Acoustics Australia (2021) 49:505–512
https://doi.org/10.1007/s40857-021-00245-2

ORIGINAL PAPER

Acoustic Effect of Face Mask Design and Material Choice

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Received: 10 February 2021 / Accepted: 21 May 2021 / Published online: 3 June 2021

Abstract
The widespread adoption of face masks is now a standard public health response to the 2020 pandemic. Although studies have shown that wearing a face mask interferes with speech and intelligibility, relating the acoustic response of the mask to design parameters such as fabric choice, number of layers and mask geometry is not well understood. Using a dummy head mounted with a loudspeaker at its mouth generating a broadband signal, we report the acoustic response associated with 10 different masks (different material/design) and the effect of material layers; a small number of masks were found to be almost acoustically transparent (minimal losses). While different mask material and design result in different frequency responses, we find that material selection has somewhat greater influence on transmission characteristics than mask design or geometry choices.

Keywords Acoustic response · Face mask · Speech intelligibility · Pandemic · Covid-19

1 Introduction

The global pandemic of 2020 has led to the widespread adoption of face masks as a recommended public health and safety measure. While initially limited to medical staff as standard Personal Protection Equipment, it is now agreed that face masks effectively limit the aerosol spread while speaking or breathing [1].

However, it may be observed that fitting on a face mask drastically affects speaking, intelligibility, and breathing [2–6]. While an obvious and non-trivial outcome is the lack of visual feedback of the speaker's lips and mouth (*cf.* McGurk Effect [7]), as well as missing out on important expressive facial cues that support intelligibility [8–10], it may be noted that speech sounds, particularly high frequencies, are perceptually important [10–12]; hence, consonants and nasal sounds may be somewhat more affected than vowel (formant) sounds through a mask, frustrating anticipatory, and intelligibility cues.

These penalties to speech intelligibility, compounded by noisy environments in crowded public settings (shopping malls, market places, etc.) require changes to both speech production (greater vocal effort, hyper-articulation, etc.) as well as speech perception, such that additional gestural cues may be needed [13, 14]. A crucial consideration is the compensatory *increase* in vocal effort and hyper-articulation employed by the speaker which increases the rate of potentially dangerous aerosol production, negating somewhat the protective effects of wearing a mask [15].

Furthermore, the choice of face mask design and material also changes the acoustic radiation boundary conditions with regard to the speaker's lips and vocal tract [16], requiring articulatory adjustments from the speaker to elicit equivalent speech sounds; but the speaker may not be mindful to make these compensatory changes, thereby further compromising intelligibility [17].

These considerations require a closer study of how mask design and material choices influence the transmission of speech sounds produced at the speaker's lips. Here, we investigate the frequency response of various masks and possible insights that may benefit the choice of mask

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design, geometry, material, or fabric layers, indicating which mask(s) may least affect speech intelligibility.

2 Methodology

In this study, ten masks of various design and material—both commercially sourced in Singapore and a number of home-made mask designs reported in literature [18, 19]—were chosen. These masks were mounted (fitted closely on the face, as per recommended use) on a life-size dummy (mannequin) head specially modified with a small loudspeaker (after Nakamichi "MiniCube," 5 × 5 × 5 cm) mounted and fully sealed *within* the dummy's "mouth"; a 15 mm diameter aperture at the "lips" allows the head to "speak" representatively (Fig. 1). The dummy head is constructed of thick heavy epoxy, such that it does not noticeably vibrate or transmit sound, except at the lip aperture; the cavity inside the head (i.e., behind the loudspeaker) is then filled-in with acoustically absorbing foam. In a single recording session, the experiment was set up in the Academic Media Studio of the Singapore University of Technology and Design (SUTD), an acoustically treated room (110 m^2) noted for excellent sound isolation (< 17 dB re 20 μPa, down to 125 Hz) and minimal reverberation (< 0.26 s down to 100 Hz). The head was mounted on a microphone stand in the middle of the room, such that it is "upright" and the lips are 1.8 m off the ground, distanced from both the floor and ceiling to minimize nearby reflections.

To create the reference excitation signal at the lips (loudspeaker), a quasi-continuous (broadband) noise was synthesized following [20] as the sum of 227 sine waves from 258 to 10,034 Hz (encompassing frequencies relevant to speech, including sibilants) with equal spacing of 43.1 Hz and generated such that each harmonic is of equal energy when measured at the lips (i.e., a "flat frequency response"; e.g., the black line in Fig. 4 is flat to ± 0.25 dB) using a reference measurement microphone (UMIK-1, miniDSP, Hong Kong; ± 0.5 dB deviation in frequency response over the frequency range studied; 133 dB maximum SPL for 1% THD @ 1 kHz). While such an excitation signal does not directly represent speech per se, it indicates frequency response across a broad, quasi-continuous range of frequencies with good resolution. Further, this "flat frequency response" condition produced *at the lips* is generalizable and allows other researchers to easily replicate the study, independent of the specific frequency response, self-noise, and total harmonic distortion of the equipment chosen [21]. (Although the acoustic radiation boundary condition at the speaker's lips can be influenced by the wearing of face masks (noted above, *cf.* [16]), subtly altering the load on the acoustic source during speech, here, we are more interested in the acoustic response of the masks themselves in response to the artificial excitation source provided by our loudspeaker.) Lastly, the "flatness" allows one to intuitively visualize the transmission (propagation and radiation) differences across the spectrum as an absolute measurement, instead of relative values.

To measure the frequency response associated with each mask, another reference microphone (UMIK-1) was placed 1 m away from the lips/mask, such that it pointed axially at the lips (i.e., $\Phi = 0°$ and $\theta = 0°$, coaxial with dummy's lip opening). The distance of 1 m is chosen because it reflects pandemic "safe-distancing" guidelines recommended in Singapore [22] and many countries around the world [23]. To create the frequency response plots in Figs. 2, 3 and 5, the resulting audio files recorded (PCM WAV, 44.1 kHz) were fast Fourier transformed using a Hamming window and averaged over several seconds of signal to improve signal-to-noise ratio.

Fig. 1 *Left*: cutaway schematic of the dummy head showing the mounted loudspeaker at the lips; the cavity behind the loudspeaker is filled with acoustically absorbing foam. *Right*: headshots of the ten masks investigated, fitted on the dummy head

In a separate investigation to better understand the relationship of fabric layers (alone) on transmission characteristics, a similar but simplified approach was taken: the "flat" quasi-continuous excitation signal was generated at another Minicube Speaker (not mounted within the head), with the measurement microphone sited at the edge of the speaker grill to produce the reference signal ("0-ply"); various fabric layers were then laid flat between the speaker grill and the microphone to yield the frequency response curves in Fig. 4.

Table 1 shows the characteristics (design, material, density, and other fabric properties) of the ten masks used. Of note,

- Mask 3 is a flat 2-ply open-cell foam mask designed for protection against pollen (15–200 μm) and dust particles (> 10 μm)
- Mask 4 is a "standard-issue" non-woven polypropylene surgical mask commonly used in clinical settings
- Mask 5 is an industrial N95 mask intended for fine particulate matter protection
- Masks 2, 6, and 7 are issued free to the public by the Government of Singapore during April, June, and September (respectively) during the 2020 pandemic response in Singapore
- Masks 8–10 are "home-made," sewn from the same material (plain-weave cotton) using designs provided by [18, 19]; the material used for these masks and its frequency response is further studied
- All masks, with the exception of Mask 4 and possibly Mask 5, are designed to be reusable

(Subsequently, in this paper, we refer to each mask using the number ascribed in Fig. 1 and described in Table 1.)

In this study, we limit our investigation to understand the frequency response of various mask design, material and also the effect of material layers.

3 Results and Discussion

The frequency response curves of Masks 1–10 are shown in Fig. 2 and 3 (absolute SPL is shown in the former and relative attenuation is shown in the latter) and their performance can be grouped into three categories: high, intermediate, and minimal attenuation (reflected, respectively, by orange-purple-green color scheme in Fig. 2 and 3); also shown in black (in Fig. 2) is the frequency response of the reference no-mask condition. Additionally, Table 2 accompanies Fig. 2 and summarizes the average dB SPL of these frequency response curves in three frequency bands and over the entire frequency range studied.

Firstly, for the no-mask condition (black line in Fig. 2), we note the measured frequency response deviates from the calibrated flat frequency response generated at the dummy's lips. This non-flat behavior at 1 m from the dummy's lips is not unexpected because radiation from the dummy's lips and face (via the mask) is not necessarily uniform, and it includes possible room interactions (e.g., dips at ~ 3 kHz and ~ 6.8 kHz). Hence, this represents a typical signal heard by a listener situated 1 m away from one speaking.

The ten masks show diverse transmission characteristics, with some masks more acoustically transparent than others and some masks exhibiting significant attenuation. Broadly, two frequency regimes may be observed here: below 3 kHz and above 3 kHz (see Fig. 2 and 3). Below 3 kHz, generally rather minimal attenuation (average attenuation ≤ 2.8 dB) is introduced by most masks compared to the no-mask condition, with the exceptions of Mask 6 (4 dB attenuation); this frequency range is important for most vowels and some consonants.

Moreover, over 3–8 kHz, we see a dramatic range of responses (see Table 2 and Fig. 3):

Table 1 Design and material characteristics of the ten masks studied

Mask	Design	Material	GSM* of mask (g/m^2)	Thickness of mask (mm)	Ply
1	Cup	Plain-weave cotton	416	1.2	3
2	Cup	Jersey-knit cotton	482	1.4	2
3	Conform	Open cell foam	286	4	2
4	Rectangular and pleated	Non-woven polypropylene	115	0.6	3
5	Rigid	Non-woven polypropylene	475	2.1	3
6	Cup	Cotton/Polyester blend	872	1.8	2
7	Rectangular and pleated	Cotton/Polyester blend	357	1	3
8	Cup	Plain-weave cotton	268	0.4	2
9	Cup	Plain-weave cotton	268	0.4	2
10	Rectangular and pleated	Plain-weave cotton	268	0.4	2

*GSM: grams per square metre

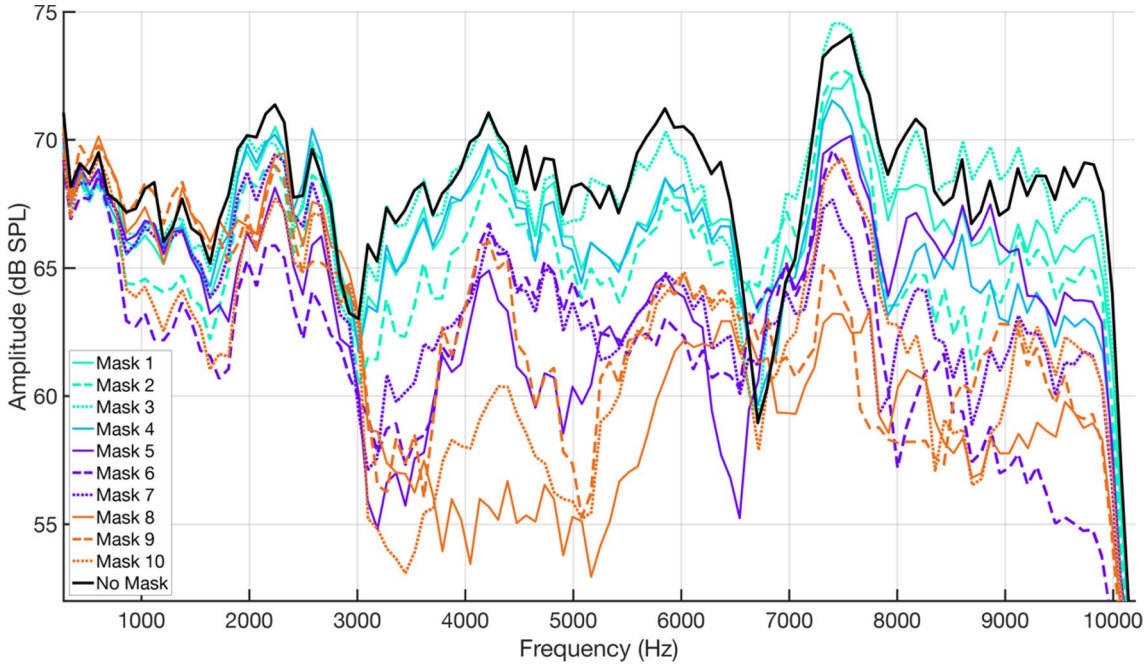

Fig. 2 Frequency response (dB SPL) of Masks 1–10. Reference (no mask)—black, minimal attenuation—green, intermediate attenuation—purple, high attenuation—orange

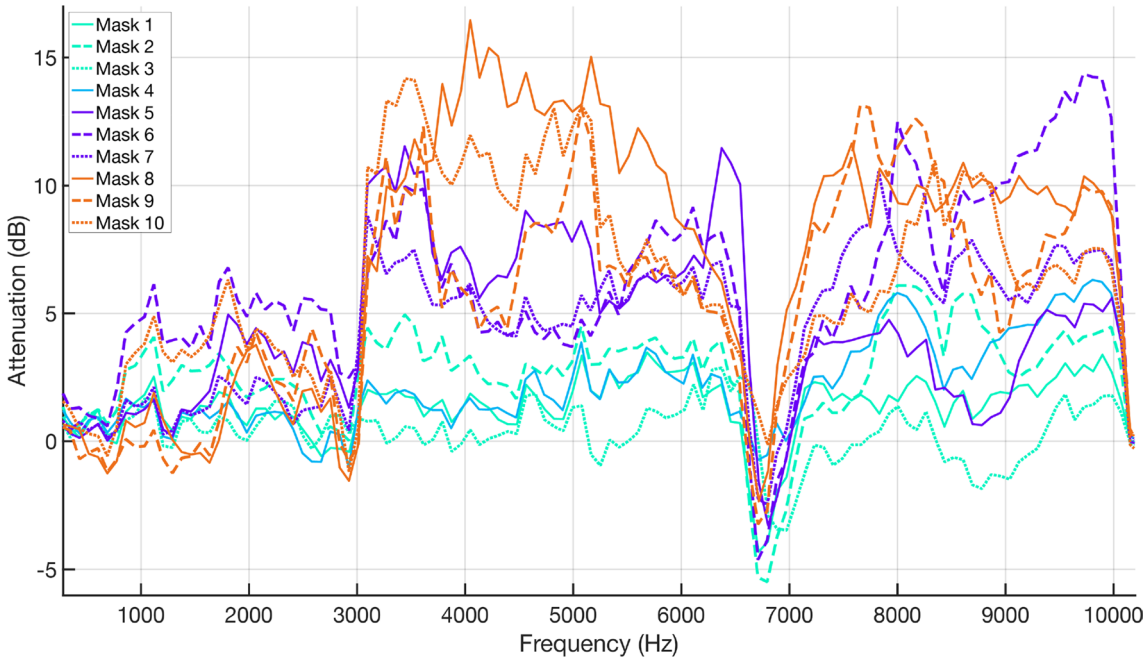

Fig. 3 Frequency response (dB attenuation) of Masks 1–10, with respect to the no-mask condition. Minimal attenuation—green, intermediate attenuation—purple, high attenuation—orange

- Minimal attenuation (green): Masks 1–4 (< 2.5 dB average attenuation)
- Intermediate attenuation (purple): Masks 5–7 (5.4–6.3 dB average attenuation)
- High attenuation (orange): Masks 8–10 (up to 15 dB attenuation at some frequencies, but 6.9–9.9 dB average attenuation)

Table 2 Average SPL associated with the ten masks studied for three frequency bands and overall frequencies measure

Mask	Design	< 3 kHz (dB SPL)	3–8 kHz (dB SPL)	> 8 kHz (dB SPL)	Overall (dB SPL)
NA	(No Mask)	68.1	68.4	68.3	68.3
1	Cup	67.3	67.0	66.2	66.9
2	Cup	66.2	66.0	63.9	65.6
3	Conform	**67.4**	**68.0**	**68.2**	**67.9**
4	Rectangular and pleated	**67.4**	66.3	63.7	66.1
5	Rigid	66.0	62.1	65.0	63.8
6	Cup	**64.1**	63.0	**57.3**	62.1
7	Rectangular and pleated	66.8	63.0	61.6	63.7
8	Cup	**67.4**	**58.5**	58.6	**61.0**
9	Cup	67.1	61.5	59.8	62.7
10	Rectangular and pleated	65.3	60.6	60.3	61.9

Highest and lowest SPL values are indicated in bold

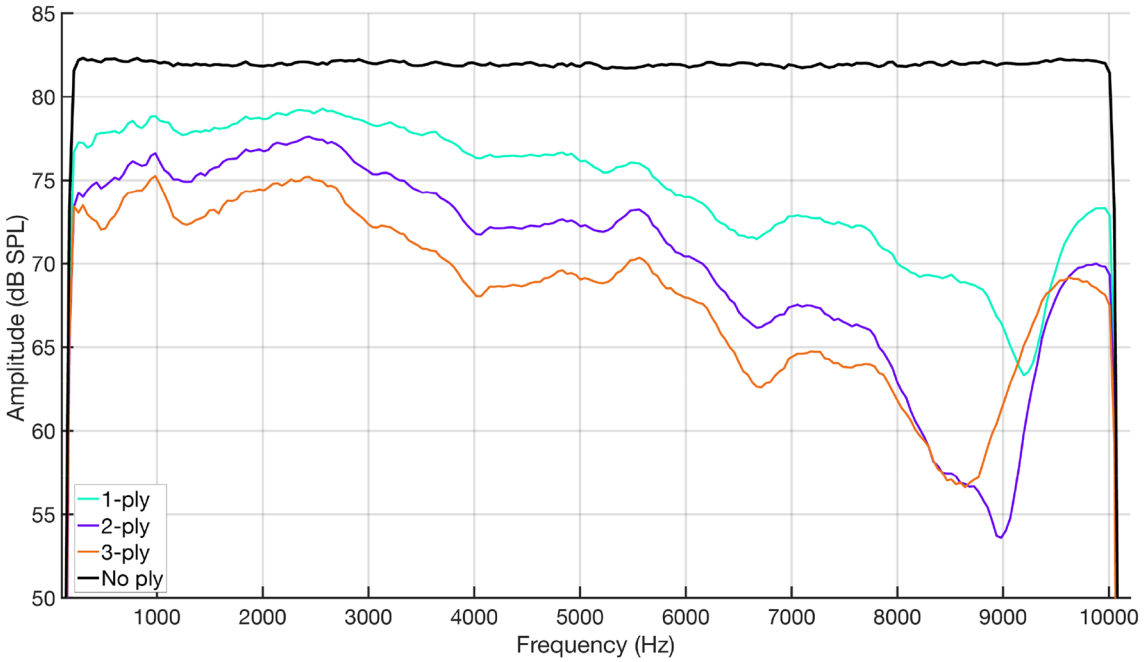

Fig. 4 Frequency response of varying layers of the cloth used in Masks 8–10. 0-ply (black) is the reference signal and is almost equal-energy (flat) to ± 0.25 dB

For frequencies above 8 kHz, while still generalizable, are rather less consistent for these masks. Curiously, between about 6.5–7 kHz, some increased transmission may be observed with some masks; while we cannot directly explain this puzzle, such similar behavior have also been reported in [4] at other frequency bands.

Among the ten masks surveyed, Masks 1–4 (green curves, Fig. 3) have relatively low attenuation (< 3 dB) for most of the frequency range. Such acoustic transparency is expected to preserve speech intelligibility, and we suggest that these masks may be most favorable for speech-intensive contexts, such as educational settings, marketplaces, religious services, etc. In particular, we note that the open cell foam mask (Mask 3), although the thickest surveyed (4 mm), performs practically transparently in terms of acoustic transmission: very modest 0.7 dB, 0.4 dB, and 0.1 dB average attenuation over the frequency bands < 3 kHz, 3–8 kHz and > 8 kHz, respectively, and a mere 0.4 dB average attenuation overall.

Masks 1–4 are also noted anecdotally to be more breathable relative to the other masks despite having different material and design characteristics: Mask 1 and 2 (triple-ply plain-weave cotton and double-ply jersey-knit cotton, respectively) have similarly high GSM with a moderate

thickness of 1.2–1.4 mm. On the other hand, Mask 3 is made from open cell foam and has moderate GSM but is the thickest (4 mm); Mask 4 is made from triple-ply non-woven polypropylene with the lowest GSM and minimal thickness. Consequently, it seems that mask design and material characteristics such as GSM, thickness, and plies are rather poor predictors of acoustic transparency. Plain weave and jersey-knit cotton (Mask 1 and Mask 2) were also identified to possess good transmission characteristics in [6].

The N95 mask (Mask 5), designed for particulate matter filtration, performed neither particularly well nor poorly in terms of acoustic response with respect to the other masks. Interestingly, Masks 6 and 7 were also found to have similar intermediate transmission responses (purple curves, Fig. 2) with Mask 5 despite the three masks having different design and material: Mask 6 has a double-ply cup structure whereas Mask 7 has a triple-ply rectangular-pleated structure, and both are made of cotton/polyester blend. Masks 5, 6, and 7 show intermediate attenuation with overall averages 4.5 dB, 6.2 dB, and 4.6 dB, respectively.

We observe the largest acoustic attenuation in Masks 8–10: up to 15 dB attenuation can be seen from 3 to 6.5 kHz. For the three frequency bands identified in Table 2, it is interesting to note that over the first band (< 3 kHz), only very modest average attenuation is observed (0.7–2.8 dB); the remaining two frequency bands, however, make up the bulk of attenuation: significant averages ranging from 6.9 to 9.9 dB and 8.0–9.7 dB, respectively, and can be expected to have a severe impact on speech intelligibility. This results in Masks 8, 9, and 10 with overall attenuation averages ranging from 5.6 to 7.3 dB.

As noted earlier, Masks 8–10 are popular homemade mask designs [18, 19] made from the same material (plain-weave cotton, dyed on one side) but possess different geometries and cuts: Mask 8 has a curved cup geometry with a prominent covering over the nose ridge, Mask 9 has a "beaky" protrusion, whereas Mask 10 is a rectangular and pleated design similar to Masks 4 and 7 (which performs better).

Next, we further investigate the frequency response (Fig. 4) of plain-weave cotton used in some masks (*cf.* Mask 8–10) and explore the effect of different materials used in the same mask design (rectangular and pleated, *cf.* Mask 4, 7, 10) (Fig. 5).

Figure 4 shows the frequency response of different layers of the plain-weave cotton used in Masks 8–10. Also shown in Fig. 4 is the response of the reference excitation signal (i.e., free radiation condition with no fabric). It is clear from Fig. 4 that below 8 kHz, attenuation increases monotonically with increasing number of layers but with somewhat diminishing returns; further, attenuation across the fabric generally increases with frequency (up to a point). Interestingly, we observe a trend reversal above ~ 9 kHz where transmission instead increases with frequency. This behavior is not understood, but it could be associated with the fabric structure interacting at short

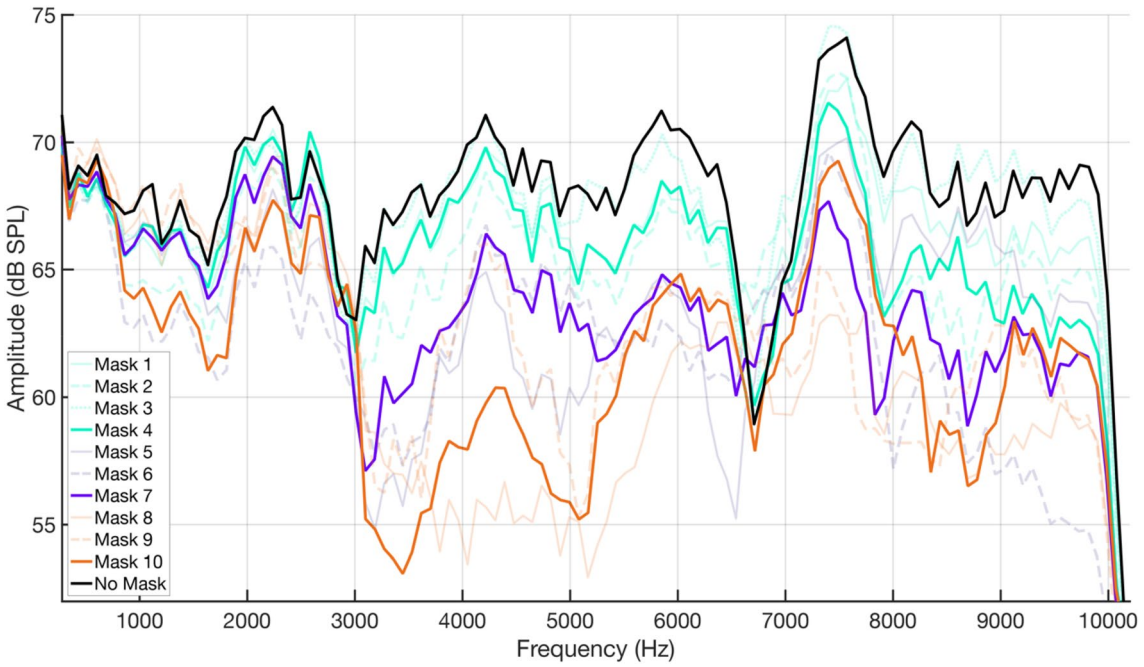

Fig. 5 Frequency response comparing rectangular pleated masks of different fabric. The no-mask (black) curve is the reference, and the other non-pleated masks are faded out

wavelengths (giving rise to a "cutoff frequency" response of sorts) and thus invites further investigation. Additionally, we also varied both inter-ply alignment and weave direction (with respect to the microphone) but no significant influence on transmission was observed, and so we do not present those somewhat identical curves here.

Figure 5 highlights and compares the frequency response curves of masks made from *different fabric* but having the *same design* (rectangular and pleated construction): Mask 4 (triple-ply non-woven polypropylene), Mask 7 (triple-ply cotton/polyester blend) and Mask 10 (double-ply plain-weave cotton). (Other masks' response are present but faded out, for comparison.) Strikingly, all three masks have similar transmission profiles (they run largely parallel) for most of the frequency range studied but with varying degrees of attenuation. Of particular note is the 3–8 kHz frequency band, where Mask 4 has the least attenuation (2.1 dB on average) and mask 10 has the greatest attenuation (7.8 dB on average, reaching ~ 12 dB at some frequencies). It is expected that such levels of attenuation, especially in the ~ 3–8 kHz band, may noticeably influence the intelligibility of nasals and some consonants, especially fricatives. Here, we observe that despite having a similar design (rectangular and pleated construction), the difference in material choice seems to have the greater impact on transmission compared to mask design.

4 Conclusion

We investigated how the design and material choice of 10 face masks influence their frequency response, identifying implications of how speech sounds produced at the speaker's lips may be affected by these masks. Although different mask designs were observed to give rise to different transmission responses, broadly speaking, material choice seems to have a greater impact on transmission than may be predicted by mask geometry and design. We also showed that while attenuation increases with the number of plies, it does so with diminishing returns. We also identified the open cell foam mask (Mask 3) to be practically transparent in terms of acoustic transmission; hence, it more desirable for maintaining speech intelligibility; other masks exhibit greater attenuation characteristics and are accordingly less desirable for speech intelligibility.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40857-021-00245-2.

Funding Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of Interest.

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