Comparing the Respirable Aerosol Concentrations and Particle Size Distributions Generated by Singing, Speaking and Breathing

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Abstract

The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic has resulted in an unprecedented shutdown in social and economic activity with the cultural sector particularly severely affected. Restrictions on performance have arisen from a perception that there is a significantly higher risk of aerosol production from singing than speaking based upon high-profile examples of clusters of

COVID-19 following choral rehearsals. However, no direct comparison of aerosol generation from singing and speaking has been reported. Here, we measure aerosols from singing, speaking and breathing in a zero-background environment, allowing unequivocal attribution of aerosol production to specific vocalisations. Speaking and singing show steep increases in mass concentration with increase in volume (spanning a factor of 20-30 across the dynamic range measured, $p<1\times10^{-5}$). At the quietest volume (50 to 60 dB), neither singing ($p=0.19$) or speaking ($p=0.20$) were significantly different to breathing. At the loudest volume (90 to 100 dB), a statistically significant difference ($p<1\times10^{-5}$) is observed between singing and speaking, but with singing only generating a factor of between 1.5 and 3.4 more aerosol mass. Guidelines should create recommendations based on the volume and duration of the vocalisation, the number of participants and the environment in which the activity occurs, rather than the type of vocalisation. Mitigations such as the use of amplification and increased attention to ventilation should be employed where practicable.

KEYWORDS: SARS-CoV-2, COVID-19, aerosol generation, airborne transmission, aerodynamic size, singing

A novel strain of a human coronavirus was first identified in late 2019, designated severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), and is responsible for the global outbreak termed coronavirus disease 19 (COVID-19).[1–3] Pandemic status was declared on 11 March 2020 by the World Health Organisation (WHO), with in excess of 21.5 million cases and 767,000 deaths reported worldwide by 17st August 2020.[4] Early in the pandemic, clusters of COVID-19 were considered to have arisen in several choirs around the world.[5,6] This rapidly led to many governments restricting or suspending singing. Concerns that woodwind and brass instruments might also be responsible for virus spread led to similar restrictions on the playing of wind instruments. Consequently, large sections of the cultural sector, along with religious institutions and educational establishments, were unable to rehearse and perform, resulting in profound artistic, cultural, spiritual, emotional and social impacts. The livelihoods of many performers have been jeopardised, and the viability of established institutions remains threatened. The economic impact to the United Kingdom (UK) from this sector alone has been substantial, costing the UK economy hundreds of millions in lost tax revenue, usually derived from the £32.2 billion cultural purse.[7]

Respiratory particulate matter is expelled during human exhalatory events, including breathing, speaking, coughing and sneezing.[8–10] The flux generated is proportional to the amplitude of phonation in speech.[11] These actions release a plume of material containing particles of varying size, ranging from macroscopic mucosalivary droplets originating from the oral cavity and pharynx, to microscopic aerosols released by the small airways of the lungs.[8,9,11,12] Traditionally, the division between droplets, which are considered to be of sufficient mass to sediment due to gravity, and aerosols, which remain airborne, is defined arbitrarily at 5 µm diameter.[13,14] However, particle composition and environmental properties like temperature, humidity and airflow influence the biophysical mechanics of the material released and the extent of transport.[13–16]

Droplets and airway secretions are established vectors of SARS-CoV-2, with expelled infectious material either directly inhaled by an individual in close proximity, or indirectly transmitted through contact with settled-out fomites.[17,18] The role of airborne transmission by respirable aerosol particles is gaining prominence.[19] Viral RNA has been detected in airborne samples collected both inside and outside the rooms of COVID-19 patients,[20–23] and SARS-CoV-2 RNA has been reported in size-resolved aerosol distributions in two hospitals in Wuhan, China.[24] Retrospective studies of COVID-19 clusters, including a shopping mall, a restaurant and a high-profile outbreak in an American choir group, found no direct or indirect interaction among the individuals contracting the virus, suggesting airborne transmission.[6,25,26] SARS-CoV-2 and other viruses, including severe acute respiratory syndrome coronavirus (SARS-CoV-1) and Middle East Respiratory Syndrome coronavirus (MERS-CoV), are stable in aerosol.[27–29] Infective airborne potential from human exhalation has been confirmed in other viruses, including respiratory syncytial virus, influenza and MERS-CoV.[30,31]

Several online reports have attempted to examine the quantities of particulate matter expelled by participants performing a range of activities including singing but have struggled to accurately quantify aerosol and droplets because of the large number of background particulates in the environment. This study is the first peer-reviewed study that explores the relative amounts of aerosols and droplets (up to 20 µm diameter) generated by a large cohort of 25 professional performers completing a range of exercises including breathing, speaking, coughing and singing in the clean air environment of an operating theatre with laminar flow ventilation. Measurements of particle number concentration alone would be insufficient to determine the total amount of viral material capable of being transmitted: the total mass of particulate matter produced may be a key factor in assessing the potential risk. Thus, measurements of particle size distributions, as well as concentration, are used to assess the mass concentration.

Overview of the Cohort of Professional Singers and the Study Design. The cohort of 25 professional singers perform a broad range of genres, including musical theatre (6), choral (5), opera (5), and other genres: gospel (2), rock (2), jazz (2), pop (1), actor with singing interest (1) and soul (1). 6 identified their voice-type as soprano or mezzo-soprano, 7 as alto, 5 as tenor and 7 as bass or baritone. Aerosols and droplet concentrations were measured with an Aerodynamic Particle Sizer (APS, 500 nm – 20 µm) in an operating theatre with each participant and researcher required to wear appropriate personal protective equipment. The high air exchange rate, filtration and laminar air flow reduced the pre-existing particle background number concentration to zero cm^{-3}, enabling the unique and extremely sensitive measurements described. Thus, any particles detected were directly attributable to participant activity, with particle concentrations returning to zero cm^{-3} between periods of singing, speaking and breathing. Temperature and relative humidity were typically $20^{o}C$ and 45%, respectively.

A standard operating procedure was adopted (see *Methods*), covering 12 activities over ~1 hour, with each activity involving up to 5 repeat actions, with a 30 s pause between each. These activities included breathing, coughing, singing single notes ("/ɑ/") at different pitches, and speaking and singing the "Happy Birthday" song at different volumes. At the beginning of each action, participants stepped forward to the funnel (Fig. 1a) such that the dorsum of the nose was aligned to the plane of the base of the cone. Participant position relative to the funnel was monitored to ensure consistency (within 10 cm of the sampling tubes) across all measurements (Extended Data Fig. 1). As in previous studies,[9,10] we report concentrations sampled through the collection funnel, which allows comparison of particle emission rates on a relative basis between activities. In reality, particle concentrations will become rapidly diluted once particles are exhaled, leading to strong spatial variations.

Aerosol Number Concentrations from Singing Compared with Other Expiratory Activities. A sequence of measurements made with one APS for one performer is reported in Fig. 1(b). The bursts of activity, interspersed with periods of no activity, are visible above a zero background in aerosol concentration.

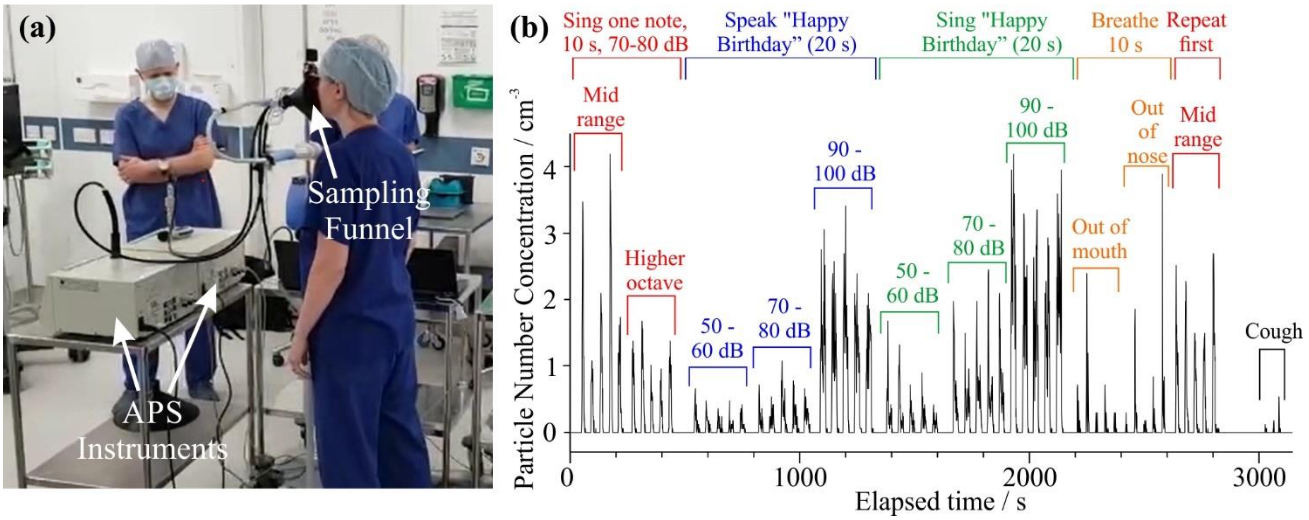

Fig. 1: (a) An illustration of the sampling position of the performer, the sampling funnel and the aerosol instrumentation. (b) Continuous time series of data recorded from one participant completing 12 activities (5 repetitions of each). The zero-background is clearly apparent between measurements.

A complete analysis of the time-averaged total particle number and mass concentrations for all 25 participants is reported in Fig. 2. The statistical analysis is described in *Methods* and the absolute results summarised in Extended Data Tables 1 and 2; data normalised to the aerosol concentration from speaking at 70-80 dB are compared in Extended Data Fig. 2 and Table 3. The distribution of aerosol number concentration generated across all participants is assumed to be log-normal, consistent with the data presented in a previous publication; concentrations must always be positive-valued and a small number of individuals generate a significantly larger aerosol flux than the median.[10] This is particularly apparent for breathing, where measurements from individuals span almost three orders of magnitude. Indeed, 4 participants produced more aerosol in number concentration while breathing than while speaking at 90-100 dB. The reproducibility of concentration from singing a single note (70-80 dB) is not only apparent in single participant data (Fig. 1b), but also across the cohort with median concentrations in good agreement (0.83 and 0.91 cm^{-3} at beginning and end, respectively). At the lowest volume (50-60 dB), neither singing (p=0.19) or speaking (p=0.20) were significantly different in particle production to breathing, with median number concentrations of 0.10, 0.19 and 0.28 cm^{-3} for speaking, singing and breathing, respectively. In the mixed model, compared to speaking, singing generates a statistically significant ($p < 1\times10^{-5}$) enhanced aerosol number concentration, although this enhancement is small relative to the much larger changes associated with increase in volume ($p < 1\times10^{-5}$). Aerosol number concentration increases by a factor of 10-13 as volume increases from 50-60 dB to 90-100 dB, suggesting that shouting should be associated with little difference in risk to singing at loud volume.

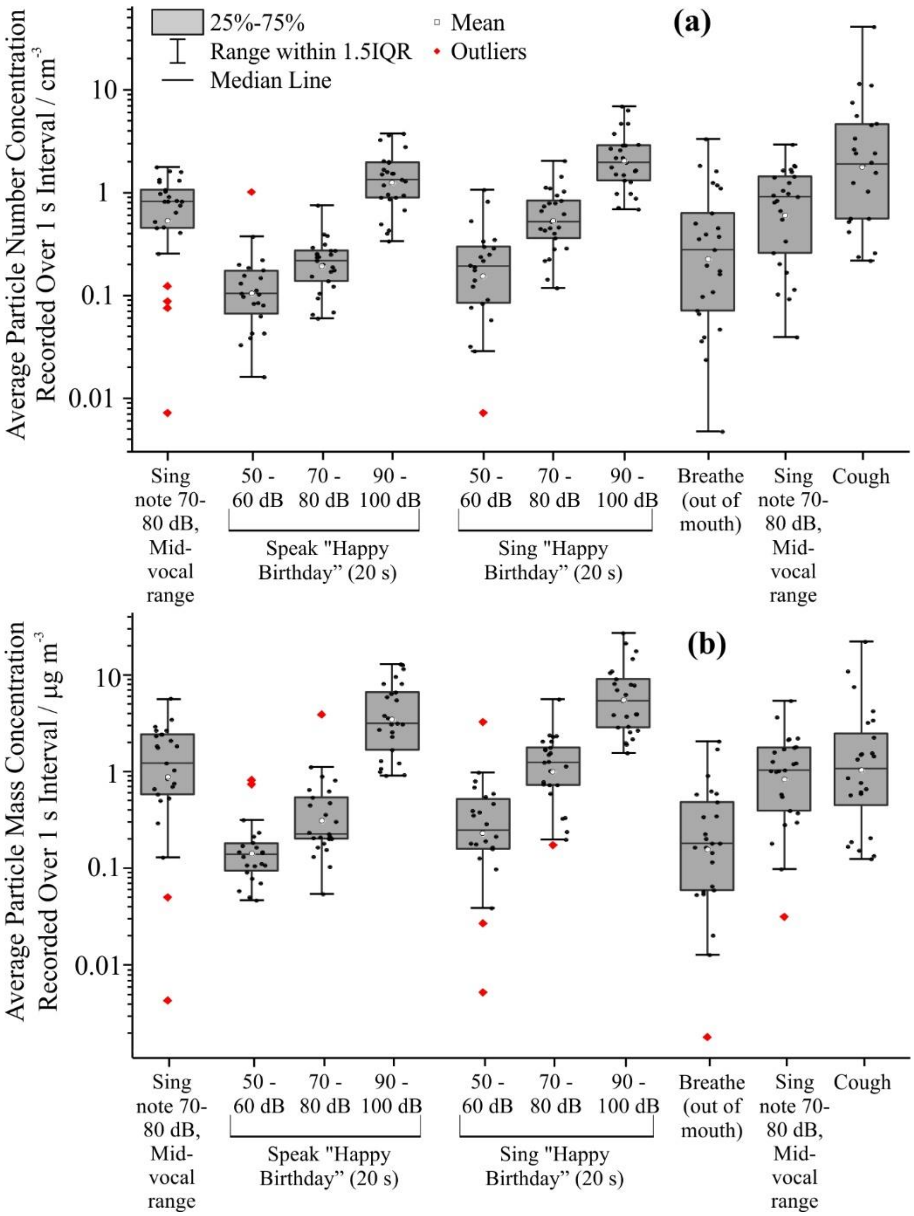

Figure 2: Box and whisker plots showing a) particle number concentration and b) mass concentrations for the same series of activities for all 25 participants. See *Methods* section ("Data and Statistical Analysis") for full description of analysis and reported values.

Figure 3 compares aerosol number concentrations from speaking and singing at 90-100 dB for male and female participants and for the different genres with the full cohort. Individual participant comparisons are provided in Extended Data Fig. 3. There are no significant differences in aerosol production either between genders (p = 0.34) or among different genres (p(choral different from "other genres") = 0.46, p(musical theatre different from "other genres") = 0.25, and p(opera different from "other genres") = 0.42). The variability among genres (almost a factor of 2 between the lowest and highest median concentrations) may be attributed to the small cohort sizes for each genre, the sensitivity of number concentration to volume and a minority of participants emitting higher concentrations than others (who could be classed as super-emitters).[10] In addition, there is no correlation between the mean aerosol number concentration generated by an individual participant when singing at 90-100 dB or breathing and the participant's body mass index or peak flow rate (Extended Data Fig. 4).

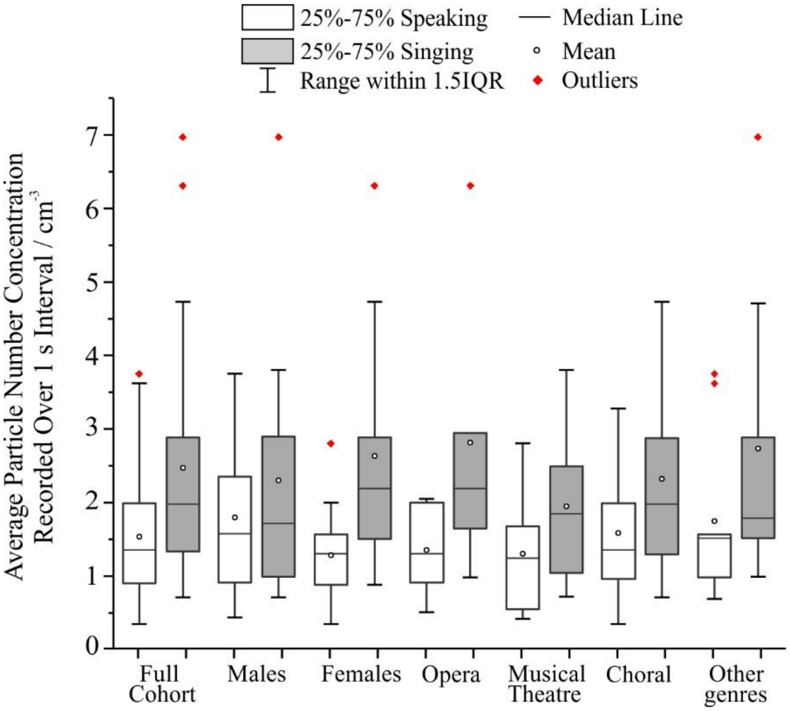

Fig. 3: Comparison of average aerosol number concentrations (linear scale) from speaking and singing at 90-100 dB by the full cohort, males (12), females (13), opera (5), musical theatre (6), choral (5) and other genres (9).

Comparing the Aerosol Particle Size Distributions and Mass Concentrations. The possibility that singing, speaking and breathing generate aerosol particles of different size cannot be inferred by comparing particle number concentrations alone. Instead, we must compare the aerosol size distributions from these activities. Previously, two overlapping modes in the size distribution of particles from speaking and coughing have been identified.[9,10] These have been attributed to distinct processes in this expiration process. The mode of lowest size is generated in the lower respiratory tract with a second mode generated in the region of the larynx, expected to be the most important in voicing. Figure 4 reports the variation in mean number concentrations with particle size averaged over the 25 participants and includes the fitted distribution from Johnson et al.[9] reported from a cohort of 15. Our distribution for speaking and singing is in excellent agreement with the shape of the distribution reported by Johnson *et al.* for particles larger than 800 nm diameter. Although the absolute concentrations are a factor of ~6 larger in our measurements, it should be recognised that the absolute value carries little meaning, reflecting only the instantaneous value recorded by the APS from the sampling funnel, which will depend on the sampling specifications.[10]

Measured size distributions for speaking and singing were fitted to bimodal lognormal distributions. The fits all gave the similar mean diameters and variance for both modes, further supporting the conclusion that speaking and singing can be treated similarly (Extended Data Table 5). However, both vocalisations generate larger particles than breathing: although the size distribution from breathing is well-represented by a bimodal lognormal distribution, the larger mode is shifted to a smaller diameter and has a narrower variance than for speaking and singing.

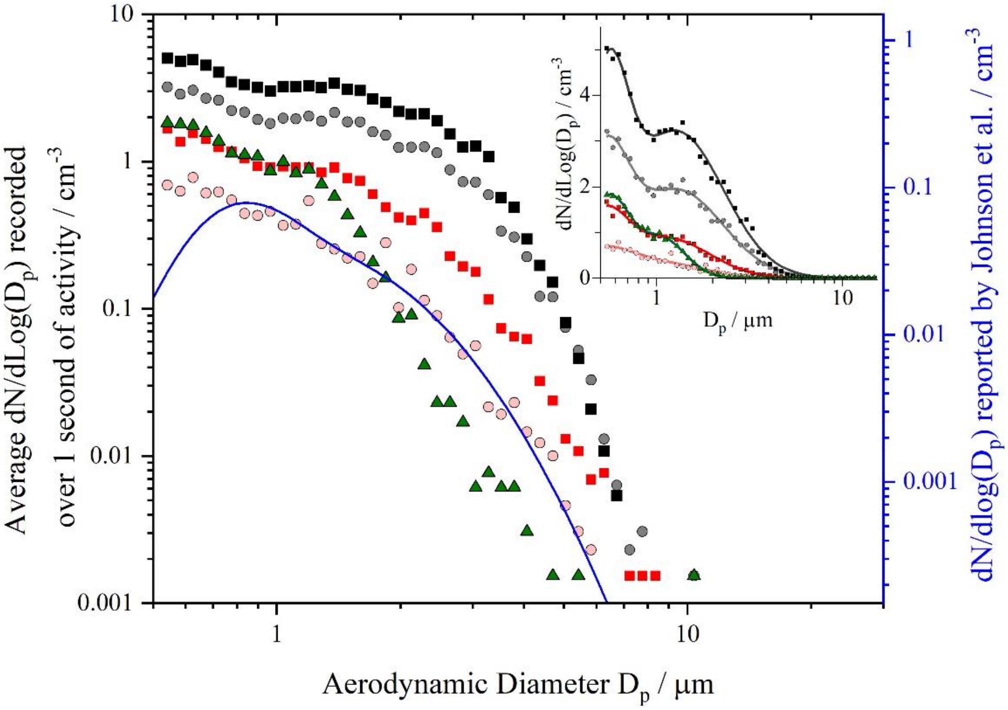

Fig. 4: Comparison of the size distributions from singing (squares) and speaking (circles) at different volumes (70-80 dB red; 90-100 dB grey/black) with breathing (green triangles). The size distribution reported for speaking by Johnson et al.[9] is shown by the blue line (right scale), data that should be most similar to the light red circles. The relative variations in concentrations represented by the two scales are equal. The inset figure compares the fitted size distributions with the experimental data with a linear scale, as reported in Extended Data Table 5.

The consequences of different size distributions are apparent when aerosol mass concentration is reported (Fig. 2b, see Extended Data Table 2 and 4). This comparison is most important when considering the potential of the different activities to transmit infection. Speaking and singing generate statistically significant differences in mass concentrations of aerosol at similar volumes; however, these are modest (median singing values only a factor of 1.5-3.4 times larger than speaking) relative to the effects of the volume of vocalization (a factor of 20-30 increase). Converting from a number concentration to a mass concentration for breathing results in the mass concentration range shifting to lower values relative to speaking and singing, a consequence of the different size distributions associated with voicing and breathing (median values 24 and 36 times higher for speaking and singing at the highest volume level, respectively, compared with breathing).

Discussion. This study demonstrates that the assessment of risk associated with the spread of SARS-CoV-2 in large groups due to respirable particles from speaking and singing should consider the number and mass concentrations of particles generated by these activities. The statistically significant, yet relatively modest differences detected between the type of vocalisation at the loudest volume studied, are eclipsed by the effects of volume on aerosol production, which varies by more than an order of magnitude from the quietest to loudest volume studied, whether speaking or singing. By contrast, the number of particles produced by breathing covers a wide range (spanning from quiet to loud volume speaking and singing) but has a size distribution shifted to smaller particle sizes, in principle mitigating some of the potential risk associated with the wider emission range.

We also find that a minority of participants emitted substantially more aerosols than others, sometimes more than an order of magnitude above the median, consistent with the long-tail of a log-normal distribution when viewed in linear-concentration space. This observation is consistent with a previous study.[10] However, the highest emitters were not consistently the highest across all activities, suggesting the magnitude of emission from an individual may be highly activity specific. It is unclear why some participants emit substantially more than others, and further studies are required to better characterise the variability of aerosol emission across the population, as well as the consistency of emission from an individual over time.

These conclusions have important policy implications in the context of creating guidelines to reduce transmission of SARS-CoV-2. Breathing produces smaller particles than singing and speaking, suggesting that vocalisation may carry higher risk than breathing if the potential SARS-CoV-2 dose delivered by an individual infected with the virus scales with particle mass. Size distributions are comparable across speaking and singing at the same volume and generate relatively similar, yet statistically significantly different, numbers of particles. Most importantly, number concentrations from speaking and singing rise in parallel with increasing volume. Given that speaking and singing produce numbers of particles of the same order of magnitude, and that increasing volume increases that number by orders of magnitude, guidelines from public health bodies should focus on the volume at which the vocalisation occurs, the number of participants (source strength), the environment (ventilation) in which the activity occurs and the duration of the rehearsal and period over which performers are vocalising.[5,6] For certain vocal activities and venues, amplification may be a practical solution to reduce the volume of singing by the performers. Based on the differences observed between vocalisation and breathing and given that it is likely that there will be many more audience members than performers, singers may not be responsible for the greatest production of aerosol during a performance, and for indoor events measures to ensure adequate ventilation may be more important than restricting a specific activity.

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METHODS

Human subjects

The Public Health England Research Ethics and Governance of Public Health Practice Group (PHE REGG) approved this study and all research was performed in accordance with relevant guidelines and regulations of the Ethical Review Board. We recruited 25 healthy volunteers (12 males and 13 females, ranging in age from 22 to 57 years old (mean 38, SD +/- 9.8) through contact and collaboration with the entertainment industry. Informed consent was obtained from all participants prior to study participation. All participants completed a pre-screening questionnaire including age, gender, professional status, singing training history and COVID 19 symptom status to fulfill inclusion/exclusion criteria. Only participants who self-reported no symptoms of COVID-19 and who had normal temperatures on the day of attendance were included. Each participant's weight, height and peak flow rate were measured before the aerosol measurements. Body mass index was calculated from the height and weight measurement.

Aerosol Measurements

Measurements were performed simultaneously with two APS instruments (TSI 3321) and one Optical Particle Sizer (OPS, 0.3 – 10 μm, TSI 3330) sampling from the same custom-printed funnel. A comparison of measurements between the two APS instruments was linear, with a slope that deviated from 1 owing to different sensitivities of the instruments (Extended Data Fig. 5). The OPS detected significantly more particles than the APS (up to a factor of 2), a consequence of the lower size detection limit of the OPS (to 300 nm) compared to the APS (to 500 nm) (Extended Data Fig. 6). Including these smaller particles in our analysis significantly increases the number concentration but does not significantly change the particulate mass concentrations from the expiratory activities.

The sampling funnel was 3D printed from PLA (1.75 mm filament) by a RAISE3D Pro2 Printer (3DGBIRE). The funnel was 150 mm wide, 90 mm deep with 3 ports at the neck for sampling aerosol into up to three aerosol instruments (some combination of APSs and OPSs). All tubing was conductive silicone and 130 cm in length (TSI Inc., product number 3001788, inner diameter 0.19 inch, outer diameter 0.375 inch).

Vocalisation experiments

"/a/" experiments

Participants voiced /ɑ/ (the vowel sound in ‘saw’) for 10 s at 70-80 dB in close proximity to the funnel followed by 30 s of nose breathing and standing 2 m away from the funnel, repeated four more times in succession. The participant repeated the series of five /ɑ/ vocalisations at the same amplitude using feedback from a decibel meter. Soprano/mezzo soprano singers sang note F4, alto note D4, tenor note F3 and baritone/bass note C3. After each set of experiments participants were asked to take a sip of water.

This set of experiments was repeated an octave above at 70-80 dB. Soprano/mezzo soprano singers sang note F5, alto note D5, tenor note F4 and baritone/bass note C4. Timed prompts with directions for the requested vocalisation were delivered by the researcher and immediate contemporary guidance given if the amplitude was out of range.

“Happy Birthday” speaking experiments

Participants spoke the “Happy Birthday” song to “Dear Susan” for 20 s at 50-60 dB followed by 30 seconds of nose breathing and standing 2 m away from the funnel, repeated four more times in succession. The participants then repeated this sequence at 70-80 dB and at 90-100 dB.

“Happy Birthday” singing experiments

Participants sang the “Happy Birthday” song to “Dear Susan” for 20 s at 50-60 dB followed by 30 s of nose breathing and standing 2 m away from the funnel, repeated four more times in succession. The participants then repeated this sequence at 70-80 dB and at 90-100 dB. Soprano/mezzo soprano singers sang in B flat major (starting note F4, top note F5), alto in G major (starting note D4, top note D5), tenor in B flat major (starting note F3, top not F4) and baritone/bass in F major (starting note C3, top note C4).

Breathing experiments

Participants breathed for 10 s inhaling through the nose and exhaling through an open mouth in a non-forced “quiet” fashion, then stood 2 m away from the funnel for 30 s in between each breathing experiment and repeated four more times. An additional set of five breathing measurements were conducted in similar fashion but where the participants inhaled through the nose and exhaled out of the nose in a “quiet” fashion.

Confirmatory “/a/” experiments.

Participants voiced /ɑ/ (the vowel sound in ‘saw’) for ten seconds at 70-80 dB followed by 30 s of nose breathing and standing away 2 m away from the funnel, repeated four more times in succession. The participant repeated the series of five /ɑ/ vocalisations at the same amplitude using feedback from a decibel meter. Soprano/mezzo soprano singers sang note F4, alto note D4, tenor note F3 and baritone/bass note C3.

Coughing

Participants were asked to cough into the funnel once, stand 2 m away for 30 seconds and then repeat this process two more times.

Data and Statistical Analysis

Data analysis was performed with custom-written software to collate and analyse temporal trends in aerosol concentration, mass concentrations and size distributions across multiple aerosol instruments. Measured total particle number concentrations were summed over the period of activity and divided by the duration of the activity, reporting a mean concentration (cm^{-3}) with a standard deviation, i.e. the average concentration of particles sampled within the funnel volume during the activity. With coughs requiring < 1 s, no averaging across a time-dependent concentration is possible and only the integrated number concentrations per single cough are reported. Further, particle size distributions were recorded by the APS at 1 s intervals with 51 size bins equally spaced in the range 0.5 to 20 μm in log(diameter) space. Average size distributions were calculated first by determining the mean size distribution for each participant and then calculating the mean and standard deviation across all participant size distributions for each activity. Mass concentrations were calculated assuming particle density was 1000 $kg \cdot m^{-3}$. Our reported number concentrations and particle size distributions for speaking and breathing are consistent with previously published data.[10]

The lme package in R-software was used to fit linear random effect models with log-base-e transformed particle concentration or mass as the dependent variable. The independent variables were vocalisation (speaking or singing) and acoustic volume (50-60, 70-80 and 90-100 dB); the random effect was participant identification number. In the Figures, the lower and upper hinges (ends of boxes) correspond to the first and third quartile (the 25th and 75th percentiles). The upper whisker extends from the upper hinge to the largest value but no further than 1.5×IQR (where IQR is the inter-quartile range, the distance between the 1st and 3rd quartiles). The lower whisker extends from the lower hinge to the smallest value at most 1.5×IQR. Data beyond the ends of the whiskers are “outlying points” and indicated in red. All components of the box plots were calculated based on the logarithmically-transformed data, owing to lognormal nature of the data, but the plotted and tabular values reported are converted back to linear space for clarity.

Acknowledgements

We acknowledge the Working Group for The Investigation of ParticulatE Respiratory Matter to InForm Guidance for the Safe Distancing of PerfOrmeRs in a COVID-19 PandeMic (PERFORM). B.R.B. acknowledges support from the Natural Environment Research Council through grant NE/P018459/1. Dyson, Inc., the Atmospheric Measurement and Observation Facility, and the Health and Safety Executive are acknowledged for APS loans. Fortius Clinic and Shoen Clinic are acknowledged for the provision of the space to conduct the measurements. We acknowledge the BBC Singers, Eleven Management and the performers for volunteering to be included in this study. We acknowledge the Department for Digital, Culture, Media and Sport and Public Health England who acted as sponsor and funded the research, respectively.

Author Contributions

FKAG, NAW and CMO are joint first authors on this paper. NAW, CMO, PLS, DC and JPR led in the study design and in securing funding. FKAG, BRB, and JPR collected the data. CMO, NAW and PLS prepared the application and secured ethical approval. NAW, CMO, DC and JC managed the registration and coordination of participant volunteers and secured access to the operating theatres. FKAG, LPM, AEH and BRB wrote analysis software and analysed the data. TF, NG and GCD undertook the statistical analysis. JPR, DC, PLS and JC provided technical guidance and advice. JPR, BRB, NAW, CMO, DC, FKAG and LPM drafted the manuscript. All authors read and approved the final manuscript.

Competing Interests

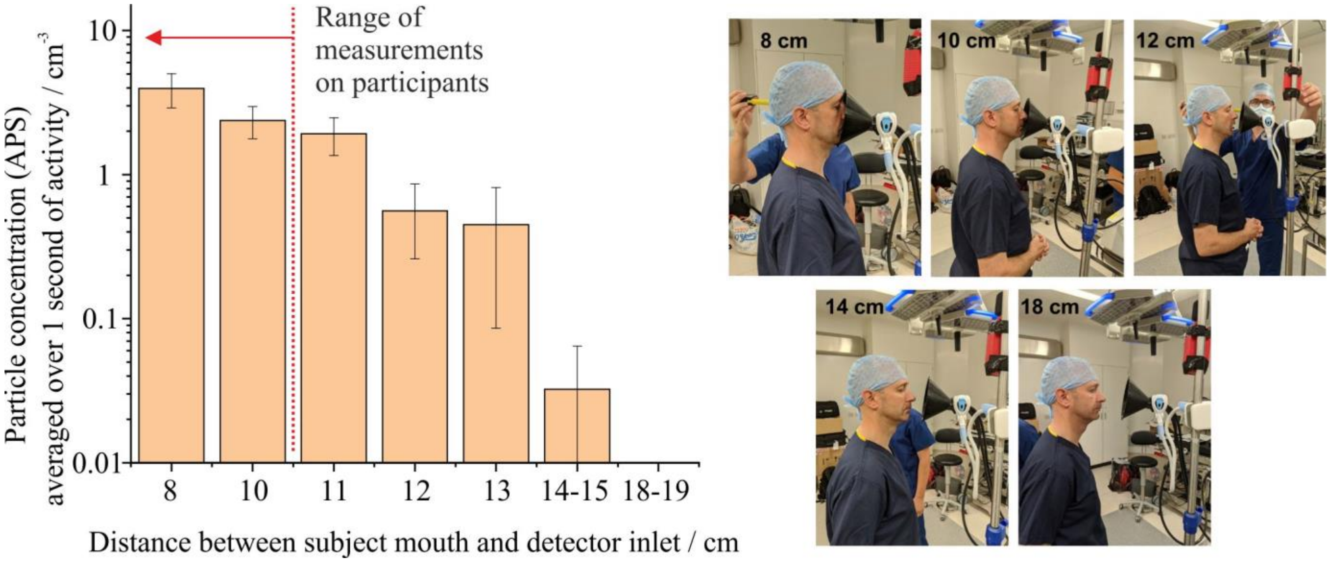
The authors declare no competing interests.

Data Availability

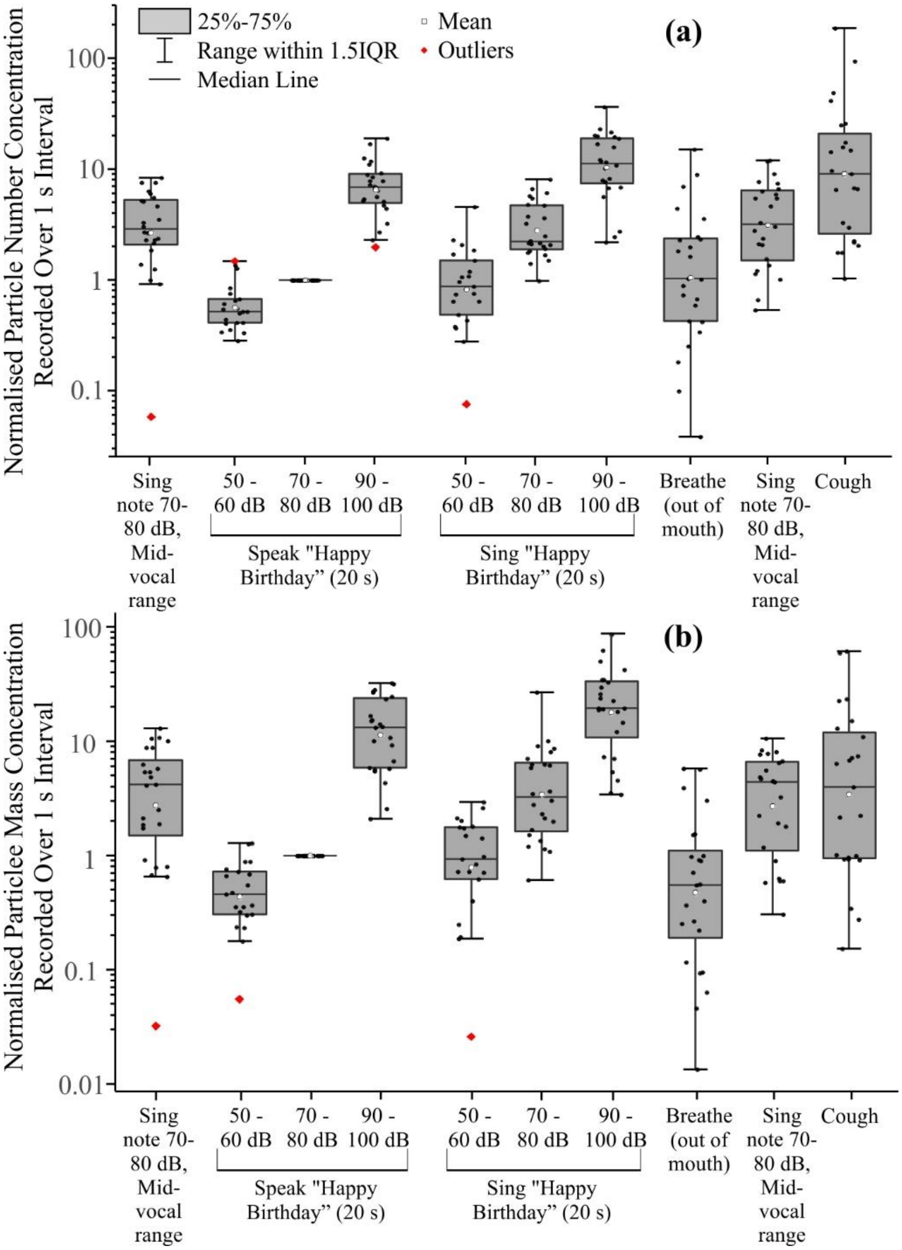
Correspondence and requests for materials should be addressed to JPR.

EXTENDED FIGURES

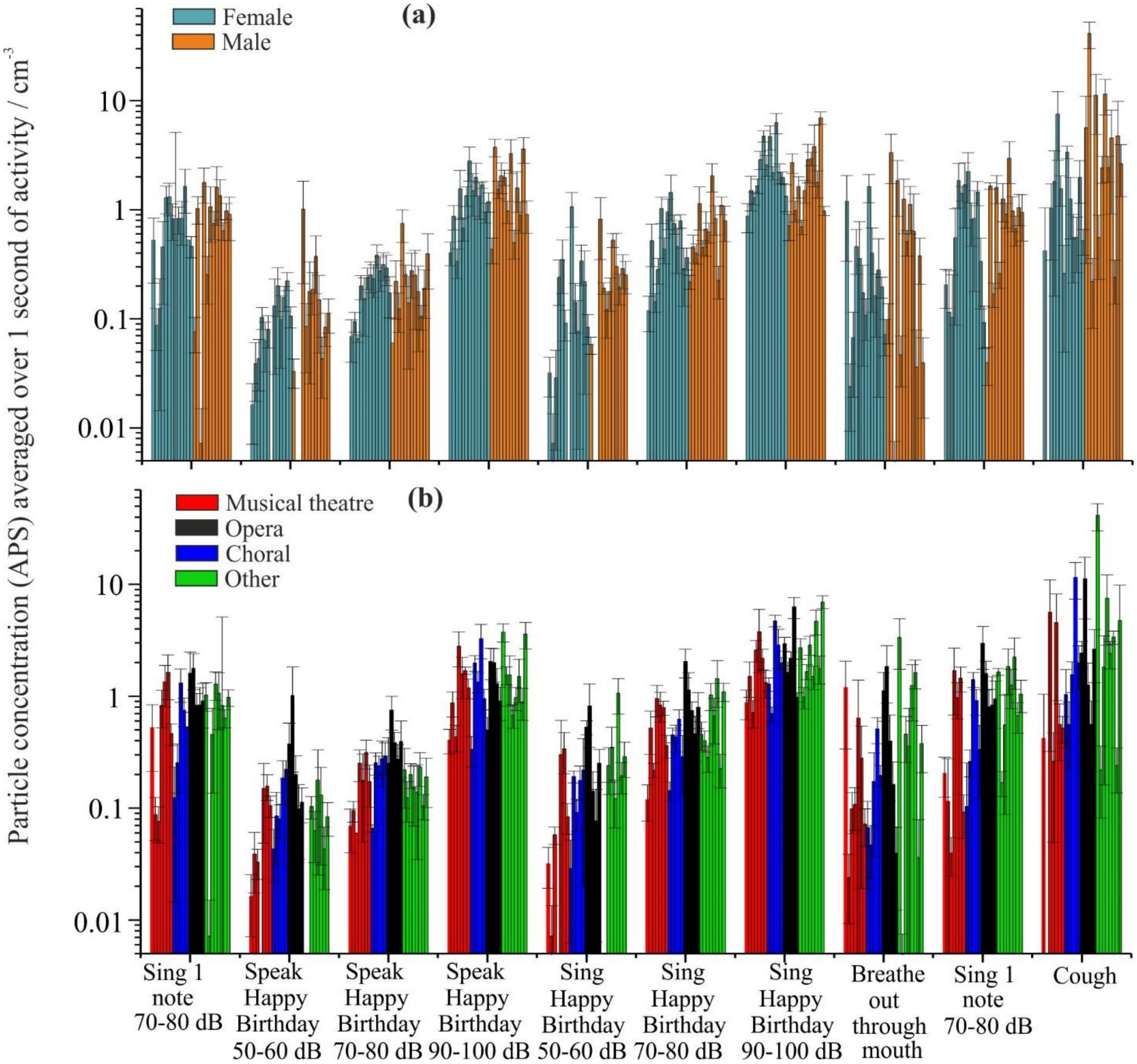
Extended Data Figure 1: Mean particle number concentration as a function of the distance from the participant's mouth to the apex of the funnel. For this experiment, a participant sang the "Happy Birthday" song for 20 s at 80-90 dB five separate times at each distance. The reported value is the mean and standard deviation for each distance. When the participant vocalised 8-10 cm from the funnel apex, the measured number concentrations did not vary significantly (factor of ~1.5), whereas beyond 12 cm the measured number concentrations decreased by an order of magnitude or greater. For all participants in this study, the distance between the subject mouth and the funnel apex was 8-10 cm.



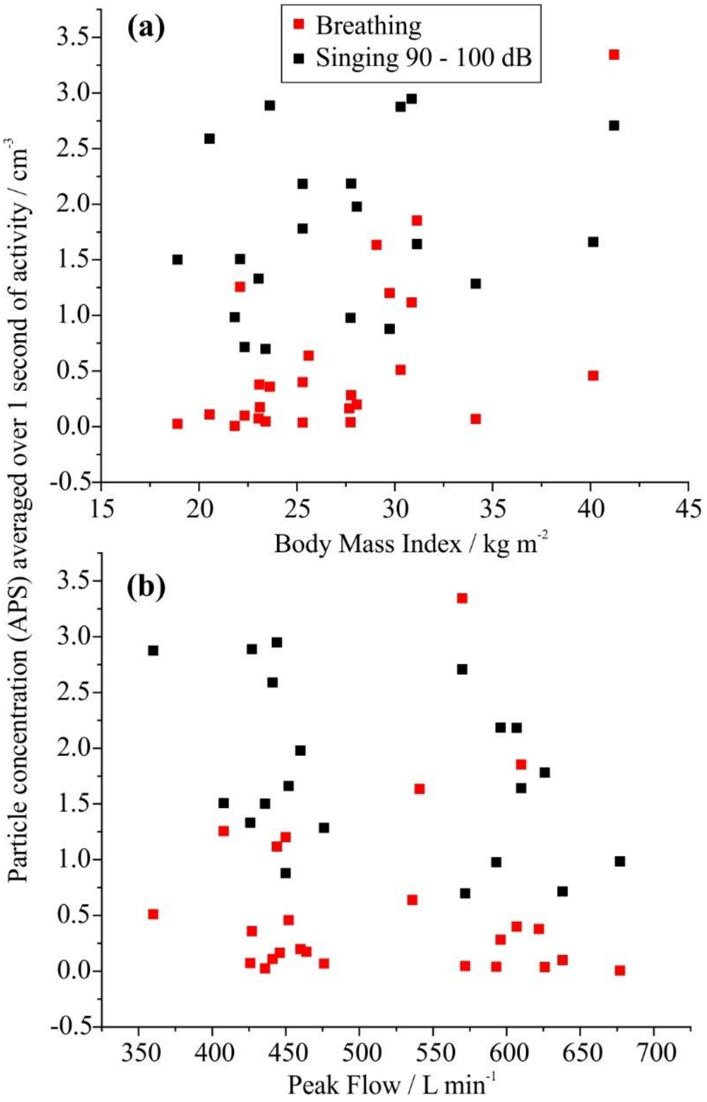
Extended Data Figure 2: Box plots showing a) number concentration and b) mass concentration normalised to each participant's mean number or mass concentration while speaking "Happy Birthday" at 70-80 dB. Box plot components are the same as in Fig. 2 of the manuscript (see *Methods*).



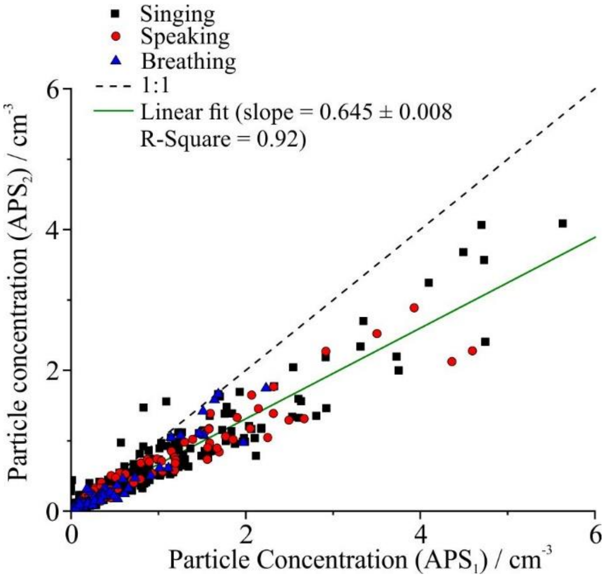
Extended Data Figure 3: Participant breakdown in particle number concentrations generated for each expiratory activity, shown by (a) gender and (b) genre.



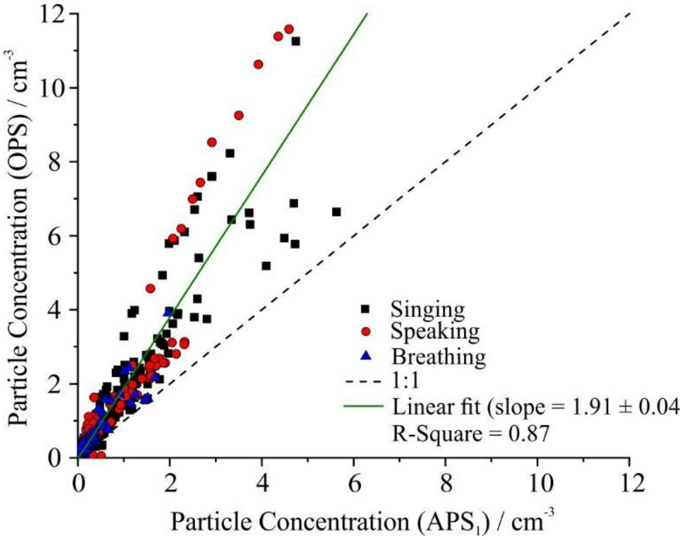
Extended Data Figure 4: a) Variation of aerosol number concentrations generated by breathing (red squares) and singing (90-100 dB, black squares) with body mass index (BMI, kg m^{-2}) for all 25 participants. There is no correlation of concentration with BMI (R-Squared is 0.3449 for breathing and 0.0004 for singing 90-100 dB). b) Variation of aerosol number concentrations generated by breathing (red squares) and singing (90-100 dB, black squares) with peak flow rate across 25 participants. There is no correlation of concentration with peak flow (R-Squared is 0.0011 for breathing and 0.0075 for singing 90-100 dB). Note that the clustering of data in part b) represents gender differences: males have a higher peak flow rate than females.



Extended Data Figure 5: Comparison of measurements from two APS instruments across 8 participants. Both instruments are linearly correlated, although the slope is less than 1 because the second APS instrument (APS_2) is less sensitive than the first (APS_1).



Extended Data Figure 6: Comparison of measurements across 8 participants from the OPS and the APS for which all data are reported in this paper. The OPS measures a larger number concentration because it detects smaller particles, which are generally more abundant than larger particles.



Extended Data Table 1: Measured absolute number concentrations from the series of expiratory activities plotted in Fig. 2a (in cm^{-3}). Provided are the statistical parameters visualised by the box plot. Note that these parameters were calculated on the logarithmically transformed data (see *Methods*). The number of participants for each activity is given by *n*.

	Activity										
Parameter	Sing *"/a/"* 70-80 dB	Speak "Happy Birthday" 50-60 dB	Speak "Happy Birthday" 70-80 dB	Speak "Happy Birthday" 90-100 dB	Sing "Happy Birthday" 50-60 dB	Sing "Happy Birthday" 70-80 dB	Sing "Happy Birthday" 90-100 dB	Breathe (nose-mouth)	Breathe (nose-nose)	Sing *"/a/"* 70-80 dB	Cough
Mean	0.53	0.11	0.19	1.3	0.16	0.53	2.0	0.23	0.16	0.60	1.8
Median	0.83	0.10	0.22	1.3	0.19	0.52	2.0	0.28	0.19	0.91	1.9
25%	0.46	0.063	0.14	0.89	0.084	0.36	1.3	0.072	0.060	0.26	0.56
75%	1.1	0.18	0.27	2.0	0.30	0.83	2.9	0.64	0.44	1.5	4.7
Bottom whisker	0.25	0.016	0.060	0.34	0.029	0.12	0.70	0.0048	0.018	0.040	0.22
Top Whisker	1.8	0.37	0.75	3.7	1.1	2.0	7.0	3.3	0.89	3.0	41
n	25	22	25	25	22	25	25	25	19	25	24

Extended Data Table 2: Measured absolute mass concentrations from the series of expiratory activities plotted in Fig. 2b (in $\mu g \cdot m^{-3}$). Provided are the statistical parameters visualised by the box plot. Note that these parameters were calculated on the logarithmically transformed data (see *Methods*). The number of participants for each activity is given by *n*.

	Activity										
Parameter	Sing *“/a/”* 70-80 dB	Speak “Happy Birthday” 50-60 dB	Speak “Happy Birthday” 70-80 dB	Speak “Happy Birthday” 90-100 dB	Sing “Happy Birthday” 50-60 dB	Sing “Happy Birthday” 70-80 dB	Sing “Happy Birthday” 90-100 dB	Breathe (nose-mouth)	Breathe (nose-nose)	Sing *“/a/”* 70-80 dB	Cough
Mean	0.87	0.14	0.31	3.4	0.23	1.0	5.5	0.16	0.097	0.82	1.0
Median	1.2	0.14	0.23	3.2	0.25	1.2	5.4	0.18	0.14	1.0	1.1
25%	0.59	0.092	0.20	1.7	0.16	0.73	2.9	0.059	0.040	0.39	0.35
75%	2.4	0.18	0.54	6.7	0.55	1.8	9.1	0.48	0.22	1.8	2.7
Bottom Whisker	0.13	0.047	0.054	0.90	0.027	0.20	1.6	0.013	0.0081	0.099	0.12
Top Whisker	5.7	0.31	1.1	13	3.3	5.6	27	2.1	1.72	5.4	22
n	25	22	25	25	22	25	25	25	19	25	24

Extended Data Table 3: Relative number concentrations from the series of expiratory activities plotted in Extended Data Fig. 2 (normalised to each participant’s mean emitted number concentration while speaking “Happy Birthday” at 70-80 dB). Provided are the statistical parameters visualised by the box plot. Note that these parameters were calculated on the logarithmically transformed data (see *Methods*). The number of participants for each activity is given by *n*.

	Activity										
Parameter	Sing *“/a/”* 70-80 dB	Speak “Happy Birthday” 50-60 dB	Speak “Happy Birthday” 70-80 dB	Speak “Happy Birthday” 90-100 dB	Sing “Happy Birthday” 50-60 dB	Sing “Happy Birthday” 70-80 dB	Sing “Happy Birthday” 90-100 dB	Breathe (nose-mouth)	Breathe (nose-nose)	Sing *“/a/”* 70-80 dB	Cough
Mean	2.7	0.57	1	6.5	0.83	2.8	10	1.1	0.68	3.1	9.1
Median	2.9	0.52	1	6.9	0.88	2.2	11	1.0	0.96	3.2	9.1
25%	2.2	0.41	1	5.1	0.46	1.8	7.7	0.43	0.25	1.6	2.6
75%	5.4	0.67	1	9.1	1.5	4.8	19	2.4	1.9	6.5	21
Bottom Whisker	0.92	0.29	1	2.0	0.28	0.98	2.2	0.039	0.061	0.54	1.0
Top Whisker	8.4	1.4	1	19	4.6	8.1	37	15	4.0	12	190
n	25	22	25	25	22	25	25	25	19	25	24

Extended Data Table 4: Relative mass concentrations from the series of expiratory activities plotted in Extended Data Fig. 2 (normalised to each participant’s mean emitted mass concentration while speaking “Happy Birthday” at 70-80 dB). Provided are the statistical parameters visualissed by the box plot. Note that these parameters were calculated on the logarithmically transformed data (see *Methods*). The number of participants for each activity is given by *n*.

	Activity										
Parameter	Sing *“/a/”* 70-80 dB	Speak “Happy Birthday” 50-60 dB	Speak “Happy Birthday” 70-80 dB	Speak “Happy Birthday” 90-100 dB	Sing “Happy Birthday” 50-60 dB	Sing “Happy Birthday” 70-80 dB	Sing “Happy Birthday” 90-100 dB	Breathe (nose-mouth)	Breathe (nose-nose)	Sing *“/a/”* 70-80 dB	Cough
Mean	2.7	0.44	1	11	0.79	3.4	18	0.47	0.25	2.7	3.4
Median	4.2	0.45	1	13	0.94	3.3	20	0.55	0.32	4.4	4.0
25%	1.3	0.31	1	5.9	0.62	1.6	9.5	0.16	0.050	1.0	0.95
75%	7.5	0.72	1	24	1.8	6.7	34	1.2	0.61	6.6	12
Bottom Whisker	0.65	0.18	1	2.1	0.19	0.61	3.5	0.013	0.031	0.31	0.15
Top Whisker	13	1.3	1	33	2.9	27	87	5.8	2.6	11	62
n	25	22	25	25	22	25	25	25	19	25	24

Extended Data Table 5: Lognormal fit parameters for speaking, singing and breathing. For each activity, the size distribution averaged across all participants was fit to a bimodal lognormal fit.

	Mode 1			Mode 2		
Activity	N / cm^{-3}	$\overline{D_p}$ / μm	σ	N / cm^{-3}	$\overline{D_p}$ / μm	σ
Speaking 70-80 dB	0.333	0.50	1.58	0.090	1.28	1.41
Speaking 90-100 dB	0.760	0.53	1.32	1.201	1.28	1.77
Singing 70-80 dB	0.397	0.52	1.33	0.497	1.14	1.69
Singing 90-100 dB	1.024	0.55	1.28	2.032	1.28	1.78
Breathing (nose-mouth)	0.489	0.55	1.29	0.272	1.07	1.34