Measurements and Simulations of Aerosol Released while Singing and Playing Wind Instruments

Tehya Stockman[a], Shengwei Zhu[b], Abhishek Kumar[c], Lingzhe Wang[d], Sameer Patel[e], James Weaver[f], Mark Spede[g], Donald K. Milton[h], Jean Hertzberg[i], Darin Toohey[j], Marina Vance[k], Jelena Srebric[l], Shelly L. Miller[m]

[a] Department of Civil, Environmental, and Architectural Engineering, University of Colorado Boulder, Boulder, CO, 80309, USA
[b] Department of Mechanical Engineering, University of Maryland, College Park, 20742, MD, USA
[c] Department of Mechanical Engineering, University of Colorado Boulder, Boulder, 80309, CO, USA
[d] Department of Mechanical Engineering, University of Maryland, College Park, 20742, MD, USA
[e] Department of Civil Engineering, Indian Institute of Technology, Gandhinagar, Gujrat, 382355, India
[f] National Federation of State High School Associations, Indianapolis, IN, 46402, USA
[g] Department of Performing Arts, Clemson University, Clemson, SC, 29634, USA
[h] Maryland Institute for Applied Environmental Health, School of Public Health, University of Maryland, College Park, MD, 20740, USA
[i] Department of Mechanical Engineering, University of Colorado Boulder, Boulder, 80309, CO, USA
[j] Department of Atmospheric and Oceanic Sciences, University of Colorado Boulder, Boulder, 80309, CO, USA
[k] Department of Mechanical Engineering, University of Colorado Boulder, Boulder, 80309, CO, USA
[l] Department of Mechanical Engineering, University of Maryland, College Park, 20742, MD, USA
[m] Department of Mechanical Engineering, University of Colorado Boulder, Boulder, 80309, CO, USA

Appendix 1: Recommendations for Musicians

The goals of the recommendations are to limit emissions and exposure to potentially infections aerosols produced by musical performance. Wind instruments, singing, and theater performance produce aerosols, which vary by intensity and pitch.[1] We recommend a layered approach to decreasing exposure to potentially infectious aerosols, larger droplets, and surfaces. The layered approach we recommend includes: wearing face masks and putting masks over the bells of wind instruments; rehearsing and performing in well-ventilated spaces; limiting rehearsal time; practicing good hand hygiene; disposing of liquids from spit valves in an appropriate receptacle.

1.1 Masks for singers and musical instruments

We found that bell "masks" for wind instruments and well-fitted masks for singers and performers were effective at decreasing aerosols and larger droplet emissions from musical performance. Aerosol concentrations measured at bell of instruments and in front of the mouth of singers decreased across a wide range of instruments and performers when a mask was worn. These control measures also decreased the jet speed and extent, decreasing the plume range of more highly concentrated aerosol exposure.

1.1.1 Note on bell covers for woodwind instruments

While air and aerosols escape from keyholes from woodwind instruments, we found that the number of particles was minimal. Using a bell cover eliminated a majority of the aerosol coming from the instrument. Because covering every keyhole of a woodwind instrument (such as playing with the instrument in a bag) makes it difficult and uncomfortable to play, we recommend bell covers as the main control measure for woodwind instruments.

1.1.2 Note on materials of bell covers

Standard 3-layer surgical masks were used for small instruments, such as woodwinds. Large instruments were tested with Merv-13 material inside of a nylon spandex material. Utilizing only a stretchy material such as spandex is not recommended. As the material stretches to fit over the bell, aerosols can more easily pass through the holes in the material.

[1] Alsved et al. 2020. DOI 10.1080/02786826.2020.1812502.

1.2 Face Shields

Face shields are only effective at close range to stop large droplets (such as the visible droplets from a cough or sneeze) and do not prevent aerosols from being emitted or inhaled. Aerosols are small and follow streamlines around face shields. Lindsley et al. found that face shields blocked approximately 2% of aerosols generated by a cough aerosol simulator.[2]

1.3 Plexiglass/Plastic/Glass Barriers are Not Recommended

We do not recommend plexiglass partitions or barriers as they have been shown to not protect against aerosol exposure[3]. Similar to face shields, aerosols follow streamlines around the barriers. There is large variability in each room and the HVAC system (or lack thereof) for each space. This makes it especially challenging to determine the effect of barriers, because the effects may vary considerably depending on these factors.

1.4 Social Distancing Recommended

Performers should follow social distancing protocols as recommended by the CDC for music activities. Aerosol concentrations are highest closest to the source, both inside and outside, and decrease with distance.

1.5 Rehearsal Space Preference Order

We recommend that musicians and performers perform in outside environments compared to indoor environments. If musicians cannot perform outside, then indoor performance spaces must be highly ventilated. Rehearsal space preference order:

1. Outdoors
2. Indoors with elevated outdoor air exchange rate from HVAC
3. Indoors with typical outdoor air exchange rate from HVAC plus recirculation air through MERV 13 filters or addition of appropriately sized HEPA air cleaners

---

[2] Lindsley et al. 2021. DOI 10.1080/15459624.2013.877591.
[3] Fried et al. 2020. DOI 10.1213/ANE.0000000000005249.

4. Indoors with outdoor air exchange rate from open windows supplemented with appropriately sized HEPA air cleaners when airflow is reduced under certain outdoor wind conditions.

1.6 Limiting Rehearsal Time

If indoor spaces are used, we recommend having at least three air changes per hour in the rehearsal room and limiting rehearsal time to 30 minutes[4,5] at a time before leaving the room for at least one air change. For a room that has three air changes per hour, one air change is 20 minutes.

1.7 HEPA Air Cleaners to Supplement Ventilation

If indoor spaces are used, we recommend using HEPA air cleaners. Portable HEPA air cleaners have been shown in previous studies to decrease risk of airborne diseases such as tuberculosis.[6] HEPA air cleaners increase air changes per hour and decrease aerosol concentrations in a room. The HEPA air cleaner should be appropriately sized for the space. This blog by Shelly Miller contains more information about CADR and HEPA air cleaners. An important number to consider when looking at HEPA air cleaners is the clean air delivery rate (CADR), which is often given in cubic feet per minute.

---

[4] Melikov et al. 2020. DOI 10.1016/j.scitotenv.2020.140908.
[5] Miller et al. 2021. DOI 10.1111/ina.12751.
[6] Miller-Leiden et al. 1996. DOI 10.1080/10473289.1996.10467523.

Appendix 2: Bell Covers

2.1 Bell Covers vs No Bell Covers for Various Instruments and Performers

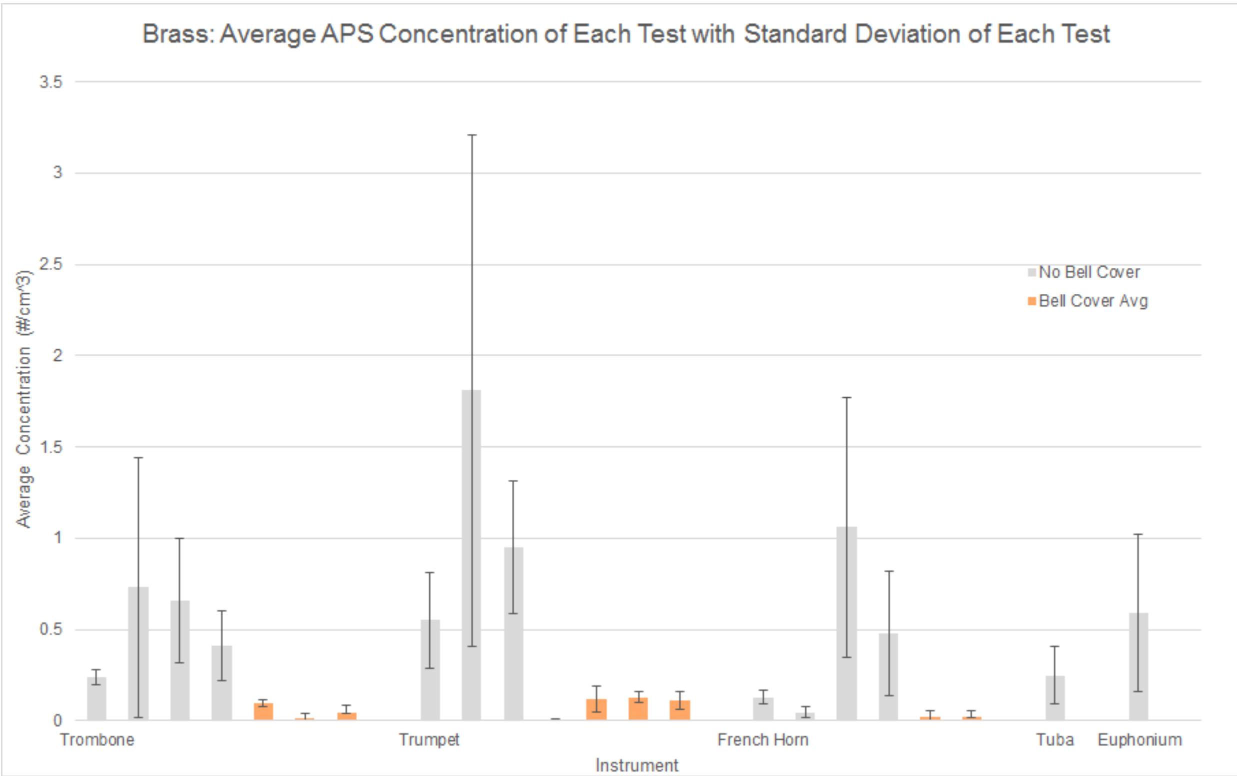

Fig S1. Each bar is the time average of each test. Each test was 4 - 5 minutes in length; the APS averages over 1 minute for each sample, each test is 4 or 5 APS samples. The error bars show the standard deviation of each test.

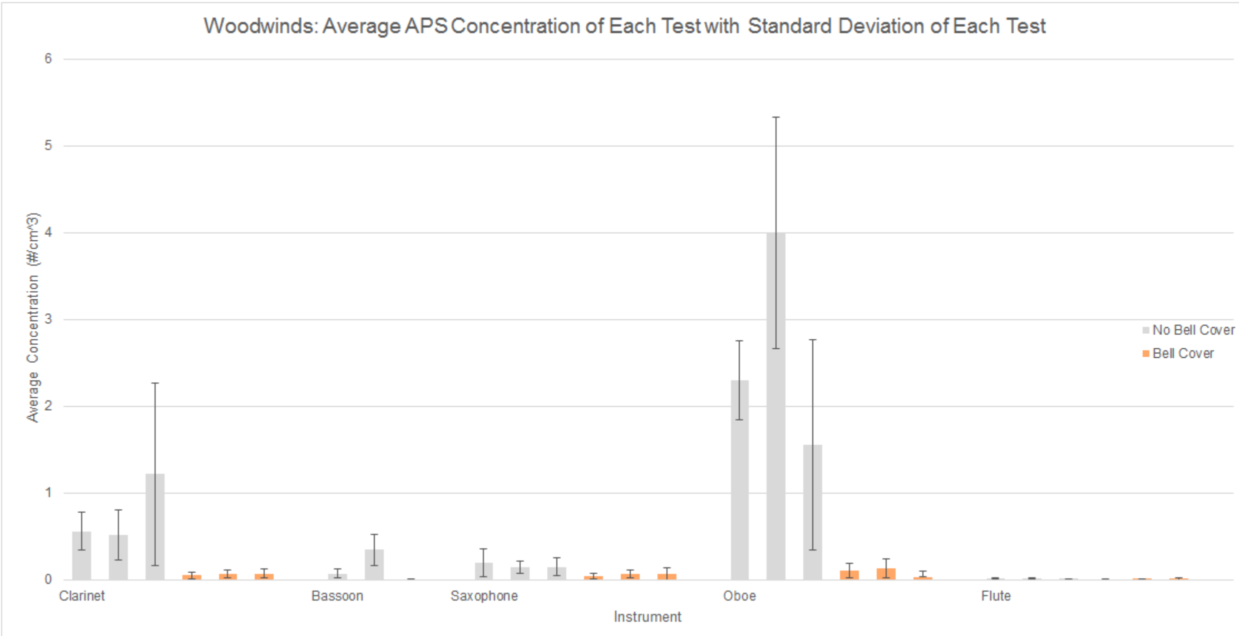

Fig S2. Each bar is the time average of each test. Each test was 4 - 5 minutes in length; the APS averages over 1 minute for each sample, each test is 4 or 5 APS samples. The error bars show the standard deviation of each test.

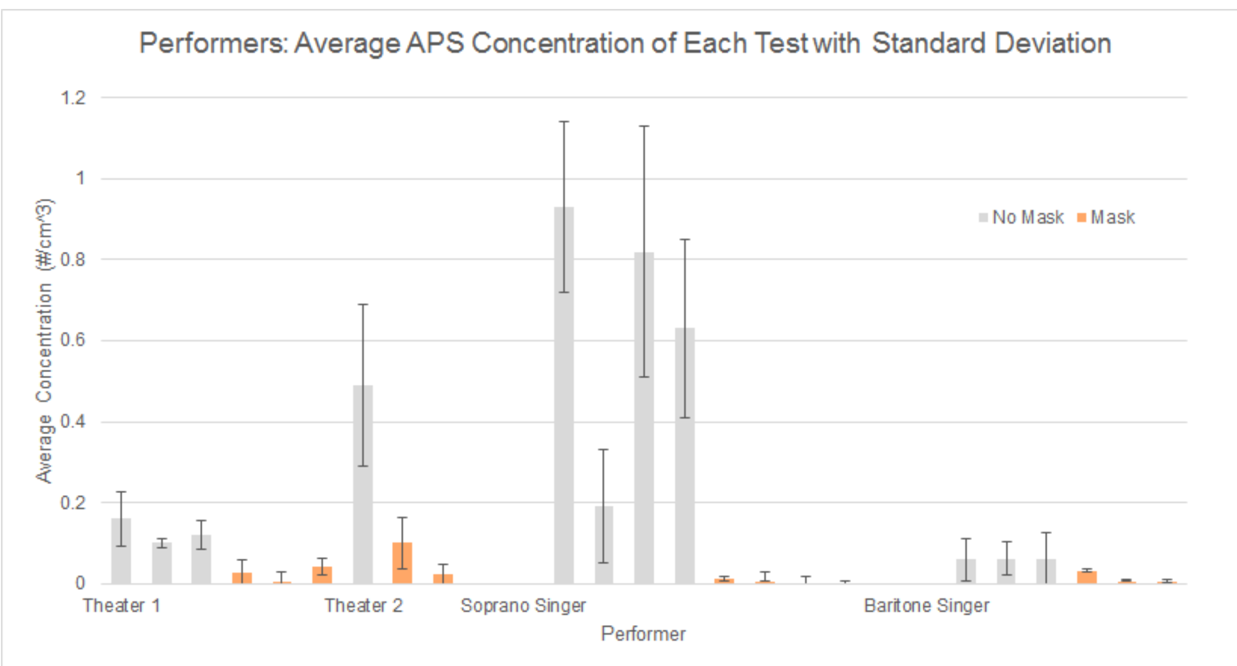

Fig S3. Each bar is the time average of each test. Each test was 4 minutes in length; the APS averages over 1 minute for each sample, each test is 4 APS samples. The error bars show the standard deviation of each test.

Appendix 3: Additional Instrument Experiments

The following section shows results of APS-sized aerosols for additional instruments tested: woodwinds (bassoon, clarinet, flute, oboe, saxophone), brass (French horn, trumpet, trombone, tuba), performers (baritone singer, soprano singer, theater performer).

3.1 Woodwinds

3.1.1 Bassoon

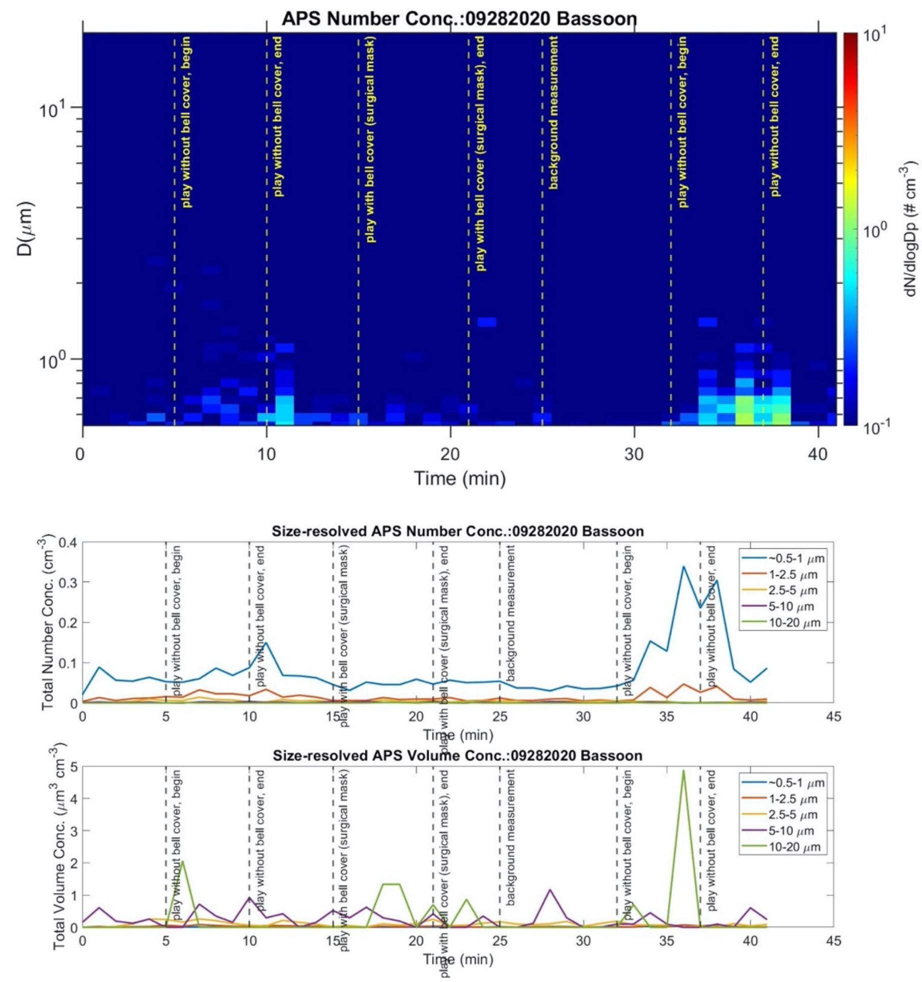

Fig S4. UHSAS size-resolved number concentration over time from 400 nm to 1000 nm for bassoon player (top). The UHSAS particle concentrations were averaged over one minute. APS size-resolved number concentrations over time of bassoon player (bottom) for particles in the ranges: 0.523 – 1 μm, 1-2.5 μm, 2.5-5 μm, 5-10 μm, and 10-20 μm. Sampling was done at the bell of the instrument.

3.1.2 Clarinet

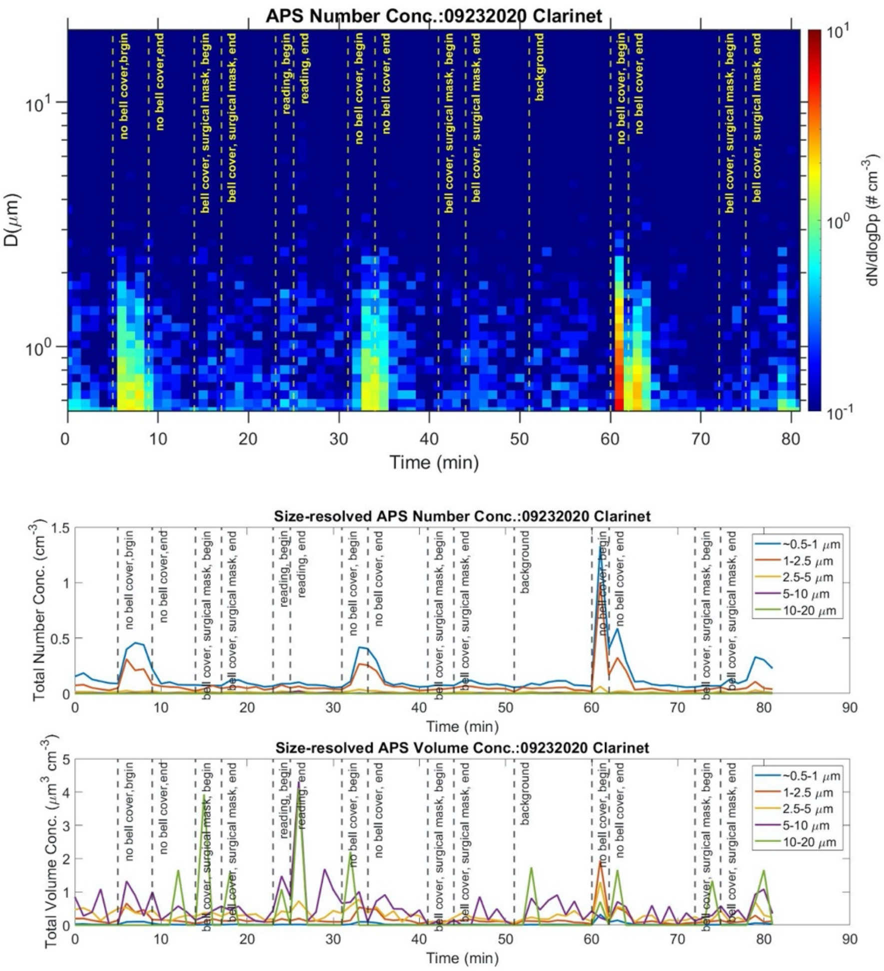

Fig S5. UHSAS size-resolved number concentration over time from 400 nm to 1000 nm for clarinet player (top). The UHSAS particle concentrations were averaged over one minute. APS size-resolved number concentrations over time of clarinet player (bottom) for particles in the ranges: 0.523 – 1 μm, 1-2.5 μm, 2.5-5 μm, 5-10 μm, and 10-20 μm. Sampling was done at the bell of the instrument.

3.1.3 Flute

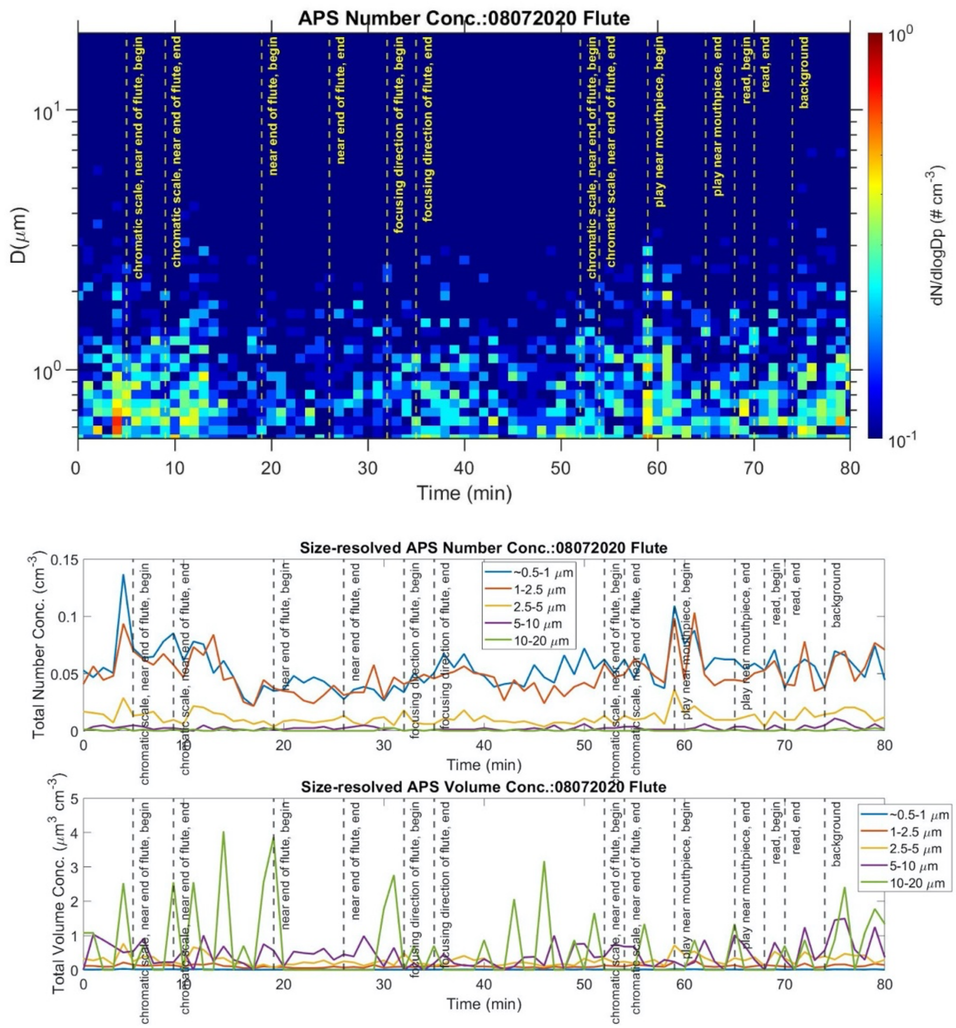

Fig S6. UHSAS size-resolved number concentration over time from 400 nm to 1000 nm for flute player (top). The UHSAS particle concentrations were averaged over one minute. APS size-resolved number concentrations over time of flute player (bottom) for particles in the ranges: 0.523 – 1 μm, 1-2.5 μm, 2.5-5 μm, 5-10 μm, and 10-20 μm. Sampling was done at the bell of the instrument.

3.1.4 Oboe

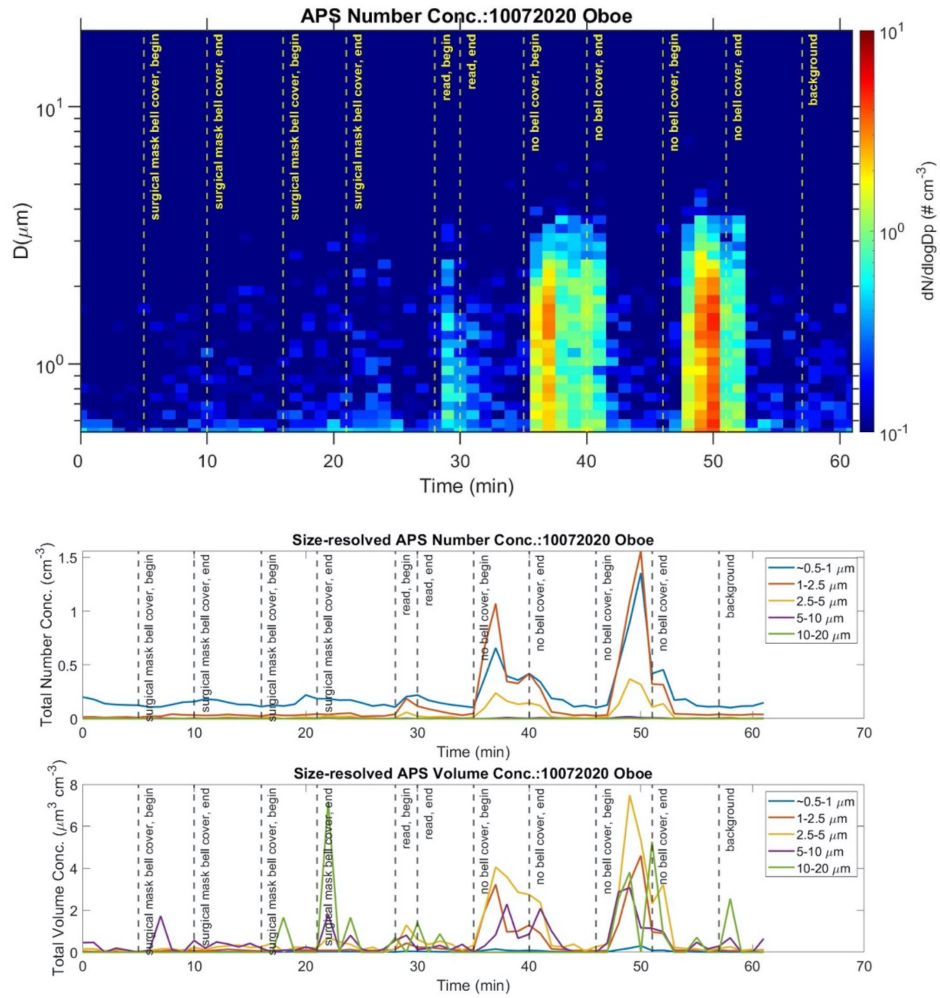

Fig S7. UHSAS size-resolved number concentration over time from 400 nm to 1000 nm for oboe player (top). The UHSAS particle concentrations were averaged over one minute. APS size-resolved number concentrations over time of oboe player (bottom) for particles in the ranges: 0.523 – 1 μm, 1-2.5 μm, 2.5-5 μm, 5-10 μm, and 10-20 μm. Sampling was done at the bell of the instrument.

3.1.5 Saxophone

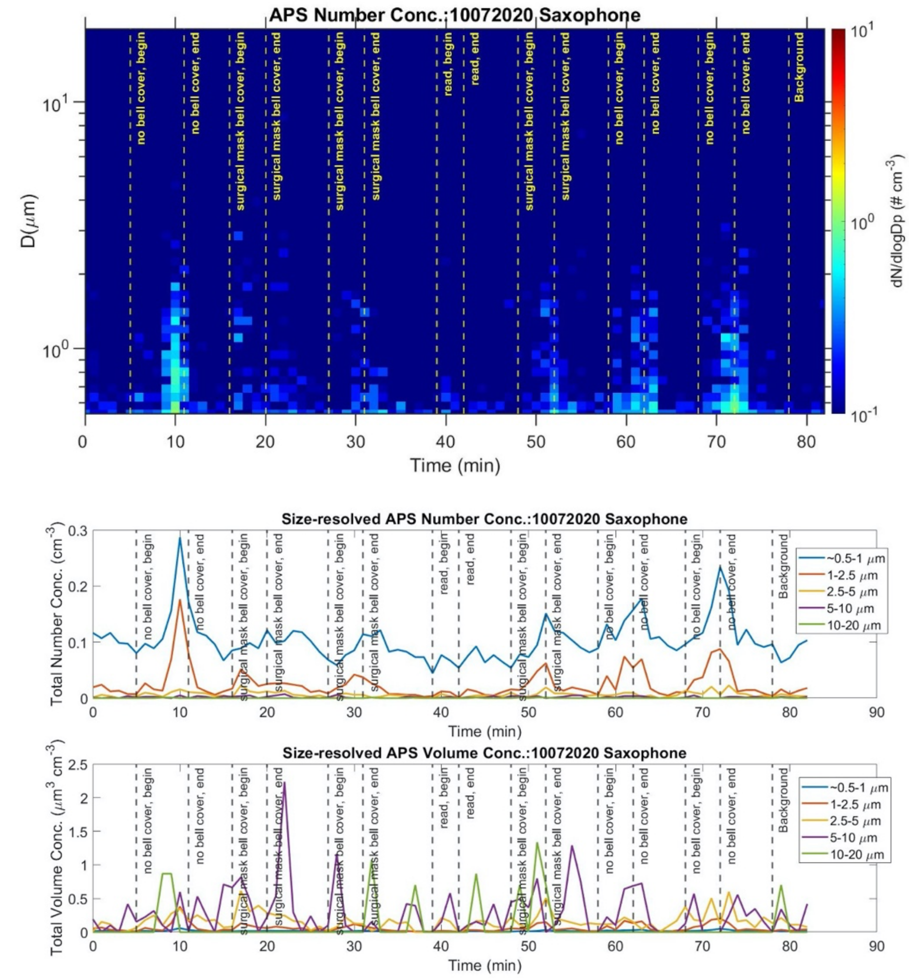

Fig S8. UHSAS size-resolved number concentration over time from 400 nm to 1000 nm for saxophone player (top). The UHSAS particle concentrations were averaged over one minute. APS size-resolved number concentrations over time of saxophone player (bottom) for particles in the ranges: 0.523 – 1 μm, 1-2.5 μm, 2.5-5 μm, 5-10 μm, and 10-20 μm. Sampling was done at the bell of the instrument.

3.2 Brass

3.2.1 French Horn

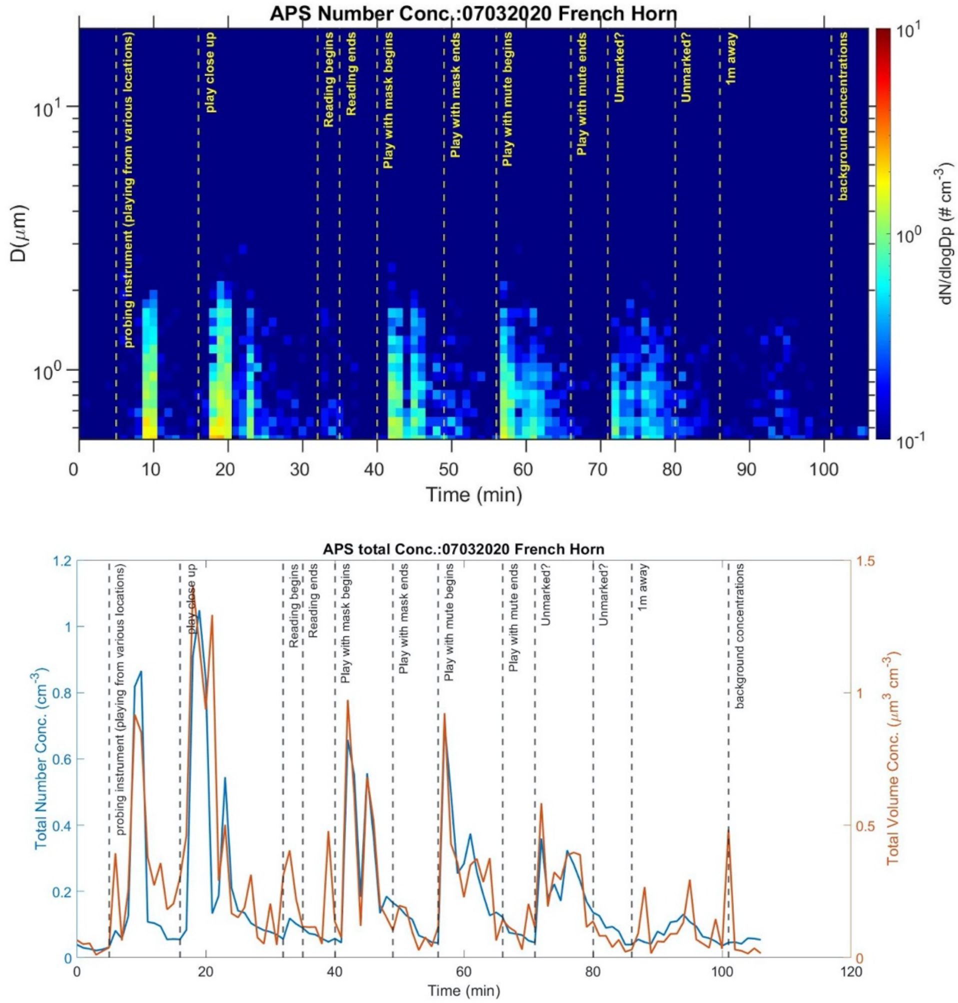

Fig S9. UHSAS size-resolved number concentration over time from 400 nm to 1000 nm for French horn player (top). The UHSAS particle concentrations were averaged over one minute. APS size-resolved number concentrations over time of French horn player (bottom) for particles in the ranges: 0.523 – 1 μm, 1-2.5 μm, 2.5-5 μm, 5-10 μm, and 10-20 μm. Sampling was done at the bell of the instrument.

3.2.2 Trumpet

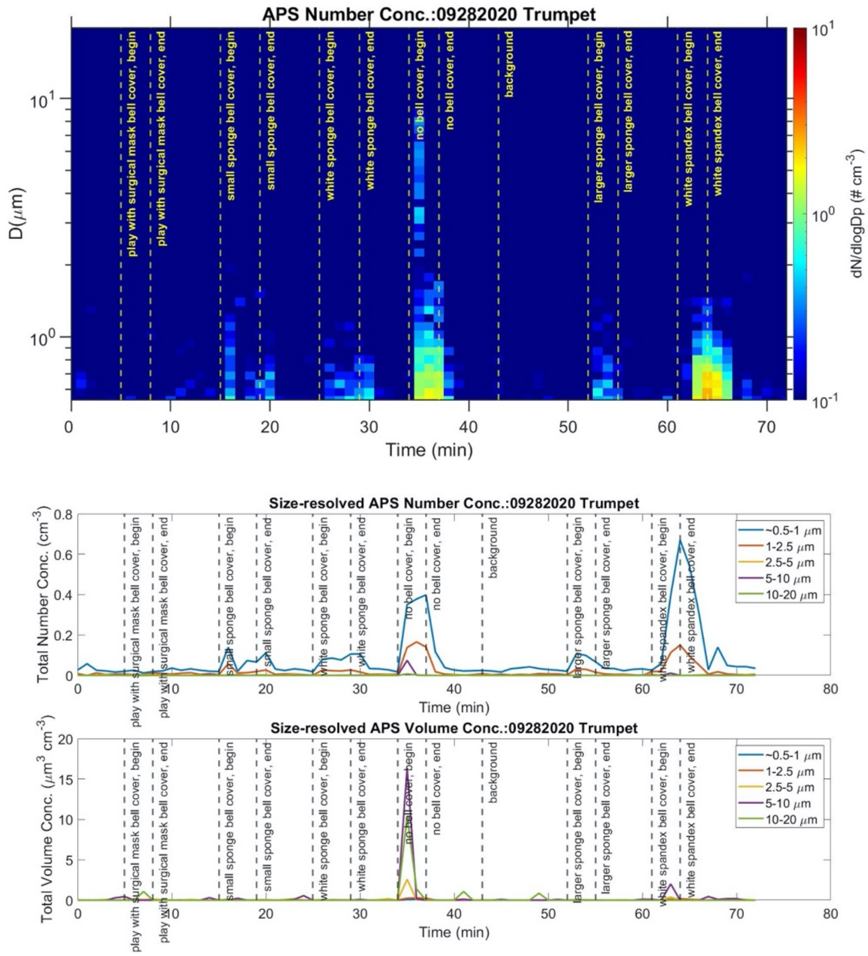

Fig S10. UHSAS size-resolved number concentration over time from 400 nm to 1000 nm for trumpet player (top). The UHSAS particle concentrations were averaged over one minute. APS size-resolved number concentrations over time of trumpet player (bottom) for particles in the ranges: 0.523 – 1 μm, 1-2.5 μm, 2.5-5 μm, 5-10 μm, and 10-20 μm. Sampling was done at the bell of the instrument.

3.2.3 Trombone

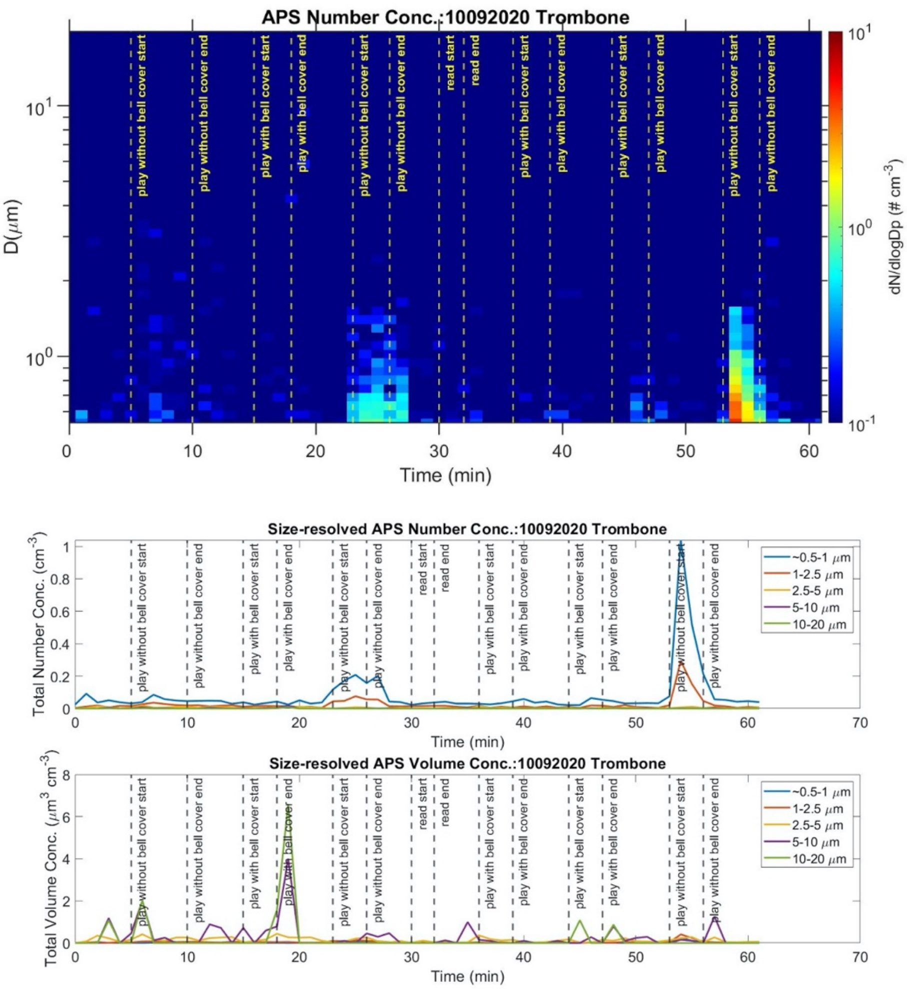

Fig S11. UHSAS size-resolved number concentration over time from 400 nm to 1000 nm for trombone player (top). The UHSAS particle concentrations were averaged over one minute. APS size-resolved number concentrations over time of trombone player (bottom) for particles in the ranges: 0.523 – 1 μm, 1-2.5 μm, 2.5-5 μm, 5-10 μm, and 10-20 μm. Sampling was done at the bell of the instrument.

3.2.4 Tuba

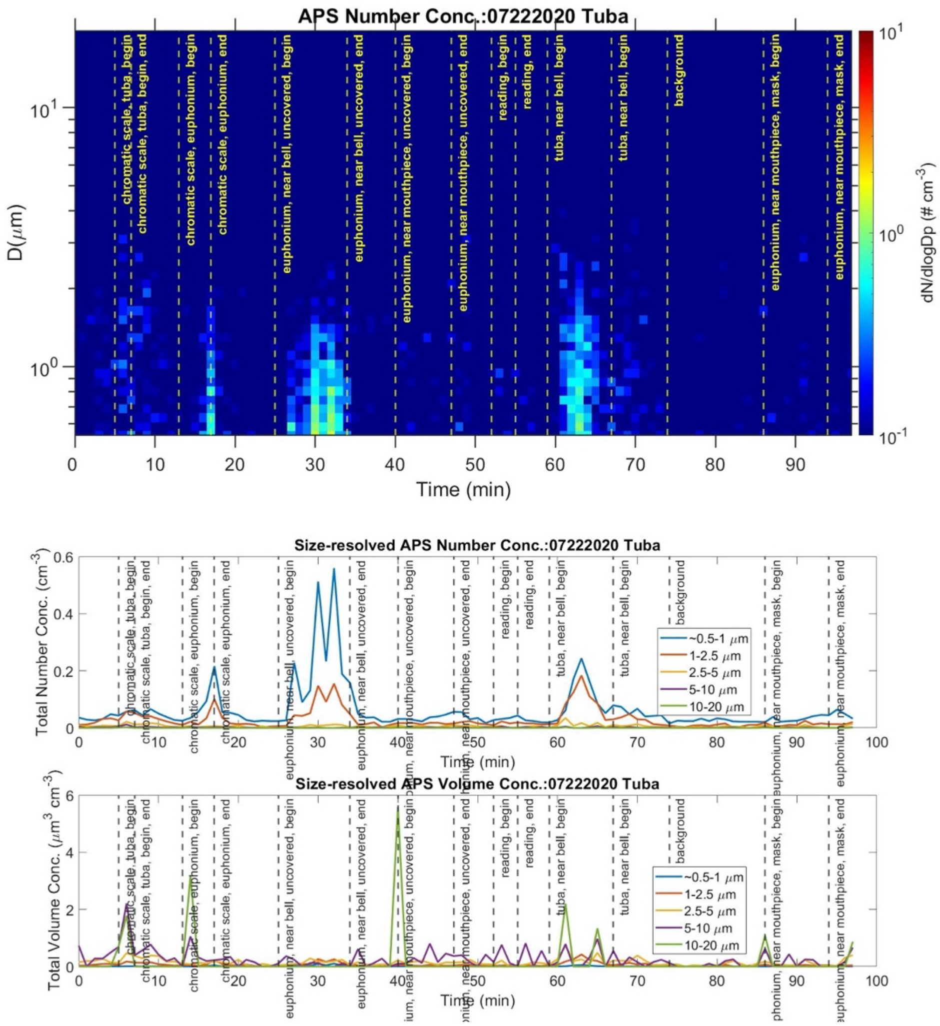

Fig S12. UHSAS size-resolved number concentration over time from 400 nm to 1000 nm for tuba player (top). The UHSAS particle concentrations were averaged over one minute. APS size-resolved number concentrations over time of tuba player (bottom) for particles in the ranges: 0.523 – 1 μm, 1-2.5 μm, 2.5-5 μm, 5-10 μm, and 10-20 μm. Sampling was done at the bell of the instrument.

3.3 Performers

3.3.1 Baritone Singer

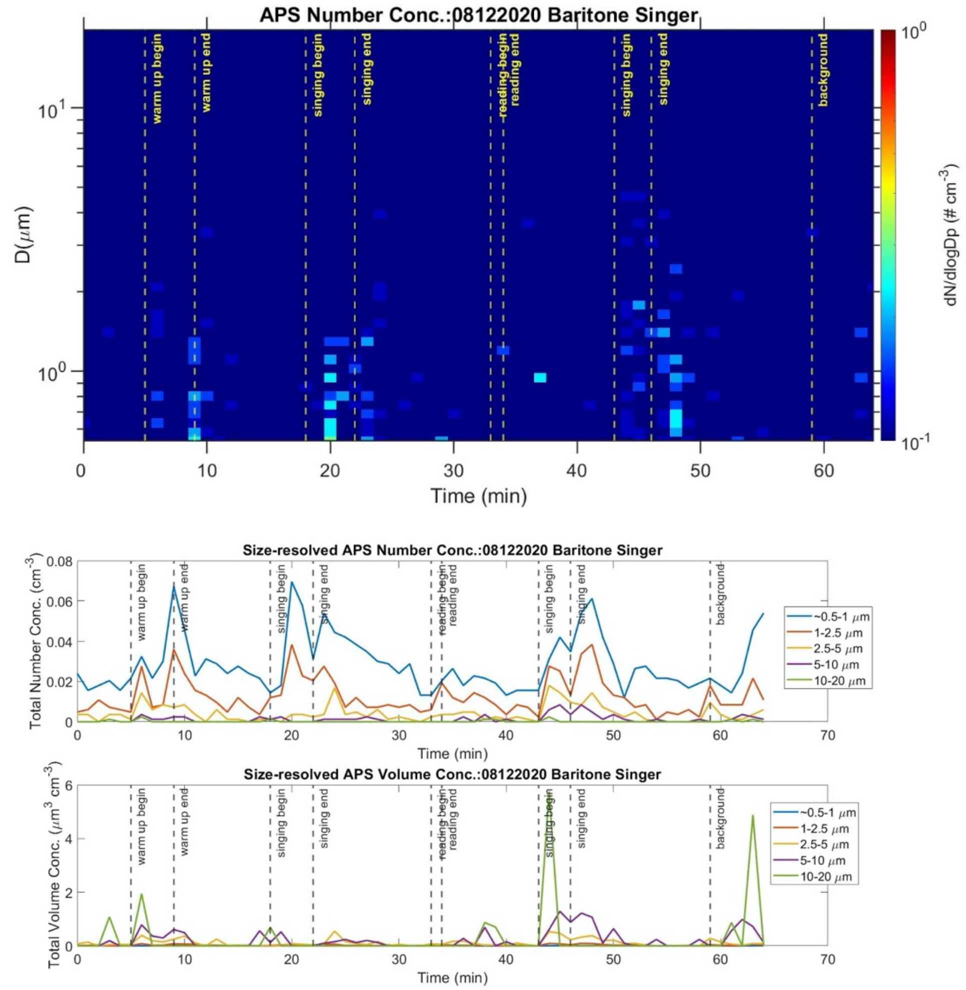

Fig S13. UHSAS size-resolved number concentration over time from 400 nm to 1000 nm for baritone singer (top). The UHSAS particle concentrations were averaged over one minute. APS size-resolved number concentrations over time of baritone singer (bottom) for particles in the ranges: 0.523 – 1 μm, 1-2.5 μm, 2.5-5 μm, 5-10 μm, and 10-20 μm. Sampling was done at the bell of the instrument.

3.3.2 Soprano Singer

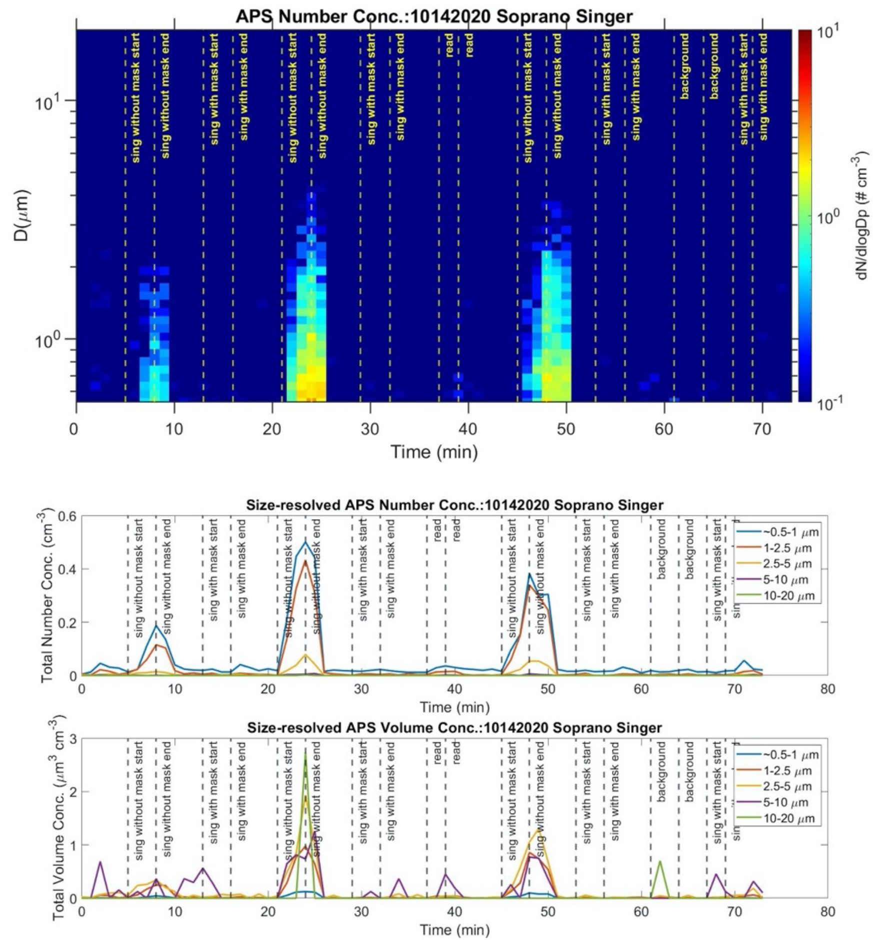

Fig S14. UHSAS size-resolved number concentration over time from 400 nm to 1000 nm for soprano singer (top). The UHSAS particle concentrations were averaged over one minute. APS size-resolved number concentrations over time of soprano singer (bottom) for particles in the ranges: 0.523 – 1 μm, 1-2.5 μm, 2.5-5 μm, 5-10 μm, and 10-20 μm. Sampling was done at the bell of the instrument.

3.3.3 Theater

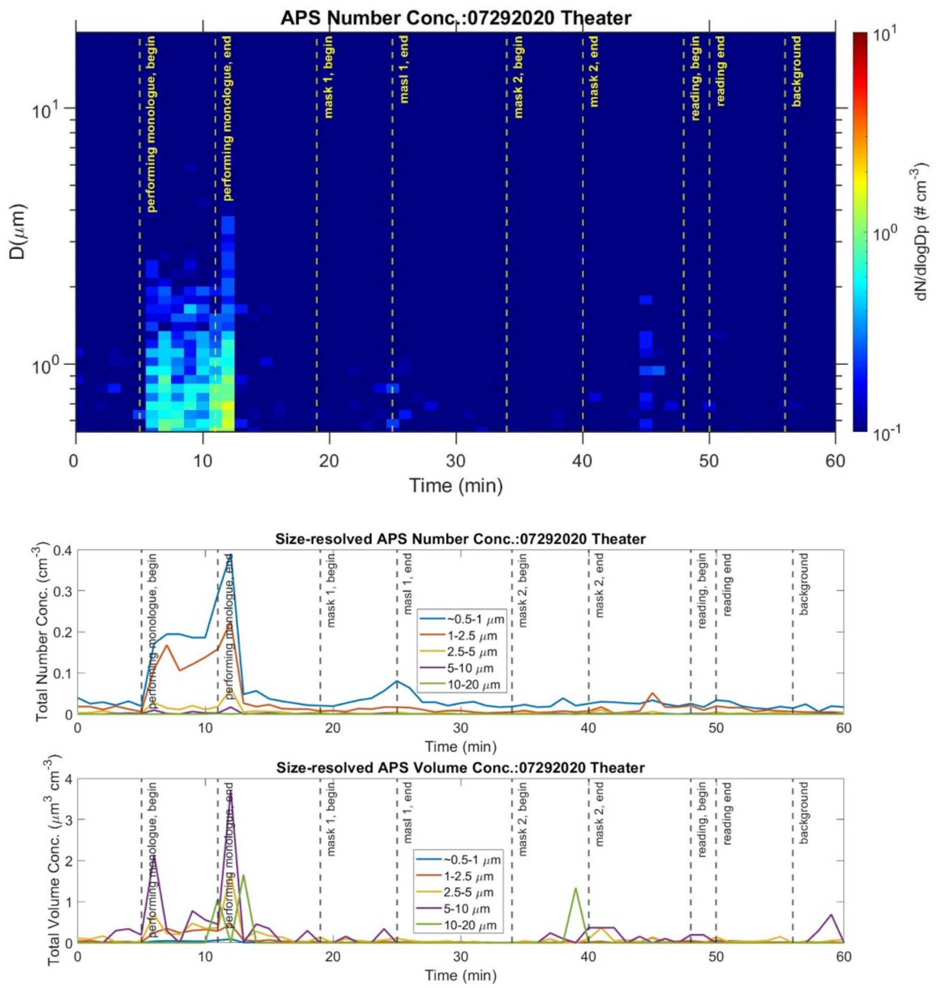

Fig S15. UHSAS size-resolved number concentration over time from 400 nm to 1000 nm for theatre performer (top). The UHSAS particle concentrations were averaged over one minute. APS size-resolved number concentrations over time of theatre performer (bottom) for particles in the ranges: 0.523 – 1 μm, 1-2.5 μm, 2.5-5 μm, 5-10 μm, and 10-20 μm. Sampling was done at the bell of the instrument.