Risk assessment of the spread of breathing air from wind instruments and singers during the COVID-19 pandemic

Lia Becher M.Sc., Amayu Wakoya Gena M.Sc., Prof. Dr.-Ing. Conrad Voelker
Bauhaus University Weimar, Chair of Building Physics, Weimar, Coudraystrasse 11a, 99423, Germany

in collaboration with the "Thüringen Philharmonie Gotha – Eisenach", Germany and
the chief conductor Markus Huber,
with the "Deutsches Nationaltheater und Staatskapelle Weimar" and
the Orchestra Director Nils Kretschmer,
and with Prof. Dr. Bernhard Richter and Prof. Dr. Dr. Claudia Spahn, head of the Freiburg Institute for Musician's Medicine, University Hospital and Freiburg University of Music, Germany

1st update on July 23, 2020. All changes to the previous version dated June 26, 2020 are marked in red font.

Weimar, July 23, 2020

Note from the authors:

The following assessment refers to playing wind instruments (both woodwind and brass) and singing. Using the schlieren method and the background oriented schlieren (BOS) method presented in the following, the spreading of the breathing air, which could contain infectious aerosols, is made visible. The actual dispersion of aerosols is not recorded. Therefore, the evaluations can only be used to determine how far and to which extent the exhaled air is transported directly into the room. Additionally, it should be noted that each musician has developed his or her own blowing technique in addition to his or her individual physical characteristics. Furthermore, the angle at which the instrument is played must be taken into account in order to estimate the direction in which the air escapes from the bell and the tone holes and when exhaling between phrases (e.g. oboe, bassoon). The illustrations and explanations shown below are only a rough guideline for how far and in which direction the air escapes from the instrument. In addition to the images shown in this report, we would like to refer to the accompanying video of the recordings in front of the schlieren mirror at https://vimeo.com/431505952.

The removal of condensation water is not considered in the following. Here, reference is made to further studies or assessments by Willich et al. (2020), Spahn and Richter (2020), and Kaehler and Hain (2020).

Furthermore, the general hygienic regulations (disinfection, ventilation, etc.) should be observed in any case to minimize possible infection risks both inside and outside the sample room.

Schlieren imaging

Figure 1 Experimental setup of the schlieren imaging system at the chair of Building Physics at the Bauhaus University Weimar, Germany

As an optical, non-invasive technique, the schlieren[1] method allows visualizing density differences in transparent media (e.g. air). These density gradients are based on differences in temperature or pressure; they cause differences in the refractive index of the fluid. Due to the refractive index gradients, the light that passes the measuring field is deflected to the extent of the gradient. The experimental setup is shown in Figure 1. It consists of a concave mirror of astronomical quality with a diameter of 1 m, a camera that captures the measuring field, a knife edge, and a light source (LED).

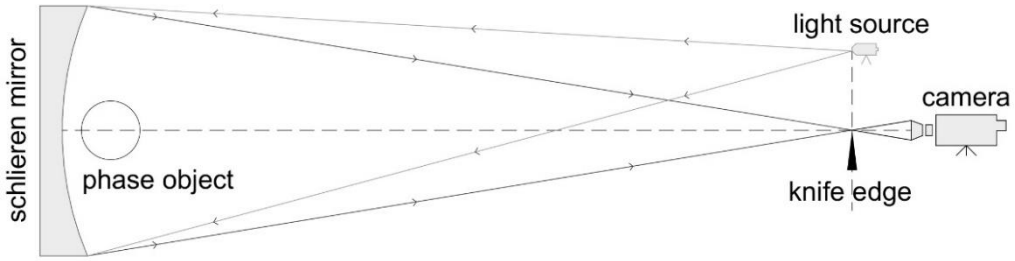

Figure 2 Schematic setup of the schlieren imaging system

The light rays from a point light source are reflected at the schlieren mirror and directed to the knife edge (in this case a conventional razor blade), which is mounted in front of the camera (Figure 2). Differences in the density of the fluid lead to refractive index gradients, which cause the light rays to deflect. The knife edge is brought into the focus of the camera to obstruct about 50 % of the light rays. Accordingly, the camera cannot capture these rays and creates dark areas. The light rays that are bend above the knife edge are detected from the camera, creating bright areas. Due to these differences in brightness, the difference in density and thus the air flow is visible (Gena et al. 2020).

The breathing air that escapes from the instruments has a higher temperature or humidity (or both) than the surrounding air. This applies even more for playing over a long period of time since the instruments warm up while playing. This allows visualizing the air escaping from the instruments using the schlieren

[1] *Schlieren* (German) describe disturbances in inhomogeneous transparent media. They appear as relatively small diffraction differences and deflect light rays in any direction other than the direction *z* of the medium (Settles 2001).

imaging system. Nevertheless, it was found that especially longer instruments with wide bores can cool the breathing air to the extent that it could not be visualized using the schlieren method (e.g. F tuba).

The streaks, which can be seen in the figures above parts of the human body such as the hands, head, or torso, are due to the human heat emission and are negligible in considering the spread of potentially infectious respiratory air. The air that escapes from the instruments is defined by lower volume flows and density gradients and, therefore, sometimes is only visible when looking closer at the images.

Regarding some instruments such as the bassoon, the Bb clarinet, the traverse and piccolo flute, the horn with a stopping mute, and singing, it can be seen that the air stream is transported further into the room than the mirror can detect. To capture these air flows completely, the background-oriented schlieren (BOS) method was used in further investigations.

Background oriented schlieren (BOS)

Similar to the schlieren imaging method, the BOS method is an optical, non-invasive method that allows for visualization of density differences in transparent media. These density gradients are based on differences in temperature or pressure and cause differences in the refractive index. This causes the light passing through the measuring field to deflect to the extent of the gradient. The BOS setup consists of an irregular background pattern (black pixels on a white background), a high resolution SLR camera, and flash light to illuminate the background (Figure 3). A schematic illustration of the BOS system is shown in Figure 4.

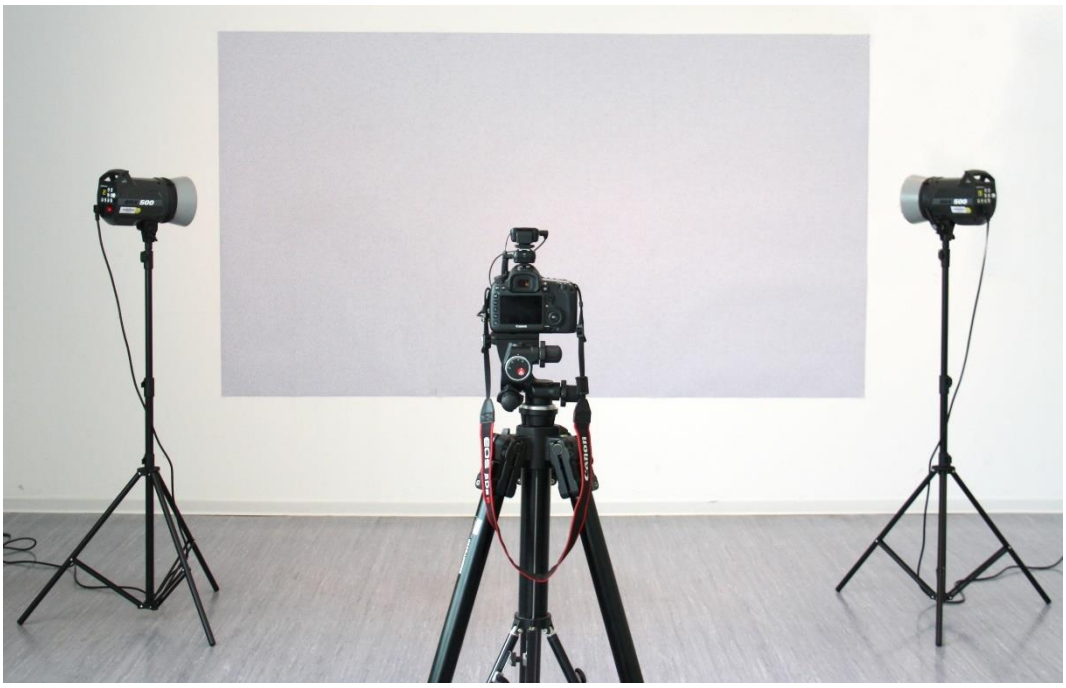

Figure 3 Experimental setup of the BOS system at the chair of Building Physics at the Bauhaus University Weimar, Germany

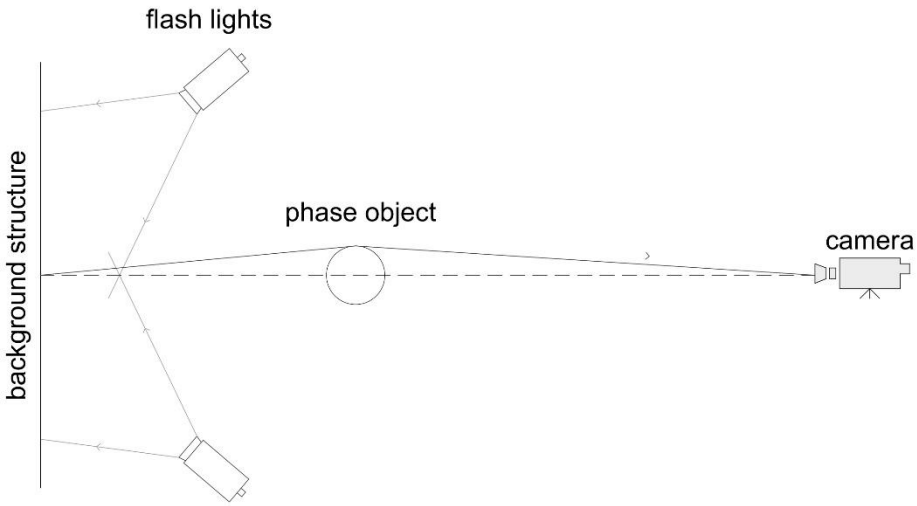

Figure 4 Schematic setup of the BOS system

To evaluate the density gradients with the BOS method, a recording of the undisturbed background structure (flow-off) as well as a recording of the density gradient in front of the background (flow-on) are required. Due to the refractive index, each light ray passing through the measuring field is refracted so that a pixel on the flow-on image appears at a different position compared to the reference image. Using computer-aided algorithms, it is then possible to determine the image shift of each individual pixel, and thus, to visualize the density gradient (Becher et al. 2020).

In contrast to the schlieren method, no video recordings (only single photos) were taken with the BOS method. The time interval between the individual frames is 0.66 s. Therefore, it might be possible that the maximum expansion of the air flow was not recorded. Due to the small flow velocities escaping from the bell and tone holes, this inaccuracy is typically only few centimeters and can therefore be neglected.

Woodwind instruments

In the case of woodwind instruments, in addition to the breathing air coming out of the bell, the air escaping from the tone holes and the air blown above the mouthpiece in the case of traverse flutes as well as the air coming out of the window in the case of recorders must also be taken into account.

Oboe

The tone holes of the oboe are covered with keys that have small holes from which a small amount of air can escape. Because of the small range, the air escaping from the tone holes is negligible. When playing at higher pitches, it can be seen that the air escapes in a smaller range than playing at lower pitches where most of the tone holes are covered (Figure 5 left and center).

The oboe is played with a high breath pressure. The air that is blown into the instrument cannot escape completely from the bell and the tone holes. Thus, the oboe player has to exhale intermittently between phrases. The air spreads around 60 cm into the room (Figure 5 right).

Figure 5 Oboe in front of the schlieren mirror: maximal range of the air escaping from the bell while playing the note Bb3 ≈ 233 Hz (left), note D6 ≈ 1175 Hz (center) and while intermittently exhaling (right) [cm] (cf. Richter et al. (2020))

Bassoon

When playing the bassoon at lower pitches, nearly all the air escapes from the instrument's bell and escapes over the edge of the schlieren mirror (Figure 6 left). At high pitches, however, hardly any air escapes from the bell. A smaller jet of air flow can be observed from the tone holes (Figure 6 center). The largest air flow escaping from the tone holes can be seen when playing the note F3 ≈ 175 Hz (Figure 6 right).

Similar to the oboe, the bassoon is played with a high breath pressure. The air blown into the instrument cannot escape completely from the bell and the tone holes. Between phrases, the air is exhaled intermittently and spreads around 80 cm into the room.

Figure 6 Bassoon in front of the schlieren mirror: maximal range of the air escaping from the bell while playing the note Bb1 ≈ 58 Hz (left) and the air escaping from the tone holes while playing the note C5 ≈ 523 Hz (center) and note F3 ≈ 175 Hz (right) [cm]

The results with the BOS method (Figure 7) show that the breathing air does not escape from the bell any further than what the schlieren images illustrated (Figure 6 left) when playing the note Bb1.

Figure 7 Bassoon in front of the BOS: maximal range of the air escaping from the bell while playing the note Bb1 ≈ 58 Hz [cm]

Bb clarinet and bass clarinet

When playing low notes, the air that escapes from the bell reaches around 20 cm into the room. When playing high notes, the air escapes over the edge of the schlieren mirror (Figure 8 left and center). At the tone holes, which are covered with keys, a small jet of air flow can be seen. Due to the small range, this is negligible. However, the air leak above the mouthpiece when the lips of the clarinet player tire has to be taken into consideration (Figure 8 right). This is typically not seen during physiologically "correct" playing, but it can be observed with untrained players (e.g. beginners and older clarinet players), especially during long rehearsals and concerts. The air spreads more than 90 cm into the room and escapes over the edge of the mirror.

Figure 8 Bb clarinet in front of the schlieren mirror: maximal range of the air escaping from the bell while playing the note C#3 ≈ 139 Hz (left), note E6 ≈ 1319 Hz (center) and the air leaking at the mouthpiece (right) [cm]

The results of the BOS method show the maximal range of the air escaping from the bell as well as the air leaking at the mouthpiece (Figure 9). However, it should be noted that when playing a tone with accent (staccato), even professional clarinet players sometimes leak air near the mouthpiece.

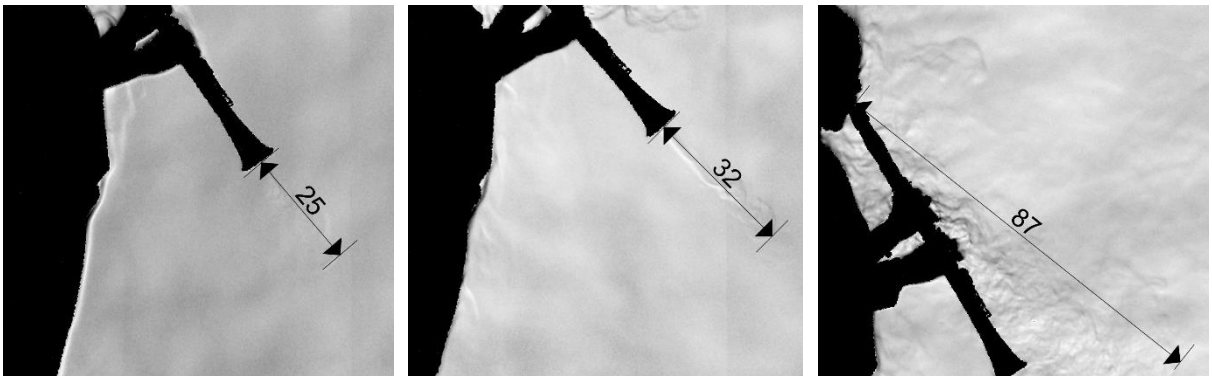

Figure 9 Bb clarinet in front of the BOS: maximal range of the air escaping from the bell while playing the note C#3 ≈ 139 Hz (left), note E6 ≈ 1319 Hz (center) and the air leaking at the mouthpiece (right) [cm]

Figure 10 Bass clarinet in front of the schlieren mirror while playing the note D2 ≈ 73 Hz (left), note Bb4 ≈ 466 Hz (center) and the maximal range of the air escaping from the bell (right) [cm]

Traverse flute and piccolo flute

The air escaping from the traverse flute and the piccolo flute is similar. When playing the instruments, a similarly large blast of air escapes from the end of the flute with a range of less than 20 cm (Figure 11 and 8 left and center). Near the tone holes, which are covered with keys, hardly any escaping air can be observed. However, a large amount of breathing air is blown above the mouthpiece (Figure 11 and 12 right). The air is slightly directed downwards since it is blown downwards into or above the instrument and because of the Coandâ effect. Here, the air spreads over 100 cm and escapes over the edge of the mirror.

Figure 11 Traverse flute in front of the schlieren mirror: maximal range of the air escaping from the foot joint while playing the note E4 ≈ 330 Hz (left), note F6 ≈ 1397 Hz (center) and the air blown above the mouthpiece (right) [cm]

Figure 12 Piccolo flute in front of the schlieren mirror: maximal range of the air escaping from the foot joint while playing the note E5 ≈ 659 Hz (left), note G#7 ≈ 3322 Hz (center) and the air blown above the mouthpiece (right) [cm]

The results of the BOS method show the maximal range of the air blown above the mouthpiece (Figure 13). It should also be noted that the higher the tone played, the more the breathing air is blown downwards.

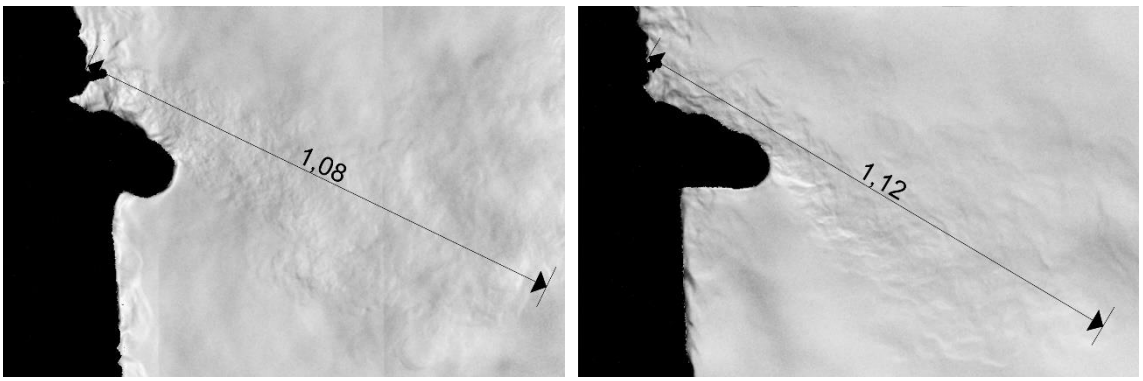

Figure 13 Maximal range of the air blown above the mouthpiece for the traverse flute (left) and the piccolo flute (right) [cm]

Soprano recorder

Usually, the beak of the recorder is completely covered with the lips of the musician. Therefore, no air can escape directly at the mouthpiece. If the instrument is played at lower pitches, most of the tone holes are covered and most of the breathing air escapes from the foot joint (Figure 14 left). At higher pitches, in which many tone holes are open and allowing the air to easily escape, less air spread can be seen at the bell (Figure 14 center). A larger amount of breathing air is cut at the labium of the head joint and escapes from the window (Figure 14 right). Near the tone holes, hardly any air flow can be observed.

Figure 14 Soprano recorder in front of the schlieren mirror: maximal range of the air escaping from the bell while playing the note C5 ≈ 523 Hz (left), note G6 ≈ 1568 Hz (center) and the air escaping from the window (right) [cm]

Brass instruments

The breathing air blown into the mouthpiece flows through the instrument and escapes from the bell. With professional brass players, no air escapes between the mouth and the mouthpiece. Therefore, the complete breathing air escapes from the bell. The various natural tones of a brass instrument can be played by varying the pressure of the lips and the breathing air. This affects the range and angle at which the air exits the bell. If dampers are used, the air flow escaping from the bell is significantly restricted. Here, the air can only escape through the narrow gap between the brass of the instrument and the damper. The range of the emitted air is reduced.

Bb trumpet

The pitch of the played note affects how far and at which angle the air escapes from the bell. It can be seen that at higher pitches the air is transported further into the room than at lower pitches (Figure 15). If dampers are used, the air flow escaping from the bell is remarkably restricted (Figure 16).

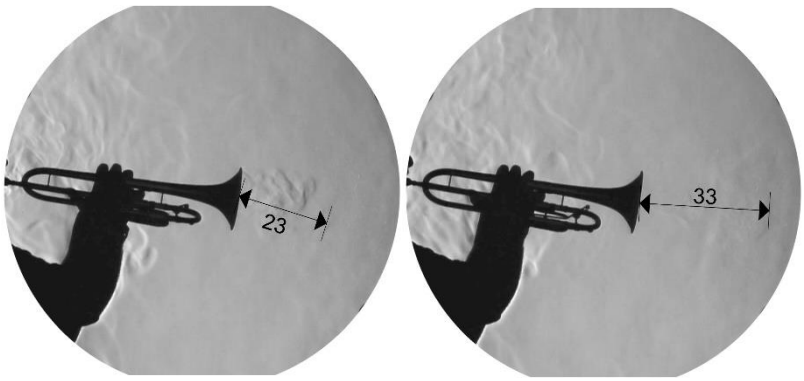

Figure 15 Bb trumpet in front of the schlieren mirror: maximal range of the air escaping from the bell while playing the note Bb3 ≈ 233 Hz (left) and note Bb5 ≈ 932 Hz (right) [cm]

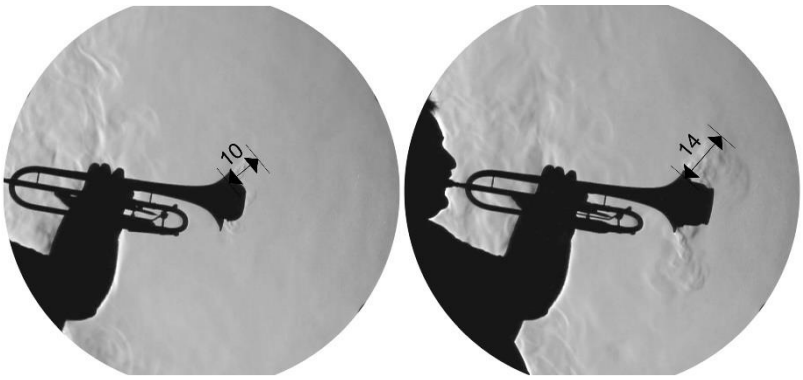

Figure 16 Maximal range of the air escaping from the bell with straight mute (left) and cup mute (right) [cm]

Tenor trombone

The pitch of the played note affects how far and at which angle the air escapes from the bell (Figure 17 left and center). It should also be noted that the escaping air is swirled when the position of the trombone slide is changed. More air escapes from the bell when playing at low pitches than playing at high pitches. However, if not only single notes but a phrase is played, the differences are hard to see because of the turbulence caused by moving the slide. If dampers are used, the air flow escaping from the bell is significantly restricted (Figure 18).

Figure 17 Tenor trombone in front of the schlieren mirror while playing the note Bb1 ≈ 58 Hz (left), note Bb3 ≈ 233 Hz (center) and the maximal range of the air escaping from the bell (right) [cm]

Figure 18 Maximal range of the air escaping from the bell with damper [cm]

Double horn

The horn is usually played with the right hand holding the bell from the inside. When playing at higher pitches, the air escapes further into the room compared to playing at lower pitches (Figure 19 left and center).

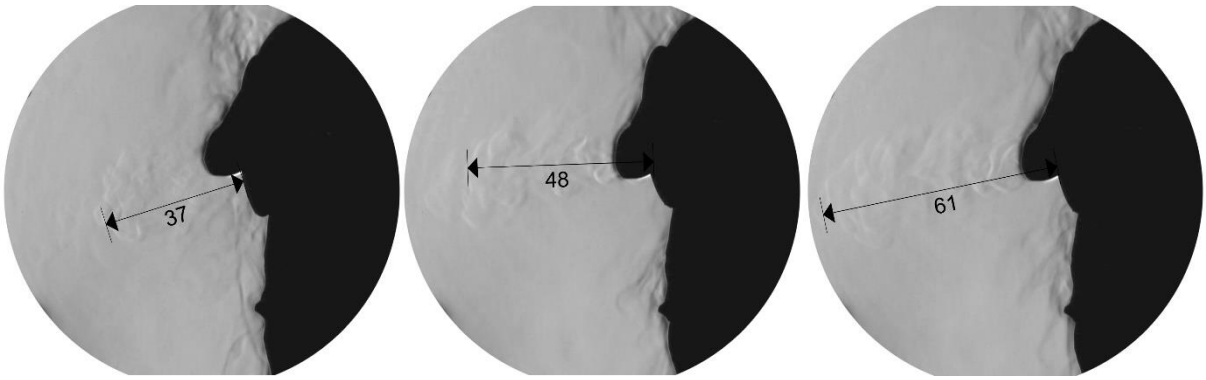

Figure 19 Double horn in front of the schlieren mirror while playing the note C2 ≈ 65 Hz (left), note D#5 ≈ 622 Hz (center) and the maximal range of the air escaping from the bell (right) [cm]

If the speed of the air flow is reduced or when using dampers, the air escaping from the bell is bent along the right hand or forearm. As with the other brass instruments, the air flow is highly restricted when using dampers (Figure 20 left and center). An exception is the stopping mute, where the air escapes from a narrow tube at higher pressure. Thus, it spreads over 70 cm into the room and escapes over the edge of the schlieren mirror. However, the flow is more difficult to detect due to the lower density gradient (Figure 20 right).

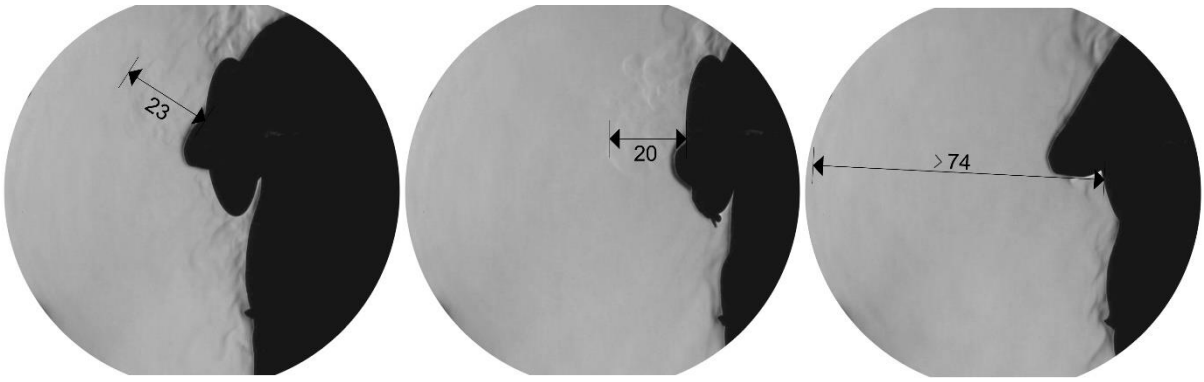

Figure 20 Maximal range of the air escaping from the bell with damper (left), hand stopping (center) and stopping mute (right) [cm]

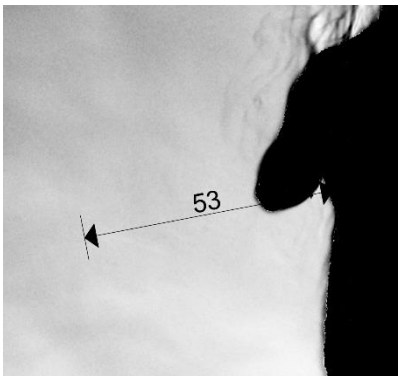

Figure 21 Double horn in front of the BOS: maximal range of the air escaping from the bell with stopping mute [cm]

Measurements of the horn with a stopping mute show that the escaping breathing air is difficult to detect due to the small density gradient. The evaluations with the BOS method (Figure 21) show that the air escapes over a smaller distance compared to the schlieren images. This may be due to various reasons such as different musician, different measuring method, etc.

F tuba

Due to the wide bore and the length of the instrument, the breathing air cools down. Therefore, it could no longer be visualized with the schlieren mirror.

To be able to visualize the air flows with the BOS method, the instrument has been played about 30 minutes before the measurements to warm up the brass of the instrument (Schurig (2020) for example shows how much brass instruments warm up when played over a longer period of time). Figure 22 shows that the air escaping from the bell is only transported into the room over short distances. If dampers are used, the air flow escapes between the instrument and the damper at a higher speed and is thus carried further into the room.

Figure 22 F tuba in front of the BOS: maximal range of the air escaping from the bell while playing the note F1≈ 44 Hz (left), note F4 ≈ 349 Hz (center) and with damper (right) [cm]

Singer

When singing a note, the greatest air spread can be observed at the beginning of the note. If a tone is held or a longer phrase is sung, only a small amount of air escapes from the mouth of the singer. The greatest air spread can be seen when singing with a lot of articulation.

Muerbe et al. (2020) also showed that singing spreads significantly more aerosols than normal speaking.

Baritone

The evaluations show that the range of the exhaled air hardly differs in the variation of the pitch (e.g. when singing scales) (Figure 23 left and center). An increasing air spread can be observed when singing demanding musical pieces that require a lot of articulation as well as a strong command of the voice (Figure 23 right). Here, the air escapes over the edge of the mirror.

The results with the BOS method (Figure 24) confirm the schlieren images.

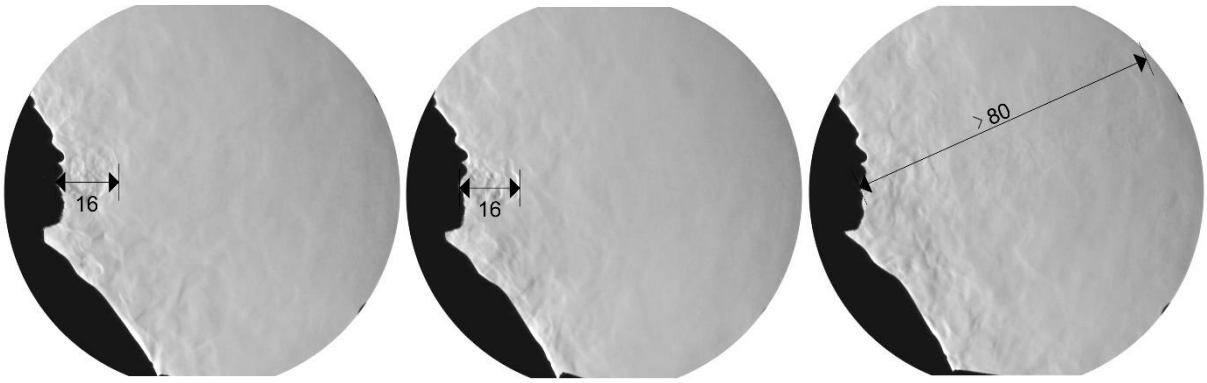

Figure 23 Baritone in front of the schlieren mirror while singing the note G2 ≈ 98 Hz (left), note D#5 ≈ 622 Hz (center) and the maximal range of the air escaping from the mouth (right) [cm]

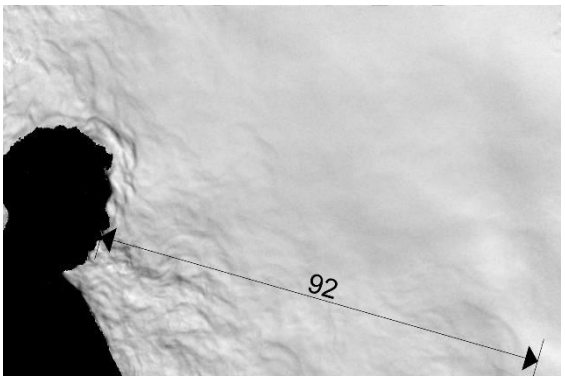

Figure 24 Baritone in front of the BOS: maximal range of the air escaping from the mouth [cm]

Soprano

The evaluations show that the range of the exhaled air hardly differs in the variation of the pitch (e.g. when singing scales) (Figure 25 left and center). An increasing air spread can be observed when singing demanding musical pieces that require a lot of articulation as well as a strong command of the voice (Figure 25 right).

Figure 25 Soprano in front of the BOS while singing the note A3 ≈ 220 Hz (left), note A5 ≈ 880 Hz (center) and the maximal range of the air escaping from the mouth (right) [cm]

Conclusion

Table 1 shows a comparison of the maximal spreading ranges of the different instruments as well as the singer. For woodwind instruments, it can be seen that the breathing air that escapes from the bell can be detected over much shorter distances in comparison to the air that escapes during various activities (air leak, exhalation, etc.), some of which are essential for sound production.

The range of the breathing air escaping from the bell of the brass instruments depends mainly on the width of the bore and the pressure of the breath with which the instrument is played. If dampers are used, it can be seen that the escaping air flow is significantly restricted. Exceptions are the horn with a stopping mute and the tuba with a damper, where the air flow is transported at least as far as when playing without a damper.

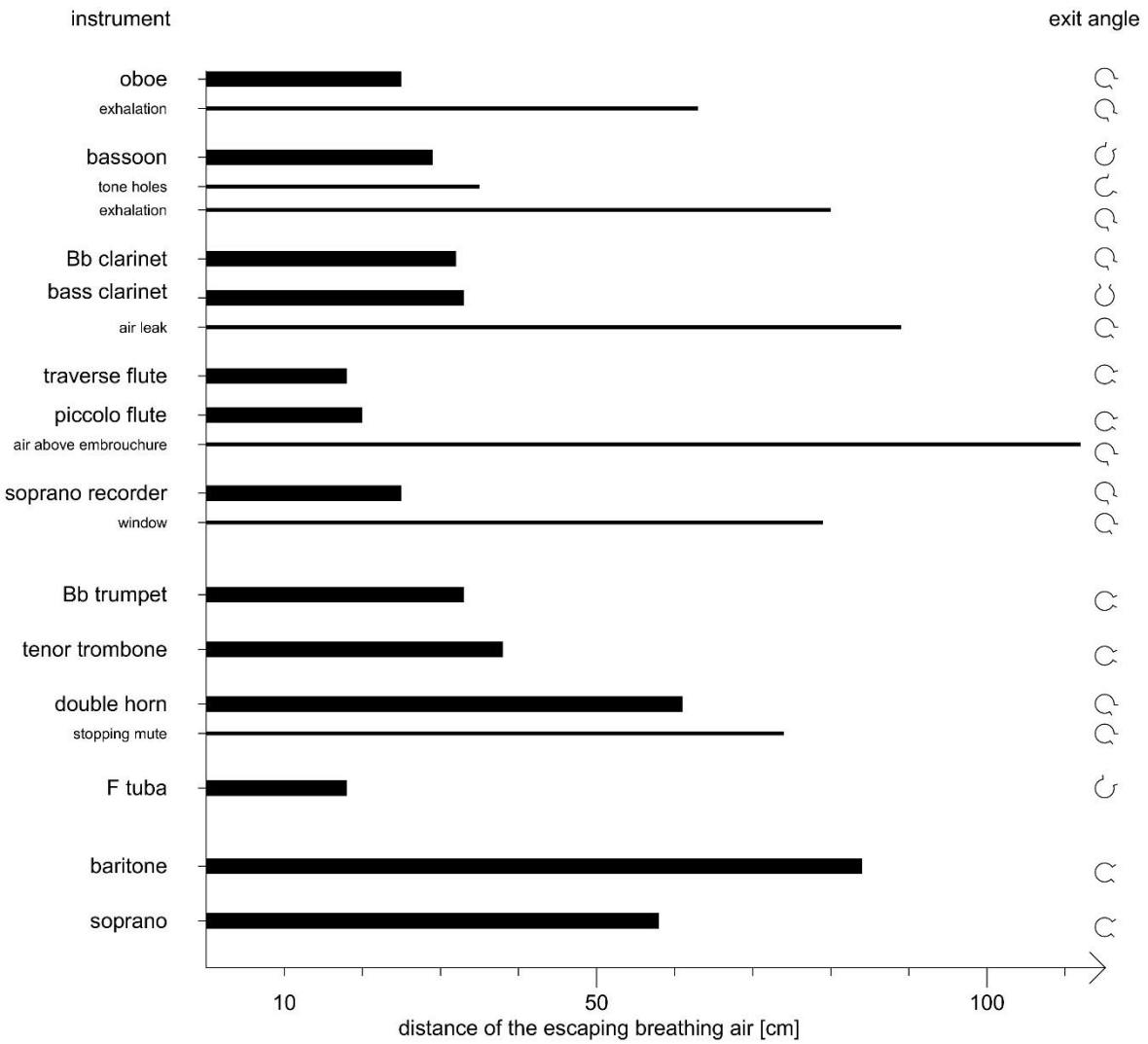

Table 1 *Maximal spreading distance of the breathing air from wind instruments and singers*

References

Becher, L.; Voelker, C.; Rodehorst, V.; Kuhne, M. (2020): Background-oriented schlieren technique for two-dimensional visualization of convective indoor air flows. In *Optics and Lasers in Engineering* 134, p. 106282. DOI: 10.1016/j.optlaseng.2020.106282.

Gena, A. W.; Voelker, C.; Settles, G. S. (2020): Qualitative and quantitative schlieren optical measurement of the human thermal plume. In *Indoor Air*. DOI: 10.1111/ina.12674.

Kaehler, C. J.; Hain, R. (2020): Singing in choirs and making music with wind instruments – Is that safe during the SARS-CoV-2 pandemic? University of the Bundeswehr Munich, Germany.

Muerbe, D.; Fleischer, M.; Lange, J.; Rotheudt, H.; Kriegel, M. (2020): Aerosol emission is increased in professional singing. DOI: 10.14279/depositonce-10375.

Richter, B.; Echternach, M.; Traser, L.; Burdumy, M.; Spahn, C. (2020): The Voice – Insights into the Physiology of Singing and Speaking. DVD-ROM and App. 2.th ed. Helbling, Esslingen, Innsbruck.

Schurig, J. (2020): "Heiße" Musik sichtbar gemacht. In *Forschung und Lehre* 27 (6), p. 534.

Settles, G. S. (2001): Schlieren and Shadowgraph Techniques. Visualizing Phenomena in Transparent Media. Berlin Heidelberg: Springer-Verlag Berlin Heidelberg.

Spahn, C.; Richter, B. (2020): Risk assessment of a coronavirus infection in the field of music. With assistance of A. Schuster, H. Hengel, H. Buerkle. Freiburg Institute for Musician's Medicine (FIM), University Hospital and Freiburg University of Music, Germany.

Willich, S. N.; Berghoefer, A.; Wiese-Posselt, M. K.; Gastmeier, P. (2020): Stellungnahme zum Spielbetrieb der Orchester während der COVID-19 Pandemie. Hospital Charité Berlin, Germany.