number of particles as a function of the participants in the loud condition. From left to right, the top two graphs show mean particle numbers for the /ɑ/ and the /i/ vowels, and the bottom two graphs the /ɛ/ and the /ə/ vowels.

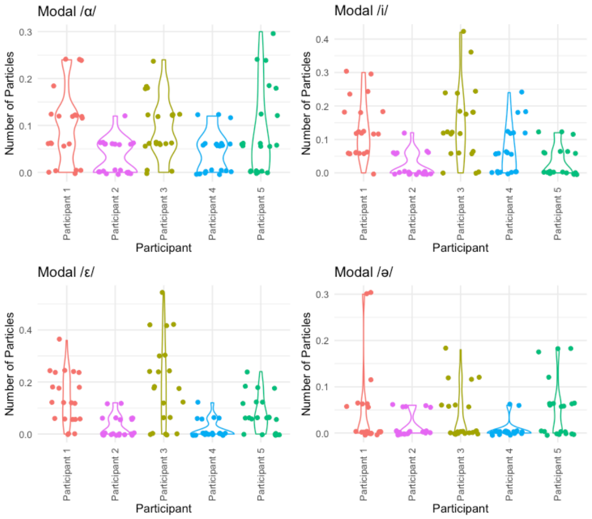

Figure 14. Four graphs are presented with number of particles as a function of the participants in the modal register. From left to right, the top two graphs show particle number for the /ɑ/ and /i/ vowels, and the bottom two graphs the /ɛ/ and /ə/ vowels. Individual particles are represented as dots overlaid by a violin distribution.

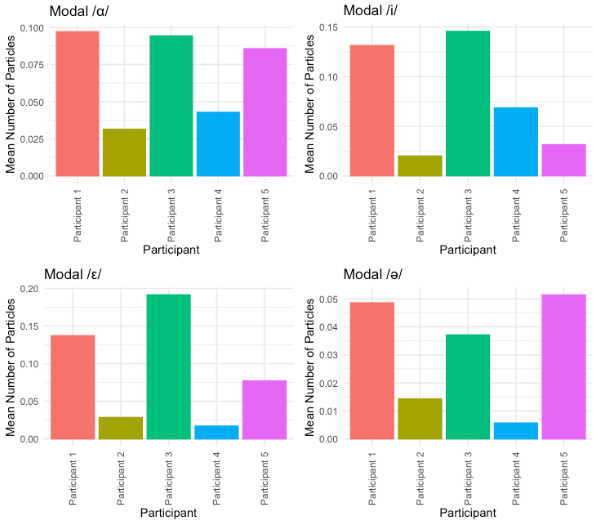

Figure 15. Four graphs are presented with mean number of particles as a function of the participants in the modal register. From left to right, the top two graphs show mean particle numbers for the /ɑ/ and /i/ vowels, and the bottom two graphs the /ɛ/ and /ə/ vowels.

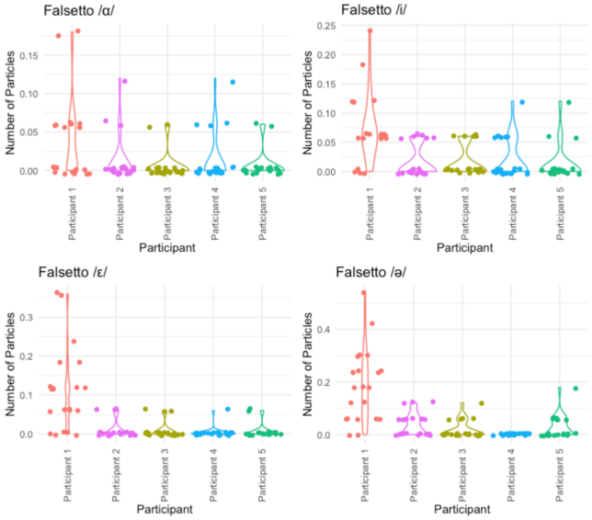

Figure 16. Four graphs are presented with number of particles as a function of the participants in the falsetto register. From left to right, the top two graphs show particle number for the /ɑ/ and /i/ vowels, and the bottom two graphs the /ɛ/ and /ə/ vowels. Individual particles are represented as dots overlaid by a violin distribution.

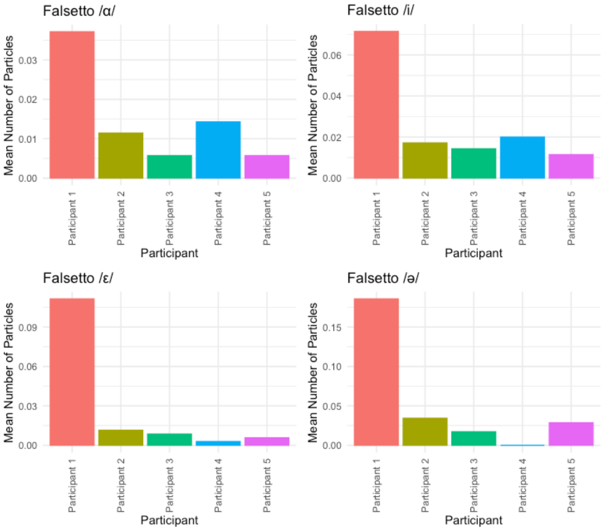

Figure 17. Four graphs are presented with mean number of particles as a function of the participants in the falsetto register. From left to right, the top two graphs show mean particle numbers for the /ɑ/ and /i/ vowels, and the bottom two graphs the /ɛ/ and /ə/ vowels.

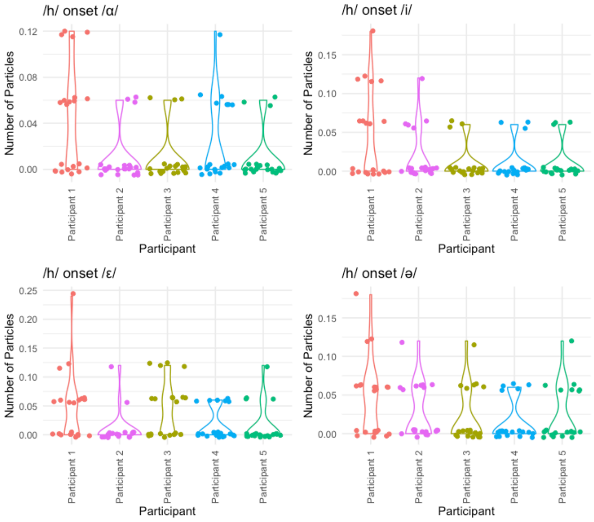

Figure 18. Four graphs are presented with number of particles as a function of the participants in the h-onset condition. From left to right, the top two graphs show particle number for the /ɑ/ and the /i/ vowels, and the bottom two graphs show the /ɛ/ and the /ə/ vowels. Individual particles are represented as dots overlaid by a violin distribution.

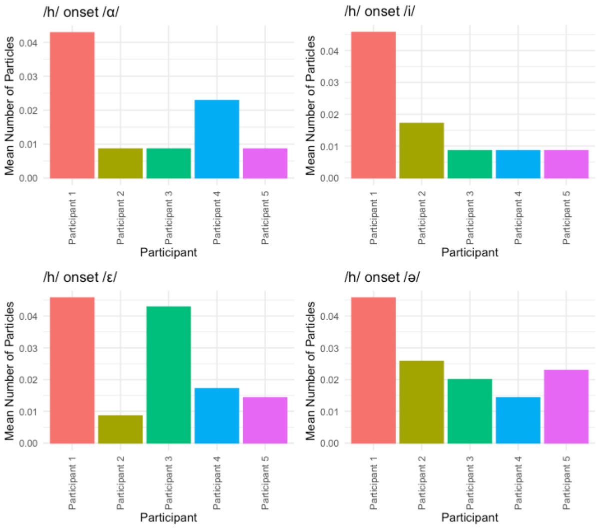

Figure 19. Four graphs are presented with mean number of particles as a function of the participants in the h-onset condition. From left to right, the top two graphs show mean particle numbers for the /ɑ/ and the /i/ vowels, and the bottom two graphs the /ɛ/ and the /ə/ vowels.

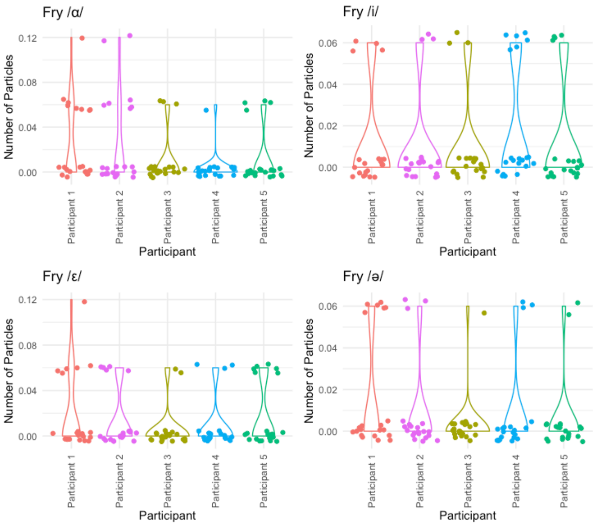

Figure 20. Four graphs are presented with number of particles as a function of the participants in the vocal fry register. From left to right, the top two graphs show particle number for the /ɑ/ and the /i/ vowels, and the bottom two graphs show the /ɛ/ and the /ə/ vowels. Individual particles are represented as dots overlaid by a violin distribution.

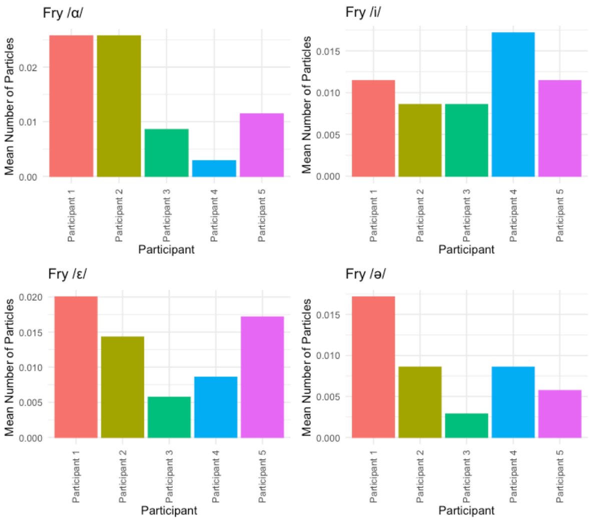

Figure 21. Four graphs are presented with mean number of particles as a function of the participants in the vocal fry register. From left to right, the top two graphs show mean particle numbers for the /ɑ/ and the /i/ vowels, and the bottom two graphs the /ɛ/ and the /ə/ vowels.

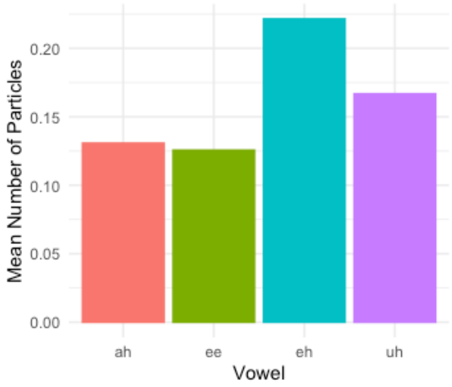

Figure 22. One graph is presented with mean number of particles as a function of all five participants across all vocal tasks and vowels.

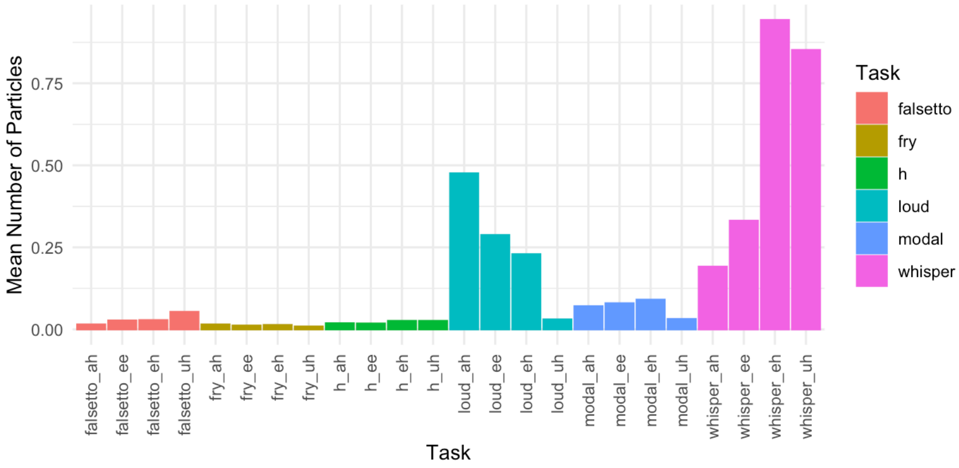

Figure 23. One graph is presented with mean number of particles as a function of all five participants across all vocal tasks and vowels broken down by task.

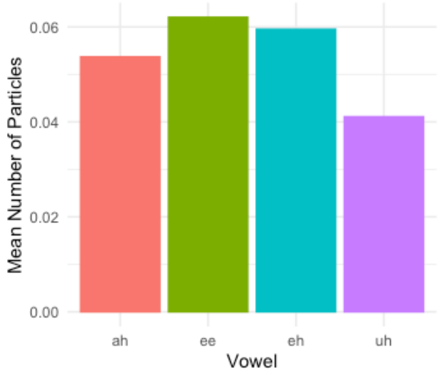

Figure 24. One graph is presented with mean number of particles as a function of the non-super emitter participants across all vocal tasks and vowels.

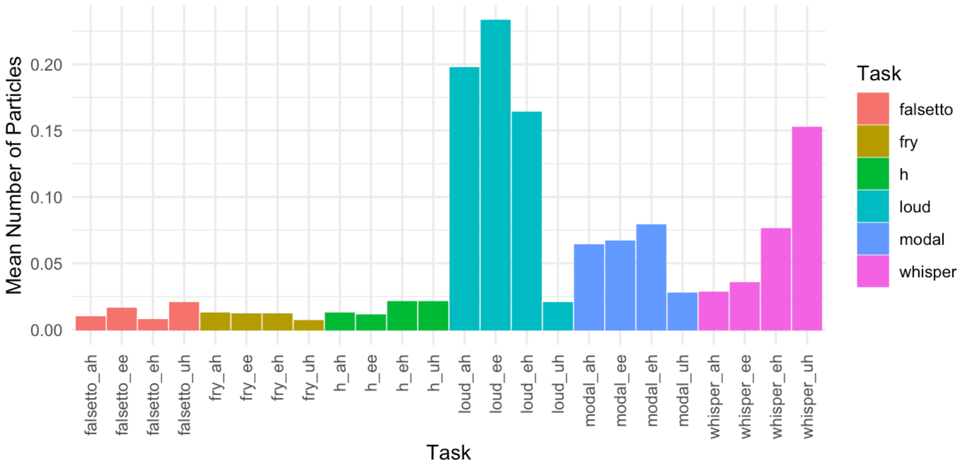

Figure 25. One graph is presented with mean number of particles as a function of the non-super emitter participants across all vocal tasks and vowels broken down by task.

Table 1. Peak Vowel and Value

Participant	Task	Vowel	Peak Value
P1	Modal	/ɛ/	0.36
	Vocal Fry	/ɑ, ɛ/	0.12
	Falsetto	/ə/	0.54
	Whisper	/ɛ/	9.54
	Loud	/ɑ/	5.34
	H-onset	/ɛ/	0.24
P2	Modal	/ɛ, i/	0.12
	Vocal Fry	/ɑ/	0.12
	Falsetto	/ə, ɑ/	0.12
	Whisper	/ə/	0.18

	Loud	/ɛ/	0.24
	H-onset	/i, ɛ, ə/	0.12
P3	Modal	/ɛ/	0.54
	Vocal Fry	/ɑ, i, ɛ, ə/	0.06
	Falsetto	/ə/	0.12
	Whisper	/ə/	0.30
	Loud	/ɑ/	0.84
	H-onset	/ə, ɛ/	0.12
P4	Modal	/i/	0.24
	Vocal Fry	/ɑ, i, ɛ, ə/	0.06
	Falsetto	/ɑ, i/	0.12
	Whisper	/ə, ɛ, ɑ/	0.18
	Loud	/i/	0.72
	H-onset	/ɑ/	0.12
P5	Modal	/ɑ/	0.30
	Vocal Fry	/ɑ, i, ɛ, ə/	0.06
	Falsetto	/ə/	0.18
	Whisper	/ə/	0.90
	Loud	/ɑ/	1.32
	H-onset	/ɛ, ə/	0.12

Table 2. Tukey Significant Comparisons.

Significance for 5 Participants										
	Difference of the means	**95% confidence lower limit**	**95% confidence upper limit**	**Adjusted p-value (5 participants)**	**Adjusted p-value (4 participants)**	**P1**	**P2**	**P3**	**P4**	**P5**
Whisper /i/- Loud /i/	0.043	-0.265	0.351	1.00E+00	4.39E-11	1.18E-02	6.48E-06	7.73E-11	5.18E-11	5.43E-08
Significance for 4 of 5 Participants										
	Difference of the means	**95% confidence lower limit**	**95% confidence upper limit**	**Adjusted p-value (5 participants)**	**Adjusted p-value (4 participants)**	**P1**	**P2**	**P3**	**P4**	**P5**
Loud /ɑ/- Fry /ɑ/	0.461	0.153	0.769	1.52E-05	4.39E-11	1.83E-07	1.00E+00	5.20E-11	1.33E-07	5.18E-11
Loud /ɑ/- Fry /i/	0.464	0.156	0.772	1.22E-05	4.39E-11	1.30E-07	9.81E-01	5.20E-11	4.75E-06	5.18E-11
Loud /ɑ/- Fry /ɛ/	0.462	0.154	0.77	1.36E-05	4.39E-11	1.59E-07	1.00E+00	5.19E-11	5.77E-07	5.19E-11
Loud /ɑ/- Fry /ə/	0.467	0.159	0.775	1.01E-05	4.39E-11	1.49E-07	9.81E-01	5.19E-11	5.77E-07	5.18E-11
Loud /ɑ/- Falsetto /ɑ/	0.461	0.153	0.769	1.52E-05	4.39E-11	2.40E-07	9.97E-01	5.19E-11	2.38E-06	5.18E-11
Loud /ɑ/- Falsetto /i/	0.449	0.141	0.757	3.29E-05	4.39E-11	5.40E-07	1.00E+00	5.24E-11	9.34E-06	5.18E-11
Loud /ɑ/- Falsetto /ɛ/	0.447	0.139	0.755	3.54E-05	4.39E-11	1.36E-06	9.97E-01	5.20E-11	1.33E-07	5.18E-11
Loud /ɑ/- Falsetto /ə/	0.422	0.114	0.73	1.66E-04	4.40E-11	7.16E-06	1.00E+00	5.30E-11	6.28E-08	5.21E-11
Loud /ɑ/- H-onset /ɑ/	0.457	0.149	0.765	1.90E-05	4.39E-11	2.75E-07	9.81E-01	5.20E-11	1.81E-05	5.19E-11
Loud /ɑ/- H-onset /i/	0.458	0.15	0.766	1.83E-05	4.39E-11	2.95E-07	1.00E+00	5.20E-11	5.77E-07	5.19E-11
Loud /ɑ/- H-onset /ɛ/	0.45	0.142	0.758	3.06E-05	4.40E-11	2.95E-07	9.81E-01	1.09E-09	4.75E-06	5.19E-11
Loud /ɑ/- H-onset /ə/	0.45	0.142	0.758	3.06E-05	4.40E-11	2.95E-07	1.00E+00	5.44E-11	2.38E-06	5.19E-11
Loud /i/- Fry /ɑ/	0.273	-0.035	0.581	1.73E-01	4.39E-11	9.61E-01	1.32E-07	5.19E-11	5.16E-11	5.20E-10
Loud /i/- Fry /i/	0.276	-0.032	0.584	1.55E-01	4.39E-11	9.47E-01	7.09E-11	5.19E-11	5.17E-11	5.20E-10
Loud /i/- Fry /ɛ/	0.274	-0.034	0.582	1.64E-01	4.39E-11	9.56E-01	4.74E-10	5.18E-11	5.17E-11	1.20E-09
Loud /i/- Fry /ə/	0.279	-0.029	0.587	1.42E-01	4.39E-11	9.53E-01	7.09E-11	5.18E-11	5.17E-11	2.41E-10
Loud /i/- Falsetto /ɑ/	0.273	-0.035	0.581	1.73E-01	4.39E-11	9.70E-01	1.43E-10	5.18E-11	5.17E-11	2.41E-10
Loud /i/- Falsetto /i/	0.261	-0.047	0.569	2.46E-01	4.39E-11	9.88E-01	1.93E-09	5.20E-11	5.17E-11	5.20E-10
Loud /i/- Falsetto /ɛ/	0.259	-0.049	0.567	2.53E-01	4.39E-11	9.97E-01	1.43E-10	5.19E-11	5.16E-11	2.41E-10
Loud /i/- Falsetto /ə/	0.234	-0.074	0.542	4.61E-01	4.39E-11	1.00E+00	6.48E-06	5.21E-11	5.16E-11	6.63E-09
Loud /i/- H-onsest /ɑ/	0.269	-0.039	0.577	1.92E-01	4.39E-11	9.74E-01	7.09E-11	5.19E-11	5.18E-11	3.49E-10
Loud /i/- H-onset /i/	0.27	-0.038	0.578	1.89E-01	4.39E-11	9.76E-01	1.93E-09	5.19E-11	5.17E-11	3.49E-10
Loud /i/- H-onset /ɛ/	0.262	-0.046	0.57	2.38E-01	4.39E-11	9.76E-01	7.09E-11	2.93E-10	5.17E-11	7.85E-10
Loud /i/- H-onset /ə/	0.262	-0.046	0.57	2.38E-01	4.39E-11	9.76E-01	1.32E-07	5.24E-11	5.17E-11	2.81E-09

Loud /ə/- Loud /ɑ/	-0.445	-0.753	-0.137	4.09E-05	4.40E-11	5.40E-07	9.97E-01	5.73E-11	1.18E-06	5.25E-11
Loud /ə/- Loud /i/	-0.257	-0.565	0.051	2.70E-01	4.39E-11	9.88E-01	1.43E-10	5.30E-11	5.17E-11	1.55E-08
Modal /ɑ/- Loud /ɑ/	-0.405	-0.713	-0.097	4.49E-04	4.42E-11	9.80E-07	1.00E+00	9.75E-05	1.26E-03	2.81E-09
Modal /ɑ/- Loud /i/	-0.217	-0.525	0.091	6.23E-01	4.41E-11	9.94E-01	1.85E-06	3.21E-05	5.18E-11	1.77E-05
Modal /ə/- Loud /ɑ/	-0.444	-0.752	-0.136	4.39E-05	4.41E-11	3.15E-07	1.00E+00	2.93E-10	2.79E-07	6.33E-11
Modal /ə/- Loud /i/	-0.256	-0.564	0.052	2.78E-01	4.39E-11	9.77E-01	4.74E-10	1.06E-10	5.16E-11	1.85E-07
Whisper /ɑ/- Loud /i/	-0.097	-0.405	0.211	1.00E+00	4.39E-11	1.00E+00	8.12E-09	5.73E-11	5.17E-11	8.20E-08
Whisper /i/- Loud /ɛ/	0.102	-0.206	0.41	1.00E+00	4.47E-11	9.50E-03	1.00E+00	9.75E-05	4.75E-06	2.83E-06
Whisper /ɛ/- Loud /ɑ/	0.467	0.159	0.775	9.71E-06	6.18E-11	5.17E-11	1.00E+00	6.37E-11	1.60E-02	4.08E-03
Whisper /ɛ/- Loud /i/	0.655	0.347	0.963	0.00E+00	4.41E-11	5.16E-11	3.34E-08	5.44E-11	5.18E-11	4.06E-01
Whisper /ə/- Loud /i/	0.564	0.256	0.872	8.49E-09	1.47E-04	5.16E-11	2.14E-04	1.65E-06	5.19E-11	6.71E-01
Significance for 3 of 4										
	Difference of the means	**95% confidence lower limit**	**95% confidence upper limit**	**Adjusted p-value (5 participants)**	**Adjusted p-value (4 participants)**	**P1**	**P2**	**P3**	**P4**	**P5**
Whisper /ɛ/- Loud /ɛ/	0.714	0.406	1.022	0.00E+00	1.41E-05	5.16E-11	1.00E+00	1.81E-05	2.17E-03	8.84E-01
Whisper /ɛ/- Modal /i/	0.863	0.555	1.171	0.00E+00	1.00E+00	5.16E-11	1.00E+00	1.29E-03	1.00E+00	1.98E-02
Whisper /ə/- Modal /ɛ/	0.761	0.453	1.069	0.00E+00	1.24E-03	5.16E-11	1.00E+00	5.19E-03	9.47E-01	5.25E-11
Whisper /ə/- Loud /ɑ/	0.376	0.068	0.684	2.20E-03	4.38E-01	5.22E-11	1.00E+00	5.58E-06	3.85E-02	1.00E+00
Modal /ɛ/- Loud /ɑ/	-0.385	-0.693	-0.077	1.36E-03	1.10E-10	2.44E-06	1.00E+00	9.99E-01	4.75E-06	7.85E-10
Whisper /ɑ/- Loud /ɑ/	-0.285	-0.593	0.023	1.17E-01	4.41E-11	2.94E-01	1.00E+00	7.73E-11	4.75E-06	5.63E-11
Loud /ɛ/- Fry /ɑ/	0.214	-0.094	0.522	6.50E-01	4.41E-11	9.72E-01	1.00E+00	4.70E-07	6.18E-09	3.59E-08
Loud /ɛ/- Fry /i/	0.218	-0.09	0.526	6.18E-01	4.41E-11	9.61E-01	8.31E-01	4.70E-07	2.79E-07	3.59E-08
Loud /ɛ/- Fry /ɛ/	0.216	-0.092	0.524	6.34E-01	4.41E-11	9.68E-01	9.81E-01	2.47E-07	2.93E-08	8.20E-08
Loud /ɛ/- Fry /ə/	0.221	-0.087	0.529	5.91E-01	4.41E-11	9.66E-01	8.31E-01	1.29E-07	2.93E-08	1.55E-08
Loud /ɛ/- Falsetto /ɑ/	0.214	-0.094	0.522	6.50E-01	4.41E-11	9.79E-01	9.32E-01	2.47E-07	1.33E-07	1.55E-08
Loud /ɛ/- H-onset /ɑ/	0.211	-0.097	0.519	6.81E-01	4.41E-11	9.82E-01	8.31E-01	4.70E-07	1.18E-06	2.36E-08
Loud /ɛ/- H-onset /i/	0.211	-0.097	0.519	6.76E-01	4.41E-11	9.83E-01	9.97E-01	4.70E-07	2.93E-08	2.36E-08
Loud /ɛ/- H-onset /ɛ/	0.203	-0.105	0.511	7.46E-01	4.40E-11	9.83E-01	8.31E-01	4.75E-04	2.79E-07	5.43E-08
Loud /ɛ/- H-onset /ə/	0.203	-0.105	0.511	7.46E-01	4.40E-11	9.83E-01	1.00E+00	5.58E-06	1.33E-07	1.85E-07
Loud /ɛ/- Falsetto /i/	0.202	-0.106	0.51	7.55E-01	4.41E-11	9.92E-01	9.97E-01	1.65E-06	5.78E-07	3.59E-08
Loud /ɛ/- Falsetto /ɛ/	0.201	-0.107	0.509	7.65E-01	4.41E-11	9.98E-01	9.32E-01	4.70E-07	6.18E-09	1.55E-08
Loud /ɛ/- Falsetto /ə/	0.176	-0.132	0.484	9.21E-01	4.41E-11	1.00E+00	1.00E+00	3.05E-06	2.81E-09	4.10E-07

Loud /i/- Loud /ɑ/	-0.188	-0.496	0.12	8.59E-01	8.59E-01	3.59E-03	1.85E-06	1.00E+00	1.81E-05	9.99E-01
Loud /ə/- Loud /ɛ/	-0.199	-0.507	0.109	7.83E-01	4.41E-11	9.92E-01	9.32E-01	1.01E-05	6.28E-08	8.97E-07
Modal /ə/- Loud /ɛ/	-0.198	-0.506	0.11	7.92E-01	4.41E-11	9.84E-01	9.81E-01	1.67E-04	1.35E-08	8.60E-06
Modal /ɛ/- Loud /i/	-0.197	-0.505	0.111	7.96E-01	4.41E-11	9.99E-01	5.05E-07	9.95E-01	5.17E-11	5.96E-06
Modal /i/- Loud /i/	-0.208	-0.516	0.1	7.07E-01	4.41E-11	9.98E-01	8.12E-09	1.10E-01	5.18E-11	1.02E-08
Whisper /i/- Loud /ɑ/	-0.145	-0.453	0.163	9.91E-01	4.41E-11	1.00E+00	1.00E+00	1.67E-10	6.56E-05	5.46E-11
Whisper /ɑ/- Loud /ɛ/	-0.038	-0.346	0.27	1.00E+00	4.41E-11	9.99E-01	1.00E+00	3.21E-05	2.79E-07	4.11E-06

Analysis of each individual’s data revealed three basic types of particle release patterns. One pattern is an increase of particle released during the task followed by a decrease of particles generated. A second pattern is an increase of particles released. Lastly, is a pattern of intermittent release of particles, usually alternating small particle readings and 0. This can be seen in Supplemental Figures 26-49.

Individual patterns emerge with particular vowels releasing the most particles. Participant 1 released the most on /ɛ/ in 3 of the 6 tasks. Participant 2 released most particles on /ə/ in 3 out of the 6 tasks. Participant 3 released most on /ɛ, ə/ in 3 out of the 6 tasks. Participant 4 released the most particles on /ɑ, i/ in 4 out of the 6 tasks. Participant 5 released the most on /ɑ/ in 4 out of the 6 tasks (see Table 1).

Discussion

The goal of this experiment was to determine if phonation quality and vowel shape influence the concentration of generated aerosol particles from speech production in healthy adults. We hypothesized that phonation quality would influence particle generation, which was supported by the data. An in-depth analysis comparing all conditions and vowels for each individual revealed that the volume of air from the lungs significantly affected the number of particles released in sustained vowels where loud, whisper, and modal produced the most particles, while the tasks in falsetto, h-onset, and vocal fry produced less. For all 5 individuals, the comparison of whisper /i/ to loud /i/ was statistically significant with a high particle release in the whisper condition. Exclusion of the superemitter revealed that loud /i/ was statistically significant in producing more particles compared to all vowels in falsetto, vocal fry, and h-onset. Furthermore, in an analysis that excluded the superemitter, three of the participants demonstrated higher particle counts for loud /ɛ, a/ in comparison to all vowels in falsetto, vocal fry, and h-onset with vowels /a, ɛ, u/.

A similar study was conducted by Asadi and colleagues (2020). One of the participants was determined to be a superemitter in their group of 10 participants. For comparison between individuals, the data was normalized by using an average for each individual's amount of particle emission over the four amplitudes tested. In contrast to the findings in the current study, Asadi et al. (2020) reported that the vowel /i/ released more particles than the vowels /ɑ, u/ which they suggest is because the vowel /i/ requires greater energy requirement for articulation. This explanation does not fit with the current understanding of the physics of speech production. Although resonance of the vocal tract is distinguished by the shape of pharyngeal and oral cavities (which alter formant frequencies), energy requirements to produce different vowels at a similar fundamental frequency do not differ. The Law of Incompressible Flow (Titze, 2000, p. 76) may be a better explanation for the phenomenon produced in their study as resonance of the vocal tract needs to be separated from the airflow of the vocal tract to understand speech aerosol production.

The findings in our study showed a higher number of mean particles generated on the vowels /ɑ, ɛ, ə/ depending on the vocal task for data including all participants and vowels /ɑ, ɛ, i/ depending on the vocal task for the non-superemitter group. More so, the non-superemitter group showed that the mean value on the vowel /i/ during the loud condition released the most particles, which aligns with the results of the Asadi et al. (2020) study. This could imply that the Law of Incompressible Flow explains the phenomenon of high particle release on the /i/ vowel in the loud condition. However, when considering the data including the superemitter, the mean value on the vowel /ɛ/ is shown to release the most particles in the whisper condition. This phenomenon may suggest that the difference in the tongue position of the vowel /ɛ/, having a flatter tongue configuration compared to the /i/ vowel, creates a relatively open tube for aerosol particles to pass, is significant for the superemitter. Alternatively, the constriction of the /i/ vowel may be such that particles are blocked by the height of the tongue and stick to the back of the tongue and other oral structures, or the particles are altered by the constriction as it moves through the oral cavity and out of the mouth.

One important question of this research was to address the role of tongue tension in particle generation. Tense tongue vowels are produced with the base of the tongue isometrically contracting in production (/ɑ, i/), while lax tongue vowels are produced with no isometric base of tongue contraction (/ɛ, ə/). This contraction could activate the salivary glands in the tongue causing a release of saliva or bringing the tongue forward to allow more space in the pharynx for particle travel. In our study, more particles were released for /ə/ than /i/ in data including the superemitter, the loud condition /ə/ was significant in comparison to loud

/ɑ/ for the group of non-superemitters, and loud /ə/ released more particles compared to loud /a/ for four out of the five participants. Additionally, whisper condition tended to show the lax vowels releasing more particles. These results support lax vowels producing more particles. However, in the loud condition the tense vowels produced more particles compared to the lax vowels. These conflicting results may suggest that tongue tension is not an important factor in particle generation.

An additional question of importance was the role of the type of phonation quality in particle generation. Vocal production changes based on the airflow through the glottis, and the tension and movement of the vocal folds. These elements can also define the vibratory patterns of the vocal folds in different registers. The vocal fry register is produced with minimal airflow through the glottis creating a “popping” sound and in our study produced the least amount of speech aerosol. Using an h-onset, which initially uses more air, produced the second least amount of speech aerosol in our study. However, this was determined by two of the participants producing less particles in this vocal condition. For the other three participants, the particle release was the same amount comparing the h-onset task to the falsetto task. From the perspective of airflow, this finding suggests that the reduction of the airstream after the initial increase of airflow diminishes particle release. The third least amount of speech aerosol was produced in the falsetto register. This register is produced with faster airflow to drive the vocal folds to vibrate at a higher rate, and only the edges of the vocal folds contact in vibration, but interestingly produced less speech aerosol than modal register in our study. The third highest releasing task was the modal register, which is produced with enough airstream to produce speech frequencies that are lower in a person’s vocal range. Although this finding was unexpected from the perspective of airflow, this result may indicate that vibration depth and contact of the vocal folds could explain why the modal register produced more particles. Loud voice and whispering were the most particle generating in this study. Both are produced by more air pushed through the system, but loud voice involves forceful opening and closing of the vocal folds. Whisper differs from the other conditions and registers, as this is the only condition where the vocal folds do not come together.

Analysis of Individual Participants

The limited number of participants in this study allowed for detailed analysis for each individual.

Analysis of each participant revealed three basic types of particle release patterns. However, these patterns were not consistent for each individual across trials of the same task, nor across vocal tasks. The first pattern of particle release is the increase of particles released during vocalization followed by a decrease of particles released. This pattern of particle release was observed in the modal condition for three of the five participants. Participant 1, the superemitter of the study, was found to consistently release particles with this release pattern across the experiment. Participant 2 and Participant 3 also produced this particle release pattern, but with more variability with intermittent readings of zero across the trial. The other vocal condition that produced the increasing-decreasing particle release pattern was in the loud vocal condition. All participants produced this pattern of particle release on the /i/ vowel in at least one of the trials. In the whisper task, Participant 1 and Participant 5 produced this pattern of particle release.

The second pattern of particle release is an increase over the duration of the trial. All participants produced this pattern of release on the third trial on the loud /i/ task and on one of the trials during loud /ə/ task. Notably, Participant 1 produced this pattern on all trials on the loud /ə/ task, and for two trials on the loud /ɑ/ task. Participant 3 produced this pattern of release for one trial on the modal /i/ and modal /ɛ/ task.

A third pattern of particle release was an intermittent release of particles, usually alternating particle readings and zero. This pattern was observed for Participant 2 and Participant 4 during the modal vocal register tasks. All patients produced this pattern in the modal condition on the vowel /ə/. In the whisper task, Participant 2, Participant 3, and Participant 4 produced this particle release pattern across all trials and vowels. This pattern of particle release was also observed for all participants during the vocal fry, falsetto, and h-onset tasks. All participants produced all types of particle release, but the intermittent pattern was produced more consistently across the experiment. It is also worth noting that the type of particle release pattern was not a determining factor for peak particle release. For instance, the highest releases in the whisper condition were with an intermittent particle release pattern, while the loud condition was produced with the peak particle release with an increasing/decreasing release pattern.

It is worth mentioning that a possible fourth speech aerosol release pattern is a decreasing of particle generation over the duration of the task. However, only two participants produced this type of particle release, but one of the participants only produced it once. The other three participants did not produce this pattern. The superemitter produced this pattern five times across the experiment: whispered /ɑ/ on the third trial, whispered /ə/ on the first trial, modal /ɑ/ on the third trial, falsetto /ɛ/ on the first and third trial, and h-onset /ə/ on the third trial. Participant 5 produced this pattern on whispered /ɛ/ on trial three. Since trial three produced this pattern consistently, it is possible that there was an internal response of the participant, which signaled the end of the task and perhaps a decrease of energy put into the trial.

Analyzing the vowel for each individual's peak particle emission for each task revealed no predictable pattern. Participant 1's peak emission during the modal task was on /ɛ/, during the vocal fry task was on /ɛ, ə/, during falsetto was on /ə/, during the whisper task was /ə/, during the loud task was /ɑ/, and during the h-onset task was /ɛ/. Participant 2's peak emission during the modal task was on both /i, ɛ/, during the vocal fry task was /ɑ/, during the falsetto register was /ɑ, ə/, during the whisper condition was /ə/, during the loud condition was /ɛ/, and during the h-onset condition was /i, ɛ, ə/. For Participant 3, the peak emission during the modal register was /ɛ/, during the vocal fry condition all vowels released the same number, during the falsetto register was /ə/, during the whisper condition was /ə/, during the loud condition was /ɑ/, and during the h-onset condition was /ɛ, ə/. Participant 4's peak emissions were as follows: modal /i/, vocal fry all vowels released the same number, falsetto /ɑ, i/, whisper /ɑ, ɛ, ə/, loud /i/, and h-onset /ɑ/. Participant 5's peak emissions were as follows: modal /ɑ/, vocal fry all vowels released same amount, falsetto /ə/, whisper /ə/, loud /ɑ/, h-onset /ɛ, ə/. However, individual patterns emerge with particular vowels releasing the most particles. Participant 1 released on /ɛ/ in 3 of the 6 tasks. Participant 2 released most particles on /ə/ in 3 out of the 6 tasks. Participant 3 released most on /ɛ, ə/ in 3 out of the 6 tasks. Participant 4 released the most particles on /ɑ, i/ in 4 out of the 6 tasks. Participant 5 released the most on /ɑ/ in 4 out of the 6 tasks.

The particle release by the superemitter was only significant compared to the others during the loud task and the whisper task. During the other conditions and vocal registers, the particle production of the superemitter was similar to the rest of the group. The vowel that the superemitter differed on was in the whisper condition; this participant released the most on /ɛ/, while the others released the most on /ə/. In the loud condition, this participant released most on /ɑ/, which matched the vowels for Participant 3 and Participant 5. In the whisper condition, four of the participants released the most on /ɛ/, which includes Participant 1. Vowel type may not be of significance in how a superemitter releases particles, but in that the interplay of particle formation and the airstream plays a much more significant role.

These results demonstrate there is wide variability of particle generation across vocal registers, conditions, and vowels. These inconsistencies may be driven by differences in vocal tract shape and size, and in the oral cavity from tongue size and dentition. More so, the body's "noises" show that no trial or task is produced in exactly the same way. The variability across trials also shows that vocal fold efficiency ("warm up" effect) does not contribute to changes in particle generation. What these results point more consistently toward is the amount of airflow determines the number of particles released.

Limitations

The outcomes of this study have several limitations. First, there were only five healthy female participants, and results are not generalizable to a larger population or sick populations.

Another limitation is that the data produced by the APS showed small readings between vocal trials and that aerosol plumes did not clear completely. This may stem from several factors. For instance, the airflow in the room is a consideration in the results reported by the APS. It is possible that the efforts to reduce particles in the air between trials were not successful. Additionally, there is human error in performance. The participants may not have followed the directions and timing of the program in production of vocal tasks exactly, there may have been differences in the distance of how close they sat to the funnel, or how much they turned their head to look at the directions causing speech plumes to miss the funnel. These all may have contributed to the small readings between the vocal tasks.

Conclusion

Speech aerosol research is in its infancy, but with the rise of infectious disease through airborne transmission there is an importance of understanding the role speech plays in aerosol disease transmission. There is also yet to be a determined threshold for the number of speech aerosol particles that will guarantee disease transmission. The goal of this experiment was to determine if phonation quality and vowel shape (/ɑ, i, ɛ, ə/) influence the concentration of generated aerosol particles from speech production in healthy adults. Our data revealed the presence of a superemitter among the participants, which demanded data analysis consider the overall group and the group without the superemitter. For the entire group, the vowels /ɑ, ɛ, ə/ released the most particles and for the non-superemitter group the vowels /ɑ, ɛ, i/ released the most particles, but this was dependent on the vocal task. Additionally, the non-superemitter group demonstrated the vowel /i/ in the loud condition to release the highest amount of particles, while the superemitter released the most on /ɛ/ in whisper. For the non-superemitters, the second constriction made by the higher tongue position may be a factor in the number of particles released. For the superemitter, the low tongue position of /ɛ/ may be more of a factor in particle release. Tongue tension does not have a role in particle release, as both tense and lax vowels were shown to release high numbers of particles in different vocal tasks. This study found that vocal conditions with increased airflow is important in the amount of particles released--whisper and loud vocal condition releases the most (depending on data inclusion of the superemitter), followed by the modal register, falsetto register, h-onset and lastly the vocal fry register. This finding points to the amount of air moving through the respiratory tract significantly matters in particle release. Individual analysis revealed three patterns of particle release; increasing/decreasing, increasing, and an intermittent particle release and zero. All release patterns varied across tasks, and all participants produced the three pattern types. The individual analysis also demonstrated the variability of the speech system confirming Titze's description of the "noises" of the body and how the larynx is susceptible to these variations. Each individual's performance on separate trials and tasks varied in particle release and in the vowel that emitted a high number of particles. Individual differences may be due to variances in the size and shape of the vocal tract. Future research may include the force of glottic closure in particle release, variances in jaw opening, comparison of sick participants and healthy participants in particle generation, using connected speech for determining particle release, and deep analysis of particle generation in superemitters.

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APPENDIX A

Supplemental Figures

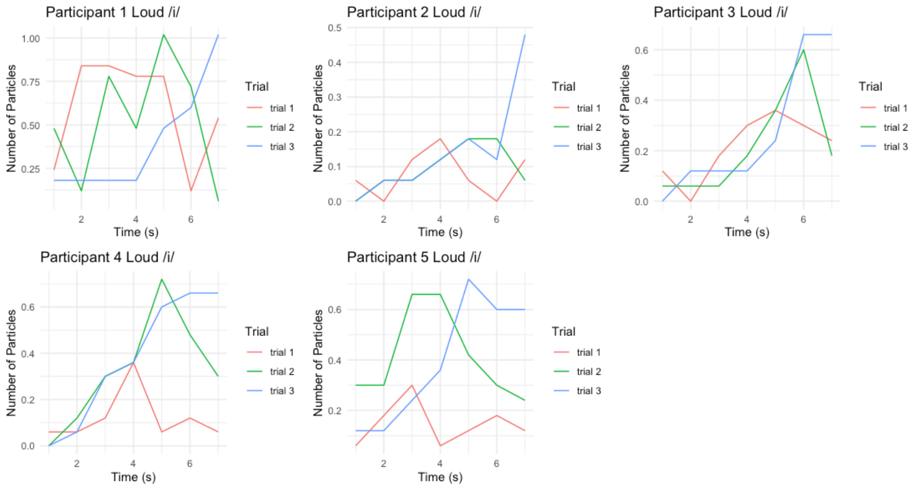

Figure 26. Individual trials of the loud /i/ task.

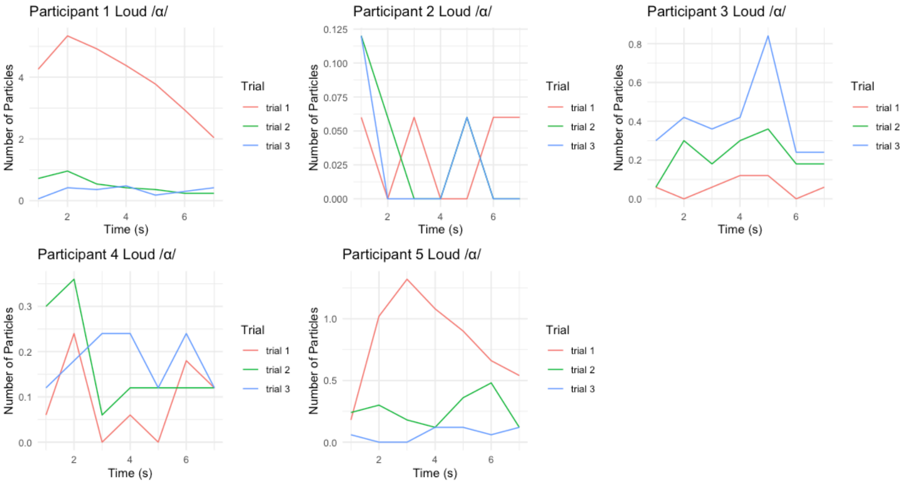

Figure 27. Individual trials of the loud /ɑ/ task.

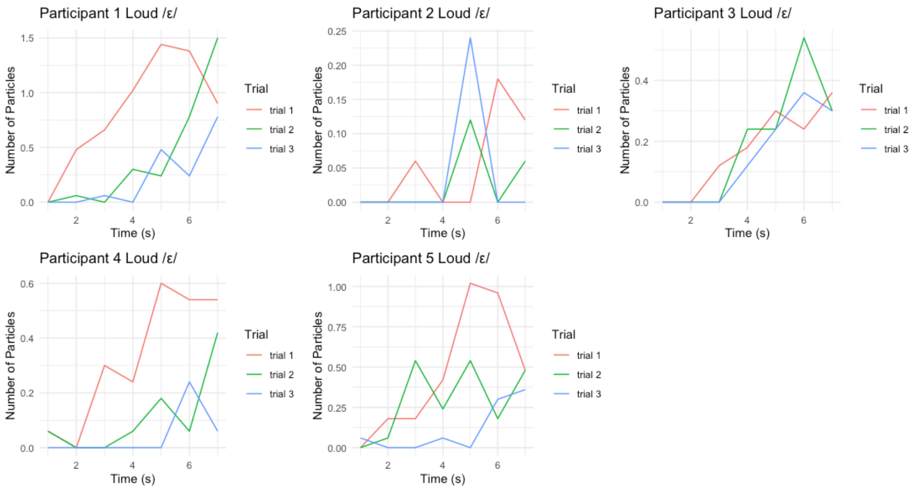

Figure 28. Individual trials of the loud /ɛ/ task.

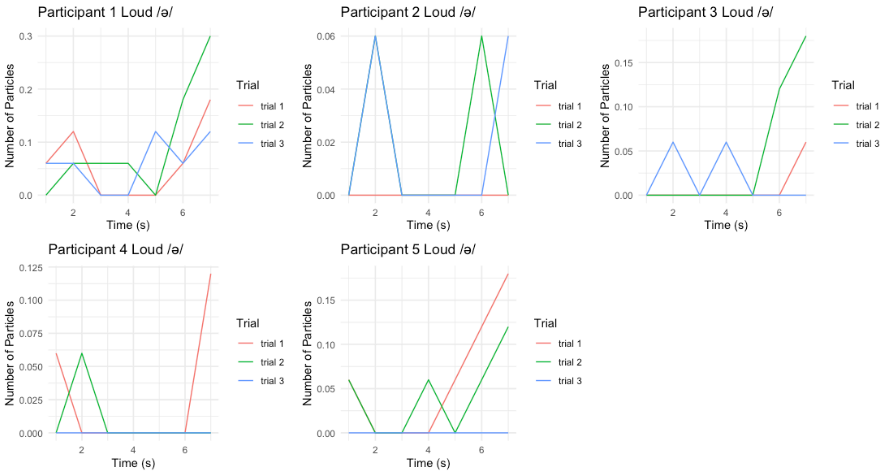

Figure 29. Individual trials of the loud /ə/ task.

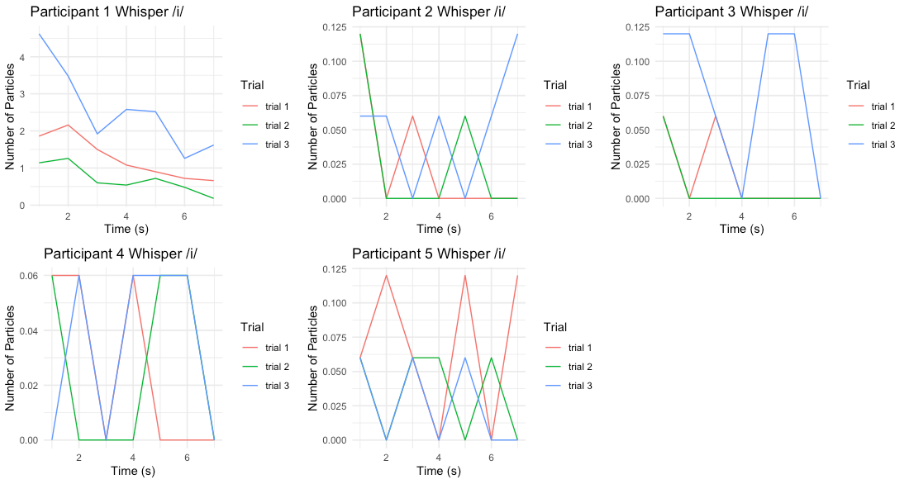
Participant 1 Whisper /i/
Participant 2 Whisper /i/
Participant 3 Whisper /i/
Participant 4 Whisper /i/
Participant 5 Whisper /i/

Figure 30. Individual trials of the whisper /i/ task.

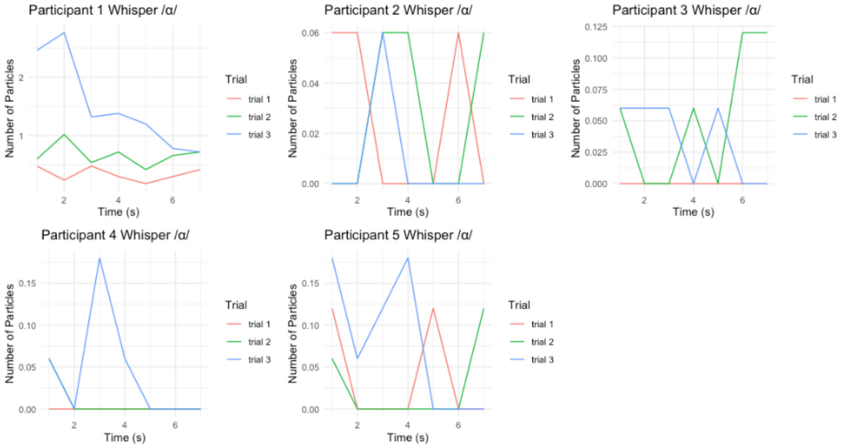
Participant 1 Whisper /ɑ/
Participant 2 Whisper /ɑ/
Participant 3 Whisper /ɑ/
Participant 4 Whisper /ɑ/
Participant 5 Whisper /ɑ/

Figure 31. Individual trials of the whisper /ɑ/ task.

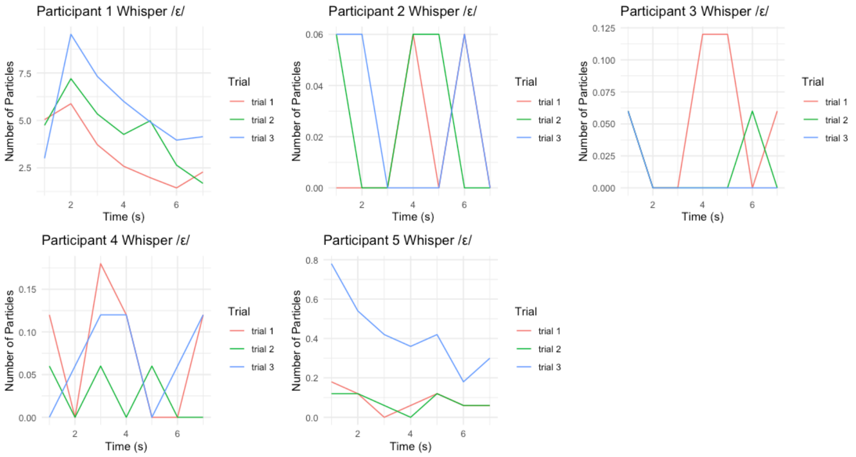

Figure 32. Individual trials of the whisper /ɛ/ task.

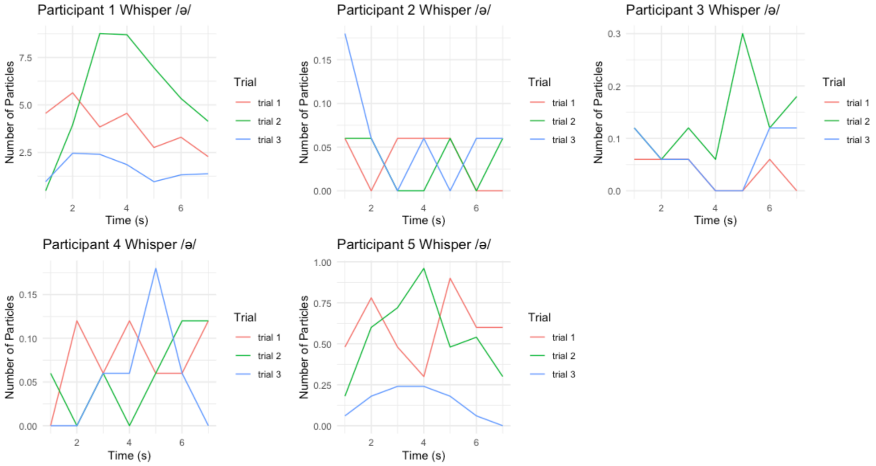

Figure 33. Individual trials of the whisper /ə/ task.

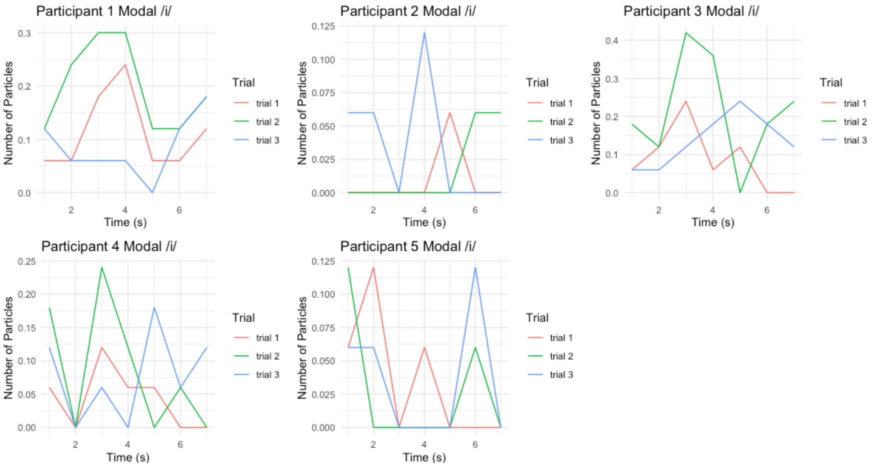

Figure 34. Individual trials of the modal /i/ task.

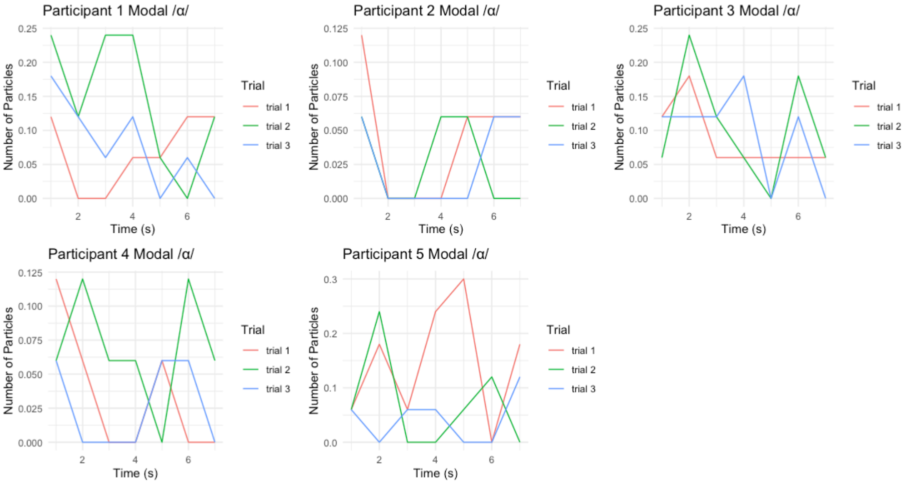

Figure 35. Individual trials of the modal /ɑ/ task.

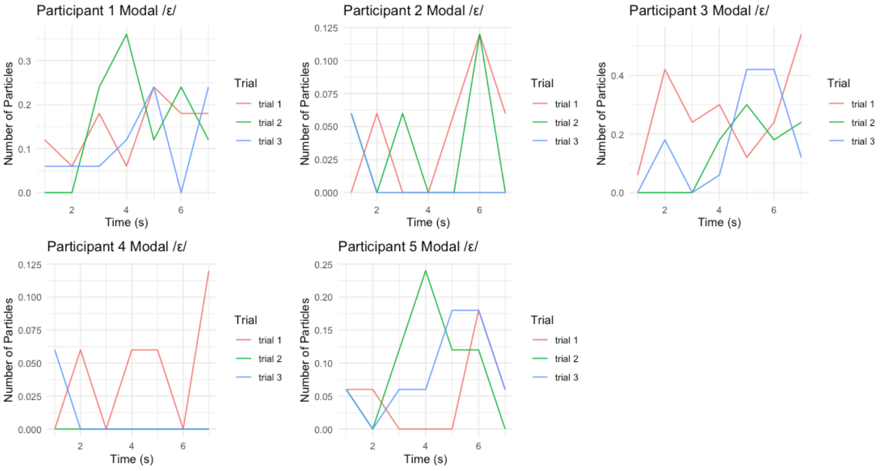

Figure 36. Individual trials of the modal /ɛ/ task.

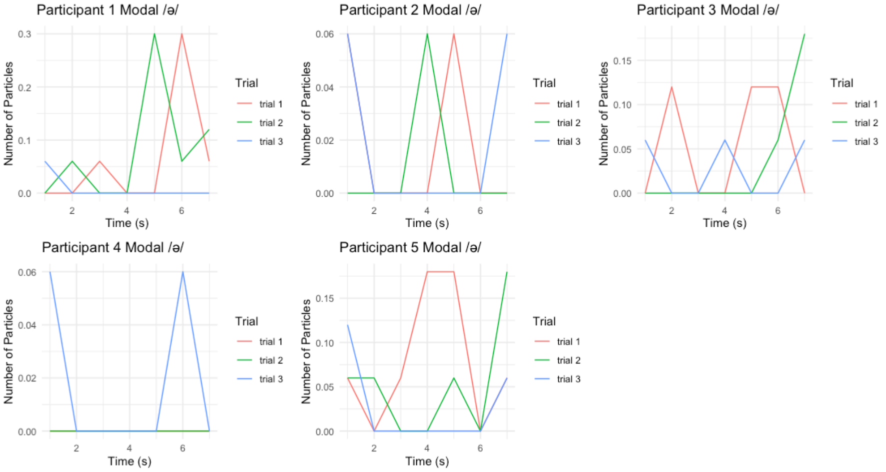

Figure 37. Individual trials of the modal /ə/ task.

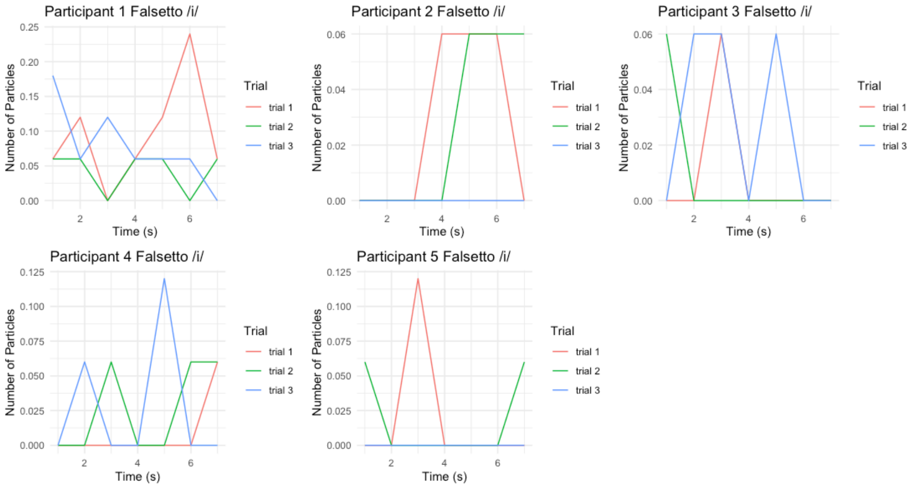

Figure 38. Individual trials of the falsetto /i/ task.

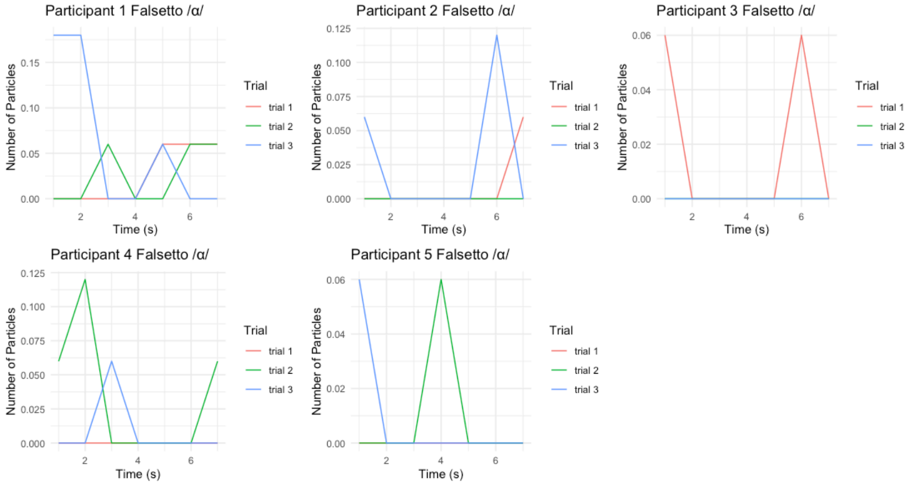

Figure 39. Individual trials of the falsetto /ɑ/ task.

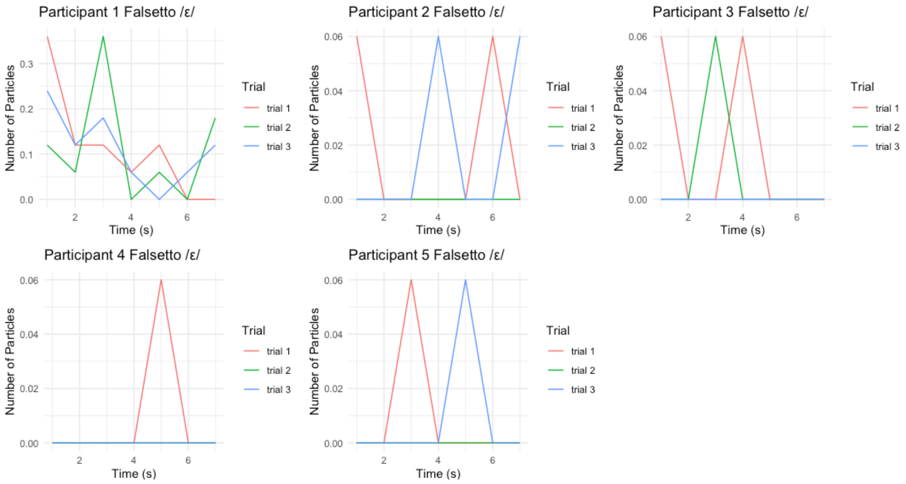

Figure 40. Individual trials of the falsetto /ɛ/ task.

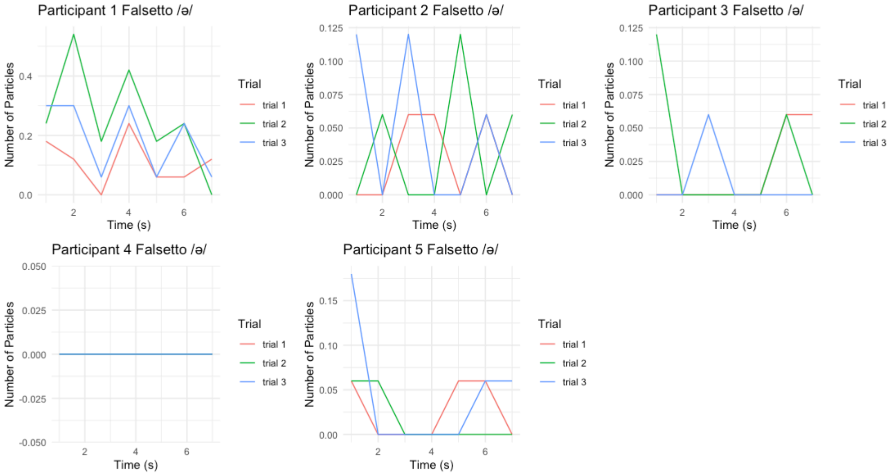

Figure 41. Individual trials of the falsetto /ə/ task.

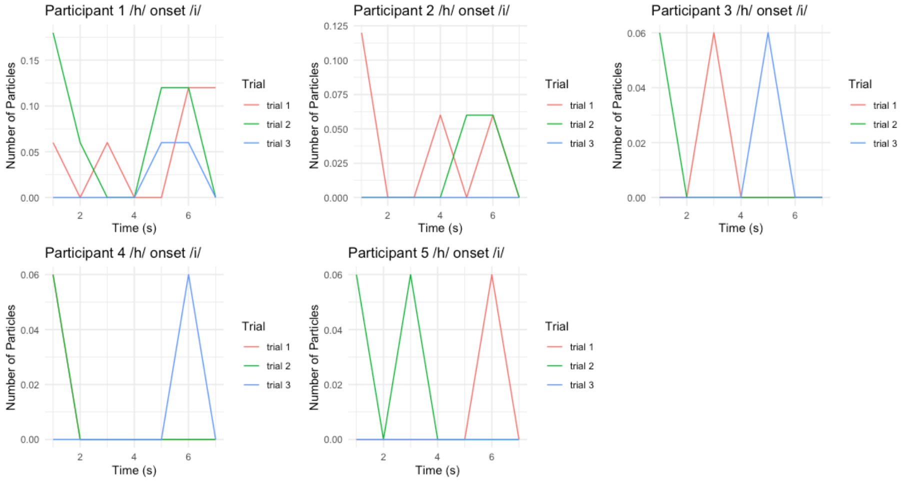

Figure 42. Individual trials of the h-onset /i/ task.

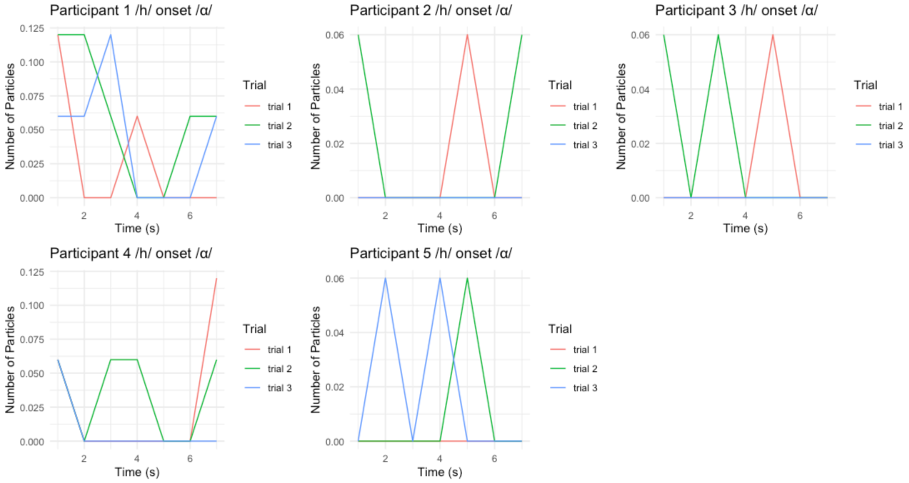

Figure 43. Individual trials of the h-onset /ɑ/ task.

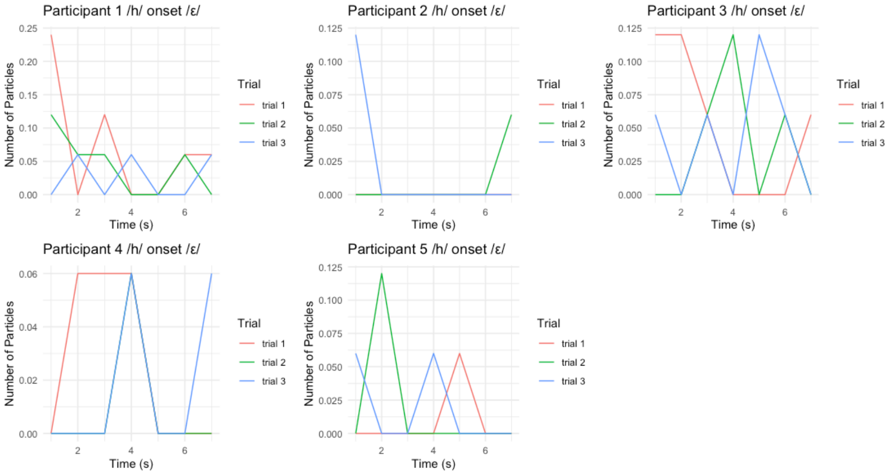

Figure 44. Individual trials of the h-onset /ɛ/ task.

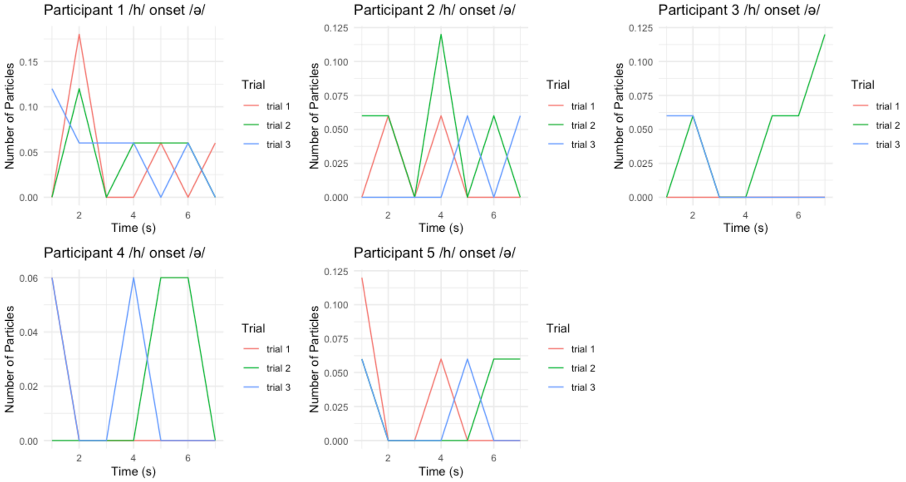

Figure 45. Individual trials of the h-onset /ə/ task.

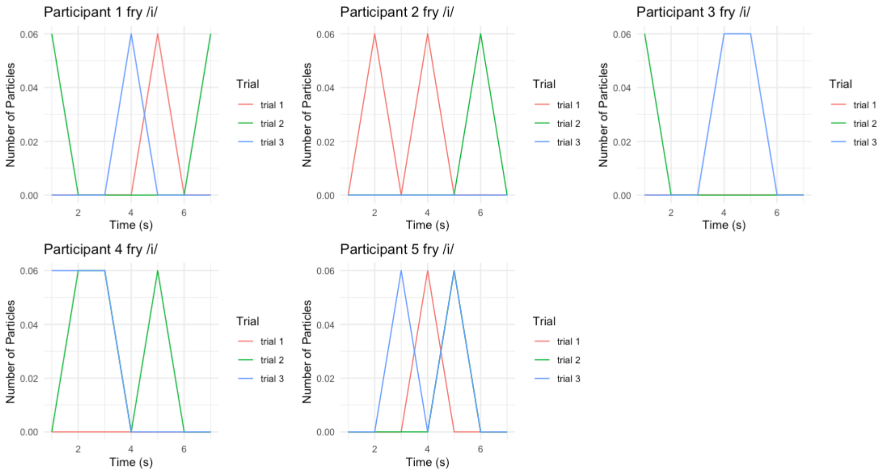

Figure 46. Individual trials of the vocal fry /i/ task.

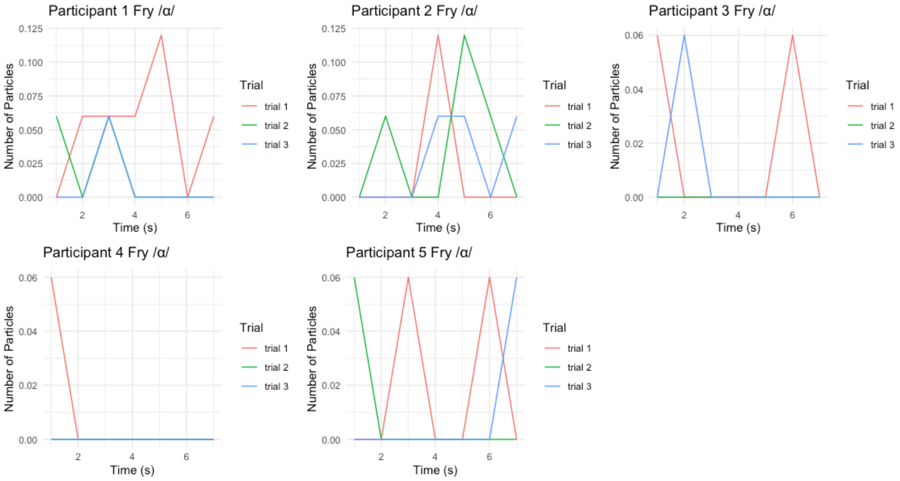

Figure 47. Individual trials of the vocal fry /ɑ/ task.

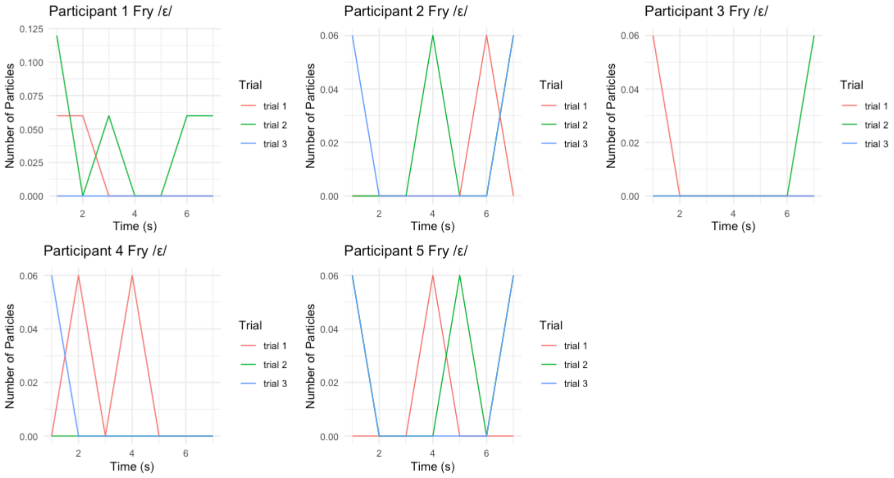

Figure 48. Individual trials of the vocal fry /ɛ/ task.

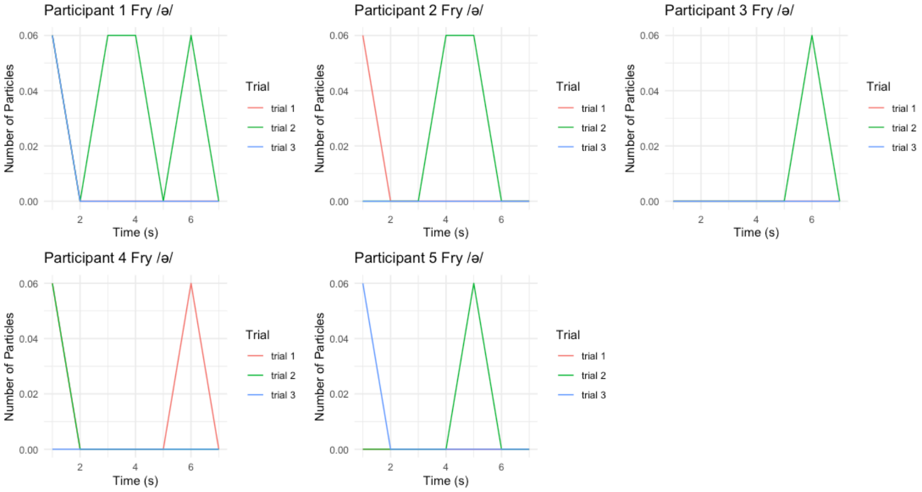

Figure 49. Individual trials of the vocal fry /ə/ task.

APPENDIX B

One-way ANOVAs

```
# 5 individuals
> h.aov <- aov(particles ~ Task_Vowel, data = y40i)
> summary(h.aov)
Df Sum Sq Mean Sq F value Pr(>F)
Task_Vowel    23  160.2   6.966   18.55 <2e-16 ***
  Residuals   2496  937.3   0.376
---
  Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

```
# 4 individuals
> h.aov <- aov(particles ~ Task_Vowel, data = y40i_4i)
> summary(h.aov)
Df Sum Sq Mean Sq F value Pr(>F)
Task_Vowel    23  8.287  0.3603   33.19 <2e-16 ***
  Residuals   1992 21.625  0.0109
---
  Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

```
#P1
> h.aov <- aov(particles ~ Task_Vowel, data = p1)
> summary(h.aov)
Df Sum Sq Mean Sq F value Pr(>F)
Task_Vowel   23    642  27.913   43.22 <2e-16 ***
  Residuals   480    310   0.646
---
  Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

```
# P2
> h.aov <- aov(particles ~ Task_Vowel, data = p2)
> summary(h.aov)
Df Sum Sq  Mean Sq F value   Pr(>F)
Task_Vowel   23 0.1950 0.008479   5.097 8.07e-13 ***
  Residuals   480 0.7985 0.001664
---
  Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

```
# P3
> summary(h.aov)
Df Sum Sq Mean Sq F value Pr(>F)
Task_Vowel   23  2.724 0.11842   16.61 <2e-16 ***
  Residuals   480  3.421 0.00713
---
  Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

```
# P4
> summary(h.aov)
Df Sum Sq Mean Sq F value Pr(>F)
Task_Vowel   23  2.017 0.08770   15.89 <2e-16 ***
  Residuals   480  2.650 0.00552
---
  Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

```
# P5
summary(h.aov)
Df Sum Sq Mean Sq F value Pr(>F)
Task_Vowel   23  8.025  0.3489   18.68 <2e-16 ***
  Residuals   480  8.965  0.0187
---
  Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Tukey comparisons all 5 participants for the different conditions

	Difference of the means	95% confidence lower limit	95% confidence upper limit	Adjusted p-value (5 participants)
Fry vs. falsetto	-0.019	-0.142	0.105	9.98E-01
h-onset vs. falsetto	-0.009	-0.132	0.115	1.00E+00
Loud vs. falsetto	0.225	0.101	0.348	3.40E-06

modal vs. falsetto	0.037	-0.086	0.161	9.56E-01
whisper vs. falsetto	0.548	0.425	0.672	0.00E+00
h-onset vs. fry	0.010	-0.114	0.133	1.00E+00
loud vs. fry	0.244	0.120	0.367	3.00E-07
Modal vs. fry	0.056	-0.068	0.179	7.91E-01
Whisper vs. fry	0.567	0.443	0.691	0.00E+00
loud vs. h-onset	0.234	0.110	0.357	1.10E-06
modal vs. h-onset	0.460	-0.078	0.1170	8.97E-01
whisper vs. h-onset	0.577	0.433	0.681	0.00E+00
modal vs. loud	-0.188	-0.311	-0.064	2.24E-04
whisper vs. loud	0.323	0.200	0.447	0.00E+00
whisper vs. modal	0.511	0.388	0.635	0.00E+00

Tukey comparisons for 4 participants for the different conditions

	Difference of the means	95% confidence lower limit	95% confidence upper limit	Adjusted p-value (5 participants)
Fry vs. falsetto	-0.019	-0.142	0.105	9.98E-01
h-onset vs. falsetto	-0.009	-0.132	0.115	1.00E+00
Loud vs. falsetto	0.225	0.101	0.348	3.40E-06

modal vs. falsetto	0.037	-0.086	0.161	9.56E-01
whisper vs. falsetto	0.548	0.425	0.672	0.00E+00
h-onset vs. fry	0.010	-0.114	0.133	1.00E+00
loud vs. fry	0.244	0.120	0.367	3.00E-07
Modal vs. fry	0.056	-0.068	0.179	7.91E-01
Whisper vs. fry	0.567	0.443	0.691	0.00E+00
loud vs. h-onset	0.234	0.110	0.357	1.10E-06
modal vs. h-onset	0.460	-0.078	0.1170	8.97E-01
whisper vs. h-onset	0.577	0.433	0.681	0.00E+00
modal vs. loud	-0.188	-0.311	-0.064	2.24E-04
whisper vs. loud	0.323	0.200	0.447	0.00E+00
whisper vs. modal	0.511	0.388	0.635	0.00E+00

Tukey comparisons for vowels based on 5 individuals

Vowel	Difference	Lower	Upper	P-adjusted
ee-ah	-0.005142715	-0.1006458293	0.09036040	0.9990537
eh-ah	0.090760119	-0.0047429960	0.18626323	0.0694800
uh-ah	0.035999265	-0.0595038493	0.13150238	0.7671104
eh-ee	0.095902833	0.0003997186	0.19140595	0.0485918
uh-ee	0.041141980	-0.0543611347	0.13664509	0.6849686
uh-eh	-0.054760853	-0.1502639680	0.04074226	0.4534081

Tukey comparisons for vowels based on 4 individuals

Vowel	Difference	Lower	Upper	P-adjusted
ee-ah	0.008333177	-0.01137214	0.028038490	0.6973474
eh-ah	0.005833213	-0.01387210	0.025538526	0.8718940
uh-ah	-0.012618803	-0.03232412	0.007086510	0.3527244
eh-ee	-0.002499964	-0.02220528	0.017205349	0.9880151
uh-ee	-0.020951980	-0.04065729	-0.001246667	0.0320279
uh-eh	-0.018452016	-0.03815733	0.001253297	0.0759388

Stats based on task

5 individuals - one-way ANOVA

```
Df Sum Sq Mean Sq F value Pr(>F)

$Task          5  105.4  21.073    53.4 <2e-16 ***

Residuals   2514  992.1   0.395

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Tukey multiple comparisons of means

95% family-wise confidence level

Fit: aov(formula = particles ~ Task, data = y40i)
```

Task	Difference	Lower	Upper	P-adjusted
fry-falsetto	-0.018713916	-0.14234471	0.10491688	0.9981035
h-onset-falsetto	-0.008856954	-0.13248775	0.11477384	0.9999512
loud-falsetto	0.224852595	0.10122180	0.34848339	0.0000034
modal-falsetto	0.037142126	-0.08648867	0.16077293	0.9565176
whisper-falsetto	0.548274693	0.42464389	0.67190549	0.0000000
h-onset-fry	0.009856961	-0.11377384	0.13348776	0.9999172

loud-fry	0.243566510	0.11993571	0.36719731	0.0000003
modal-fry	0.055856042	-0.06777476	0.17948684	0.7914940
whisper-fry	0.566988609	0.44335781	0.69061941	0.0000000
loud-h-onset	0.233709549	0.11007875	0.35734035	0.0000011
modal-h-onset	0.045999080	-0.07763172	0.16962988	0.8966894
whisper-h-onset	0.557131648	0.43350085	0.68076245	0.0000000
modal-loud	-0.187710469	-0.31134127	-0.06407967	0.0002241
whisper-loud	0.323422099	0.19979130	0.44705290	0.0000000
whisper-modal	0.511132567	0.38750177	0.63476337	0.0000000

4 individuals – One-way ANOVA

Df Sum Sq Mean Sq F value Pr(>F)

Task 5 5.132 1.0263 83.25 <2e-16 ***

Residuals 2010 24.781 0.0123

\---

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Tukey multiple comparisons of means

95% family-wise confidence level

Fit: aov(formula = particles ~ Task, data = y40i_4i)

Task	Difference	Lower	Upper	P-adjusted
fry-falsetto	-0.002678524	-0.02711424	0.02175719	0.9996029
h-onset-falsetto	0.003035658	-0.02140005	0.02747137	0.9992688
loud-falsetto	0.140354343	0.11591863	0.16479006	0.0000000
modal-falsetto	0.045891948	0.02145624	0.07032766	0.0000014
whisper-falsetto	0.059641686	0.03520597	0.08407740	0.0000000

h-onset-fry	0.005714182	-0.01872153	0.03014990	0.9854850
loud-fry	0.143032867	0.11859715	0.16746858	0.0000000
modal-fry	0.048570472	0.02413476	0.07300619	0.0000002
whisper-fry	0.062320210	0.03788450	0.08675592	0.0000000
loud-h-onset	0.137318685	0.11288297	0.16175440	0.0000000
modal-h-onset	0.042856290	0.01842058	0.06729200	0.0000091
whisper-h-onset	0.056606027	0.03217031	0.08104174	0.0000000
modal-loud	-0.094462395	-0.11889811	-0.07002668	0.0000000
whisper-loud	-0.080712658	-0.10514837	-0.05627694	0.0000000
whisper-modal	0.013749738	-0.01068598	0.03818545	0.5952760

Stats based on Vowel

5 individuals

Df Sum Sq Mean Sq F value Pr(>F)

Vowel 3 3.7 1.2310 2.832 0.037 *

Residuals 2516 1093.8 0.4347

\---

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Tukey multiple comparisons of means

95% family-wise confidence level

Fit: aov(formula = particles ~ Vowel, data = y40i)

Vowel	Difference	Lower	Upper	P-adjusted
ee-ah	-0.005142715	-0.1006458293	0.09036040	0.9990537
eh-ah	0.090760119	-0.0047429960	0.18626323	0.0694800
uh-ah	0.035999265	-0.0595038493	0.13150238	0.7671104
eh-ee	0.095902833	0.0003997186	0.19140595	0.0485918
uh-ee	0.041141980	-0.0543611347	0.13664509	0.6849686

uh-eh	-0.054760853	-0.1502639680	0.04074226	0.4534081

4 individuals

```
Df Sum Sq Mean Sq F value Pr(>F)
Vowel         3  0.132 0.04403   2.975 0.0305 *
  Residuals   2012 29.780 0.01480
---
 Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Tukey multiple comparisons of means
95% family-wise confidence level
Fit: aov(formula = particles ~ Vowel, data = y40i_4i)
```

Vowel	Difference	Lower	Upper	P-adjusted
ee-ah	0.008333177	-0.01137214	0.028038490	0.6973474
eh-ah	0.005833213	-0.01387210	0.025538526	0.8718940
uh-ah	-0.012618803	-0.03232412	0.007086510	0.3527244
eh-ee	-0.002499964	-0.02220528	0.017205349	0.9880151
uh-ee	-0.020951980	-0.04065729	-0.001246667	0.0320279
uh-eh	-0.018452016	-0.03815733	0.001253297	0.0759388