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The impact of face shields on speech communication

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ABSTRACT

Face shields have routinely been used in a wide variety of workplaces as the primary prevention measure against COVID-19. Because they represent a physical barrier positioned in front of the mouth, they inevitably alter the spectral profile of the human voice. More in detail, the acoustic transmissibility of face shields is characterized by a marked dependence on frequency, which is more pronounced in the spectral region above 800 Hz where several resonances show up. While the effect on the overall sound pressure level is moderate, clarity of communication may be strongly impaired.

This paper investigates the impact of wearing a face shield on speech intelligibility, as quantified by the Speech Transmission Index (STI). A polyethylene (PET) shield has been tested both as a standalone device and in combination with cloth face masks. A large variety of cases has been explored with respect to the properties of the acoustic environment (anechoic/reverberant) and the signal-to-noise ratio (-15 dB to +15 dB).

Results show that face shields may improve communication in noisy environments with limited reverberation. Significant performance deterioration occurs whenever communication was initially good, i.e. in low-noise environments. The increase in the voice emission level required to offset the decrease in STI associated to decreasing S/N ratios, is found to be much larger in high reverberation than in low reverberation environments.

Keywords: Speech, communication, face shields, reverberation

INTRODUCTION

Although many different pathways for COVID-19 transmission have been identified, inhalation of airborne droplets is well established as playing the dominant role. Face masks and face shields were immediately recognized as key factors in contrasting the diffusion of the virus. Because face masks are very cheap and widely available, easy and quick to put on/off and impose a limited burden to respiration in most environments, they have been largely accepted by the general population. On the opposite, face shields have become popular mostly at the workplace, possibly because they provide a more substantial physical barrier for droplets.
A face shield can be used either as standalone protection device or in combination with a cloth mask. While the acoustic transmissibility of cloth masks is largely flat, the acoustic transmissibility of face shields is strongly frequency-dependent: it is close to zero up to a few hundred Hz, goes through a resonance peak (that is an amplification region) around 800 – 1000 Hz and eventually declines[1,2,3]. Several minor resonances may show up at frequencies 1500 to 8000 Hz, with variable sizes[1,2]. This highly fluctuating profile likely impacts speech intelligibility. Quality of verbal communication is a key element to safe operations in a variety of workplaces. Low quality speech communication has the potential to determine a wide range of consequences ranging from mild (extra time to convey a message) to extreme (accidents due to a misunderstood emergency communication). The impact of face shields on the overall quality of communication should not be underestimated.
In this study we investigate the effect on verbal communication of face shields, making different assumptions with respect to room absorption properties (ranging from fully anechoic to fully reverberant) and different signal-to-noise (S/N) ratios. Both attenuation, quantified by the Insertion Loss (IL) and speech intelligibility, quantified by the Speech Transmission Index (STI) are investigated for a few shield-based configurations. The primary target of this work is to understand if the use of specific devices, or combination thereof, should be encouraged/discouraged in specific environments due their acoustic performance. Additionally, we determine the change (usually the increase) in the vocal sound emission required to offset the changes in STI due to the presence of a face shield.

MATERIALS AND METHODS

The Speech Transmission Index (STI)

The Speech Transmission Index (STI), originally developed in the late 70's by Houtgast, Steeneken and Plomp[4], and subsequently codified into IEC 60268-16[5], is widely recognized as the most reliable index to objectively assess speech intelligibility. STI is based on the concept of modulation transfer function: the original and transmitted signals are compared and a direct calculation of the modulation reduction is carried out by dividing the modulation depth of the output signal by the modulation depth of the input signal. An indirect approach has also been developed[6,7] where the modulation transfer function at the modulation frequency F, called m(F), is calculated as the product of two terms,

$$m(F) = \left[\frac{\left| \int_0^\infty h^2(t) e^{-i2\pi F t} \mathrm{d}t \right|}{\int_0^\infty h^2(t) \mathrm{d}t} \right] \left[1 + 10^{-(\mathrm{SNR}/10)} \right]^{-1} \qquad (1)$$

as shown in equation (1). The first term describes the effect of reverberation and is given by the Fourier transform of the squared impulse response h(t), normalized by the total energy of the squared impulse response. The second term describes the effect of background noise on modulation reduction and is a function of the signal-to-noise ratio (SNR) only. The indirect method that we adopt in this work requires that two quantities are measured: the impulse response function h(t) and the signal-to-noise ratio.

Signal and Noise

Signals approximating the male voice according to IEC 60268-16[5] were generated through a Brüel & Kjær Type 4128 Head and Torso Simulator (HATS). Pink noise was used for background noise, adopting a directional electroacoustic speaker in the anechoic room (see Figure 1a) and an omnidirectional electroacoustic speaker in the reverberation room (see Figure 1b). The impulse response function of the electroacoustic speech chain h(t) was measured with the ESS tecnique[8,9], using the free software audio editor Audacity® with Aurora plug-ins®.

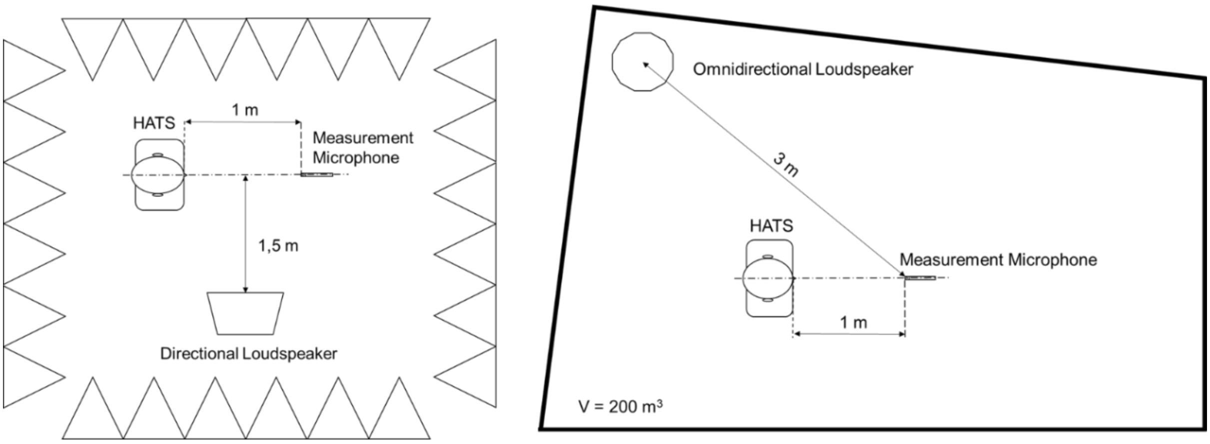

Figure 1 – Positions of HATS, speaker and microphone. a) anechoic chamber (left panel); b) reverberation room (right panel)

Tested devices

The investigated sample consists of four configurations: one with only a rigid Polyethylene (PET) face shield; the other three consisting of the PET face shield and one/two face masks. Table 1 summarizes the details (including the structure and the materials used) of the four tested configurations.

Table 1 – Characteristics of the four tested configurations

Code	Name	Description	Materials/composition
0	REF	Reference case, no shield or mask	
1	FS	Face shield	Polyethylene
2	FS+MED	Face shield + medical face mask	Shield: Polyethylene Mask: 3 layers: Non-woven Polypropylene, Meltblown Polypropylene, Non-woven Polypropylene
3	FS+FFP2	Face shield + PPE face mask (N-95 respirator)	Shield: Polyethylene Mask: 3 layers: Non-woven Polypropylene, Meltblown Polypropylene, Cotton
4	FS+MED+FFP2	Face shield + medical face mask + PPE face mask (N-95 respirator)	See previous entries

Outline of experimental tests

The sound pressure level of the test signal was initially adjusted so to have about 60 dB(A) at the microphone position, in the reference (no shield) configuration. The test was then carried out by positioning the device (face shield with possible additional face masks) on the HATS. Figure 2 provides a pictorial illustration of the four tested configurations.

Figure 2 – The four tested configurations

Each test was repeated three times and the arithmetic mean of sound pressure levels was stored for further signal processing and analysis. Tests were replicated for seven different values of S/N (from -15 to + 15 dB in steps of 5 dB) and in two extreme acoustic environments (anechoic chamber and reverberation room) giving a total of 4 × 7 × 2 = 56 tests. For each configuration, the one-third octave band levels and the overall A-weighted level were measured. The degradation of communication was quantified using the indirect method for the calculation of the modulation transfer function m(F). This allowed the effect of the signal-to-noise ratio and the effect of room absorption to be independently taken into account.

RESULTS

Attenuation

Signal attenuation A was quantified as the difference between the sound pressure levels measured at a distance of 1 m from the source, with (SPL_{1w}) and without (SPL_{1wo}) the device under investigation

$$A = SPL_{1w} - SPL_{1wo} \qquad (2)$$

Figure 3 shows that the transmissibility of the four tested configurations has a large (8 - 11 dB) resonance with a peak frequency near 800 Hz, followed by a steep (about 18 dB/octave) decline at higher frequencies, a behavior typical of weakly damped 1-d resonating systems. This behavior closely mimics that reported in previous literature studies[1,2,3]. In particular, both the peak frequency and the resonance amplitude are in excellent agreement with those reported by Corey et al.[1] and Cox et al.[3], while the resonance amplitude found by Atcherson et al.[2] is slightly smaller. The exact nature of the resonance is currently unclear. Only a tentative identification as a “cavity resonance between the face and the shield” has been provided[10]. This is consistent with experimental evidence of very limited, if any, variation of the peak frequency in different experiments where tested mechanical systems were presumably quite different from one another in terms of shield mass, rigidity and damping of coupling. The physical mechanisms acting to create the observed transmissibility shall be investigated in a separate paper.

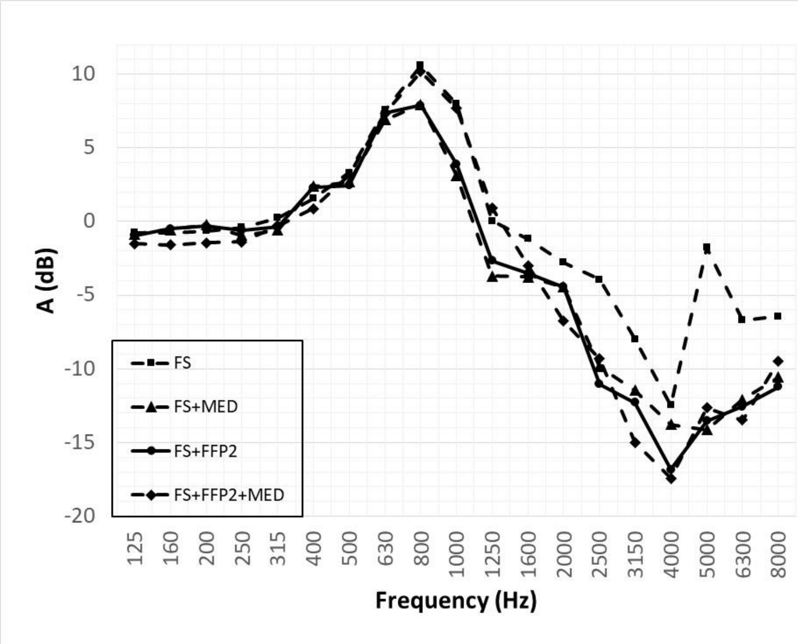

Figure 3 – Attenuation as a function of frequency in 1/3 octave bands, for all four tested configurations (see Table 1 for details of configurations)

When used in the standalone configuration, the PET shield also exhibits a second resonance at a frequency near 5000 Hz. This feature is however insignificant for vocal communication because the human voice has virtually no energy at these very high frequencies.

A-weighted sound pressure levels

Table 2 summarizes the A-weighted sound pressure levels L_A, measured at 1 m from the HATS. The observed large resonance peak determines substantial sound amplification in the spectral region extending up to 1250 Hz, which in its turn determines a significant increase in the A-weighted sound pressure levels. The largest A-weighted sound pressure level was found for the standalone face shield. In the other configurations, the presence of cloth mask(s) introduces a very strongly damped resonance which results in a small but positive attenuation, and lowers the A-weighted sound pressure level.

Table 2 – A-weighted sound pressure levels at 1 m from the HATS, for the four tested configurations

Code	Name	L_A (dBA)
0	REF	60.2
1	FS	64.6
2	FS+MED	63.0
3	FS+FFP2	63.1
4	FS+MED+FFP2	64.2

Speech Transmission Index (STI) – Anechoic chamber

Values of STI have first been obtained for the reference case where no device is worn (baseline STI, hereafter STI_b). Figure 4 shows the departure of STI from its reference value

$$\Delta STI = STI - STI_b \qquad (3)$$

as a function of the S/N ratio, for all four tested configurations. All four configurations are remarkably performing in the low S/N limit. The amplification in the 630 - 1250 Hz range due to the weakly damped resonance keeps sound pressure levels in these bands large enough to determine an appreciable increase of STI over the reference case. Given the very low values of the reference case ($STI_b < 0.25$ at S/N ≤ -5 dB), values of STI remain somewhat below the threshold of acceptability (0.45[5]). This said, the use of PET shields in very noisy environments appears to be beneficial to communication. In the opposite high S/N limit, these devices' performance is very poor, because of the large attenuation at frequencies above the resonance which play a significant role in verbal communication.

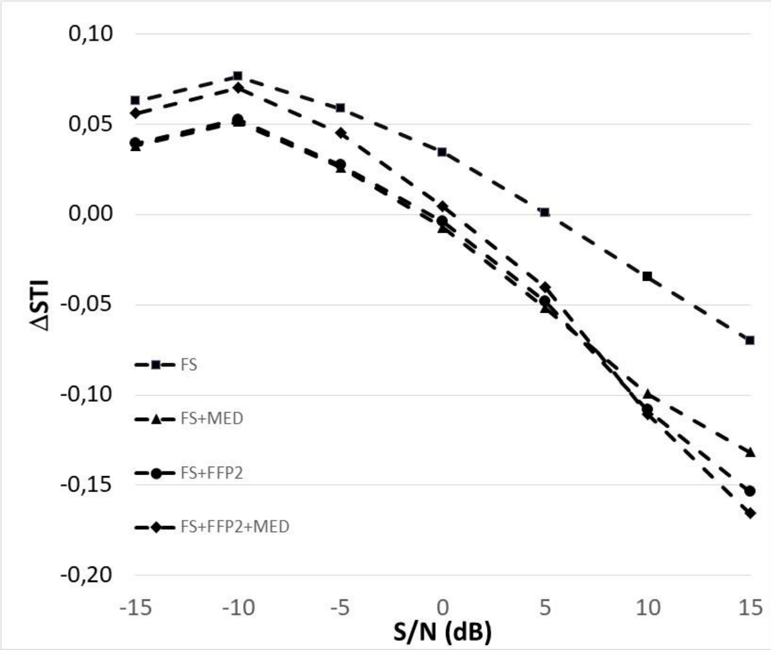

Figure 4 – Differential Speech Transmission Index (ΔSTI) for different values of the signal-to-noise ratio in the anechoic chamber; reference case: no device

Obviously, all curves must eventually converge again to zero in the high S/N limit as communication becomes very good in all cases. This however occurs outside the range of S/N explored in this work.

Speech Transmission Index (STI) – Reverberation room

Similarly to Figure 4, Figure 5 shows ΔSTI in a reverberation room, for all four tested configurations. In the limit where S/N << 0 (the left side of the figure), ΔSTI is always very close to zero for all configurations, as the values of STI also tend to zero themselves in extremely noisy and reverberant environments.

Rigid devices such as the ones investigated in this work still exhibit a minor rise of ΔSTI as S/N rises from the lowest value of -15 dB, but its size is much smaller than in the anechoic acoustic field. As S/N increases, all devices show the same qualitative trend characterized by a decline of ΔSTI at intermediate values of S/N, and a flat section (with some hint of a final rising trend) for high values of S/N.

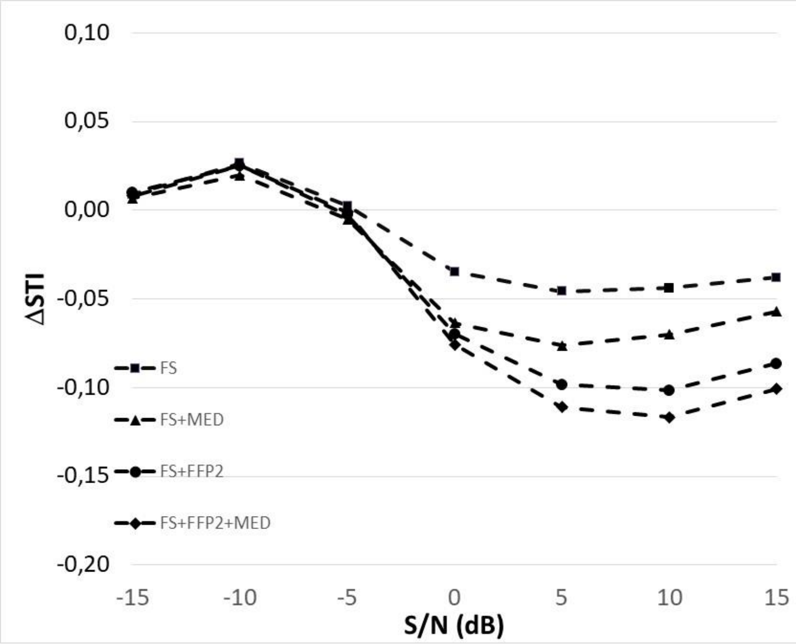

Figure 5 – Differential Speech Transmission Index (ΔSTI) for different values of the signal to noise ratio in a reverberation room; reference case: no device

DISCUSSION

Speech emission level

When a human speaker is forced to convey his/her message through a face shield, he/she is obviously aware of the lower intelligibility compared to unimpeded communication. However, because of the (at least initial) absence of a feedback, he/she is unaware of the actual understanding of his message by the listener. He/she would then be tempted to raise his/her speech emission level by a large enough amount to make sure that the essence of the message is successfully conveyed. The extent of this excess speech emission level over what would be strictly required (here indicated with ΔL_A) is however unknown, unless custom experiments are carried out. The approximation that we adopt in our work is to assume that the speech emission level would be optimally gauged to restore normal (no-device) conditions for the listener. This corresponds to imposing that the value of STI achieved with the face mask is the same as the value achieved without a face mask. Based on the previous discussion, this is most likely only a lower limit on ΔL_A.

Restoring STI to its original values

Figure 6a shows the increase in the sound emission level (ΔL_A) required to restore the STI at its reference (“no-device”) value for all seven tested values S/N = -15 to +15 dB, in the anechoic chamber. The value of ΔL_A is an estimate of the additional effort required by the speaker to overcome the distortion introduced by the face shield or mask. As expected, there is a very tight correlation between the STI variation (ΔSTI) and the required rise of the emission level (ΔL_A). The very limited spread is presumably due to the finite resolution of the calculated ΔL_A, set at 0.5 dB. The two linear fits calculated for the points with positive and negative values of $\Delta STI/\Delta L_{Aeq}$ are statistically indistinguishable and are not shown.
Figure 6b shows the increase in the sound emission level (ΔL_A) required to restore the STI at its reference (“no-mask”) value, in the reverberation room. The most striking feature is that values of ΔL_A are much larger than those seen in Figure 6a for the anechoic chamber and the slope is much higher, in absolute terms. In other words, very large increases of the vocal

emission level are needed to offset the strong negative action of reverberation. Another impressing feature of Figure 6b is the dispersion of points in the region ΔSTI < -0.04. Two points in particular show much larger values of ΔL_A than would be expected based on their ΔSTI. Both points belong to the S/N = 15 dB case, that is where STI is near its highest possible value taking into account the effect of reverberation. Under these circumstances, an extremely large increase in L_A is needed to recover from even a moderate loss in STI. The slope of the sample with positive values of ΔSTI might be even steeper, but the explored range of ΔSTI is too limited (0 ≤ ΔSTI ≤ 0.02) to allow any firm conclusion on this point.

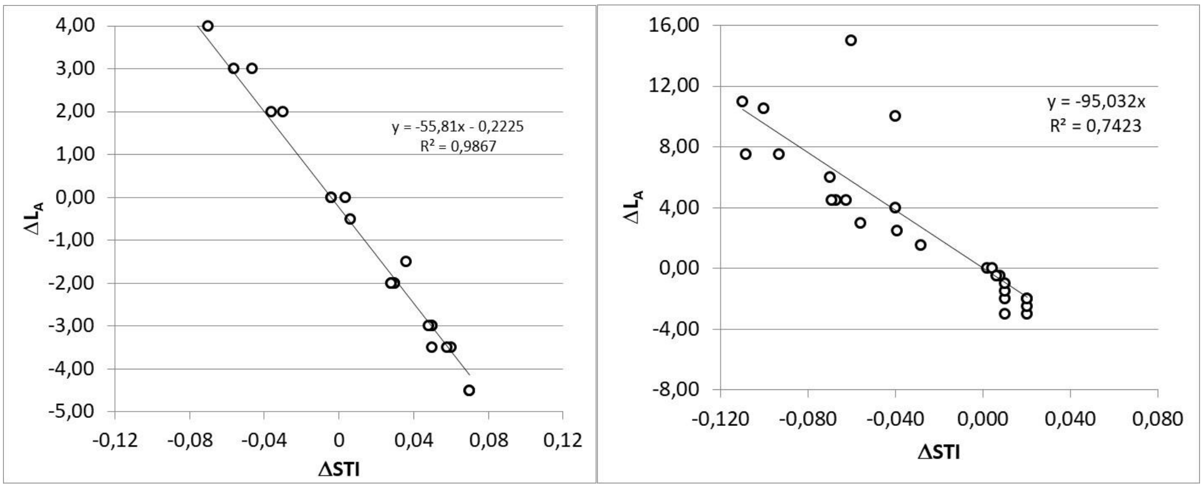

Figure 6 – Increase in the global level of the emitted signal required to keep STI equal to the reference value. a) Anechoic chamber (left panel) – b) Reverberation room (right panel)

Taken together, results shown in figures 6a and 6b provide clear indications that a much smaller vocal effort is needed in low-reverberation environments. This strongly supports actions aimed at keeping reverberation times as low as possible in all these environments where the use of voice is prolonged, use of face masks/shields is widespread and clarity of communication is a fundamental requisite.

CONCLUSIONS

We have investigated the acoustic performance of four configurations where a polyethylene face shield is used both as a standalone device or in combination with cloth face masks.
The transmissibility of the face shield is dominated by a strong resonance peak in the 630 – 1250 Hz spectral region. This confirms the results obtained by previous research groups. It also indicates that the resonance is largely set by the geometrical properties of the cavity between the face and the shield, rather than by the structural properties of the shield itself. Configurations where both a face shield and a face mask are used together show a reduction in the resonance peak amplitude, which can be attributed to the attenuation produced by the face mask.
In low-reverberation environments, the impact on the Speech Transmission Index (STI) induced by the use of a face shield with/without additional cloth masks is positive and quite large when the signal-to-noise ratio is very low. This improvement can be attributed to the weakly damped resonance around 1000 Hz. The impact on STI worsens drastically when S/N increases. In high-reverberation environments, changes are more limited and the positive impact for low S/N values is almost non-existent.
Finally, we have calculated the increase in the vocal sound emission level needed to restore the STI at its reference (no mask/no shield) value. This is intended to provide an estimate of the additional effort required by the speaker to overcome the distortion introduced by the face shield. Results show that a much smaller vocal effort is needed in low-reverberation

environments, thus underlining the benefits of keeping reverberation times as low as possible in all these environments (primarily in schools) where the use of voice is prolonged and clarity of communication is a must.

Acknowledgements

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