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Comparing respiratory aerosol emissions between children and adults during sustained phonation

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ABSTRACT

Respiratory aerosols arise due to bronchial fluid film bursting within the pulmonary tract, the vibration of the vocal folds during phonation, and articulation of the tongue/lips/teeth. We expect respiratory aerosol emission rates to be lower in children than adults due to the smaller size of their laryngeal structure, reduced sub-glottal pressure created during speech, and reduced number of alveoli. However, few studies have evaluated respiratory aerosols for children. We recruited 50 participants from three age categories: children aged 6–11 years, children aged 12–18 years, and adults (>18 years). We investigated particle emissions for three different 5 s sustained vocalizations of /a/ or /pa/ at 262 Hz, as well as for running speech and breathing. The particle generation rate ranged from 0 to 488 particles/s. Children aged 6–11 years produced fewer particles (mean 12 ± SD 9 particles/s) than children aged 12–18 years (23 ± 19 particles/s) and adults (70 ± 73 particles/s). Taking a deep breath before vocalizing /a/ resulted in higher aerosol emission rates than the baseline case. The particle number size distributions for all vocalizations and age groups consistently showed two modes at ≈0.6 μm and ≈ 2 μm. Children had a slightly smaller primary mode location and larger secondary mode location than adults. Superemitters (statistical outliers) were found in all groups. Experiments repeated over time revealed large intrapersonal variability indicating additional variables (e.g., environmental, physiological, behavioral) may significantly influence emission rates. The lower respiratory aerosol emission rates for children indicate a need to consider population demographics when predicting airborne disease transmission risks.

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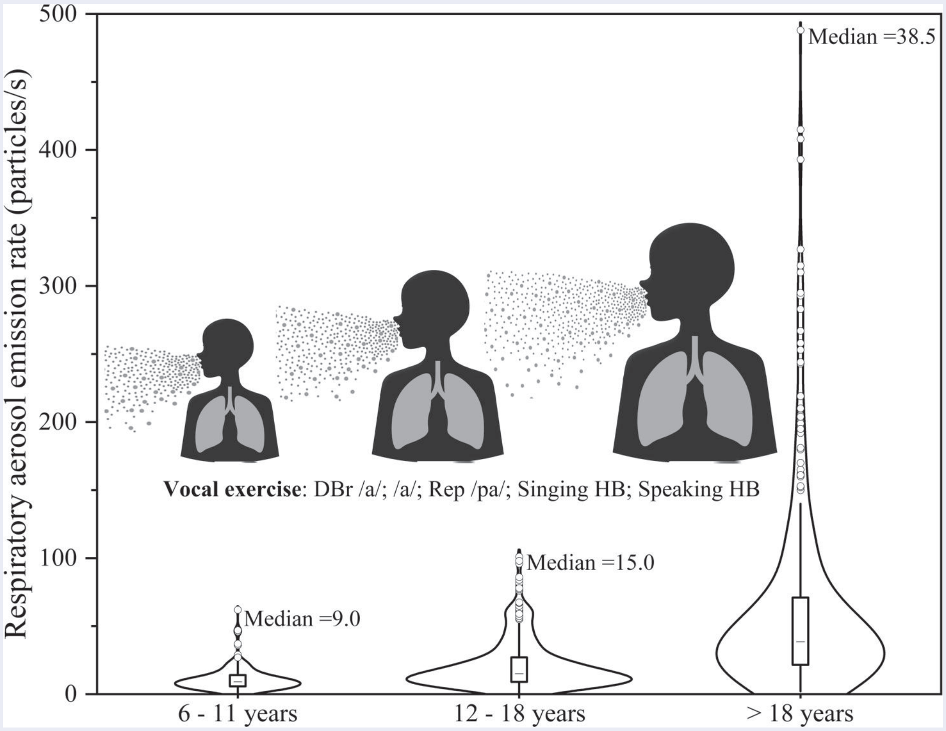
GRAPHICAL ABSTRACT



1. Introduction

Infectious aerosols and droplets are generated during respiratory activities such as coughing, breathing, sneezing, shouting, talking, and singing, and can serve as vectors for the SARS-CoV-2 virus and other respiratory pathogens (Asadi et al. 2019; Gorbunov 2019; Gralton et al. 2011; Hamilton et al. 2022; Han, Weng, and Huang 2013; Lee et al. 2019; Mürbe et al. 2021; Wang, Xu, and Huang 2020; Yang et al. 2007). To develop accurate infection risk models, a comprehensive understanding of viral loading for aerosol emissions and transmission rates is needed. This includes identification of respiratory particle generation sites, particle emission rates and size distributions, and transport mechanics (Domino 2021; Issarow, Mulder, and Wood 2015; Li et al. 2022; Shao et al. 2021; Singhal et al. 2022).

To this end, it has been hypothesized that respiratory particles are produced in different parts of the respiratory tract. Specifically, three dominant modes and locations of production have been proposed: bronchial (B), laryngeal (L), and oral (O) modes (Johnson et al. 2011; Morawska et al. 2009). Various studies of aerosol emissions have identified the existence of a bimodal behavior in the standard lognormal particle size distribution (Asadi et al. 2019; Johnson et al. 2011). This has been attributed to the existence of the B and L modes of particle production, with the dominant B mode peak centered around 0.8 μm, and the secondary L mode peak centered around 2.0 μm (Asadi et al. 2019). A larger mode with a peak near 100 microns was also identified by Johnson et al. (2011) and was associated with the O mode. Harrison et al. (2023) and Bagheri et al. (2023) reported the location of the O mode for children and adults was smaller, between 40 to 60 microns (Harrison et al. 2023) and between 30 to 40 microns (Bagheri et al. 2023). While the different modes of particle production have been identified, the relative importance of these modes as a function of varying voicing patterns, respiratory behaviors, etc. on respiratory particle number and mass emission rates remains unexplored.

The observation that respiratory emissions are a function of physiology highlights that variables such as age, sex, health status, etc., can be reasonably expected to influence particle emission rates. Good et al. (2021) reported that the production rate of respiratory particles during vocalization is a function of the volume of exhaled air and the level of exhaled carbon dioxide, which are affected by age, sex, and health status. It is interesting, then, to note that although respiratory aerosol emissions during speech have been well quantified for the adult population

(Ahmed et al. 2022; Asadi et al. 2019, 2020; Archer et al. 2022; Eiche and Kuster 2020; Fleischer et al. 2022; Gregson et al. 2021; Mürbe et al. 2021; Nazaroff 2022; Van Mersbergen et al. 2022; Wang, Xu, and Huang 2020; Harrison et al. 2023), there are few studies examining speech emissions in children.

Age is an important distinction for predicting aerosol emissions from speaking and singing because laryngeal maturity is achieved during puberty, with the vocal folds becoming longer, increasing in mass, and the vocal membrane becoming stiffer (Kahane 1978, 1982; Spazzapan et al. 2019; Zhang et al. 2019). Pulmonary growth also progresses through childhood, achieving maturing at approximately 8 years of age, although the number of alveoli continues to increase through puberty (Burri 1984; Han, Weng, and Huang 2013). This timeline for pulmonary system maturity may explain the reported aerosol emission results for adolescents compared with those of adults. Mürbe et al. (2021) studied aerosol emissions from 13–15 year old semiprofessional singers, finding that their emission rates were very similar to prior studies with adults. Archer et al. (2022) also reported that median particle exhalation rates in 12–14 year old subjects were similar to adults, although adults emitted 1.5 times more aerosols by number when speaking. They found that the adolescents produced slightly higher particle mass concentrations and similar particle number concentrations in their exhaled breath as adults, but had lower minute ventilation rates. Archer et al. (2022) also measured the particle size distributions in both population groups, which allowed them to show that the total exhaled particle mass was only 10% higher for adults versus adolescents. Good et al. (2021) reported that 12–18 year old adolescents had lower particle emission rates than adults, although only by $\approx 15\%$. A recent study found that oral mode droplets, produced during speaking and singing, but not during breathing, were not statistically different for adults and children 12–14 years of age (Harrison et al. 2023). Taken together, these results are not particularly surprising, based on the largely post-pubescent age groups that were studied.

Interestingly, only two studies (Fleischer et al. 2022; Bagheri et al. 2023) have considered aerosol emissions in prepubescent children. Bagheri et al. (2023) recruited a total of 132 individuals ranging in age from 5 to 80 years, several of whom were professional or semiprofessional singers. They reported that age plays a significant role in the concentration and volume of exhaled particles $< 5\ \mu$m. For particles with optical diameters 1.5 to 5.7 μm, they found a doubling in the particle number concentration over a 7 year period for children and adolescents and over a 30 year period for adults. Furthermore, they found that adults release from 2 to 8 times more cumulative emitted volume of PM_5 than children. These results indicate that emission rates determined for adults cannot be applied to exposure scenarios that include young children. Fleischer et al. (2022) recruited 8–10 year old singers, comparing particle emission rates with adults. After correcting for loudness variations between the two population groups during testing they found that across the range of test conditions (speaking, singing, and shouting), the particle emission rate of the adults was 3.3 times greater than the 8–10 year old children. This is a unique finding that lends credence to the theory that pulmonary and laryngeal development in young children will likely have a significant influence on particle emissions. However, detailed particle size distributions of aerosol emissions from the pre-pubescent children were not acquired due to limitations of the measurement technique. In addition, it is unclear how the use of singers may have influenced the results, as prior studies have reported that adult professional singers consistently generate higher emissions than the general adult population (Alsved et al. 2020; Mürbe et al. 2020).

The need to further elucidate particle emissions in child population groups is particularly relevant within the context of the ongoing COVID-19 pandemic, as existing educational regulations and guidance are based on risk models developed from adult respiratory aerosol emission data, as opposed to children (Fleischer et al. 2022). Currently, the role that children play in COVID-19 transmission within schools and households is a matter of debate. However, studies have consistently found that schools with mask mandates had lower COVID-19 case rates than those without mask mandates (Alonso et al. 2022; Budzyn et al. 2021; Donovan et al. 2022; Public Health Ontario Report, 2022). Nevertheless, common aerosol mitigation practices, such as masking among children, are also often viewed as contradictory to educational goals (Esmaeilzadeh 2022), which is why increased outdoor or filtered air ventilation has been proposed as the preferred mitigation approach (Allen, VanRy, and Jones 2022).

Schools play a critical role in society as they provide equal education and health opportunities, especially for people in rural areas, immigrants, and immobilized individuals (Centers for Disease Control and Prevention 2022). Consequently, efforts at balancing education and health needs can create challenges.

For this reason, accurate age-based emission data is critically needed to support informed health-risk decision-making. In response, the objective of this study is to quantify the respiratory aerosol size distributions and emission rates among both pre- and post-pubescent children, as well as adults. Subjects who did not have experiences as professional singers were recruited to avoid bias. A variety of specific vocal exercises were performed to also gain preliminary insight into the physiological locations where respiratory particles are produced.

2. Method

2.1. Experimental method

A total of 50 healthy participants were recruited from three different age groups: children aged 6–11 years, children aged 12–18 years, and adults (>18 years). There were 14 participants in the children aged 6–11 years group (8 girls, 6 boys), 22 in the children aged 12–18 years group (10 girls, 12 boys), and 14 in the adults group (6 female, 8 male). Because professional singers tend to generate more respiratory particles than untrained individuals (Mürbe et al. 2021), no professional or semiprofessional singers were included in the recruitment in order to obtain a sample population that was representative of the general public. The study was conducted at Clarkson University and was approved by the Clarkson University Institutional Review Board (IRB Approval No. 20–56.5).

The experimental protocol consisted of six different vocal exercises performed at a comfortable vocal intensity. (1) Take a deep breath and then immediately phonate the vowel /a/ at a vocal frequency (pitch) of 262 Hz (C4, or middle C) for 5 s, followed by 10 s of comfortable breathing. This exercise will be referred to as DBr /a/. (2) Breathing normally, phonate the vowel /a/ at a vocal frequency of 262 Hz for 5 s, followed by 10 s of comfortable breathing. This exercise will be referred to as /a/. (3) Repeat the utterance /pa/ at a vocal frequency of 262 Hz for 5 s, followed by 10 s of comfortable breathing. Repeat the /pa/ utterance 5 times (1 s per utterance) during the 5 s measurement time. This exercise will be referred to as Rep /pa/. (4) Sing the song "Happy Birthday to You" at comfortable loudness and tempo. This will be referred to as Singing HB. (5) Speak the lyrics to the song "Happy Birthday to You" at comfortable loudness and tempo, referred to as Speaking HB. (6) Breathe at a comfortable rate for 30 s, referred to as Breathing. Vocal exercises were conducted in the following order: /a/, Rep /pa/, and DBr /a/. Each exercise was repeated six times sequentially. These phonation exercises were followed by Singing HB and Speaking HB, which were repeated two times with a 5 s gap between the repetitions. Breathing was conducted once as the final exercise. Distinct measurements were obtained for DBr /a/, /a/, and Rep /pa/ for each 5 s phonation. For Singing HB and Speaking HB, emissions captured for the full song were considered as one distinct measurement. To assess the repeatability of the results and explore intrapersonal variability in the data, a subset of the child participants repeated the experiments, with a separation of at least two weeks between the measurements.

Each participant followed the same experimental protocol, which was designed to accentuate different particle production modes and sites within the respiratory tract through specific vocalizations. Previous work has hypothesized that respiratory particles are produced due to bronchial, laryngeal, and oral modes of production (Johnson et al. 2011; Morawska et al. 2009). Vocal exercise /a/ served as a baseline case. The Dbr /a/ case was prescribed to increase activation of the pulmonary mode of particle generation relative to the baseline case. The Rep /pa/ case was prescribed to activate the oral mode relative to the baseline case due to articulation of the lips. The singing, speaking and breathing exercises were included to provide a comparison to other studies as well as to directly compare the sustained vocalization exercises with running speech.

All participants were guided through the experiments by the investigators and asked verbally to start and stop each vocalization as well as shown placards with symbols for "start" and "stop." An online piano keyboard and metronome were played in the background to facilitate pitch-matching and timing. To control for hydration, participants were asked to drink 0.5 L of water 1 h before the experiments and were not allowed to drink any beverages immediately before or during the experiments.

A schematic of the laboratory facility used for all measurements is shown in Supplementary Figure S1, which is the same facility used in prior work (Ahmed et al. 2022). Briefly, the participants vocalized into the inlet of a horizontally-oriented 10 cm diameter plastic funnel. The speaker position was carefully controlled to ensure the mouth was horizontal to, and centered about, the funnel inlet. A 25 cm long section of conductive tubing (1.9 cm inner diameter, 10^5 Ohm/m^2 surface resistivity) connected the funnel to a TSI (Shoreview, MN, USA) Model 3321 Aerodynamic Particle Sizer (APS). The APS measures and sizes particles with aerodynamic diameters 0.54–20 μm in 32 size channels using time-of-flight technology. To minimize background aerosol concentrations, the APS was placed inside a Labconco (Kansas City, MO, USA) laminar flow hood equipped with a HEPA filter. Prior experiments using this same facility (Ahmed et al. 2022) demonstrated near-zero background level particle concentration in this orientation.

The aerosol measurements were recorded using a 5 s sample window. Particle emission rates were computed by summing the total particle count over both the 5 s phonation and 10 s rest times and then dividing by the phonation time. This was to account for the time delay needed for particles exiting the mouth to enter the APS. By the end of the rest time, particle concentrations consistently decreased to zero. The APS draws in air at a volumetric flow rate of 5.0 L/min, but detects the particle number concentration using a sampling flow rate of only 1.0 L/min. Thus, the particle emission rates were multiplied by 5 to account for the additional 4.0 L/min sheath flow rate that was filtered. We estimate that there was some loss of particle-laden flow outside the funnel due to the expiratory flow rate periodically exceeding the total inlet flow rate of the APS. The loss depends on the participant's ventilation rate pattern, which varies by the participant and vocal task (Archer et al. 2022).

Particle number size distributions were analyzed to estimate the particle production modes for the different vocal exercises and age groups. We applied a polynomial regression fit to illustrate the size distribution curves. The two predominant modes were then identified by applying a bimodal lognormal distribution fit using commercial software Origin (OriginLab Corporation, Northampton, MA, USA).

A Logitech Blue SNOWBALL iCE microphone was positioned obliquely, relative to the participant and the funnel, at a distance of 22.9 cm from the participant's mouth. All audio files were recorded at 44.1 kHz. The 6 measurements for each vocal exercise were recorded as a single audio file for each participant. The start of the audio recording and the corresponding aerosol emission measurement was synchronized to the start of phonation. To evaluate the fundamental frequency (f_0) of each audio signal, spectral analysis was conducted (Averbuch 2021). An example of a spectrogram plot of the audio file for a participant phonating /a/ is shown in Supplementary Figure S2. The beginning and end of each phonation segment were identified using a custom-written Matlab program, and the average phonation frequency for each utterance was computed as the average of the fundamental frequency over the phonation time. Likewise, the vocal intensity of the sustained phonation segments was evaluated by calculating the root-mean-square (RMS) of the raw audio signal over the same time. The temperature ($23.5 \pm 0.71^\circ$ C) and relative humidity ($49.8 \pm 7.6\%$) of the room were recorded with an Onset HOBO UX 100–003 data logger.

2.2. Statistical analyses

Particle emission rates, vocal frequency, and vocal intensity were obtained from the experiments in this study. Violin plots (a hybrid of box plots and kernel density plots) were produced to depict the variables. Plots were constructed as a function of the three age groups (children aged 6–11 years, children aged 12–18 years, and adults) for the three sustained phonation exercises: DBr /a/, /a/, and Rep /pa/. In this study, we used the individual measurements for developing models and creating plots and did not average the values. The order-restricted inference (ORI) technique (Farnan, Ivanova, and Peddada 2014; Jelsema and Peddada 2016; Vanbrabant, Van De Schoot, and Rosseel 2014) was used to determine trends between the mean particle emission rates for each vocal test within the three age groups defined for this study. In our analysis, we employed a linear mixed-effects model using the CLME package in R. The emission rate (particles/s) was chosen as the dependent variable. The vocal task (DBr /a/, /a/, Rep /pa/) was the independent variable, which can be considered a fixed, nonrandom quantity. To account for the repeated measurements by each subject, the subject ID was incorporated as a random effect. We used ORI as our statistical method and assumed that repeated measurements have a random effect on the model, hence satisfying the requirement of independence between trials across individuals (Farnan, Ivanova, and Peddada 2014). The model formulation can be expressed as:

$$\text{particles/s} = \text{Vocal task} + (1 \mid \text{subject ID})$$

The major advantage of using ORI is to gain power using a smaller sample size. The following hypotheses were constructed:

$$H_0 : \mu_1 = \mu_2 = \mu_3 \quad \text{vs.} \quad H_1 : \mu_1 > \mu_2 > \mu_3 \quad \cup \quad \mu_1 > \mu_2 < \mu_3 \tag{1}$$

where $\mu_1, \mu_2, \mu_3 =$ mean particles/s for DBr /a/, /a/, and Rep /pa/, respectively.

With statistical evidence, we wanted to determine the overall pattern of the three vocal exercises. Here we performed two separate tests for the ORI approach. The first test detected the overall pattern and the second identified pairwise comparison patterns (given that the first test turned out to be statistically significant). We discovered an overall pattern for the defined alternative hypothesis using the first test, which we call the global test. Following the identification of patterns using the global test, we employed the second test to determine if there were statistically significant pairs. Using Equation (1), the alternative hypotheses were formulated as a combination of simple decreasing order and umbrella order (middle value either higher or lower than outside values) using the three vocal exercises DBr /a/, /a/, and Rep /pa/.

To show the impact of the explanatory independent variables (age, vocal intensity, and frequency) on the response variable (particle emission rate), and to determine the relative importance of each explanatory variable, we employed linear models as the next part of the analysis. The assumptions of the derived linear models' homoscedasticity and normality were verified (P-value > 0.05). In addition, the contribution of each independent variable to the regression model was reported (Grömping 2006; Tonidandel and LeBreton 2011).

To compare the particle emission rates between the first three vocal exercises and singing and running speech, we combined the DBr /a/, /a/, and Rep /pa/ into one category (referred to as Grouped phonation). We also employed ORI to determine the trend of the mean particle emission rates of each vocal test for each age group based on the following hypotheses,

$$H_0 : \mu_4 = \mu_5 = \mu_6 \quad \text{Vs.} \quad H_1 : \mu_4 > \mu_5 > \mu_6 \quad \cup \quad \mu_4 > \mu_5 < \mu_6, \tag{2}$$

where $\mu_4, \mu_4, \mu_6 =$ Mean of particles/s for Grouped phonation, Singing HB, Speaking HB, respectively.

Repeated experiments were conducted for a subset of the children. To find the statistical differences between repeated experiments (Test 1 and Test 2 vocal exercises for the same vocalization), we conducted two-sample Mann-Whitney U tests (McKnight and Najab 2010) after checking the normality assumptions. Mann-Whitney test was used to compare the median particles/s between the groups children aged 6–11 years, and children aged 12–18 years for the vocal exercises DBr /a/, /a/, and Rep /pa/.

3. Results

3.1. Particle emission rates

Figure 1 presents the measured particle emission rate, vocal intensity, and vocal frequency for the three different age groups (children aged 6−11 years, children aged 12–18 years, and adults) for three different respiratory activities (DBr /a/, /a/, Rep /pa/). As shown in Figures 1a–c, the particle emission rate increases with the age of the group. The median emission rates for adults were 61.0, 36.5, and 37.5 particles/s for the respective respiratory activities of DBr /a/, /a/, and Rep /pa/. These were 2.3 to 3.3 times more than those for children aged 12–18 years (18.0, 16.0, and 15.0 particles/s, respectively) and 3.7 to 4.7 times more than those for children aged 6–11 years (10.0, 10.5, and 8.0 particles/s, respectively). These results are consistent with Fleischer et al. (2022) and Bagheri et al. (2023), both of whom reported that age plays a significant role in the concentration and emission rate of exhaled particles. Fleischer et al. (2022) found that the emission rates for breathing, speaking, singing, and shouting for children (8–10 year old, $N = 15$) were reduced by a factor of 4.3 as compared with those for adults ($N = 15$). Bagheri et al. (2023) reported that the emission of PM_5 by children and adolescents (5–19 year old, $N = 61$) is approximately one-fourth to one-third of emissions generated by adults (i.e., PM_5 emissions from children were reduced by a factor of 3–4 compared with adults).

The particle emission rate has been shown to be positively correlated with both vocal intensity (Asadi et al. 2019; Alsved et al. 2020; Gregson et al. 2021; Bagheri et al. 2023) and frequency (Ahmed et al. 2022). Thus, we evaluated the potential impact of these factors on the particle emission rate. The median vocal intensity, quantified as the root-mean-square of the amplitude (A_{RMS}) was slightly higher for adults (≈ 0.07) when compared to children aged 6–11 years and children aged 12–18 years ($A_{RMS} \approx 0.05$) for all three vocal exercises. These data are presented in Figures 1d–f. The median vocal frequency was statistically equivalent for groups children aged 12–18 years (average 262.4 Hz) and adults (average 261.7 Hz) but slightly higher for group children aged 6–11 years (average 269.4 Hz). Although all the participants were requested to phonate at a frequency of 262 Hz, some participants were unable to consistently match the target frequency, resulting in slight variations, as shown in Figures 1g–i. For the younger children, their higher voice register may have resulted in the observed tendency toward a slightly higher frequency. The vocal intensity variation is slightly larger than the frequency

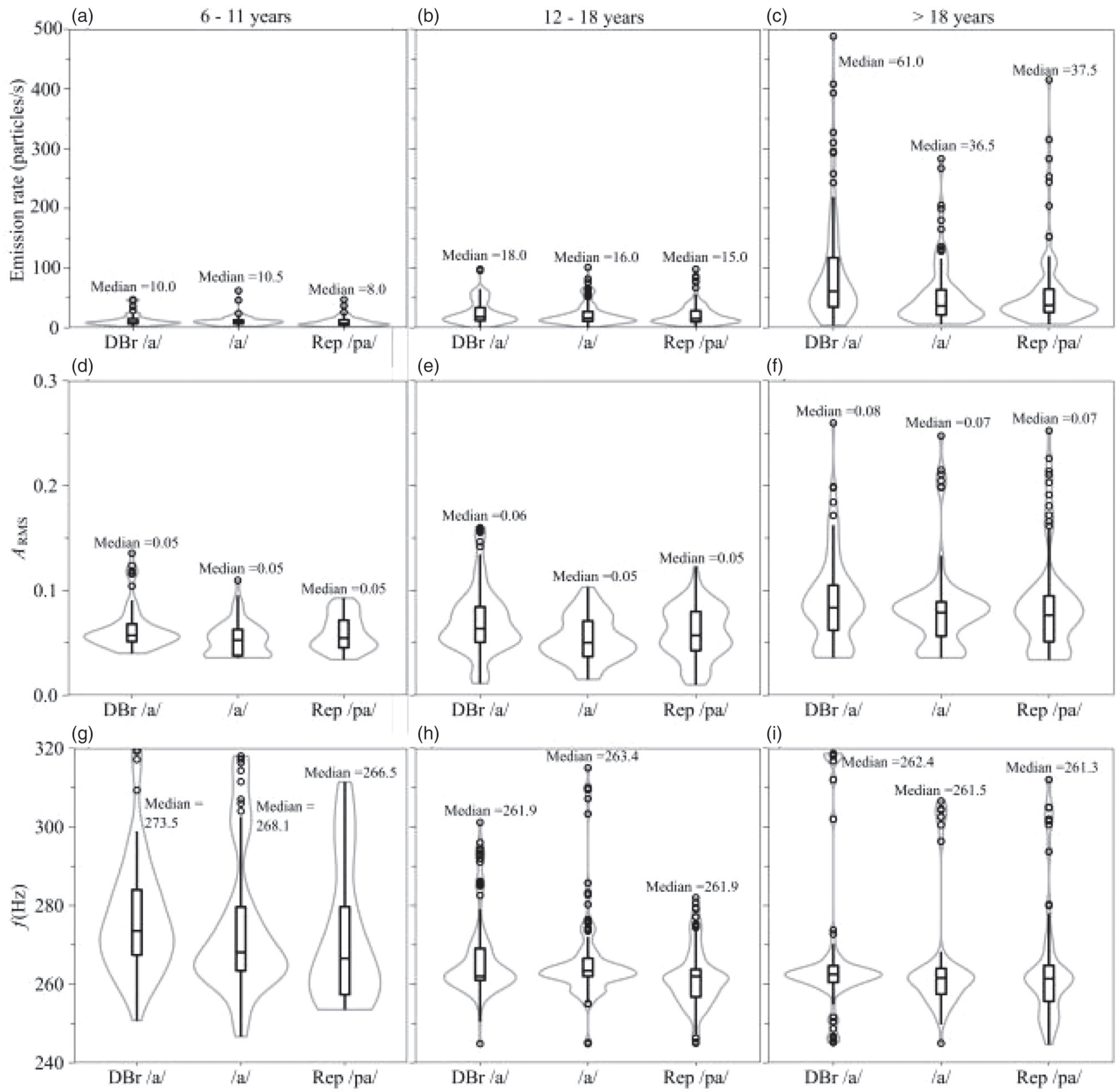


Figure 1. Distribution of particle emission rate (a–c), vocal intensity (d–f), and vocal frequency (g–i) as a function of target vocalizing DBr /a/, /a/, and Rep /pa/ for all of the subjects in age groups children aged 6–11 years children aged 12–18 years, and adults (>18 years).

variation because the vocal intensity was not controlled in the study (i.e., the participants were asked to phonate at a comfortable volume).

3.2. Statistical comparison of variables

A statistical comparison of the variables was performed to determine how aerosol emission rates were affected by the differences in amplitude and frequency (Figures 2 and 3 and Supplementary Figures S3 and S4). In Figure 2, the particle emission rate is plotted as a function of vocal intensity for each age group (children aged 6–11 years, children aged 12–18 years, and adults) for the three different vocal exercises. The slope of the least squares linear fits for all three vocal activities are all positive, consistent with previous findings, although the correlation is weak to moderate ($R^2 = 0.34 - 0.66$ as shown in Table 1) and regression line intercept was forced through zero. The vocal frequency range in the present study was relatively small and was not expected to measurably affect the particle emission rate. Accordingly, Figure 3 shows little to no association between the particle emission rate and the vocal frequency ($R^2 = 0.00 - 0.06$ as shown in Table 2).

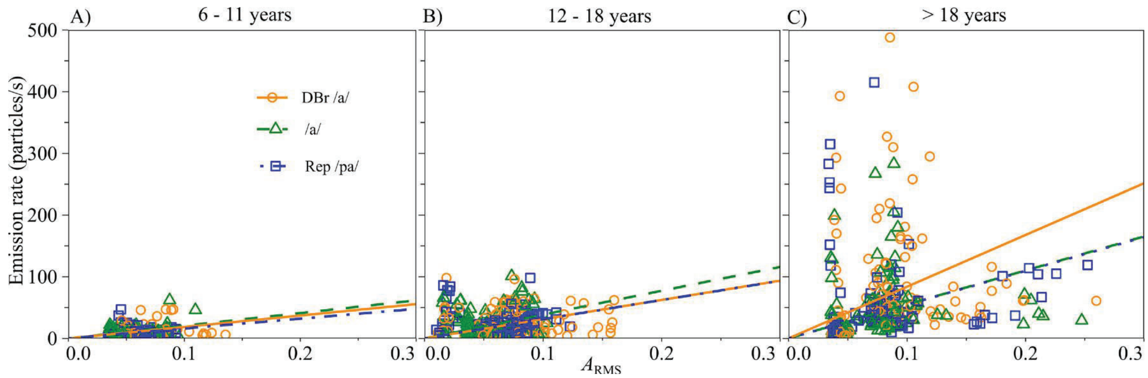


Figure 2. Association between particle emission rate with vocal intensity for (a) children aged 6 – 11 years, (b) children aged 12 – 18 years, and (c) adults (> 18 years) for three different vocal exercises DBr /a/, /a/, and Rep /pa/.

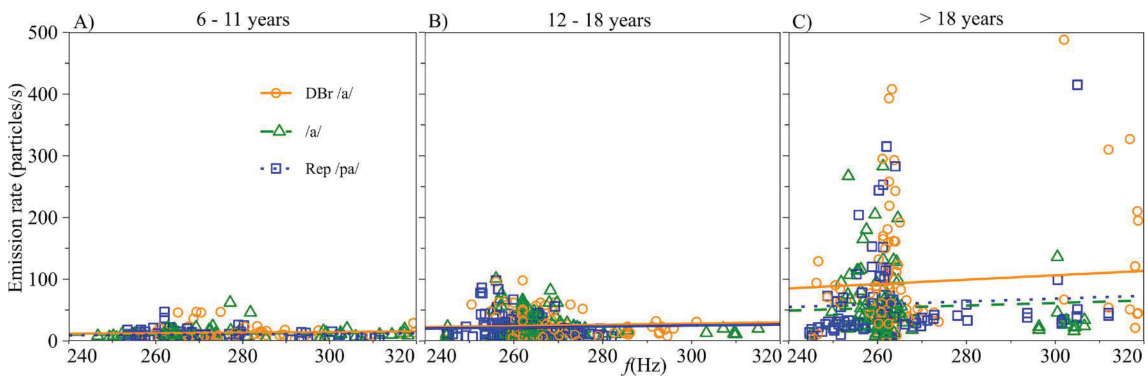


Figure 3. Association between particle emission rate with vocal frequency for (a) children aged 6 – 11 years, (b) children aged 12 – 18 years, and (c) adults (> 18 years) under three different vocal exercises DBr /a/, /a/, and Rep /pa/.

A relative importance analysis was performed using a regression model to further investigate the impact of the predictor variables, frequency, amplitude, and age, on particle emission rate. The results from the relative importance calculations indicate that the frequency and amplitude contributed 1% and 5%, respectively, to the overall particle emission rate, whereas the age contributed 94% to the particle emission rate. Additionally, the linear models created for the response variable, the emission rate in particle/s, confirmed that vocal intensity and frequency are not statistically significant (P-value > 0.05) whereas age is statistically significant (P-value < 0.05). See Supplementary Table S5 for the linear model results. Therefore, the relatively minor variations that participant groups exhibited in vocal intensity and frequency were statistically significant but had a relatively small/negligible effect on the aerosol emission rate. Note, these results do not indicate that vocal intensity and frequency do not influence aerosol emission rates. Rather, they indicate that the design of the experiment was effective in constraining the range of variations in vocal intensity and frequency such that their influence on the aerosol emission rate was exceedingly small relative to changes due to age differences.

To assess whether the trend of increasing aerosol emission rate with increasing age, which was observed for the phonation exercises of DBr /a/, /a/, and Rep /pa/, held for singing and running speech, we compared the combined results of these three phonation exercises (Grouped phonation) with the aerosol emission rates from Singing HB and Speaking HB. In this manner, the variation in aerosol emission rates as a function of age for vocal activities more closely representative of daily behaviors (e.g., singing or talking in a classroom) was assessed. Figure 4 presents violin plots of the particle emission rates for the three different age groups (children aged 6–11 years, children aged 12–18 years, and adults) and for the three different vocalization activities: Grouped phonation, Singing HB, and Speaking HB. In general, the Grouped phonation vocal activities resulted in a broader distribution of particle emission rates. The median aerosol emission rates were very similar for the Grouped phonation and Singing HB activities. Speaking HB was consistently lower than the two other activities across the three age groups, consistent with results from prior studies (Mürbe et al. 2021; Gregson et al. 2021; Alsved et al. 2020; Fleischer et al.

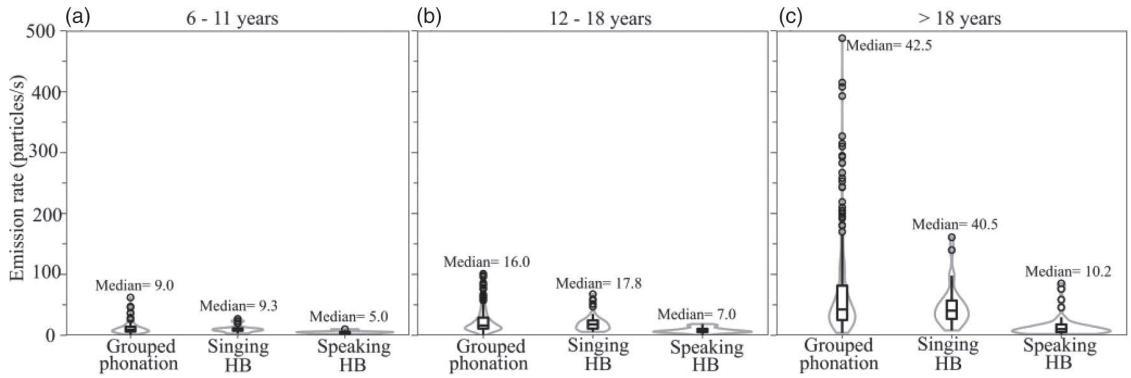


Figure 4. Distribution of particle emission rate for all of the subjects. Violin plots show the (a) children aged 6 – 11 years, (b) children aged 12 – 18 years, and (c) adults (> 18 years) as a function of vocalizing tests Grouped phonation, Singing HB, and Speaking HB with their median values.

Table 1. Model R^2 values and slope coefficients for each line in particles/s vs. amplitude.

	6–11 years		12–18 years		> 18 years	
Vocal test	Slope coefficient	R^2	Slope coefficient	R^2	Slope coefficient	R^2
DBr /a/	185.30	0.58	311.93	0.54	838.50	0.39
/a/	205.48	0.66	386.32	0.56	551.10	0.42
Rep /pa/	159.83	0.57	311.25	0.49	547.41	0.34

Table 2. Model R^2 values and slope coefficients for each line in particles/s vs. frequency.

	6–11 years		12–18 years		> 18 years	
Vocal test	Slope coefficient	R^2	Slope coefficient	R^2	Slope coefficient	R^2
DBr /a/	−0.005	0.00	−0.338	0.03	1.283	0.06
/a/	0.037	0.00	−0.228	0.01	−0.596	0.02
Rep /pa/	−0.089	0.03	−0.481	0.03	0.498	0.01

2022). Similar to Figures 1a–c, Figure 4 shows a clear trend with the median particle emission rates being the highest for the oldest age group (adults) and the lowest for the youngest age group (children aged 6–11 years) across all three vocal exercises. For the Grouped phonation, the median particle emission rate for group adults is 2.7 times more than that of group children aged 12–18 years, and 4.7 times more than that of group children aged 6–11 years. For Singing HB, the median particle emission rate for group adults is 2.3 and 4.4 times more than those for groups children aged 12–18 years and children aged 6–11 years, respectively. For Speaking HB, the median particle emission rate for group adults is 1.5 and 2.0 times more than those for groups children aged 12–18 years and children aged 6–11 years, respectively.

3.3. Statistical outliers

As shown by the outliers in Figures 1a–c and 4, each age group contained a subset of participants with emission rates much higher than their peers. Asadi et al. (2019) defined participants whose emission rates were at least an order of magnitude higher than the mean as "superemitters." Using this definition, none of the participants in our study would be defined as superemitters. Ahmed et al. (2022) proposed defining superemitters as statistical outliers, based on the emission rate exceeding the value of the third quartile (Q3) plus 1.5 times the interquartile range (Q3–Q1). Using this second definition, all three age groups contained multiple statistical outliers. To further differentiate the outliers, we define "mild outliers" as those with emission rates exceeding the value of the third quartile (Q3) plus 1.5 times the interquartile range (Q3–Q1), and "extreme outliers" as those with emission rates exceeding the value of the third quartile (Q3) plus 3 times the interquartile range (Q3–Q1). For group children aged 6–11 years, there were 4 mild outliers, 2 of which were extreme outliers; for group children aged 12–18 years, there were 7 mild outliers, 3 of which were extreme outliers; and for group adults, there were 7 mild outliers, 6 of which were extreme outliers. After averaging the emission rate data by participant, we observed a reduction in the occurrences of mild and extreme outliers across all age groups. For children aged 6–11 years, there were 2 mild outliers, 1 of which was an extreme outlier; for children aged 12–18 years, there were 4 mild and no extreme outliers; and for adults, there were 4 mild outliers, 2 of which were extreme outliers. Detailed information about the number of statistical outliers with and without averaging the data for each of the respiratory exercises performed during the study is reported in Supplementary Table S1.

Defining superemitters based on particle emission does not provide insight into the infectivity of the emissions. However, if the particles emitted by a superemitter have similar viral content to those emitted by a non-superemitter, the increased viral emissions could lead to increased disease transmission. Coleman et al. (2021) found that the viral load (gene copies per expiratory activity per patient) generated *via* respiratory aerosols from patients infected with COVID-19 was highest during singing followed by talking and then breathing. These results support the hypothesis that higher aerosol emission rates can be correlated with a higher risk of infection. For respiratory aerosols, particles with diameters smaller than 5 μm have been found to contain more SARS-CoV-2 copies than particles greater than 5 μm, which would play an important role in the transmission of the disease (Coleman et al. 2021; Adenaiye et al. 2022). As reported by Pan, Lednicky, and Wu (2019), the smaller viral-laden respiratory particles are more virulent as they contain more virus of the viral load, stay airborne for longer due to their reduced settling velocity (Hinds and Zhu 2022; Thatcher and Layton 1995; Thatcher et al. 2002), and, when inhaled, can penetrate deeper into the lungs (Hatch 1961). Jones et al. (2021) quantified the viral load in sputum and reported that adults and young children generate a similar viral load. If these results are consistent for viral aerosol emissions for adults and children, our results for aerosol emissions might serve as a comparison for potential transmission amongst different age groups. However, other respiratory pathogens may behave differently due to the location of microbial shedding in the respiratory system.

3.4. Constrained inference analysis

In order to explore how the activation of different respiratory modes influences particle emission rates we compared aerosol emission rates from the three sustained phonation exercises (DBr /a/, /a/, and Rep /pa/). We expected the DBr /a/ vocal exercises, which involved inhaling deeply prior to phonating /a/, to activate the pulmonary mode and increase the submicron particle emissions when compared with the baseline case of /a/. The Rep /pa/ exercises were expected to activate the oral mode due to articulation of the lips, thereby increasing the emission of larger droplets in comparison with the baseline case /a/. Figure 5 depicts the estimated coefficients of the mean particle emission rate for all three vocal exercises. The difference in emission rates between the DBr /a/ and /a/ vocal exercises is statistically significant (P-value < 0.05, see Table 3) for all age groups, with the DBr /a/ resulting in higher emission rates, as hypothesized. The difference in emission rates between /a/ and Rep /pa/ was not, however, consistent, nor statistically significant. The particle emissions generated from the oral mode would be relatively few in number and are primarily larger than the particle size range measured by the APS (0.54–20 μm). Consequently, increases in oral mode particles were likely not captured by our experimental methods. The

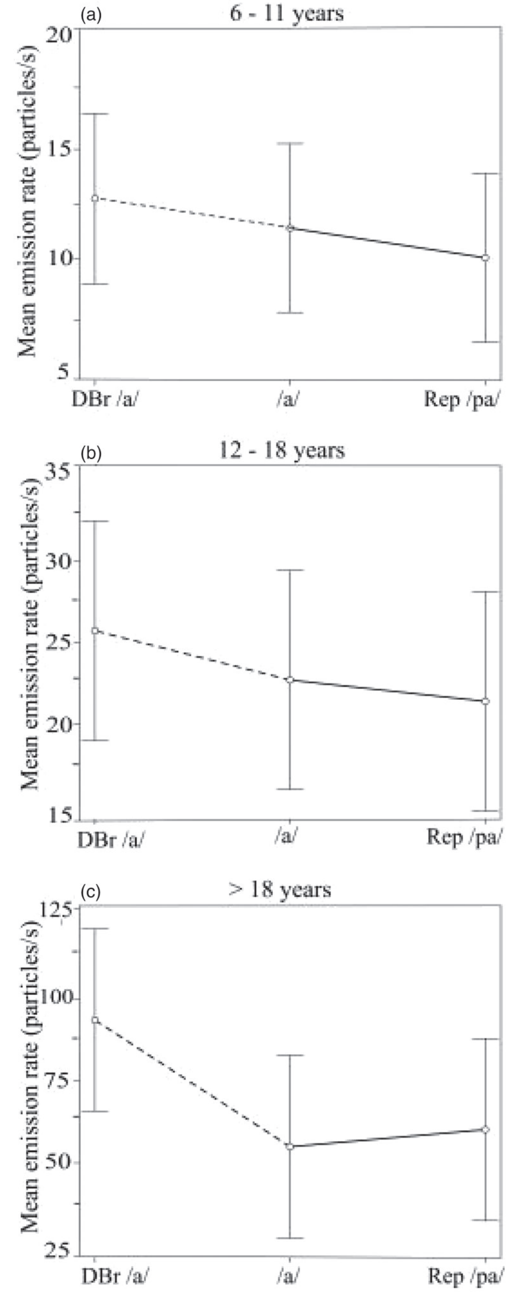


Figure 5. Plot of estimated coefficients of mean particle emission rate for (a) children aged 6 – 11 years, (b) children aged 12 – 18 years, and (c) adults (> 18 years) for three different vocal exercises DBr /a/, /a/, and Rep /pa/. The model assumed a combination of decreasing simple order and umbrella order homogeneity of variances across vocal exercises. Solid lines denote no significant difference, while dashed lines denote statistical significance.

Table 3. Constraint inference results for mean particle emission rate for vocal exercises DBr /a/, /a/, and Rep /pa/ for children aged 6 – 11 years, children aged 12 – 18 years, and adults (> 18 years).

	6–11 years		12–18 years		> 18 years	
Test contrast	Statistic	*P*-value	Statistic	*P*-value	Statistic	*P*-value
Global test	2.35	0.041	3.24	0.012	4.78	< 0.001
DBr /a/–/a/	1.54	0.043	2.9.	0.003	38.68	< 0.001
/a/ – Rep /pa/	1.27	0.082	1.34	0.097	5.22	0.307

reduced phonation time during the Rep /pa/ exercises due to the slight pause between vocalizing /pa/ may also explain the decreasing trend in emission rate from /a/ to Rep /pa/ that was observed for the children. However, the pause was not measured or accounted for in the emission rate calculations.

The overall pattern for particle emission rates by phonation exercise is statistically significant in decreasing order from DBr /a/ to /a/ to Rep /pa/ (*P*-value < 0.05, see Table 3) for age groups children aged 6–11 years and children aged 12–18 years. However, the overall pattern for particle emission rates by phonation exercise for the adults group indicates a statistically significant increasing umbrella order at /a/ (alternative hypothesis in Equation (1)) with a *P*-value < 0.05, see Table 3). Again, the pairwise comparison of /a/ and Rep /pa/ showed no significant difference for any of the age groups, but the overall pattern is statistically significant and differed for the children and adults due to the relationship between /a/ and Rep /pa/. This result could have physiological reasons and requires further investigation.

We compared the combined sustained phonation exercises, Grouped phonation, with our running speech exercises, Singing HB and Speaking HB. The running speech exercises were included to be more representative of the vocalization occurring in normal occupied environments than the Grouped phonation exercises. Figure 6 presents the estimated means of particle emission rates for all three age groups, for which the difference between Singing HB and Speaking HB is statistically significant (*P*-value < 0.05, see Table 4). This result is consistent with Alsved et al. 2020; Bagheri et al. 2023; Gregson et al. 2021 and Good et al. 2021, who reported singing resulted in higher emission rates than speaking in a normal tone. Moreover, the difference between Grouped phonation and Singing HB is statistically significant (*P*-value < 0.05, see Table 4) except for the children aged 6–11 years age group. The increased emission rate for Grouped phonation relative to Singing HB and Speaking HB is likely a result of the continuous phonation that occurred in the Grouped phonation measurements, versus more intermittent phonation that occurs when singing and speaking (e.g., pausing to breathe and when producing unvoiced speech sounds). Yunusova et al. (2016) evaluated the percent pause time during normal speech, and they reported the pause time for 32 controls (normal adults) was approximately 15% of the speaking time. For the present study, the mean emission rate for the "Grouped

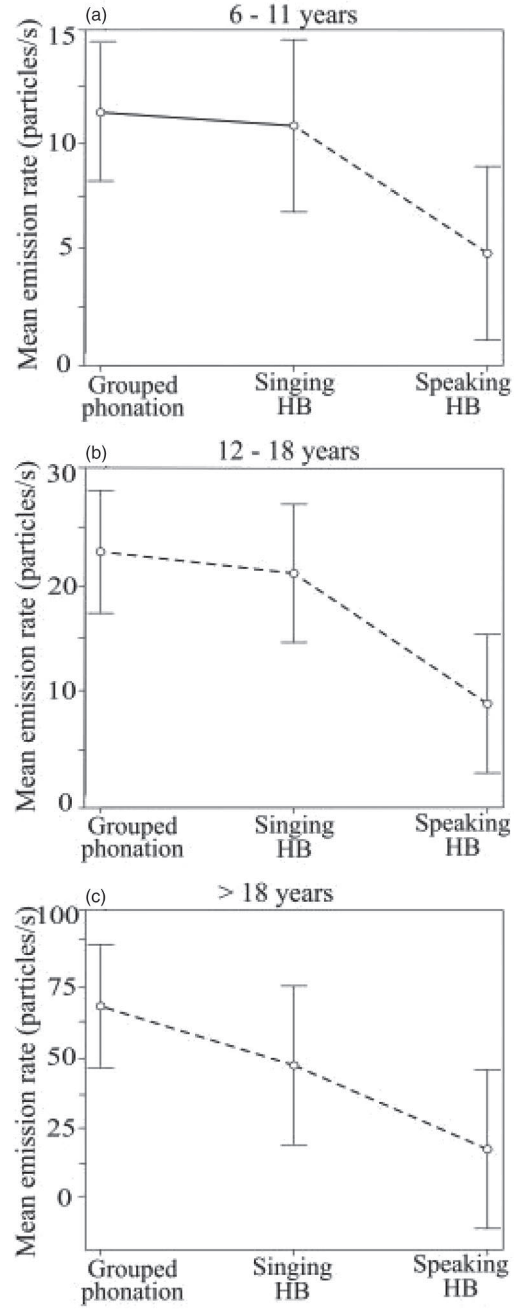


Figure 6. Plot of estimated coefficients of mean particle emission rate for (a) children aged 6 – 11 years, (b) children aged 12 – 18 years, and (c) adults (> 18 years) for three different vocal exercises: Grouped Phonation, Singing HB, and Speaking HB. The model assumed a combination of decreasing simple order and umbrella order homogeneity of variances across vocal exercises. Solid lines denote no significant difference, while dashed lines denote statistical significance.

Table 4. Constraint inference results in for mean particle emission rate for vocal exercises Grouped phonation, Singing HB, and Speaking HB for children aged 6 − 11 years, children aged 12 − 18 years, and adults (> 18 years).

	6–11 years		12–18 years		> 18 years	
Test contrast	Statistic	*P*-value	Statistic	*P*-value	Statistic	*P*-value
Global test	4.64	<0.001	8.34	<0.001	4.98	<0.001
Grouped phonation – Singing HB	0.45	0.177	0.41	0.024	2.01	0.001
Singing HB – Speaking HB	3.15	<0.001	2.49	<0.001	2.18	<0.001

phonation" is 5%, 9% and 31% more than the mean emission rate for Singing HB for children aged 6–11 years, children aged 12–18 years and adults, respectively, which roughly accounts for the expected amount of pause time. The mean emission rate for the "Grouped phonation" is 58%, 62% and 75% more than the emission rate for Speaking HB for children aged 6–11 years, children aged 12–18 years and adults, respectively, but this larger difference can also be attributed to higher emissions for singing (Grouped phonation) versus speaking (Speaking HB). There are also additional factors, such as the difference in the emissions from the open vowel /a/ and other phonemes that occur during speech and the expected differences in emissions for singing (Grouped phonation and Singing HB) and speaking (Speaking HB). Constrained inference statistical results with test statistics and *P*-values for each test are reported in Tables 3 and 4.

3.5. Particle size distribution

The particle size distribution of the aerosols emitted during vocalization is a primary factor in determining the transport and deposition of the particles in the environment, as well as the deposition in the respiratory system of the receptor inhaling the aerosol (Hofmann 2011). Prior work has presented particle emission rates in preadolescent children (Fleischer et al. 2022), although the differences in the size distribution between adults and children were not explored. Figure 7 presents the mean particle number size distributions for all respiratory activities for the three age categories. Figure 7 indicates that the locations for the modes for the particle number size distributions across all the age groups are similar, with a primary mode (mode with the larger amplitude) at ≈ 0.6 μm and secondary mode at ≈ 2.0 μm. Consistent with Figure 1, Figure 7 shows that the magnitude of the normalized aerosol concentrations increases with increasing age and vocal activities. DBr /a/ produced the highest emissions, followed by /a/ and Rep /pa/; Singing HB produced higher emissions than Speaking HB; and Breathing produced the lowest emissions. The size distributions for the younger age groups (children aged 6–11 years and children aged 12–18 years) are similar to the bimodal particle number size distributions presented in the present study and prior work for adult populations (Alsved et al. 2020; Archer et al. 2022; Good et al. 2021; Gregson et al. 2021). However, the locations of the modes of the particle number size distributions for some of the vocal exercises appear to be slightly shifted for the children compared to those for the adults.

To compare the locations of the modes, we fit a bimodal lognormal distribution to the mean particle number size distribution for each of the respiratory activity and age group combinations (see Figures 8, S5, and S6 for age groups children aged 6–11 years, children aged 12–18 years, and adults, respectively). The summary data for the modeled primary mode and secondary mode locations for children aged 6–11 years, children aged 12–18 years, and adults are shown in Table 5. The modeled primary mode location is always smaller for children (particle diameter $D_p \approx 0.5\ \mu$m) than for adults ($D_p \approx 0.6\ \mu$m). However, the increase in the modeled primary mode location with the age group from children aged 6–11 years to adults is not consistent across all vocal exercises. For some vocal exercises (e.g., Singing HB and Speaking HB), children aged 12–18 years had a smaller primary mode location than children aged 6–11 years. For children and adults, breathing resulted in smaller secondary mode location than for the vocal exercises ($D_p \approx 1.6\ \mu$m for children aged 6–11 years; $D_p \approx 1.3\ \mu$m for children aged 12–18 years; $D_p \approx 1.5\ \mu$m for adults). The secondary mode location generally decreased with age for the vocal exercises, being larger for children ($D_p \approx 2.0\ \mu$m for children aged 6–11 years; $D_p \approx 1.8\ \mu$m for children aged 12–18 years) than for adults ($D_p \approx 1.7\ \mu$m for adults). However, the results were not consistent across all vocal exercises, and the small sample size, limited measurement range of the APS, and error in the curve fitting exercise add to the uncertainty of the comparison. Based on these preliminary findings, further investigation into size distributions for different age groups and vocal exercises is warranted.

3.6. Intrapersonal variability

To assess intrapersonal variability in the data we compared data from a subset of the child participants who repeated the experiments following a separation of at least two weeks. Figure 9 provides a comparison of the

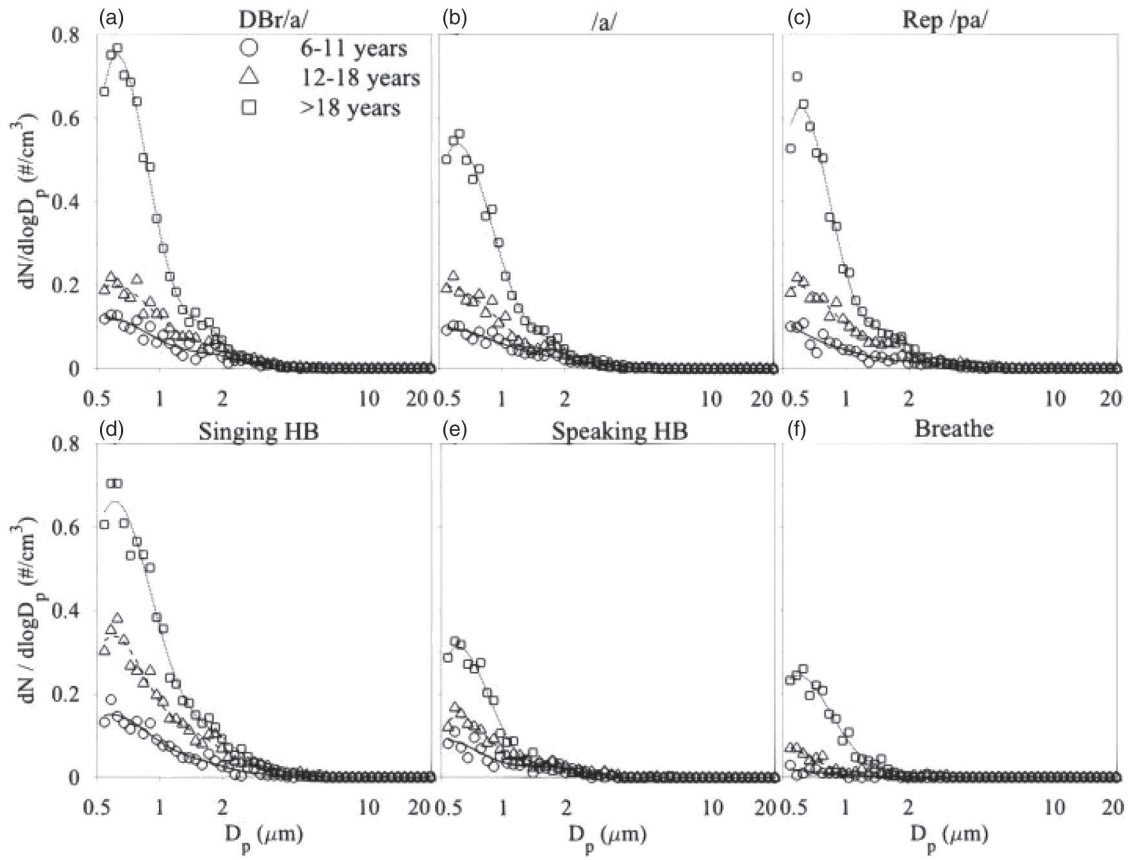


Figure 7. Mean particle number size distribution for particle diameters from 0.5 to 20 μm for children aged $6-11$ years, children aged $12-18$ years, and adults (>18 years) cohorts vocalizing DBr /a/, /a/, and Rep /pa/ at comfortable loudness at 262 Hz, as well as Singing HB, Speaking HB and Breathing. Symbols denote the mean of the measured values ($N = 53$), and lines represent the high-order polynomial fit (order of 20).

repeated tests (T1 and T2) for groups children aged 6–11 years and children aged 12–18 years (8 participants in each group) for respiratory exercises DBr /a/, /a/ and Rep /pa/. For DBr /a/ and Rep /pa/, the difference between the emission rates for the repeated tests was insignificant. However, for vocal exercise /a/, we found a statistically significant difference between the emission rates reported for the two tests, with an increase in the median value from 10 particles/s to 12.5 particles/s from test T1 to test T2. A detailed summary of statistics for the comparison of the two tests for all three respiratory activities is provided in Supplementary Tables S2–S4. The particle emission rates for most individual subjects either increased or decreased from test T1 to test T2. With median values ranging from 10 to 13 particles/s, the mean change in particle emission rate for individual subjects from test T1 to test T2 for all three vocalizations was 9 particles/s. This represents a mean percent change for the individual subjects of 83% for DBr /a/, 117% for /a/, and 64% for Rep /pa/ (see Supplementary Figure S7).

Interestingly, when comparing the same experiment with a subset of the participants, we also found that the list of outliers changed, although there was some overlap in the outliers designated for the two tests. That is, subjects who were designated as outliers for the test T1 were not necessarily designated as outliers for the test T2. Although the sample size is small, the results indicate that there can be high intrapersonal variability. This may arise due to physiological and environmental factors such as hydration, time of day (morning, afternoon, or evening), tiredness level, health condition, etc. Also, as shown in previous studies, amplitude and frequency are important factors for respiratory emission rates, although the amplitude range was relatively small and the frequency was controlled for the present study. While the factors affecting both inter- and intrapersonal variability should be further explored, the difference between emission rates reported for the test T1 to test T2 is smaller than the differences between age groups. Thus, the observed intrapersonal variability does not affect the main results of this study.

4. Discussion

In this study we measured the respiratory particle emission rates and particle number size distributions

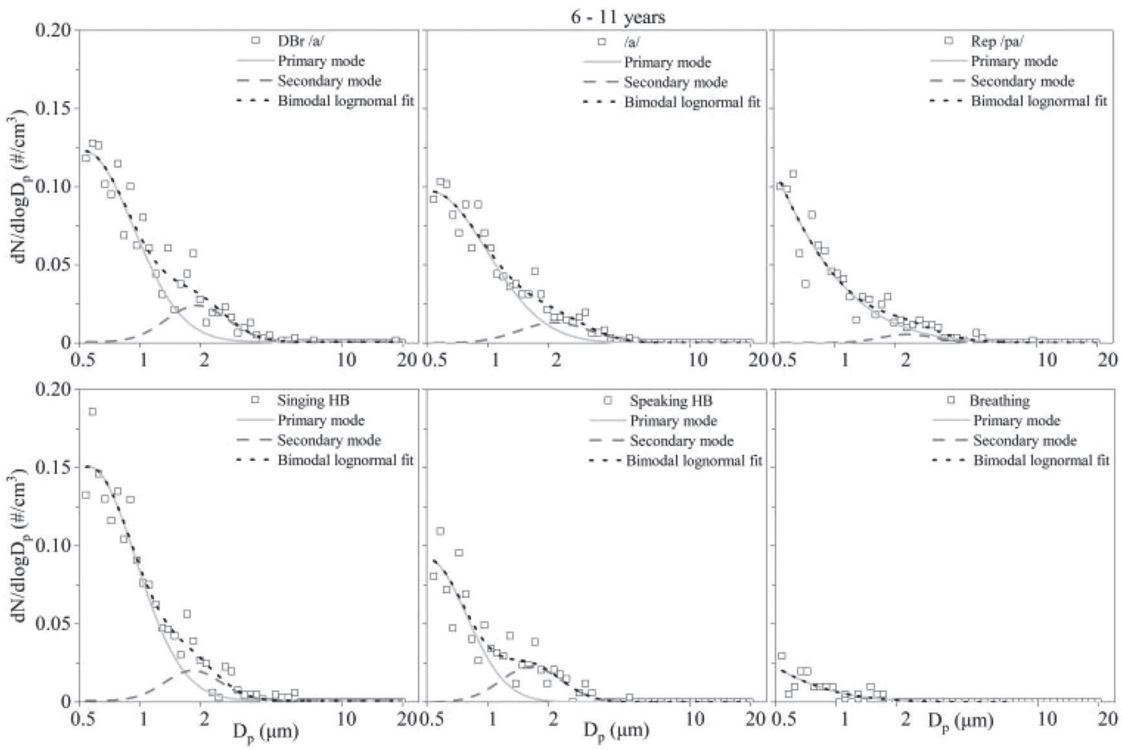


Figure 8. Particle number size distribution for particle diameters from 0.5 to 20 μm for children aged $6-11$ years for 6 different respiratory activities shown with a bimodal lognormal fit.

Table 5. Estimated primary (B mode) and secondary (L mode) modes of bimodal lognormal fits for mean particle size distribution of children aged $6-11$ years, children aged $12-18$ years, and adults (> 18 years) for 6 different respiratory activities including 3 sustained phonations (DBr /a/, /a/ and Rep /pa/), Singing HB, Speaking HB and Breathing.

	6–11 years		12–18 years		> 18 years	
Vocal test	Primary mode μm	Secondary mode μm	Primary mode μm	Secondary mode μm	Primary mode μm	Secondary mode μm
DBr /a/	0.53	2.09	0.59	1.82	0.62	1.62
/a/	0.52	2.10	0.51	1.77	0.61	1.73
Rep /pa/	0.01	2.24	0.46	1.69	0.53	1.79
Singing HB	0.55	1.80	0.49	1.90	0.61	1.88
Speaking HB	0.50	1.60	0.43	1.84	0.61	1.61
Breathing	0.26	1.62	0.51	1.27	0.59	1.47

for a total of 50 children and adults. Furthermore, vocal exercises were selected to target specific physiological locations for particle production. Our experimental protocol was designed to limit the range of values and impacts of frequency and loudness, two factors that have been previously identified to substantially impact respiratory particle emissions (Ahmed et al. 2022; Asadi et al. 2019; Gregson et al. 2021). Using multiple linear regression analysis, we found that the major contributor to the difference in aerosol emission rates for our experimental protocol was age (94%). Deviations in loudness and frequency from the target values were identified as minor contributors, 5% and 1%, respectively, to the difference in aerosol emission rate, confirming that these factors were adequately controlled by the experimental protocol. Using the constrained inference approach, we realized good statistical power for the comparisons between groups even with the relatively small sample size.

We found that taking a deep breath before phonation (DBr /a/) significantly increased particle emission rate as compared with the baseline /a/ phonation, which would be expected to arise due to a larger amount of particles produced in the bronchial region. The repeated /pa/ sound did not result in an increase in particle emission rate above the baseline phonation /a/. However, the larger aerosol/droplet emissions produced *via* the oral mode would be primarily larger than the size range detected by the APS (0.54–20 μm) (Johnson et al. 2011). In the future, size-resolved measurements for aerosols smaller than 0.5 μm, such as measurements based on particle electromobility, as well as for aerosols and droplets larger than 20 μm, such as water-sensitive paper (e.g., Good et al. 2021;

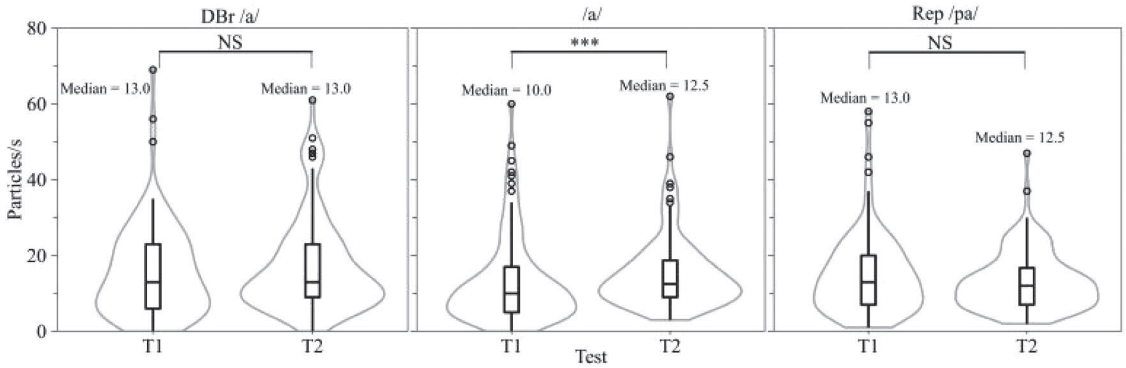


Figure 9. Comparison of the repeated test (T1 and T2) with 8 participants each from children aged 6 – 11 years and children aged 12 – 18 years groups for three different respiratory activities, including phonating DBr /a/, /a/ and Rep /pa/. The two experiments (T1 and T2) are separated by at least 2 weeks with similar protocols. (*** denotes statistical significance, while NS denotes no statistical difference.)

Bagheri et al. 2023), should be included in the experimental protocol. In addition, randomizing the order of the vocal exercises would reduce the possibility for bias due to fatigue, hydration, or other factors. Because we were working with young children, all vocal exercises followed the same progression from simplest to most complicated (DBr /a/, /a/, and Rep /pa/) to maximize compliance.

Children in both age groups (children aged 6–11 years and children aged 12–18 years) produced fewer respiratory particles than adults, and the estimated primary mode of the particle number size distribution was slightly smaller for the children ($D_p \approx 0.5$ μm) than for the adults ($D_p \approx 0.6$ μm). This shift in the size distribution may be a result of the 5s vocal exercises. With a smaller tidal volume, the children may have been accessing more of their expiratory reserve volume than the adults, which would increase the contribution of the smaller bronchial mode particles in the expiratory flow (Lofrese, Tupper, and Lappin 2018). The estimated secondary mode of the particle number size distribution was slightly larger for the children ($D_p \approx 1.9$ μm for groups children aged 6–11 years and children aged 12–18 years combined) than for the adults ($D_p \approx 1.7$ μm).

While these results suggest that there are differences in particle number size distribution due to physiological changes, further study is warranted. The modeled mode estimates are dependent on the deviation of data points from the fitted line. The goodness of fit generally ranged from 0.71 to 0.99; however, the estimated mode was sometimes below the measurement range of the APS (0.54–20 μm) which may lead to uncertainty in determining the precise location of the primary mode. This limited the accuracy of the fitting exercise. The modeled primary mode for breathing for children aged 6–11 years (0.26 μm) was much smaller than the mean for the other vocal exercises (0.53 μm), and for Rep /pa/ the estimated primary mode for children aged 6–11 years was extremely small (0.01 μm). Without measuring the particles <0.5 μm in diameter, we can only conclude that the primary mode is likely <0.5 μm for these vocal exercises. Further study is warranted to investigate the effect of age on particle size distribution using a wider range of particle size measurements. Determining the full-size distribution is important for predicting the transport of the particles in the room once they are released, especially for children in a classroom.

There are other factors that may have affected our results, including the relatively small sample size, the limited range for amplitude and frequency, and the impact of other human factors, such as hydration and health status. The number of participants was recruited by applying a power analysis based on the ORI technique with a value of 0.80, which indicates that there is an 80% chance of detecting a difference between the population means and the target when a difference actually exists (Vanbrabant, Van De Schoot, and Rosseel 2014). The statistical power would of course improve with larger sample sizes. In our protocol, the vocal amplitude and frequency were limited to control the variance and enable comparison of respiratory emissions across age groups. However, it is possible that these comparisons may also vary with amplitude and frequency. For hydration and health status, our protocols were designed to assure that the participants were properly hydrated and healthy at the time of the experiment. However, some participants reported throat dryness during the experiment and some may have been impacted by undetected respiratory infections or other health conditions. The human factors affecting both interpersonal and intervariability, including hydration, health condition, diet, and other factors, require further investigation.

The comparative results are consistent with those of previous studies, but the magnitude of the reported respiratory particle emission rates vary widely. The particle emission rates for the individual participants in the present study ranged from 0 to 101 particles/s for children and 2 to 488 particles/s for adults for the vocal exercises (excluding breathing), which are lower than some previously reported emission rates. Good et al. (2021) reported mean emission rates of 239 and 411 particles/s for talking and singing, respectively, Archer et al. (2022) and Fleischer et al. (2022) reported emission rates of 4–1000 particles/s for different vocalizations, Ahmed et al. (2022) reported 2 to 22 particles/s for phonating /a/ from low to high vocal frequency, Asadi et al. (2019) reported 1 to 50 particles/s for low to high vocal intensity and Mürbe et al. (2021) reported median particles emission rate ranged from 16 to 1240 particles/s for speaking and singing.

Most studies reporting respiratory aerosol emissions have used similar experimental methods to measure the expelled respiratory aerosols. However, the methods for calculating the emission rates from the instrument measurements differ. Gregson et al. (2021) and Archer et al. (2022) multiplied the measured aerosol concentration by the assumed (Gregson et al. 2021) or measured (Archer et al. 2022) minute ventilation to estimate the emission rate. This assumes the aerosol concentration is constant throughout the duration of phonation. Asadi et al. (2019) used a 1 s sampling time with the APS to record the particle emission rates during phonation. They noted a lag time of 2 s for the particles to reach the instrument. They also noted that their results represent approximately 20% of the emissions given that the sample flow rate of the APS is 1 L/min and the sheath flow rate is 4 L/min. Our method for calculating the aerosol emission rate was similar to that of Asadi et al. (2019), but we determined the total particle emissions by counting particles captured during both the phonation time (5 s) and the rest time following the phonation (10 s). This value was then multiplied by 5 to account for the sheath flow, and the particle emission rate was calculated by dividing this number by only the phonation time. Because the expiratory flow rates were not directly measured as part of the experimental protocol, it is possible that there could have been some particle-laden expiratory flow spillover outside of the collection funnel. With the 5 L/min inlet flow rate of the APS, and a funnel volume of 0.21 L, we estimated the funnel spillover losses for expiratory flow rates of 6 L/min, 10 L/min, and 16 L/min, representing the range of typical human expiratory flow rates (Pleil et al. 2021), to be 8%, 25%, and 44%, respectively. The particle emission rates were not corrected to account for any mismatched expiratory phonatory flow rate and the APS collection flow rate. However, because adults generally speak with a higher ventilation rate than children, the adult data were most likely to be underreported. Interestingly, this would actually increase the difference between particle emission rates in the adults and children age groups.

5. Conclusions

In this study, we recruited 50 healthy participants from three different age categories and investigated the effect of age progression on the particle emission rate by controlling for vocal intensity and frequency. Despite large interpersonal variability, a relationship between age and emission rate was evident. Mean emission rates for adults were $\approx$ 3 times more than those for the children ages 12–18 years and $\approx$ 5 times more than those for the children ages 6–11 years. There were multiple statistical outliers, called super-emitters, identified in all three age groups.

We found that the vocal exercise DBr /a/ resulted in higher emissions than /a/, consistent with an expected increase in particles produced in the bronchial region. Differences in emission rates between /pa/, which was the baseline vocalization, and Rep /pa/, which activated the oral model of particle emission, were not statistically significant.

The locations of the estimated primary and secondary modes of the particle size distribution also appear to be a function of age. For children, the primary mode corresponded to a slightly smaller particle diameter and the secondary mode corresponded to a slightly larger particle diameter than for adults. The particle size distribution affects the transport of the respiratory particles from source to receptor. Therefore, the size distribution of the viral aerosol can greatly impact the disease transmission rate.

Tests repeated several weeks apart indicated a large intrapersonal variability, potentially due to changes in physiological and behavioral variables such as hydration state, diet, health condition, engagement level, etc. Because the study did not explicitly test for the response to these variables, understanding the factors affecting intrapersonal differences requires additional investigation.

The importance of this work is in the characterization of respiratory aerosol emissions for children, which was shown to vary both in magnitude and size distribution relative to adults emissions. These findings can improve exposure assessment and guidance for reducing airborne disease transmission in schools and other indoor environments that are predominantly populated by children.

Author contributions

All authors contributed to the article and approved the submitted version. MSR: Writing – original draft, data curation, formal analysis, visualization, coding. MA: Writing – original draft, data curation, formal analysis, visualization, coding. TA: Data curation, visualization. BDE: Supervision, conceptualization, validation, editing, and project administration. DS: Formal analysis, visualization, coding. SM: Statistical methodology, validation, editing. ARF: Supervision, conceptualization, validation, editing, and project administration.

Disclosure statement

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