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Comparisons of aerosol generation across different musical instruments and loudness

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ABSTRACT

Respiratory aerosols can serve as vectors for disease transmission, and aerosol emission is highly activity-dependent. COVID-19 severely impacted the performing arts due to concerns about disease spread by respiratory aerosols and droplets generated during singing and playing musical instruments. Aerosol generation from woodwind and brass performance is less understood compared to singing due to uncertainty about how the diverse range of musical instruments may impact respiratory aerosol concentrations and size distributions. Here, aerosol number and mass concentrations along with size distributions were measured for breathing, speaking, and playing four different woodwind and brass instruments by 23 professional instrumentalists. We find that a 1 dBA increase in sound pressure level corresponds to a ~10% increase in aerosol number concentration. The aerosol size distribution is consistent with that of breathing. Differences in aerosol emission across musical instruments can be partly explained by the loudness of performance. Measuring aerosol generation from single notes or simple songs may be sufficient to characterise the aerosol emission range during actual performance, provided a range of loudnesses are accessed. These results provide insight into the factors contributing to aerosol emission during musical performance and facilitate risk assessments associated with infectious respiratory disease transmission in the performing arts.

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1. Introduction

The COVID-19 pandemic caused unprecedented economic and social challenges, including disruption to live musical performance (Harari & Keep, 2021; United Nations, 2020). The inhalation of airborne particles and droplets has been identified as a significant route of respiratory infectious disease transmission (Morawska & Cao, 2020; Stilianakis & Drossinos, 2010). Strong empirical evidence exists for the emission of respiratory pathogens (such as COVID-19) in exhaled aerosols and droplets (Katelaris et al., 2021; Lednicky et al., 2020). These exhaled aerosols and droplets span a wide size range from the nano- to millimetre scale (Alsved et al., 2020; Gregson et al., 2021; Harrison et al., 2023). Their emission arises from activities including breathing, speaking, singing, musical instrument playing, exercise, coughing, and sneezing, and their size distributions depend on the type of activity being performed.

Previous studies of pathogen transmission risk while playing wind instruments have examined the dynamics of emitted aerosol plumes (Abraham et al., 2021; Becher et al., 2021; Köberlein et al., 2022; Stockman et al., 2021; Viala et al., 2022; Wang et al., 2022) and measured the amount of aerosol generated (Firle, Steinmetz, Stier, Stengel, & Ekkernkamp, 2022; Lai, Bottomley, & McNerney, 2011; McCarthy et al., 2021; Volckens et al., 2022). Knowledge about the source aerosol emission rate and plume influence distances can inform about the associated risk of pathogen transmission during musical performance (Stockman et al., 2021; Wang et al., 2022). Furthermore, simulated plume dynamics of aerosol emissions during musical performance with and without protection (such as using a bell cover for clarinet or a surgical mask for singers) suggest these mitigations effectively reduce the amount of particles emitted and alter air flow patterns (Stockman et al., 2021; Viala et al., 2022).

Studies of air flows and aerosol dispersion during wind instrument playing have provided insight into the short-range transport of airborne particles from performers, supporting assessments of risk and guidance on the physical distancing of performers. Becher et al. (2021) visualised the dispersion and mixing of air from instruments to infer transport distances of large (100 μm) droplets size in indoor settings, measured from recorded changes in air density using laser Schlieren methods. Other approaches have measured the dispersal of aerosol plumes during playing, with the aerosol first inhaled by performers from, for example, e-cigarettes (Köberlein et al., 2022). Using tracer plumes such as these can provide insight into dispersal, but the aerosol size distributions may not match those actually emitted during musical instrument performance. In all cases, plumes from musical performances have been shown to be highly directional over short range and variable with time and space. Over a distance of a few meters, turbulent mixing leads to a breakdown of the plume.

For studies focusing on aerosol concentration measurements, McCarthy et al. (2021) found that instrument playing generates less aerosol (defined here as particles <10 μm diameter) than speaking or singing at high loudness (sound pressure level (SPL) 90–100 dBA) and that loudness is positively correlated with aerosol number concentration. Similar trends were observed by Volckens et al. (2022) in brass emissions, but not in woodwind instruments. Firle et al. (2022) argued that aerosol emission depends on physiological factors and playing techniques rather than on the type of instrument, with their measurements made at an unspecified loudness. In addition, the comparative risk of instrument playing is also categorised by several studies to inform the associated risk of infection transmission. For example, He, Gao, Trifonov, and Hong (2021) suggested the trumpet, bass trombone, and oboe should be assigned high risk based on their aerosol generation relative to that generated by breathing and speaking. Moreover, Wang et al. (2022) reported that woodwind instruments present the highest risk, with a 20% higher source emission rate when compared with singing and brass instruments. In contrast, Schlenczek et al. (2023) pointed out that wind instruments present lower risk than speaking or singing since the large droplets can be filtered out by impaction. Indeed, McCarthy et al. (2021) reported no evidence of large droplet (>20 μm) production during the playing of wind instruments.

Despite several studies having examined aerosol number and mass concentrations generated when playing wind instruments, there remain numerous measurement challenges to address, contradictions among studies, and ambiguities in their interpretation. In particular, the primary challenge of identifying the aerosol generated in the lung by breathing and playing is significant. Measurements must be undertaken in spaces where performers inhale air uncontaminated by background aerosol (Gregson et al., 2021; McCarthy et al., 2021), ensuring that every particle measured when playing originates from the performer and not from indoor and outdoor aerosol sources. If the background aerosol concentration is non-zero, even the amplitude of the noise in the background aerosol concentration can be significantly larger than the very small concentrations of exhaled aerosol from the participant, compromising any conclusion from an aerosol measurement (Gregson et al., 2022). A few studies of aerosol generation from musical instrument performance have explicitly considered background aerosol concentrations and reported values that are sufficiently low to measure confidently respiratory aerosol concentrations (i.e. background concentration <0.1 cm^{-3}) (Firle et al., 2022; McCarthy et al., 2021; Schlenczek et al., 2023; Viala et al., 2022; Volckens et al., 2022; Wang et al., 2022).

Even if the issue of background aerosol is addressed, many studies have compared aerosol concentrations produced by multiple wind instruments, with only a single (and different) performer for each (He et al., 2021; Stockman et al., 2021). Indeed, in our original study we were limited to a cohort of wind players who each performed on different instruments (McCarthy et al., 2021). Recognising that the exhaled aerosol concentrations from individuals can span 2–3 orders of magnitude when breathing (Archer et al., 2022; Edwards et al., 2004), interpreting differences among wind instruments as inherently attributable to the instrument and not the performer must be avoided. Identifying unambiguously potential differences in aerosol generation across different instruments requires comparison among multiple cohorts of performers on different instruments, not individual performers for each instrument. To avoid this ambiguity, in our previous study we compared the distributions of aerosol generated by all wind instruments (i.e., grouped as a single cohort) to those generated during breathing, speaking, and singing (McCarthy et al., 2021). While many studies only compare individual performers on different wind instruments, a few have compared measurements made by multiple (>3) performers on the same instrument (Firle et al., 2022; Schlenczek et al., 2023; Volckens et al., 2022).

A final ambiguity in reported aerosol concentrations from wind instrument playing arises from the complexity of understanding the airflow pattern for different instruments. While the entire airflow passes through brass instruments, carrying aerosols through to dispersal from the bell, the airflow from woodwind instruments is considerably more complex (Abraham et al., 2021). Air does not just pass from the mouthpiece to the bell but may exit the instrument through open keys over the entire length of the instrument. Although relative aerosol number concentrations between brass and woodwind instruments can be compared at the bell exit, the absolute number or mass of exhaled aerosols cannot be compared without knowledge of the relative flow rates through various open keys and through the bell.

In this study, we compare the aerosol concentrations and size distributions generated by breathing, speaking, singing, and playing several wind instruments in an environment with a zero aerosol number concentration background. Measurements are presented for separate cohorts of performers for each instrument, specifically the flute (and piccolo), clarinet, and trumpet. The roles of loudness and articulation are also explored. The results are discussed in the context of recent investigations on aerosol generation from musical instrument performance.

2. Materials and methods

2.1. Human participants

The PERFORM study was approved by the Public Health England Research Ethics and Governance of Public Health Practice Group (PHE REGG: PERFORM-1 PHE study number NR0221, PERFORM- 2 R&D reference 429). 23 professional instrumentalists (11 male, 12 female) were recruited in the sampling cohort, including 8 trumpet players, 8 clarinet players, and 7 flute players. The flute players also played piccolo. All instrumentalists were pre-screened as free from cardiac, metabolic, or respiratory disease, including severe asthma and COVID-19 symptoms. All participants tested negative for COVID-19 prior to participation using a lateral flow test.

2.2. Respiratory aerosol concentration and sound intensity measurement

The number concentrations and size distributions of respiratory aerosol particles were measured during breathing, vocalisation, and instrument playing tasks. The sampling setup was identical to that used in our past studies to allow comparative measurements across breathing, speaking, singing, and woodwind and brass instrument playing (Gregson et al., 2021). Aerosol concentrations were measured using an Aerodynamic Particle Sizer (APS, 0.53–20 μm diameter, TSI 3321) in a laminar flow orthopaedic operating theatre. Because all particles <0.53 μm are grouped into the same bin with no discrimination on the basis of size, we do not include this bin in our analysis of APS data. The APS detection efficiency is known to decrease by a factor of 2–3 from 0.8 to 10 μm (Volckens & Peters, 2005). However, this drop in detection efficiency is much smaller than the 3 orders of magnitude decrease in number concentration observed for respiratory aerosol from 1 to 5 μm diameter, with very few particles >5 μm detected and therefore contributing little to the total number concentration. The accuracy of our measurements at these larger sizes is limited by counting statistics (Gregson et al., 2022). The air handling system within this operating theatre was such that the background aerosol concentration in the 0.5–20 μm diameter size range was 0 cm^{-3} (Gregson et al., 2022). Three APS instruments were used during this study. Reported aerosol concentrations are averages over the period particles were detected from the activity. Volumetric flow rates through the musical instruments were not measured in this study. Therefore, only the intensive property of aerosol concentration is reported here (Gregson et al., 2022). The SPL of vocalisation and instrument playing (in dBA) was recorded by a decibel meter (UNI-T, UT353) placed 30–40 cm away from the sampling funnel. Temperature and relative humidity in the orthopaedic operating theatre were 20°C and 45%, respectively, consistent with ambient conditions in our previous study of aerosols generated by musical instrument performance (McCarthy et al., 2021). As described in the experimental protocol below, gaps both between sets of activities and between repeats within one set of activities ensured that dry, particle-free room air was regularly pulled through the sampling tubing. Consequently, it is unlikely that relative humidity could build up within the sampling tubing and substantially alter the measured aerosol size distributions.

2.3. Breathing, speaking, and singing experiments

Each participant performed a series of tasks to quantify aerosol generation during breathing, speaking, and singing. Each task included five repetitions in total. First, participants were instructed to breathe in through the nose and out through an open mouth for 10 s. In between repetitions, participants were instructed to stand approximately 2 m away from the sampling funnel for 30 s in order to ensure a return to the background aerosol concentration (0 cm^{-3}).

Participants were also instructed to perform two tasks involving vocalisation, consistent with our previous studies (Archer et al., 2022; Gregson et al., 2021; McCarthy et al., 2021). Participants first spoke the words to the “Happy Birthday” song to “Dear Susan” at 70–80 dBA for 20 s, with a 30 s break between repetitions. Participants also sang a single note at 70–80 dBA for 10 s, with a 20 s break between repetitions. Additionally, participants sang the “Happy Birthday” song to “Dear Susan” at 70–80 dBA for 20 s, with a 20 s break between repetitions.

2.4. Musical instrument experiments

Participants were invited to perform a series of tasks while playing their respective musical instruments. First, participants played a single note in the low, middle, and high range of their instrument, along with the lowest pitch note on their instrument (Table S1 details the tonal range.). These single note experiments were conducted at three dynamic levels (*piano*, *mezzo forte*, *forte*), each for 20 s and repeated a total of three times. Participants were asked to play at the loudness level they associated with the specified dynamic marking, recognising there would be variability in SPL among the different instruments and performers for the same dynamic marking. Therefore, the SPL associated with a specific dynamic was also recorded using the decibel meter. The range of SPL recorded by the decibel meter across the three dynamic ranges (*piano* to *forte*) spanned 60–100 dBA, a range very similar to that explored in our previous vocalisation studies (Archer et al., 2022; Gregson et al., 2021), but wider than that investigated in our previous study on aerosol generation by musical instruments, 70–90 dBA (McCarthy et al., 2021). Continuous playing activities were also investigated. Participants played the "Happy Birthday" song at *forte* with *legato* and *staccato* articulation types for 30 s (3 repetitions for each technique). Lastly, participants were asked to play any piece they desired for 1.5 min (free play) with the SPL recorded along with aerosol generation.

In addition to playing their primary musical instrument, the flute sub-cohort was asked to play piccolo. These experiments were designed to assess whether the musical instrument played an important role in aerosol generation (rather than the performer).

2.5. Data processing and statistical analysis

The raw data of aerosol counts from the APS instrument were collected with the Aerosol Instrument Manager software (TSI) and

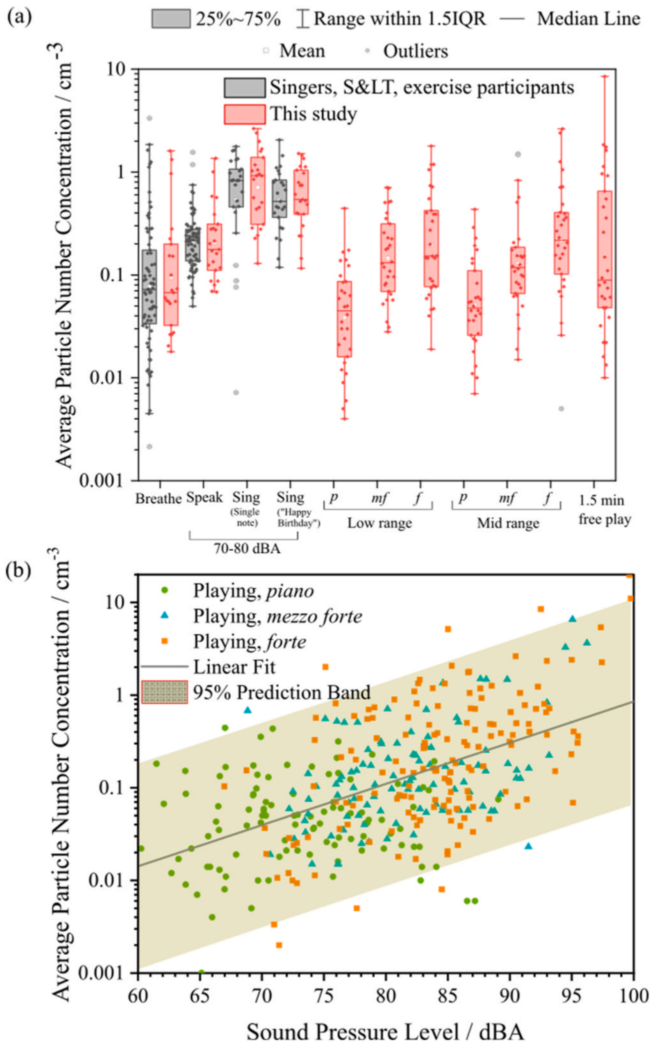

Fig. 1. (a) Box and whisker plot showing particle number concentration for the same series of activities for all 23 participants (red box) compared with a breathing and vocalisation study done with a larger cohort (grey box); (b) Average particle number concentration plotted against SPL for professional musicians playing their instruments at *piano* (*p*), *mezzo forte* (*mf*), and *forte* (*f*). Participants were asked to play at the loudness they associate with the specified dynamic marking, recognising that there would be variability in SPL among the different instruments and performers for the same dynamic marking. The shaded area around the linear fit is a 95% prediction band. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

post-processed with a custom-written software in LabVIEW (Gregson et al., 2021; McCarthy et al., 2021). The post-processed files were analysed in Origin (OriginLab®). For the statistical analysis, variables were aggregated to the individual level due to different sampling regimes across studies. Data were inspected and log transforms were used when the data were skewed. For pairwise comparisons between different instrumentalist cohorts, independent sample *t*-tests were used while for comparisons of different activities within individuals paired *t*-tests were used. Multilevel models were also fitted using MLwiN v3.06 to consider overall effects of instrument type and sound intensity when combining data across notes and playing styles with the data exhibiting a 3-level hierarchy of observations nested within instruments nested within players (Charlton, Rasbash, Browne, Healy, & Cameron, 2022). Full details of the statistical analysis are provided in the Supporting Information (Supplementary Statistical Information).

3. Results and discussion

Initially, we compare the aerosol number concentrations measured during breathing, vocalising, and playing musical instruments across all instrument cohorts. Then we compare aerosol generation across different instruments. Finally, we compare the aerosol size distributions and mass concentrations during breathing, vocalising, and playing.

3.1. Aerosol number concentrations generated while breathing, vocalising, and playing a single note across all participants and instruments

Fig. 1a presents particle number concentrations generated by breathing, vocalisation, and playing musical instruments across the entire instrumentalist cohort. These results are compared to other participants in the PERFORM study (25 singers, 23 speech and language therapy (S&LT) participants, and 25 exercise participants; grey symbols and bars) sampled using the same or nearly identical protocols (Archer et al., 2022; Gregson et al., 2021; McCarthy et al., 2021; Orton et al., 2022; Saccente-Kennedy et al., 2022). Number concentrations generated by the instrumentalist cohort while breathing, speaking, singing a single note at 70–80 dBA, and singing "Happy Birthday" at 70–80 dBA are consistent with the number concentrations generated by other cohorts performing the same activity ($p > 0.05$ for each of the four activities, see SI Statistics 1).

The amount of aerosol generated while playing a single note in the low and mid-range of an instrument generally increases with increasing loudness, consistent with our previous study (Fig. S1) (McCarthy et al., 2021). Playing at *forte* generated significantly higher aerosol number concentrations compared to playing at *piano* for both low and mid-range (both $p < 0.001$, see SI Statistics 2). The pitch at which the note was played did not substantially affect the measured number concentration (Fig. S2), and the observations of increasing emitted aerosol concentration with increasing sound intensity are consistent for flute and piccolo when measured either at the mouth or at the end of the instrument (Fig. S3). The 1.5 min free play task inherently incorporates multiple dynamic ranges and articulations (e.g. *legato* vs. *staccato*). The range of aerosol generated during the free play task is largely encompassed by the range generated by playing single notes at specific dynamic markings (with one outlier at high concentration). This observation suggests that measurements of single notes may be representative in characterising the limiting emissions scenarios. Overall, aerosol generation during musical instrument playing is similar to or less than that generated by singing at moderate loudness (70–80 dBA), an observation broadly consistent with our previous work (McCarthy et al., 2021). In our previous study, we reported that across multiple performers the differences in the amount of aerosol emitted while playing a single note qualitatively scaled with that emitted by those

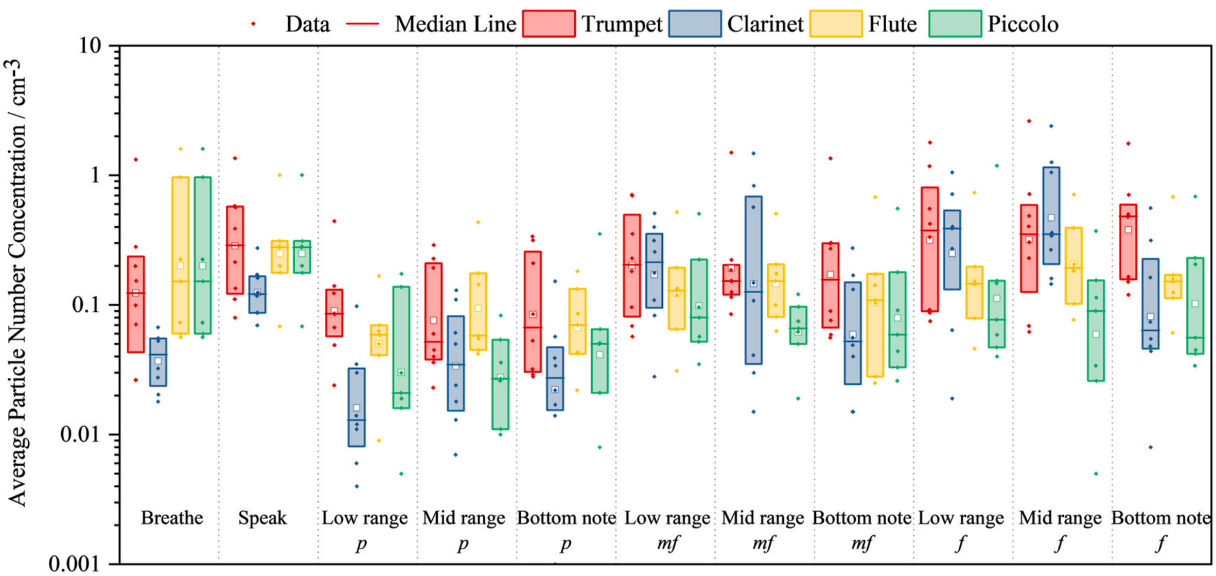

Fig. 2. Comparison of particle number concentration during breathing, speaking, and single-note playing among different types of instrument players.

performers while breathing (McCarthy et al., 2021). Although no unambiguous statistical significance between breathing and single note playing emission emerges from the current study, the p-value ($p = 0.064$) when adding (logged) breathing emission to the playing one note multilevel model (see SI Statistics 3) controlling for instrument and sound intensity is close to the significance threshold (0.05), suggesting a larger cohort may be required to ascertain this relationship.

Fig. 1b explores the comparison of aerosol generation and sound intensity with finer detail by reporting the measured particle number concentration against sound intensity for every participant playing a single note in the low and middle range as well as the bottom note of their instrument. Colours indicate the dynamic marking (*piano*, *mezzo forte*, and *forte*) suggested to the participant. There are several interesting points to draw from this plot. First, while most measurements at *piano* and at *forte* are clustered in different portions of the plot, there is still some overlap in SPL, with some notes played at *piano* having similar SPL to other notes played at *forte*. This observation is due to different instruments accessing different dynamic ranges and instrumentalists gauging dynamic markings differently. Second, at a given SPL range, aerosol generation can vary up to ~2 orders of magnitude. This level of variability is consistent with the large interpersonal variability associated with respiratory aerosol generation (Archer et al., 2022; Gregson et al., 2021; McCarthy et al., 2021). Third, number concentration is positively correlated with SPL. The correlation shows a power law relationship between SPL and number concentration and suggests that, across the 60–100 dBA range, aerosol generation can span 2–4 orders of magnitude. From the multilevel model, we can infer that a 1 dBA increase in SPL corresponds to an increase in number concentration by 10% (95% CI 8%–12%), which is broadly consistent to values reported previously for brass instruments by Volckens et al. (2022).

3.2. Aerosol number concentrations generated during breathing, speaking, and single-note playing in the musical instrument sub-cohorts

After presenting aggregated data for all participants, we now consider each instrument cohort (trumpet, clarinet, flute, and piccolo) in order to identify if there is an instrument-specific contribution to the amount of aerosol generated. Fig. 2 reports the number concentration of single-note playing for four instruments as well as breathing and speaking from instrumentalists for comparison. Note that the flute and piccolo were played by the same performers. Substantial instrument-to-instrument variability is observed, in part a consequence of the much smaller cohort sizes. Flute players (the same sub-cohort as piccolo players) generated more aerosol while speaking than while playing a single note at different loudness levels, consistent with observations from Volckens et al. (2022). However, this is not the case for clarinet and trumpet players. Trumpet players generated the highest number concentrations while speaking compared to the other sub-cohorts, and the number concentrations for the majority of trumpet playing tasks are between breathing and speaking. In addition, trumpet players generated the highest aerosol emissions in the majority of the single-note playing activities (apart from playing at mid-range *mezzo forte* and *forte*).

Fig. 3 shows the aerosol emissions from different instruments grouped into 10 dBA SPL bins. Overall, the dependence of aerosol generation on SPL is apparent but less obvious than when reported across all cohorts in Fig. 1b. This observation is a consequence of 40% and 59% of data points for flute and piccolo, respectively, falling within the 70–80 dBA bin, whereas 70% and 60% of data points for trumpet and clarinet, respectively, are in the 80–100 dBA range. Therefore, grouping the data into these SPL bins effectively reduces the measurement resolution, hindering observation of SPL dependence. This result also suggests that the higher number concentrations reported for trumpet and clarinet players in Fig. 4a arise in part because these performers were more likely to play louder than flute and piccolo players when provided the same dynamic marking suggestion. Indeed, when fitting a multilevel model with

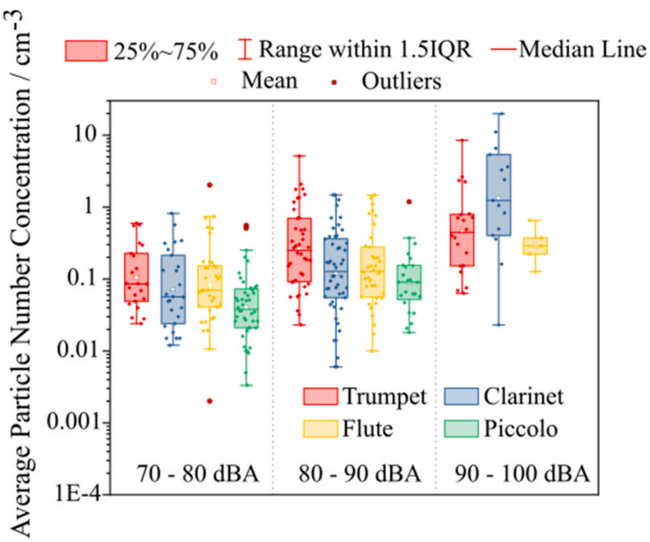

Fig. 3. Comparison of particle number concentration grouped by the sound intensity ranges at a 10 dBA interval. Note that flute and piccolo data were sampled at the performer's mouth.

instrument type and sound intensity (as a continuous measure) there was a significant effect of SPL ($p < 0.001$). The only statistically significant difference between instruments that is not explained by SPL is a modest one (multiplication factor of 1.8, 95% CI 1.3–2.5) between flutes and piccolos ($p = 0.001$), with all other instrument pairs not statistically significantly different (see SI Statistics 3).

3.3. Aerosol number concentrations and sound intensity generated during continuous playing activities

In Fig. 4a, we report the aerosol number concentration produced by playing “Happy Birthday” legato (*forte*) and staccato (*forte*). For most trumpets, flutes, and piccolos, playing legato generated more aerosol than playing staccato, presumably because a larger portion of the performance time is spent generating sound while playing legato. Trumpet players generated aerosol concentrations at least one order of magnitude higher than observed for clarinets, flutes, or piccolos while playing “Happy Birthday”. As shown in Fig. 4b, trumpet players also performed this task at a significantly higher SPL than all other instrument groups for both legato and staccato ($p < 0.001$ for each comparison, see SI Statistics 4). Comparing the aerosol generated by all instruments while playing “Happy Birthday” to the 1.5 min free play task (purple box) shows that playing “Happy Birthday” (both legato and staccato) generates similar number concentrations to free play ($p > 0.05$, see SI Statistics 5). The corollary to this observation is that the specific musical piece played may not determine the amount of aerosol generation, provided it covers an appropriate range of loudness.

3.4. Explorations of instrument-to-instrument variability

Next we compare aerosol emissions from different instrument cohorts. The aim of this comparison is to identify if a specific musical instrument impacts the amount of generated aerosol (i.e., there is instrument-to-instrument variability) or if observed variations

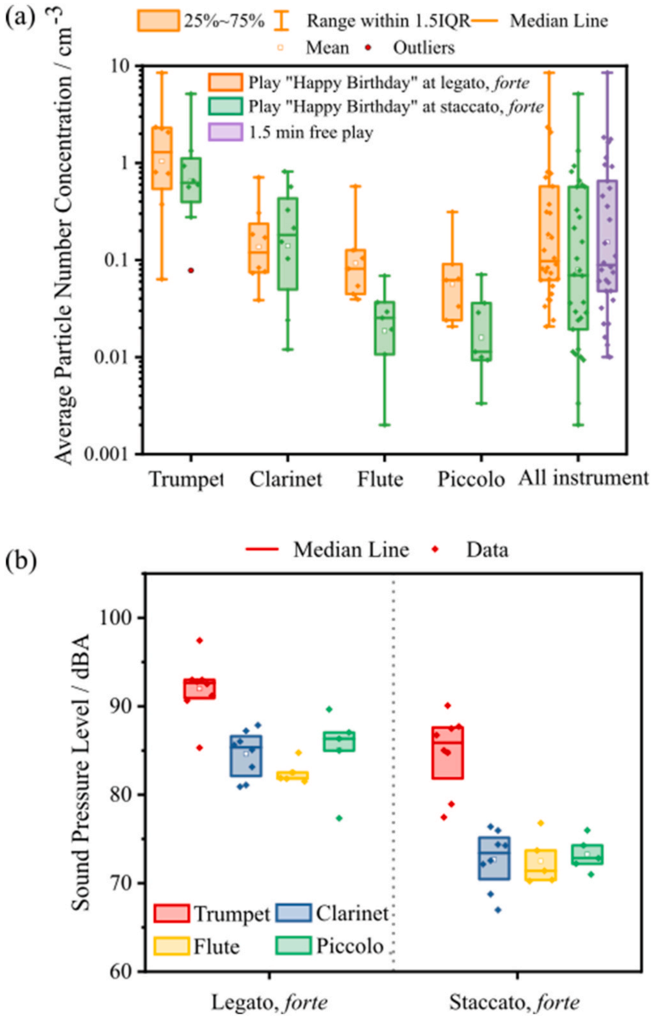

Fig. 4. The aerosol (a) particle number concentration generated by playing “Happy Birthday” at legato (*forte*) and staccato (*forte*); (b) the SPL recorded while playing “Happy Birthday” for trumpet, clarinet, flute, and piccolo.

among instruments may instead result from variations among performers' emissions alone. Participants who played flute also performed a subset of the tasks with a piccolo, allowing comparison of two different instrument cohorts playing the same instrument. Fig. 5 shows aerosol number concentrations measured while playing "Happy Birthday" at legato (*forte*) compared to breathing for each cohort. Trumpet players generated modestly more aerosol than clarinet players when breathing, and the same trend is observed when playing at legato (*forte*). However, when playing "Happy Birthday", clarinet players generated modestly, but not significantly, more aerosol than flute (or piccolo) players ($p > 0.05$), whereas trumpet players generated substantially more than all three other instruments ($p < 0.05$, see SI Statistics 6). From the multilevel modelling, which includes the differences in SPL at which each instrument was performed (SI Statistics 7), we find that an increase in 1 dBA corresponds to an increase in aerosol number concentration of 8% (95% CI 3%–11%), a value consistent with the single note measurements. Moreover, SPL explains a proportion (but not all) of the observed difference. There are still significant differences between trumpet and flute (multiplication factor 5.5, 95% CI 1.7–18, $p = 0.004$) or piccolo (multiplication factor 24, 95% CI 7.6–78, $p < 0.001$), but when accounting for SPL the difference between trumpet and clarinet (multiplication factor 2.7, 95% CI 0.96–7.8 $p = 0.06$) is not statistically significant. This observation is in contrast to the single note experiments discussed above, where no significant instrument-to-instrument differences were observed among trumpet, clarinet, and flute. We hypothesise that the difference observed while playing "Happy Birthday" may arise from the manner in which sound is generated in different instruments. Trumpets generate sound through the lips (two mucosal surfaces) in oscillation against the mouthpiece, whereas clarinets generate sound through the oscillation of a reed against one lip. Flutes and piccolos, however, generate sound without requiring oscillation of any mucosal surface. There is a difference between clarinet and piccolo (multiplication factor 8.9, 95% CI 3.0–26, $p < 0.001$) and a difference between flute and piccolo (multiplication factor of 4.4, 95% CI 1.9–10, $p < 0.001$). This final observation for flute and piccolo is consistent across both the "Happy Birthday" and single note experiments. However, as highlighted in Figs. 1a and 4, both single note and "Happy Birthday" playing encompass the range of aerosol concentrations generated during free play.

3.5. Aerosol size distributions and mass concentrations

Measured size distributions for breathing, speaking, and singing were fit to bimodal lognormal distributions, consistent with previous studies (Asadi et al., 2019; Gregson et al., 2021; Johnson et al., 2011; Morawska et al., 2009). The fits for the different levels of loudness and types of vocalisation all gave very similar mean diameters and variance for both the lower respiratory tract and laryngeal modes.

Fig. 6a compares the number size distribution for breathing, speaking, and singing (70–80 dBA) with those from Gregson et al. (2021). When the mean size distributions are normalised with respect to $D_p = 1$ μm for each activity (Fig. 6b), both datasets converge on each other for the same activity (breathing or vocalising). Consistent with previous studies, vocalising generated more and larger particles than breathing. Consequently, as shown in Fig. 6c, mass concentrations during vocalisation are significantly higher than those for breathing ($p < 0.001$ for all activities compared to breathing, see SI Statistics 8 for details). The main difference between the instrumentalist cohort and the rest of the PERFORM cohort is that the instrumentalist cohort systematically generated aerosol on the lower range of the distribution, as shown in Fig. 6c. The reasons for this observation are unclear but could be a consequence of the multiple APS instruments used in this study having differing sensitivities across the multiple days of measurement.

The normalised aerosol size distributions for playing and breathing from this cohort are compared to our previous cohort of

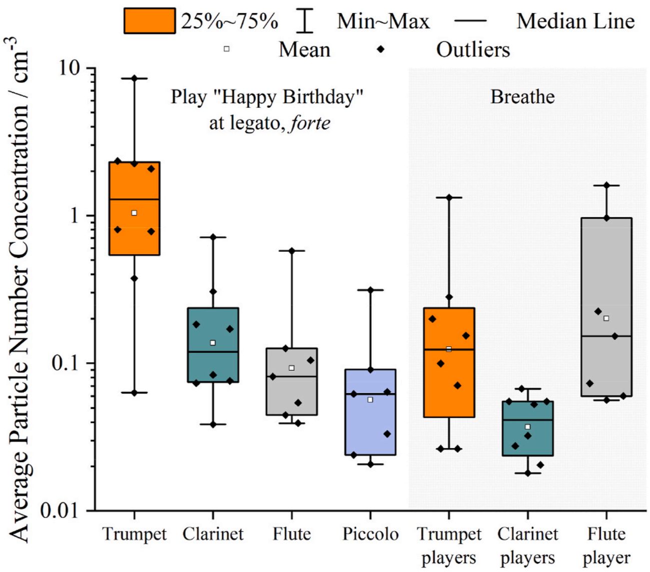

Fig. 5. The average particle number concentration while playing "Happy Birthday" at legato (*forte*) compared with breathing.

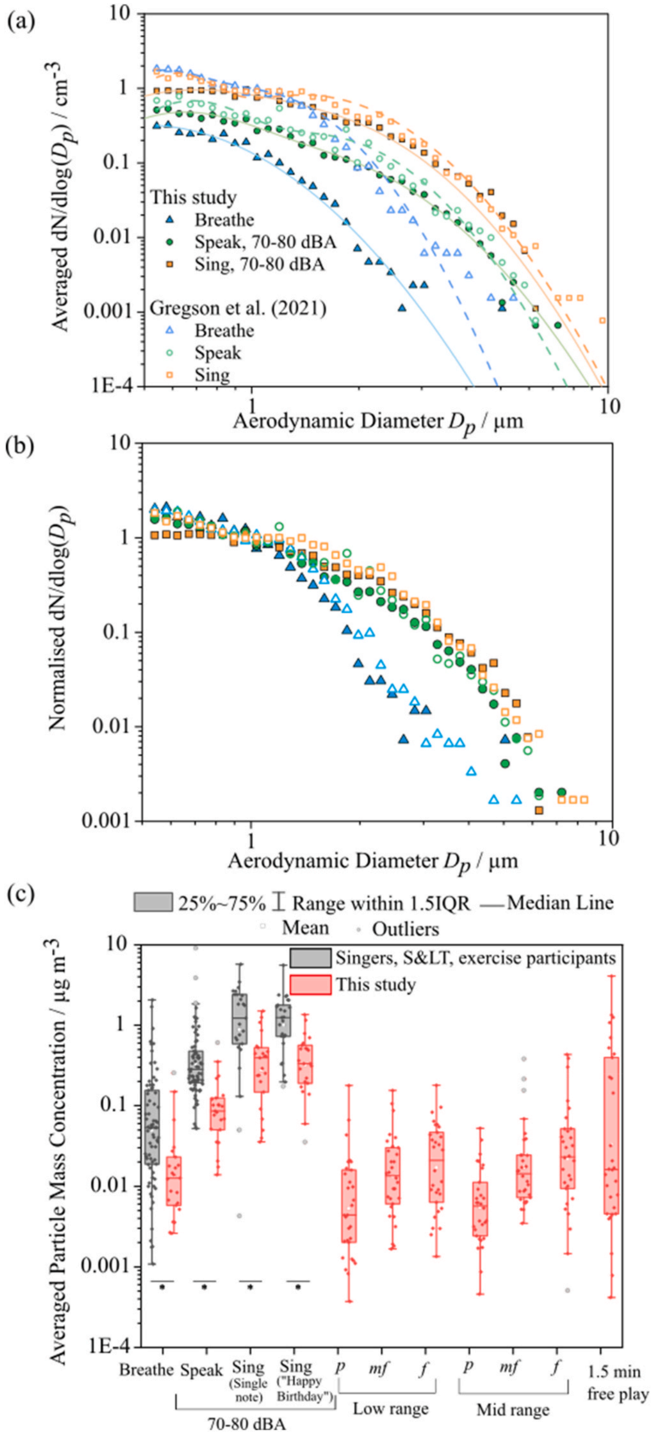

Fig. 6. (a) Comparison of mean aerosol size distributions generated by instrumentalists and singers (from previous studies) when breathing, speaking and singing at 70–80 dBA, and (b) the normalised mean number concentrations compared to Gregson et al. (2021). Curves of similar colour show the bimodal lognormal fit for each dataset. The solid lines correspond to data from this study whereas dashed lines indicate the fit to data from Gregson et al. (2021). (c) The particle mass concentrations from this study (red box) compared with our previous studies including 25 singers, 23 S&LT, and 25 exercisers (grey box). In (c), the asterisk (*) indicates a statistically significant difference between cohorts ($p < 0.05$, see SI Statistics 9 for details). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

instrumentalists in Fig. 7 (McCarthy et al., 2021). Both sets of size distributions are broadly consistent with each other. The breathing and instrument playing size distributions lack the prominent mode associated with vocalisation at larger particle size and are instead dominated by the particles in the smaller bronchiolar mode common across all respiratory activities and presumably arising from aerosol generated in the lower respiratory tract. Fig. S4 shows that the instrument playing size distributions are consistent across all four instrumentalist sub-cohorts.

3.6. Comparisons to previous studies

Numerous studies have reported aerosol generation during musical instrument performance, sometimes with conflicting results. However, on some areas there is consensus. First, aerosol number concentrations generated by musical instrument performance can span a range of ~0.01–100 cm^{-3} (He et al., 2021; McCarthy et al., 2021; Schlenczek et al., 2023; Stockman et al., 2021; Volckens et al., 2022; Wang et al., 2022). While broad, this concentration range is consistent with the range of aerosol number concentration generated by respiratory activities like breathing (Archer et al., 2022; Asadi et al., 2020; Gregson et al., 2021; Johnson et al., 2011; Pöhlker et al., 2021). Second, there is agreement that musical instrument performance does not result in significant emission of large respiratory droplets (McCarthy et al., 2021; Schlenczek et al., 2023; Tanner et al., 2023; Viala et al., 2022). McCarthy et al. (2021) and Schlenczek et al. (2023) both showed, using different experimental methods, that large droplets (normally generated during vocalising and articulation but not during breathing) were absent during musical instrument performance (McCarthy et al., 2021; Schlenczek et al., 2023). Additionally, Tanner et al. (2023) found that musical instrument performance generated very few large droplets compared to speaking and singing. These experimental results are supported by computational fluid dynamics modelling of aerosols and droplets transiting through musical instruments, which show that most particles >1 μm (if generated) are lost to the walls of the musical instrument (Viala et al., 2022). This conclusion may have implications in terms of disease transmission risk, as larger droplets contain most of the respiratory aerosol mass despite accounting for a small portion of aerosol number (Bagheri, Thiede, Hejazi, Schlenczek, & Bodenschatz, 2021; Harrison et al., 2023; Johnson et al., 2011; Srinivansan & Mayya, 2020; Srinivasan, Krishan, Bathula, & Mayya, 2021).

Areas on which there is more disagreement across studies generally relate to instrument-specific differences, as well as the role of dynamics and articulation. For instance, although a loudness dependence to vocalisation is well-recognized (Alsved et al., 2020; Archer et al., 2022; Asadi et al., 2020; Good et al., 2021; Gregson et al., 2021; Murbe et al., 2021; Srinivansan & Mayya, 2020; Srinivasan et al., 2021), a loudness dependence to musical instrument performance is more ambiguous. He et al. (2021) reported a loudness dependence to musical instrument performance that was highly instrument specific, with some dependence for woodwinds but none for brass instruments. Meanwhile, Volckens et al. (2022) observed a loudness dependence to aerosol generation for brass instruments, but not for woodwinds. By contrast, our studies demonstrate that loudness is an essential determining component for aerosol generation during musical instrument performance. This observation is most apparent from measurements across individual performers spanning a wide range in SPL (in dBA, see Fig. 1). We find that a 1 dBA increase in SPL corresponds to a 10% (95% CI 8%–12%) increase in number concentration, broadly consistent with the conclusions of Volckens et al. (2022). We note that He et al. (2021) do not report quantitative loudness measurements, which can vary significantly across different instruments, with some instruments generating sound in a relatively limited range compared to others (see our Figs. 3–4b). On the other hand, Schlenczek et al. (2023) found clarinet and trombone emitted the most aerosol. The SPL range that we access in our measurements (60–100 dBA) is wider than that accessed Volckens et al. (2022) (70–90 dBA for woodwinds and 75–90 dBA for brass). Articulation can also affect the aerosol generation (Firle

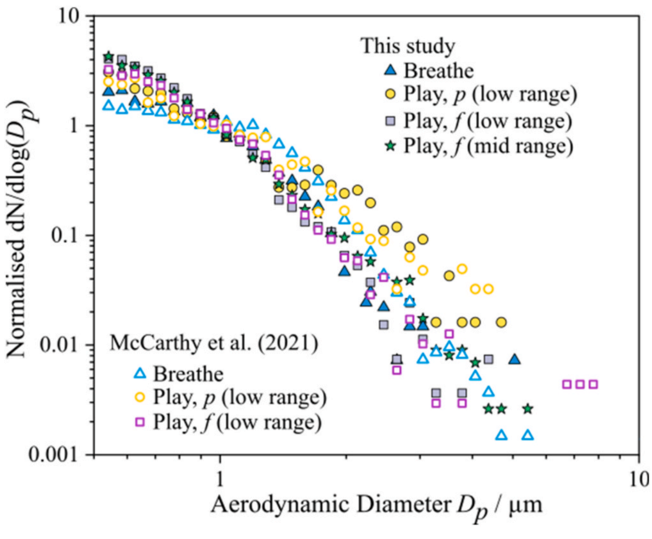

Fig. 7. Comparison of mean aerosol size distributions generated by breathing and single-note playing task at *piano* and *forte* dynamics with a previous study by McCarthy et al. (2021).

et al., 2022; He et al., 2021), an observation borne out in our comparison of *legato* and *staccato* performance.

Playing some instruments has been perceived to present a higher risk of generating respiratory aerosol than other instruments. He et al. (2021) ranked instruments into different risk categories, with trumpets deemed high risk, and clarinets and flutes as intermediate risk. Stockman et al. (2021) found that clarinet playing generated a large amount of aerosol. It is important to note that cohort sizes for these studies were extremely small (1–3 performers per instrument). Volckens et al. (2022) found that playing brass instruments generated nearly three times more aerosol than playing woodwind instruments. Meanwhile, Wang et al. (2022) found that playing woodwind instruments generated more aerosol than playing brass or singing. Our study sheds some light on these apparent differences, although it cannot fully resolve them. When playing single notes, the variation in aerosol concentration across instrument sub-cohorts is largely explained by differences in loudness. However, when playing "Happy Birthday", loudness can only explain a portion of the difference in aerosol generation measured for the trumpet relative to flute and piccolo and for the clarinet relative to piccolo. We also find that, even after controlling for loudness, the flute generates more aerosol than piccolo both during single note playing and while playing "Happy Birthday". Nonetheless, across all instruments, the single note and "Happy Birthday" experiments encompass the range of aerosol generated during the free play measurement, suggesting that these diagnostic experiments are sufficient to characterise the range of aerosol generated during musical performance.

Comparisons to generic respiratory activities (i.e. breathing and speaking) have also led to disagreements. In our work, we find that musical instrument performance generates less aerosol than speaking or singing at 70–80 dBA (this study) and at 90–100 dBA (McCarthy et al., 2021). Such comparisons are somewhat fraught, however, as key parameters are the loudness of the activity (for both musical instrument playing and vocalising). Many studies have compared instrument playing to vocalising, but the loudness was not reported quantitatively, which hinders a more direct comparison of the two activities (Firle et al., 2022; Stockman et al., 2021; Volckens et al., 2022; Wang et al., 2022). The comparison is also inexact because the aerosol size distribution generated by musical instrument playing is consistent with that of breathing and inconsistent with that of vocalising (Firle et al., 2022; McCarthy et al., 2021), which contains larger particles and droplets.

Overall, we suggest that loudness is an essential parameter for accurately comparing aerosol generation during musical performance. We propose that all future studies systematically quantify the loudness in SPL at which each activity is performed as well as the exhalation rate for each activity (to quantify emission rates) to make more direct comparisons across activities and cohorts.

4. Conclusions

In conclusion, respiratory aerosols generated by breathing, speaking, and playing woodwind and brass instruments were measured in a cohort of professional instrumentalists (23 participants playing four instruments). Overall, aerosol number concentrations generated during musical instrument playing were largely similar to those generated by singing at moderate loudness (70–80 dBA). Aerosol size distributions generated while playing musical instruments are consistent with those for breathing, regardless of the instrument type, and lack the larger diameter particles generated during sustained vocalisation. Consequently, aerosol mass generated from musical instrument playing was generally less than that generated while singing at moderate loudness.

Measured number concentration increased with increasing loudness. However, dynamic level markings (i.e. *piano, forte*) are not necessarily a good indicator of aerosol emission because the SPL associated with these dynamic levels can vary significantly among instrument cohorts. A 1 dBA increase in SPL is associated with approximately a 10% increase in aerosol number concentration. Flute playing generally emits more aerosol than piccolo playing. For single note playing, average differences in aerosol emission by trumpets, clarinets, and flutes can be largely explained by variations in the loudness of the performance. However, trumpets emit more aerosol than flutes when playing "Happy Birthday", and all instruments emit more aerosol than piccolo in this case. These differences can only partially be explained by differences in loudness. Measurements of aerosol generation while playing single notes at different loudnesses or playing simple songs like "Happy Birthday" may be sufficient to characterise the range of aerosol emission during actual performance provided sufficient loudness ranges are accessed. The results of this study contribute to managing the risk associated with infectious respiratory disease transmission in the performing arts.

CRediT authorship contribution statement

Jianghan Tian: Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Henry E. Symons:** Investigation, Methodology, Validation, Writing – review & editing. **Natalie A. Watson:** Conceptualization, Funding acquisition, Investigation, Methodology, Writing – review & editing. **Justice Archer:** Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – review & editing. **Lauren P. McCarthy:** Investigation, Validation, Writing – review & editing. **Joshua Harrison:** Investigation, Writing – review & editing. **Malcolm Kittle:** Investigation, Writing – review & editing. **William J. Browne:** Conceptualization, Data curation, Formal analysis, Methodology, Validation, Writing – review & editing. **Brian Saccente-Kennedy:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Ruth Epstein:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Christopher M. Orton:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **James D. Calder:** Conceptualization, Funding acquisition, Writing – review & editing. **Pallav L. Shah:** Funding acquisition, Writing – review & editing. **Declan Costello:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Jonathan P. Reid:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. **Bryan R. Bzdek:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing, Formal analysis, Investigation, Methodology.

Data availability

Data underlying the figures are publicly available in the BioStudies database (https://www.ebi.ac.uk/biostudies/) under accession ID S-BSST1256.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jaerosci.2023.106318.

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