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Citation: The Journal of the Acoustical Society of America **151**, 2931 (2022); doi: 10.1121/10.0010384
View online: https://doi.org/10.1121/10.0010384
View Table of Contents: https://asa.scitation.org/toc/jas/151/5
Published by the Acoustical Society of America

JASA ARTICLE

Improving the measurement and acoustic performance of transparent face masks and shields

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ABSTRACT:
Opaque face masks harm communication by preventing speech-reading (lip-reading) and attenuating high-frequency sound. Although transparent masks and shields (visors) with clear plastic inserts allow speech-reading, they usually create more sound attenuation than opaque masks. Consequently, an iterative process was undertaken to create a better design, and the instructions to make it are published. The experiments showed that lowering the mass of the plastic inserts decreases the high-frequency sound attenuation. A shield with a clear thermoplastic polyurethane (TPU) panel had an insertion loss of (2.0 ± 1.1) dB for 1.25–8 kHz, which improves on previous designs that had attenuations of 11.9 dB and above. A cloth mask with a TPU insert was designed and had an insertion loss of (4.6 ± 2.3) dB for 2–8 kHz, which is better than the 9–22 dB reported previously in the literature. The speech intelligibility index was also evaluated. Investigations to improve measurement protocols that use either mannikins or human talkers were undertaken. Manufacturing variability and inconsistency of human speaking were greater sources of experimental error than fitting differences. It was shown that measurements from a mannikin could match those from humans if insertion losses from four human talkers were averaged.
 https://doi.org/10.1121/10.0010384

(Received 25 November 2021; revised 14 April 2022; accepted 16 April 2022; published online 29 April 2022)
[Editor: Zhaoyan Zhang] Pages: 2931–2944

I. INTRODUCTION

Face masks are widely used in medical settings to reduce the spread of disease via aerosol dispersion. They have also become widely used by the public during the SARS-CoV-2 pandemic. Unfortunately, face masks can hinder communication by attenuating speech, especially at high frequencies. Furthermore, the most common type IIR surgical[1] and cloth masks are opaque, which further harms communication by preventing speech-reading (also known as lip-reading). For example, in 2021, Truong *et al.*[2] measured the word recognition rate in an audiovisual listening experiment. They compared the speech intelligibility with and without a two-layer cloth face mask. Putting on the face mask lowered the word recognition rate from 58% to 53%, and Truong *et al.* attributed this to the loss of visual cues. Smiljanic *et al.*[3] found no significant change in intelligibility with and without a surgical mask in quiet conditions for conversational speech. But when noise was added, there was a significant drop in intelligibility for conversational speech through the face mask when compared to the case of no mask. With the face mask, the word recognition accuracy dropped from about 80% in quiet to 38% in 5 dB signal-to-noise ratio (SNR) six-talker babble. Similar trends were found by Toscano and Toscano,[4] including the result that standard surgical masks are relatively sound transparent and, thus, no significant degradation of speech intelligibility was found for their audio-only experiments. In other studies, Choi[5] and Bottalico *et al.*[6] investigated speech intelligibility with and without masks in university classrooms. Rahne *et al.*[7] measured how the speech perception threshold was decreased and listening effort increased in various background noise conditions for a surgical and N95 mask.

Transparent masks allow lip-reading but at the cost of more sound attenuation. Atcherson *et al.*[8] performed speech intelligibility tests with and without visual information for people with and without a hearing impairment. They found listeners with a hearing impairment benefitted from being able to speech-read through a transparent surgical mask. In contrast, Brown *et al.*[9] found that for cloth, surgical, and a transparent design, speech intelligibility dropped substantially when moderate background noise was present. This was true for both younger and older adult listeners. Yi *et al.*[10] found that for clearly spoken speech and speech-spectrum-shaped noise as an interferer, the visual cues provided by a transparent mask overcame the effects of sound attenuation by the mask in a speech intelligibility test. But this was not the case for conversational speech or when the background noise was four-talker babble. Thibodeau *et al.*[11] found that for a face mask with a clear panel, the availability

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of speech-reading improved speech intelligibility, but the percentage of words correct was still lower than for the no-mask condition due to the sound attenuation of the mask.

The contradictions in the findings from these four studies in the previous paragraph[8–11] are likely to have arisen from differences in the methodologies used and face masks tested. Unfortunately, there is a lack of details on the geometry and material properties of the masks being tested in most papers. Nevertheless, these papers do suggest that by minimizing sound attenuation, it should be possible to construct a mask with a clear panel that recovers some or all of the speech intelligibility performance of the no-mask condition.

Singh *et al.*[12] examined word recognition in two-year-old infants with and without face masks and shields. They found that while a surgical mask had no effect on word recognition, a transparent face shield worsened word recognition. The fact that the shield's clear plastic would have attenuated sound more than the surgical mask, where transmission is dominated by discrete vibration modes, might explain this. Not only would the voice be quieter, but the timbre of the voice would also have been altered due to the uneven frequency spectrum created by the vibration modes of the shield.

Several papers have reported measurements on sound attenuation by opaque masks, which are useful benchmarks against which to compare our masks. These previous studies also highlight potential methodological issues. Rahne *et al.*[7] measured significant attenuation over 1000 Hz. But this was performed with the mask stretched over a loudspeaker and not a mannikin. Any transmission due to the vibration of the mask will depend on the tension and boundary conditions and, consequently, it is unclear how representative these results would be when masks are worn by a person. Pörschmann *et al.*[13] used a HEAD acoustics dummy head with mouth simulator (HEAD acoustics GmbH, Germany), therefore, the morphology was like a human head. They measured transmission loss from several opaque face masks. The attenuation of the sound was most significant about 2000 Hz. Balamurali *et al.*[14] used a mannikin made from thick heavy epoxy with a small loudspeaker mounted in the mouth to measure ten opaque masks. The attenuations ranged from 0 to 5 dB from 1000 to 3000 Hz with many masks also showing a significant increase in sound loss above 3000 Hz. The losses varied considerably depending on construction with material choice being the most important factor.

To allow access to the benefits of speech-reading, face masks with clear panels in front of the mouth have proliferated. As noted above, however, what is gained through speech-reading can be lost due to greater sound attenuation because the clear panels are impervious. Corey *et al.*[15] and Atcherson *et al.*[16] measured transparent face masks and shields. They used mannikins, but in both cases, the morphology was somewhat different from a human. Corey *et al.* used a head shaped loudspeaker made from plywood with a 2 in. driver mounted on a large flat piece of wood at the mouth. Atcherson *et al.* used a Styrofoam head with a 92 mm wide loudspeaker, which is considerably bigger than a human mouth.

Both studies found little effect for masks below 1000 Hz with attenuations above that varying with the frequency depending on the mask construction. The transparent masks tended to have more mid–high-frequency attenuation than opaque designs. For full-face shields (or visors), there is typically amplification of 3–8 dB around 630–800 Hz, which increases the SNR in that bandwidth. At higher frequencies, however, there is attenuation with measurements around the mannikins showing how these shields deflect significant sound toward the side and rear.[15] For the cloth masks with clear plastic inserts, mid-frequency amplification is absent or less pronounced than for the shields. Again, attenuation is found for frequencies at and above 2000 Hz.

Corey *et al.*[15] also measured the sound attenuation with human talkers. Masks might provide different attenuations with human talkers because of air flow, the movement of the face changing the fit of the mask, and nonlinear behavior as the mask is close to the mouth where there is higher pressure. For cloth masks, Corey *et al.*[15] obtained similar attenuations for tests on humans and a mannikin, but for masks with transparent panels, the results were significantly different. Nguyen *et al.*[17] measured human voice characteristics with a surgical mask, a KN95 mask, and no mask. In the 1000–8000 Hz region, the KN95 mask provided an average of 5.2 dB attenuation and the surgical mask provided an average of 2.0 dB. No effect below 1000 Hz was found.

While the focus of the above work has been on sound attenuation and loss of intelligibility, it is worth noting that nonphysical factors, such as stress and effort on the listener and talker, are also increased when face masks are used.[18]

In this paper, measurements that use human talkers and a head and torso with a mouth simulator (mannikin) are presented. These are used to quantify the differences between the more convenient measurements on a mannikin and those using people talking. Many of the previous studies listed above lack a full analysis of measurement uncertainty, and so this is considered. Further, the study builds on this growing body of literature to examine face masks with clear panels. For the mannikin tests, the face masks were measured with more realistic mounting conditions than were provided for previous studies on transparent designs. Alongside measured sound attenuations, Doppler laser vibrometer measurements are used for the first time to examine mask behavior. These are supplemented with measurements of the flow resistance of the cloth. Through these experiments, it is shown how sound losses can be reduced by a careful choice of materials, especially decreasing the acoustic mass of the clear plastic inserts. The measured attenuations are also used to evaluate the speech intelligibility index (SII) to quantify the effects of sound attenuation on speech intelligibility.

The research questions for this work were

- Does the acoustic performance vary significantly due to a changing fit or manufacturing variability?;

- can measurements on a mannikin replicate those on real talkers? And what are the measurement uncertainties? and
- how can a face mask with a clear panel be made less attenuating?

II. METHODOLOGY

A. Measurements on the mannikin

1. Acoustic measurement

The measurements were performed in a listening room as this is more representative of real listening conditions than an anechoic chamber. The listening room conforms to ITU-R BS.1116 standard across the speech bandwidth with a mid-frequency reverberation time of 0.25 s.[19] The background noise level is NR10.

The mask was mounted on a GRAS 45BC KEMAR Head and Torso with Mouth Simulator (GRAS Sound & Vibration, Holte, Denmark), which for brevity will be called a mannikin—see Fig. 1. The output of a universal serial bus (USB) sound card [MOTU 4Pre (MOTU, Inc., Cambridge, MA) or Focusrite 2i2 (Focusrite PLC, High Wycombe, UK), depending on what was available on the day of the measurements] was connected to the mannikin's integrated preamplifier and from there to the loudspeaker of the mouth simulator. A 1/2 in. condenser measurement microphone (GRAS 40AF with Brüel and Kjær 2669 preamplifier, Brüel & Kjær, Nærum, Denmark) was placed facing the mouth of the mannikin at 1 m. This was fed to a Norsonic type 336 front end interface (Norsonic, Tranby, Norway) and from there to the input of the soundcard. The microphone position was set with a Leica Disto D110 laser measure (Leica Geosystems, St. Gallen, Switzerland) using the center of the mannikin's bottom lip as a reference point. The laser level base was placed flat against the microphone grid and pointed at the mannikin to check on-axis alignment and the distance to the lips (1 m). The distances to the carpeted floor from the center of the microphone grid and bottom lip were set to 1.22 m. (This height was chosen based on the measurements on two seated humans.)

FIG. 1. (Color online) The measurement using the mannikin.

The impulse response between the output and input of the sound card was measured using a sine sweep from 20 Hz to 21 kHz (48 kHz sampling frequency, 8 s sine sweep, and 10 s acquisition time). The impulse response was calculated through deconvolution.[20] The measurements were taken with and without the mask present. The two frequency responses (in dB) were subtracted to obtain the mask's insertion loss.

To explore the experimental errors arising from the fitting of a mask, each sample was measured six times with the mask being completely removed and replaced between each measurement to obtain an average over different fittings. A basic visual-fit check was performed each time the mask was donned to ensure the position was consistent across measurements, e.g., the nose wire was molded into place, ear elastic was not twisted or pulling the mask toward one side of the face, and there were no obvious defects in the mask.

To explore the experimental errors arising from manufacturing variability, a repeatability exercise was undertaken where the above measurement protocol was repeated for six cloth masks of the same model. Hence, for these tests on manufacturing variability, there were six measurements for each of the six masks.

2. Surface velocity measurements

A Polytech PSV-400 Doppler laser vibrometer (Polytec, Baden-Württemberg, Germany) was used for noncontact measurement of the surface velocity of the mask while on the mannikin. These measurements were undertaken to examine the vibration of the mask and inserts and better understand one of the transmission mechanisms. The transparent parts of the mask were speckled with white cellulose paint to allow the laser to reflect from the surface. The laser head was approximately 1 m from the mask. The masks were placed on the mannikin, and the white noise generated by the Polytech system radiated from the mouth simulator. To gain a greater SNR for high frequencies where the mask vibration is naturally less, a 1/3-octave graphic equalizer was used to increase the level of the noise above 1000 Hz.

The quality of the measurement was monitored by examining the coherence function. This measures the fractional portion of the mean square vibration that can be attributed to the noise signal driving the loudspeaker. The coherence was greater than 0.75 from 75 to 9000 Hz for the transparent masks and from 75 to 1000 Hz for the cloth v1 mask.[21] The results are given as the transfer function between the internally generated noise and surface vibration.

An opaque cloth mask was measured as a baseline, and then an opaque cloth mask was measured with an acetate insert to observe how the transparent panel altered the vibration. It is important to note that a Doppler laser vibrometer cannot measure the sound passing through the pores of the cloth and, consequently, one transmission path is not quantified by this technique. Two impervious shields, one with and one without a thermoplastic polyurethane (TPU) insert, were also measured. For these samples, the Doppler laser vibrometer will fail to capture sound that diffracts around the sides of the plastic shields.

B. Measurements on people

Ethical approval for the work involving human subjects was obtained from the University of Salford ethics committee (ID 1399). The physical setup was identical to the mannikin measurements with a person on the chair instead of the manikin. The same microphone, preamplifier, and interface as were used for the mannikin setup were applied. The interface gain was set to +20 dB and the signal was sent to an Edirol R44 portable audio recorder (Roland Corp., Shizuoka, Japan; gain = −32 dBu/0 dB (sensitivity/level); 24-bit; 48 kHz; 100 Hz low cut filter on).

Four talkers, two males and two females, were used. They each read aloud the first four sentences from the rainbow passage,[22] which is a standard piece of linguistic text with a wide range of phonemes. On average, the extract took readers (29 ± 1) s to read. The words were printed in large text on a sheet of A4 paper and taped to a stand slightly behind the microphone. Participants were instructed to try and keep a consistent speaking level whether or not they were wearing a mask. They were asked to use a normal conversational level as if talking to someone at the position of the printed text.

Each person was given the opportunity to practice reading the passage before starting. For each mask, participants read the passage aloud first without the mask, and then read the passage again after putting on the mask. A recording was restarted if a participant made a mistake that either stopped them from reaching the end or altered the content of the passage significantly, e.g., misspeaking a word and then repeating part of a sentence to correct themselves. This was necessary in only a few trials.

The participants were clean-shaven. Each person was provided with a fresh mask sample and asked to try it on ahead of recording to make sure that the nose wire was molded across their noise and the ear elastics were adjusted to provide a snug and comfortable fit. The experimenter performed a visual check of the fit each time a participant donned a mask.

Different versions of the masks were made using various cottons; see Table I. The masks tested with humans and compared to mannikin measurements were all of the masks using cloth v2 with and without inserts (masks 3–7 in Table I). The v2 masks were used because they were the latest design available when the human trials were done. The experiments into the accuracy of human tests were performed with cloth v1 masks and a surgical mask (masks 2, 9, and 10) because these tests took place before the v2 masks were available.

A key methodological issue is whether people talk consistently with and without the face mask. If the speaking level changes, then the measured insertion loss will be inaccurate. Cohn *et al.*[23] carried out speech intelligibility tests with and without a face mask. They found that for clear speech, the word recognition rate by listeners increased. But for casual and emotional speech, the word recognition rate decreased. The suggestion is that when talkers were asked to make clear speech while wearing a mask, they adjusted the way they spoke to aid communication. Asadi *et al.*[24] reported that people spoke more loudly while wearing a variety of opaque face masks. They measured similar root mean square (rms) pressures on an external microphone with and without the masks and inferred that the talkers must have spoken more intensely with the mask on to overcome the sound attenuation of the face mask. Lin *et al.*[25] also measured only a small 1 dB increase in the speaking level with masks on compared to that with no mask.

For our experiments below, one difference from previous work is that talkers were instructed to maintain the same speech level with and without the mask. To check that this instruction was sufficient, the sound power below 1000 Hz was compared with and without the mask. This bandwidth was chosen because it is where the face mask creates only a small amount of attenuation.

C. SII

To aid interpretation of the attenuations provided by face masks, the SII (Ref. 26) was calculated using code developed by the Acoustical Society of America Working Group S3-79, 2005.[27] The SII is an objective measure that has been shown to correlate with the intelligibility of speech as evaluated by listeners in psychoacoustic experiments. The SII is suitable for face masks because it can deal with the linear filtering caused by the mask's sound attenuation. It works well for additive noise interferers but less so for fluctuating maskers such as competing speech. The normal vocal effort speech spectrum defined in Ref. 26 was used for the speech with this being attenuated by the mask's insertion loss. The interfering noise used the same normal vocal effort speech spectrum with a broadband gain applied to obtain various SNRs.

D. Flow resistance

The air permeability was measured as an indication of the breathability of masks and to aid the selection of the cloth. This was then converted to flow resistance[28] as this is the normal measure used in porous absorbents. The tests were performed with an air permeability tester (AirPerm, M021A, SDL Atlas, Rock Hill, SC) using a test area of 20 cm.[29] The air permeabilities of 19 cotton samples and 2 masks (FFP2 NR, type IIR surgical mask) were evaluated at pressure drops of 60, 70, 100, and 120 Pa. The rationale of using 100 Pa was one of the BS EN ISO 9073–15:2008 recommendations and it was used in a previous study.[30] Pressure drops of 60, 70, and 120 Pa were used because of the testing of the maximum inhalation resistance to certify the filter class.[31] For each material, three measures were

TABLE I. The masks and how they were tested. All were constructed by Salford's Maker Space unless otherwise stated.

Number	Description	Repeatability tests across identical masks	Repeated reading	Mannikin vs human tests	First mannikin tests	Second mannikin tests	Third mannikin tests	Laser Doppler vibrometer
1	Cloth v1; opaque Brilliant Mask (Ref. 44)	X			X			X
2	Cloth Brilliant Mask with printed design		X					
3	Cloth v2, opaque			X		X		
4	Cloth v2 with TPU film insert panel			X		X		
5	Same as that for 4 with acetate scaffold around edge of TPU insert			X		X		
6	Same as that for 4 with acetate honeycomb scaffold			X		X		
7	Same as that for 6 with extra cloth around chin/neck			X		X		
8	Cloth v2 with cling film panel and honeycomb scaffold					X		
9	Surgical mask, disposable		X		X			
10	Cloth v1 with acetate panel		X		X			X
11	Cloth v1 with clear polyvinyl chloride (PVC) panel				X			
12	Cloth v1 with clear FEP (fluorinated ethylene propylene) plastic panel				X			
13	Cloth v1 with cling film panel; film taped to edge of cloth				X			
14	Cloth v1, cling film insert, and honeycomb scaffold				X			
15	Cloth v1 with sandwich bag plastic insert				X			
16	Shield made from 3d printed Polylactide PLA and 0.75 mm polyethylene terephthalate glycol (PETG) transparent sheet.							X
17	Shield with TPU insert; laser cut aperture for TPU, overlapped in attachment using double-sided tape							X
18	Cloth v3 (including extra cloth around chin/neck)						X	
19	Cloth v4 (including extra cloth around chin/neck)						X	
20	Cloth v3 with TPU insert, honeycomb + scaffold, and extra cloth around chin/neck						X	
21	Cloth v4 with TPU insert, honeycomb + scaffold, and extra cloth around chin/neck						X	

taken at each of the four pressures, and the average taken at each pressure.

E. The face masks and shields

The masks that were measured are listed in Table I. Figure 2 shows pictures of many of the masks. The first round of mannikin testing was based on a commercially available cloth mask, which is referred to as cloth version 1 (or v1)—masks 1 and 2 in Table I. An aperture was cut out of the cloth mask and various clear plastic inserts added and sewn into place—masks 10–15. It was hypothesized that to a first approximation, transmission would be dominated by the acoustic mass of the plastic inserts. Therefore, various masks were made with plastic inserts with different mass per unit area. The lightest material (cling film) was also tested with a clear honeycomb scaffold cut from a thin acetate sheet. This was to provide support and prevent the film from being drawn into a talker's mouth when speaking. It was hypothesized that the scaffold would make a negligible difference to the attenuation because transmission would be dominated by sound passing through the film away from the honeycomb.

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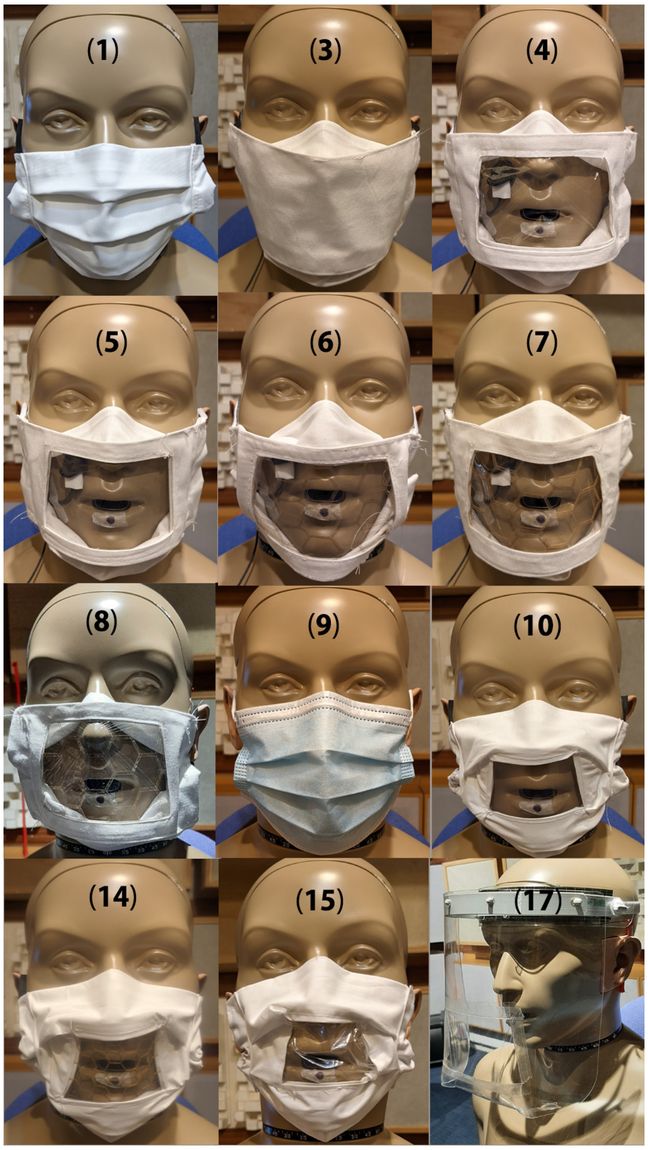

FIG. 2. (Color online) Photos of most of the face masks with numbers corresponding to Table I. Mask 2 is not shown because it is the same as mask 1 but with a printed design on it. Masks 10–12 looked similar and so are represented by mask 10. Mask 13 (not shown) looks like mask 15. Masks 18 and 19 (not shown) look like mask 3. Mask 20 and 21 (not shown) look like mask 7. The dot on the lower lip of the mannikin was used to align the microphone.

Table II gives the material properties for the masks; these were measured by the authors. Table III gives the construction details and geometry. Figure 3 shows microscopy pictures of the cloths used in the masks. The microscopy images and ImageJ software were used to estimate the porosity of the cloths.[32,33] The porosity values are shown in Table II. As a reference, a standard type IIR surgical mask was also tested—mask 9 in Table I and Fig. 2.

Cloth v1 was a pleated cotton design, and the position of the pleats made it difficult to neatly sew plastic inserts into the mask. Consequently, other masks were made from scratch with sheet materials to make it easier to add clear panels. These masks and shields were constructed by Salford's Maker Space. The iterations to create each mask were refined with initial user testing within the Maker Space team encompassing three different face shapes. The second round of testing was on version 2 (or v2)—masks 3–8 in Table I. Cloth v2 was from a cotton sheet, pattern cut using a laser cutter for accuracy and consistency, and this created a flat plane to insert a clear panel. Additionally, the design incorporated a threefold pleat for additional material under the chin to provide extra surface area for breathability. On advice from users of British Sign Language, the clear panel in v2 was made larger than had been possible in v1 so that speech-reading would be easier.[34] The panel size is a

TABLE II. Some measured properties for mask materials.

Description	Material	Thickness (mm)	Mass/unit area (kg/m^2)	Porosity
TPU film	A transparent thermoplastic polyurethane (TPU) elastomeric film sold as Tuftane®	0.05	0.062	
Acetate		0.24–0.25	0.312	
Cling film	Low-density polythene (LDPE)	0.02–0.03	0.016	
PVC	Polyvinyl chloride	0.24–0.25	0.348	
FEP	Fluorinated ethylene propylene	0.1–0.2	0.232	
Sandwich bag	LDPE	0.1	0.03	
Cotton for cloth v1	400 thread count Supima cotton	0.15	0.13	5%
Cotton for cloth v2	100% cotton sheet	0.21–0.23	0.13	13%
Cotton for cloth v3	95% cotton, 5% elastane (lycra), French terry jersey with looped back	0.5	0.257	4%
Cotton for cloth v4	100% cotton, interlock, double knit t-shirt jersey	0.37	0.183	4%
Shield	PETG sheet	0.75	0.78	

TABLE III. Mask construction details and geometry.

Material	Construction details
Cloth v1	Two layers of cotton with three pleats
Inserts into cloth v1	Trapezoid hole in cloth with area ranging from 2625 to 3625 mm^2, $a = 5.5$–6.5 cm; $b = 7$–8 cm; $h = 4.2$–5.0 cm[a] [see Fig. 3(f)]
Cloths v2–v4	Two layers of cotton with three pleats, extending under chin
Inserts into cloth v2	Trapezoid hole in cloth with area of 6825 mm^2, $a = 10$ cm; $b = 11$ cm; $h = 6.5$ cm
Honeycomb scaffold	Laser cut acetate sheet 0.2 mm thick; see Fig. 3(e) for dimensions; through stitched
Edge scaffold	Laser cut acetate 0.2 mm thick; through stitched with edge of insert; 4.5 mm wide.
Insert into shield	Trapezoid aperture in shield $a = 9.7$ cm; $b = 12.1$ cm; $h = 6.6$ cm

[a]The difficulty of sewing into the v1 pleated designs meant that the size of the aperture varied between the various inserts.

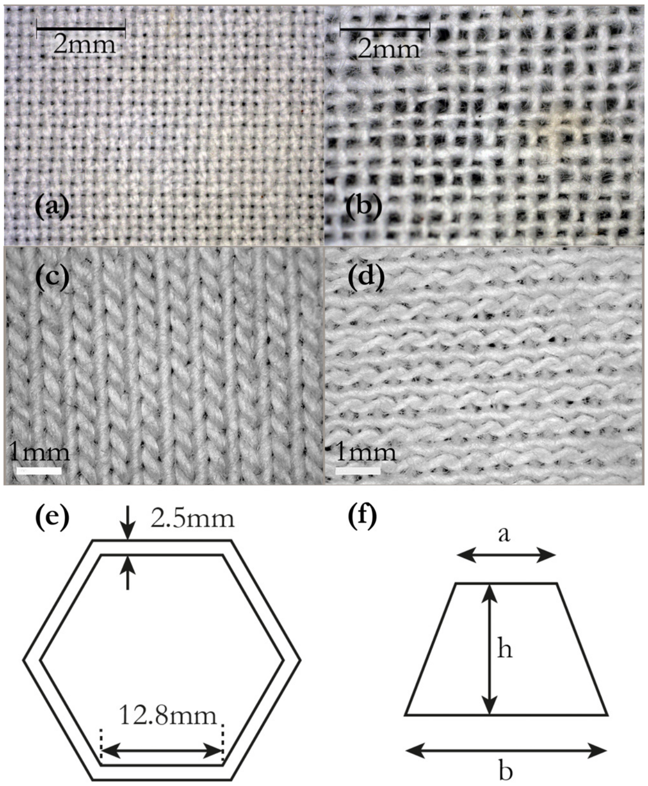

FIG. 3. (Color online) The microscopy image of cloths (a) v1, (b) v2, (c) v3, and (d) v4 are shown. The dimensions of (e) a honeycomb scaffold and (f) trapezium used in Table III for the inserts.

compromise because the cloth area is needed for low-resistance filtration. Too big of a clear panel constrains how much filtration can be provided.

The first round of testing showed that the lightest insert of cling film had the best acoustic performance, but this was too fragile to be useful in practice. Consequently, a light and robust insert was sought and an appropriate 50-μm thick TPU film sourced. While not as thin and light as cling film, the TPU film was much stronger and durable to manipulation. This was tested in three configurations (masks 4–6): sewn straight into the cloth v2 mask, with a rectangular acetate scaffold around the edge of the insert, and with a honeycomb scaffold backing the insert. The scaffolds were used to counter the problem of the TPU film being sucked into the talker's mouth. Mask 7 included extra cloth around the chin to aid breathability and fit. See the supplementary material[35] for the templates and instructions for constructing the final mask (same as that for mask 7 but with simplified scaffold).

As shown in Table II, cloth v2 has a relatively high porosity and, consequently, the ability of masks made with this material to protect the spread of COVID-19 through droplets will be compromised. Therefore, other cloths were sourced with a lower porosity of around 4% (cloths v3 and v4 were used in masks 18–21). Aydin *et al.*[36] showed that for two layers of a 1% porosity cloth, the median blocking efficiency was 98.1% for high momentum droplets, and for two layers of a 11% porosity cloth, it was 94.1%. (For a standard disposable surgical mask, 98.5% median blocking efficiency was measured.) Thus, it would be expected that cloths v3 and v4 would provide a median droplet blocking efficiency somewhere between 94.1% and 98%.

In addition to the cloth masks, shields with and without a TPU insert were tested (samples 16–17 in Table I).

III. RESULTS

The raw data measured for this project are available for download.[37] This includes the impulse responses for every measurement with and without the mask; the audio files recorded with the human talkers with and without the masks; and the laser Doppler vibrometer transfer function, coherence, and mode shape animations.

A. Cloth flow resistance

The flow resistance measurement was used to characterize the cloth used. Table IV shows the flow resistance for the cotton used in the two versions of the face masks, along with two standard masks for comparison.

B. Variation due to fit and between nominally identical masks

This experiment was only performed for cloth v1. Figure 4 shows the insertion loss for six nominally identical cloth masks that are all from the same supplier with a line for each mask. Each mask was measured six times, hence, the variability caused by differing fits on the mannikin was captured as denoted by the error bars on each line. For each individual mask, the confidence intervals created by differing fits are $\leq$0.3 dB for the frequency range with relevance for speech intelligibility (100–8000 Hz), showing the robustness of the measurements. While this quantifies the variability due to fit

TABLE IV. The measured flow resistances (rayl) for various materials and masks and the pressure drops across the material.

Pressure drops across material (Pa)	Single layer of cloth				Double layer of cloth		FFP2 NR mask	IIR surgical mask
	v1	v2	v3	v4	v3	v4		
60	902 ± 23	139 ± 14	706 ± 32	148 ± 10	1600 ± 36	294 ± 27	1462 ± 88	345 ± 22
70	859 ± 36	142 ± 11	744 ± 28	149 ± 29	1634 ± 92	325 ± 13	1520 ± 140	354.2 ± 8.3
100	870 ± 37	106 ± 15	766 ± 90	114 ± 3	1480 ± 130	333 ± 13	1420 ± 110	377 ± 16
120	901 ± 59	88.6 ± 1.0	657 ± 25	88.8 ± 12	1434 ± 79	336 ± 13	1660 ± 130	398 ± 37

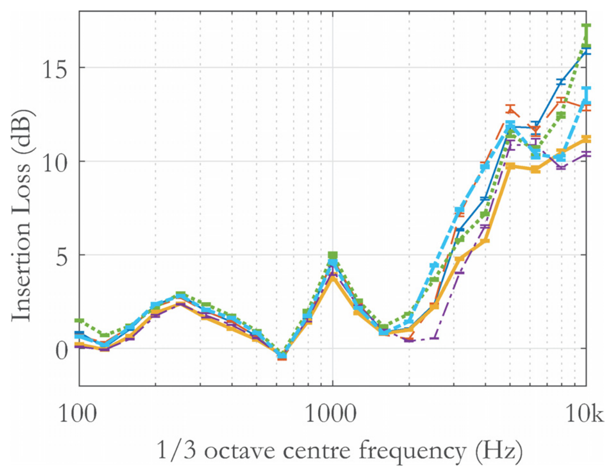

FIG. 4. (Color online) The insertion loss vs 1/3-octave frequency for six nominally identical cloth v1 masks with each shown as a separate line. Each mask was fitted and measured six times, and the error bars are the 95% confidence intervals from those repeated measurements.

on one head, it does not capture the effects of different head shapes.

The difference in the performances among the nominally identical masks was more than that due to fitting at and above 2000 Hz. At 2000 Hz, the mean insertion loss across the masks is (1.1 ± 0.6) dB rising to (12.0 ± 1.9) dB at 8000 Hz as also illustrated by the divergence of the lines in Fig. 4.

C. Measurements on real people

To assess the error in the insertion loss due to random variations in how a person talks, a repeatability study was performed. This was done for three masks as noted in Table I. One speaker read the extract from the rainbow passage six times with each mask off, and then read it six times with each mask on. The standard deviation of the 1/3-octave insertion losses across these repeated measurements allows an estimate of the random experimental error. The standard deviation of the insertion loss was not significantly correlated with the frequency between 100 and 10 000 Hz (correlation coefficient = 0.17), therefore, a single error is reported for all 1/3-octave bands. For one talker reading the shortened rainbow passage once, the median 95% confidence interval for any 1/3-octave sound pressure level is estimated to be 1.5 dB, where 95% of these confidence intervals are in the interval 0.4–3.7 dB.

Our measurement protocol used four talkers to account for effects, such as different head morphology, such that the error from the repeated readings by four talkers needs to be estimated. If the sound pressure level is calculated by averaging over four talkers speaking the passage once, the median confidence interval is estimated to be 0.9 dB, where 95% of those are in the interval 0.2–2.1 dB. The measurements reported are insertion losses, which is the subtraction of the sound pressure level with and without the masks. Combining the uncertainties for two measurements of the level gives an expected 95% confidence interval of 1.8 dB due to the variation in speaking in our tests.

As stated earlier, the talkers were instructed to maintain the same speaking level with and without the mask. To explore whether this was achieved, the power spectrums on the 1 m microphone with and without the mask were measured. (The power spectra are shown in the supplementary materials.[35]) This was then analyzed across the bandwidth 100–1000 Hz because the masks showed little sound attenuation in this frequency range for the mannikin tests. Averaged across the four talkers and five masks used for the human tests, the difference between the sound pressure level with the mask on and with the mask off was (-0.3 ± 0.3) dB for ≤ 1000 Hz. For the mannikin tests, the corresponding difference was (-0.5 ± 0.3) dB. A t-test revealed no significant difference between the values measured on the mannikin and humans [$t(23) = 0.38$, $p = 0.7$], thus, giving confidence that the human talkers were maintaining a constant speaking level with and without the mask.

Asadi *et al.*[24] assumed that their comparable measurements, which yielded the same level with and without the mask on an external microphone, were an indicator that people talked more intensely with the mask on to compensate for the mask's sound attenuation. This assumption will now be explored. First, it was determined whether there was a significant change in the overall sound pressure level with and without the mask for our tests. Next, what that means for the speaking intensity will be detailed.

An A-weighting filter was applied to the recording of speech across the full audio bandwidth (from 0 to Nyquist, 24 kHz). Examining the A-weighted, broadband difference in level on the external microphone with and without the mask, a difference of (-0.2 ± 0.4) dBA is found. The difference is not significant as demonstrated with a three-way analysis of variance (ANOVA) with the groups mask on/mask off, talker, mask type, and with no interactions in the model. No significant difference between the groups mask on and mask off case was found [$F(1) = 1.79$, $p > 0.05$].

The A-weighted sound pressure levels with and without the masks are the same within experimental error, but this does not provide evidence that the talkers were speaking more intensely with the masks on to overcome sound attenuation. Attenuations due to the mask are only significant above 2000 Hz, and speech is less powerful at these higher frequencies. For talkers without masks, the sound pressure level dropped by (5.3 ± 0.6) dB per octave at and above 1000 Hz. This means that the sound pressure level from the talkers without masks between 100 and 1600 Hz was 14 dB greater than that between 2000 and 10 000 Hz (only 4% of speech energy was in the upper frequency range at and above 2000 Hz). Consequently, the effect of mask attenuation on A-weighted broadband levels is small and within measurement uncertainties. To illustrate this further, even if the mask was to filter out all energy about 2000 Hz, there would only be a 0.6 dB change in the A-weighted sound pressure level.

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Next, consider a comparison of the tests on humans and mannikins based on five mask designs as indicated in Table I. The results for real talkers are averaged across the four participants. Four of the masks had plastic inserts and one was completely cloth (v2). Figure 5 shows the insertion loss for human and mannikin testing. For the cloth mask [Fig. 5(a)], the insertion loss is underestimated on the mannikin measurements by 2 dB at 8000 and 10 000 Hz. But these frequencies are at or above the bandwidth carrying the greatest importance for speech.[26] Also, they are of a size similar to the estimated experimental errors due to reading variability (confidence interval = 1.8 dB). Corey *et al.*[15] measured nine cloth mask designs on a mannikin and a single human talker. Averaged across the nine masks, the mannikin and human results were within 1 dB of each other, except for the 125 Hz band. Therefore, both sets of results demonstrate that measuring using a mannikin gives a good representation of what happens with real talkers for a cloth mask within experimental error.

The results for the four TPU inserts were similar (masks 4–7) probably because the only difference in the mask was the scaffold used to support the inserts. Therefore, these four measurements have been averaged and are shown in Fig. 5(b). The insertion loss is underestimated by the mannikin measurement by around 1 dB above 2000 Hz, again, indicating that the mannikin gives a good measurement of the insertion loss within experimental errors.

D. First mannikin experiments on masks comparing different clear plastic inserts

Figure 6 shows the insertion loss for the experiments on the first mask prototypes. Two opaque masks, a standard surgical mask and cloth V1 opaque mask, are shown for comparison, but the focus here will be on the other designs that have a clear window. In general, the insertion losses are in line with the attenuations that others have found.[8–10,13–16]

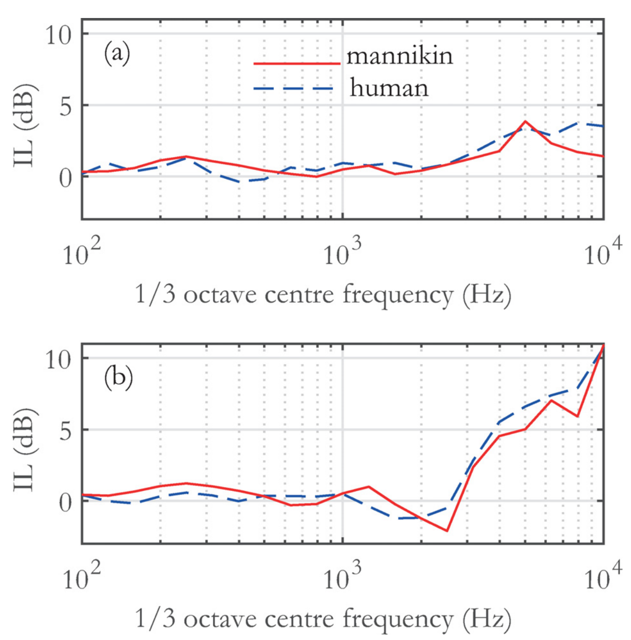

FIG. 5. (Color online) Human and mannikin measurements of the insertion loss (IL) vs 1/3-octave center frequency. The (a) cloth v2 mask and (b) average of four masks with TPU inserts are shown. The results for real talkers are averaged across the four participants.

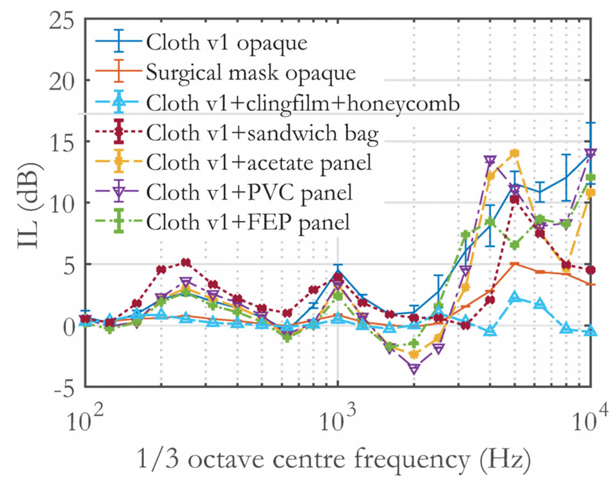

FIG. 6. (Color online) The insertion loss (IL) for various masks vs the frequency.

In our measurements, one transparent mask offers virtually no insertion loss: the face mask with a cling film insert and honeycomb support. The insertion loss at higher frequencies is also considerably less than any transparent masks measured by others.[15,16] The simplest model of the insertion loss provided by the transparent panel is that it behaves like a limp mass offering an impedance of $j\omega m$, where ω is the angular frequency and m is the mass per unit area of the transparent material (density $\times$ thickness).[38] Consequently, the material with the lightest mass per unit area, which is the cling film, will have the lowest impedance and most readily allow sound through the mask. This is borne out by the measurements shown in Fig. 6 and even more clearly shown in Fig. 7, which gives the average insertion loss per 1/3-octave band vs the mass per unit area for all of the masks with a clear insert.

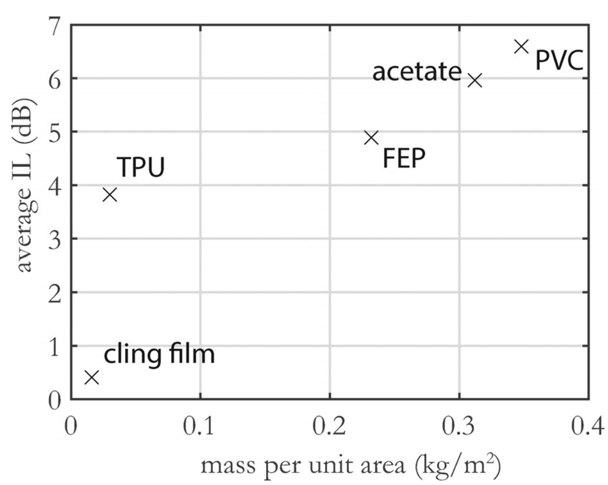

FIG. 7. The average 1/3-octave insertion loss for five masks (100–10 000 Hz) with clear panels vs mass per unit area of the transparent insert. The insertion loss vs frequency for the TPU masks are shown later in Fig. 11.

The insertion loss for the masks with a transparent insert does not fit the simple model impedance model of $j\omega m$, which would yield a 6 dB increase in the insertion loss for each doubling of the mass. The first reason is that the masks do not move like a limp mass with constant velocity because they have vibration modes. This is shown in the laser Doppler vibration measurements. For example, Fig. 8 shows the surface velocity across the measurement positions on the acetate mask. The velocity is plotted for two frequencies where there were visible peaks in the noise-to-vibration transfer function, and evidence of the vibration modes appears. A second reason is that sound will also pass through the cloth surrounding the transparent inserts as well.

Taken together, these results demonstrate that a lower mass per unit area is needed to reduce the attenuation of the impervious parts of the transparent masks. However, there is a limit to how light they can be because a material like cling film would tear too easily either during manufacture or everyday use. This led us to source the TPU film, which is light and robust for handling, and this was used in subsequent designs of cloths v2, v3, v4, and a shield.

E. Shield experiment

A full-face shield (visor) was tested on the mannikin and using a Doppler laser vibrometer (sample 16 in Table I). Also, a shield was tested with a TPU insert in front of the mouth (sample 17). As the TPU is a lighter material than the shield plastic, it should more readily allow transmission. The insertion losses are show in Fig. 9. Figure 10 shows the surface vibration measured around 900 Hz. For the full shield, the whole of the visor vibrates in a complex mode. For the shield with the TPU insert, the dominant feature is high velocity across the TPU insert.

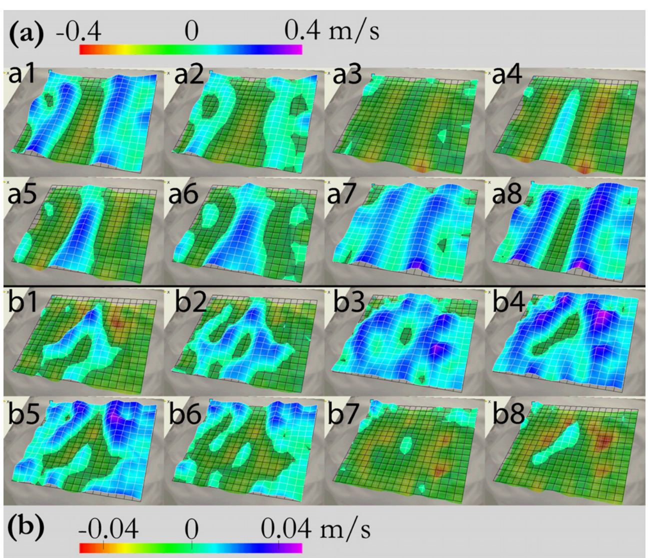

FIG. 8. (Color online) Snapshots from animations of the laser Doppler vibration measurements showing one period of vibration for the cloth v1 mask with acetate insert. There are two rows for each frequency as depicted in [(a1)–(a8)] 791 Hz and [(b1)–(b8)] 2000 Hz.

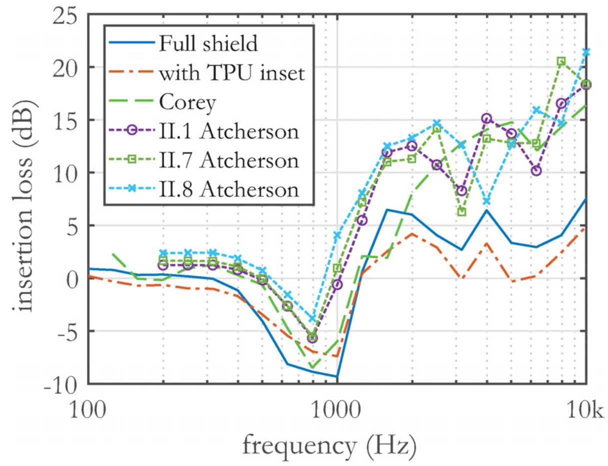

FIG. 9. (Color online) The insertion loss for a full shield and the same shield with a TPU insert in 1/3 octaves. Also shown are four shields, one measured by Corey *et al.* (Ref. 15) and three measured by Atcherson *et al.* (Ref. 16). The Atcherson data were originally in narrow band with a frequency resolution of 172 Hz, and this has been converted to 1/3-octave estimates for the graph.

Figure 9 shows that a set of vibration modes around 800 Hz leads to amplification (negative insert loss) for the full shield of up to 9.3 dB. Adding the TPU insert disrupts these modes and decreases the amplification. At higher frequencies above 1250 Hz, the full shield is attenuating sound by 2.7–7.5 dB. The addition of the TPU insert allows greater sound transmission and, therefore, decreases the attenuation to between –0.3 and 4.9 dB.

Figure 9 also shows measurements for other shields as reported in two previous papers.[15,16] The new full shield has

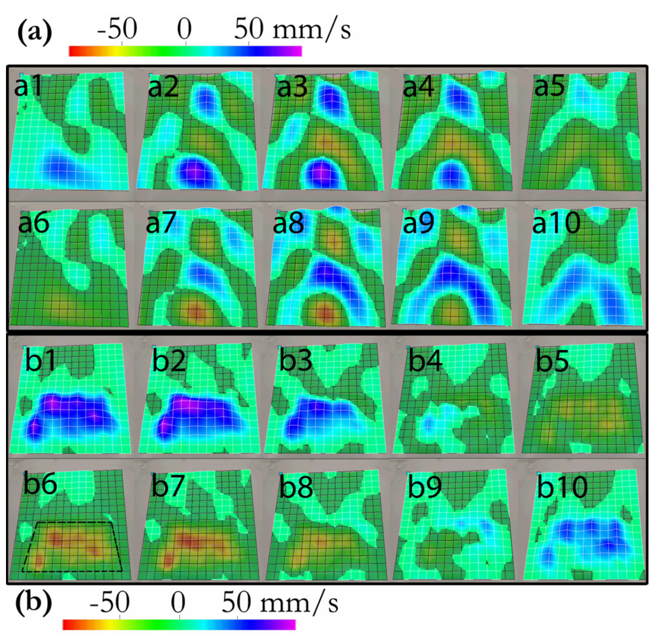

FIG. 10. (Color online) Snapshots from animations of the surface velocity showing one period of vibration for two masks as depicted in [(a1)–(a10)] a full shield at 856 Hz and [(b1)–(b10)] a shield with a TPU insert at 912 Hz. The approximate location of the TPU insert is marked by the dashed trapezium in the (b6) snapshot.

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less attenuation than any of the others previously reported, and the TPU insert gives a further reduction in the insertion loss. The sound attenuation for the design with the TPU insert is better than a standard surgical mask (data in Fig. 6) with the added advantage that speech-reading is possible.

F. Further experiments of masks with clear plastic inserts

Figure 11 shows the insertion losses for the second experiment on the transparent masks. As before, the face mask with the cling film insert has the smallest values. Cling film is not a practical material, however, but this does confirm the previous findings that, ideally, the plastic inserts should be as light as possible. The insertion losses for four different masks using the TPU insert are shown. The variants were examining the effects of different constructions. The performances of the various TPU inserts are similar, especially given the expected variation from mask to mask due to material and construction (Fig. 4). Consequently, the choice of which mask is best is based on non-acoustic factors. There are two problems with using the TPU insert without a scaffold: the plastic sometimes get sucked into the talker's mouth, and the movement of the plastic can cause visual disturbance of light reflections, hindering speech-reading. The edge scaffold is easier to construct than the honeycomb design. The extra chin material makes little difference to the insertion loss but it helps (i) reduce pressure build-up in the mask by allowing extra cloth for the air to escape, filtered through the 2-ply cotton, and (ii) make the mask easier to fit and less prone to slipping down the face due to chin movements.

Figure 12(a) gives the insertion losses for the new v3 and v4 face masks with clear windows. For comparison, Fig. 12(b) shows the insertion losses for six masks with transparent windows measured in two previous papers.[15,16] The three new designs with TPU inserts, shown in Fig. 12(a),

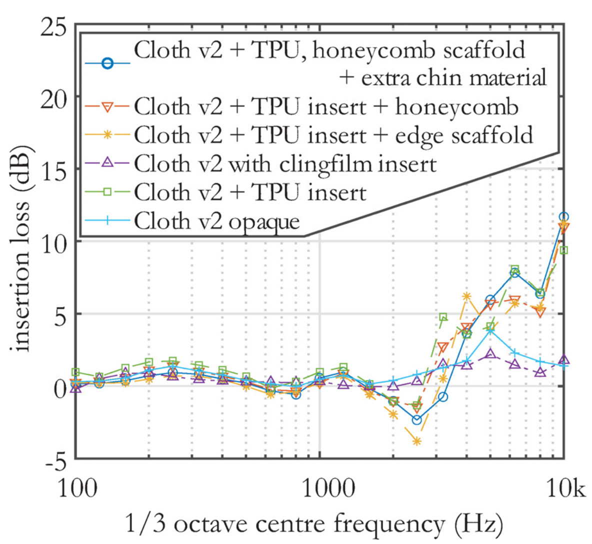

FIG. 11. (Color online) The insertion loss vs 1/3-octave frequency for various masks in the second experiment.

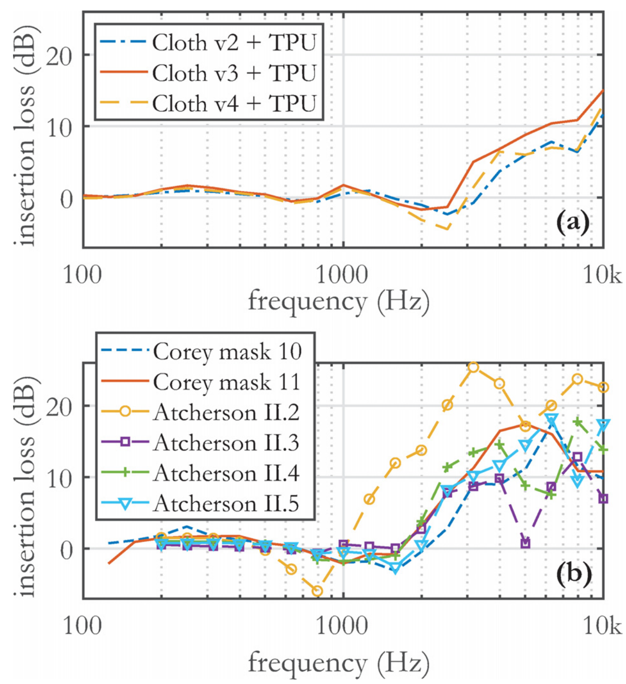

FIG. 12. (Color online) The insertion loss from various masks with transparent windows vs the frequency. (a) New designs with all masks having honeycomb scaffold and extra material around the chin and (b) data from six masks from previous publications by Corey *et al.* (Ref. 15) and Atcherson *et al.* (Ref. 16) are shown.

attenuate the sound by less than the previously measured designs in Fig. 12(b). The cloth v4 mask with a clear TPU insert has an insertion loss of (4.6 ± 2.3) dB for 2–8 kHz, whereas the best design shown in Fig. 12(b) has an insertion loss of (8.8 ± 2.6) dB over the same bandwidth.

G. Evaluation using the SII

Figure 13 shows the SII vs SNR for some of the face masks and shields that have been tested, focusing on the better, later designs. There are also two calculations based on measurements from Corey *et al.*[15] A higher score of SII indicates better speech intelligibility.

First, consider the shields shown in Fig. 13(a). Adding the TPU insert to the full shield shifts the curve by 1.0 dB to the left. This means that the use of the TPU insert enables the modified shield to perform as well as the full shield in scenarios where the SNR is 1.0 dB worse. Although only a small improvement, it is worth noting that this is 4.8 dB better than the shield measured by Corey *et al.*[15]

Now, consider the insertion loss for face masks with clear panels shown in Fig. 13(b). The two with the best SII values are the cloth v4 with TPU insert and the surgical mask with both having a similar performance. The new cloth v4 with TPU insert improves on the two Corey *et al.* transparent face masks by 4.0 dB and 1.9 dB. Adding the TPU insert into the cloths v3 and v4 masks improves the SNRs by 2.5 and 1.1 dB, respectively. This improvement is due to a resonance of the masks around 2000–2500 Hz, as evidenced by the insertion losses in Fig. 12.

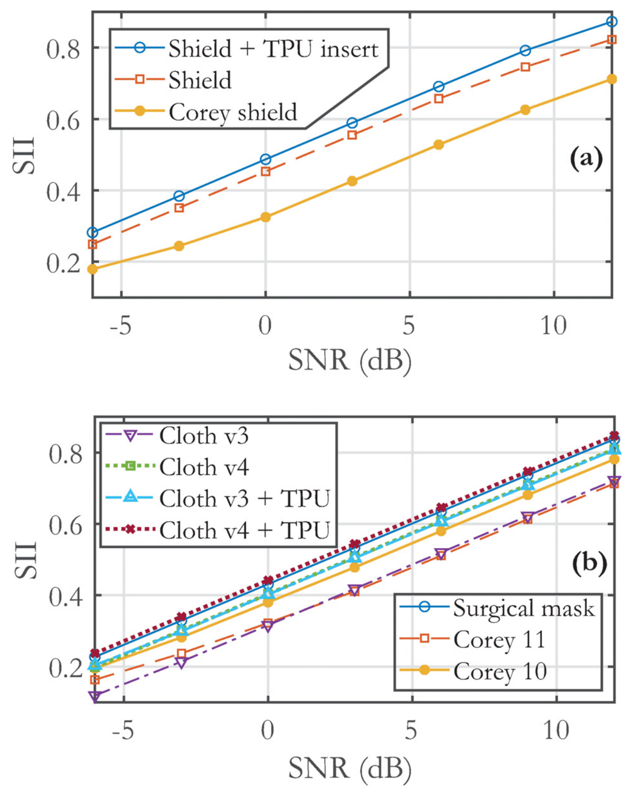

FIG. 13. (Color online) The SII vs SNR for a variety of (a) shields and (b) face masks are shown.

IV. DISCUSSION

Consider the first two research questions, which were about measurement uncertainties. The tests have quantified the experimental errors that are involved in measuring the sound attenuation by face masks on a mannikin and humans. This is important because robust standard methods for acoustic testing of face masks need to be established. Furthermore, previous studies published results without fully considering the experimental errors.

For cloth masks, there is variability between masks that are nominally the same design with the differences increasing with frequency. This variation between masks was expected as similar issues with sample variability have been seen before in round-robin measurements of porous absorbers.[39] It is likely to be caused by changes in the thread and weave of the cloth as well as variations in the mask morphology—differences in the amount of material overlap created by the pleats were observed among the samples. It would be anticipated that the variability would be less for the face shields and face masks with thin clear inserts because the transmission properties of the plastic would be more consistent, but this hypothesis needs testing in future experiments.

The errors due to fit were quantified by repeatability studies and found to be small. But these were only done on one mannikin and, therefore, variations due to differences in the head shape changing the tension in the mask and the distance from the lips to the masks were not captured.

The protocols developed for measurement with real talkers gave results that were the same as the mannikin within experimental errors. This contrasts with measurements by Corey *et al.*[15] on two masks with transparent windows, however. They found a significant disparity between the human and mannikin testing with peak differences of 11 dB at 4000 Hz for one mask and 12 dB at 6300 Hz for the other mask. Given that the differences are frequency dependent, it is suggested that this might be due to the modal frequencies of the mask shifting between the human and mannikin due to a changing fit. The mannikin used by Corey *et al.* was less human-like than the mannikin used in our experiments. Another possibility is that the transparent masks measured by Corey *et al.* allowed less sound transmission, making it harder for the talker to maintain a constant speaking level because the airborne feedback path was altered.

It was hypothesized that having a mask close to the mouth of a real talker might give different results to the mannikin because of air flow, nonlinear absorption in the cloth due to high pressures, or changeable fit when the face moves during talking. However, no evidence for this appeared in our results. This confirms that mannikins can be used for these experiments. An open question is whether a variety of mannikins with different morphologies should be used to capture how tension and fit of the face masks alters the attenuation. It is worth noting, though, that the tests on four human people with their different head morphologies gave the same results as the single mannikin. This suggests that the use of a variety of mannikins might be unnecessary.

The third research question concerned reducing the insertion loss of transparent face masks and shields. This is needed so that the benefits of being able to speech-read are not cancelled out by the reduced sound transmission through the clear plastic. For face masks and shields, reducing the acoustic masses of the clear plastic panels produced a smaller insertion loss. This idea arose from the mass-law principle that treats the material as a limp mass and is often used to explain sound transmission through partitions.[38]

The Doppler laser vibrometer results were useful in demonstrating that the masks were vibrating in complex modes, but to fully exploit this measurement method to design face masks and shields requires further research. The Doppler laser vibrometer does not capture sound propagating through the pores of the cloth, and it does not account for how efficiently each of the measured surface vibration modes radiate to the far field microphone. A prediction model using finite and boundary element method is needed to explore this further.[40]

The calculations of SII from the insertion losses allowed the sound attenuations to be related to the effects on perceived speech. Improvements between 1.9 and 4.8 dB were found for the face masks and shields with thin plastic inserts compared to previous results from other studies. This improvement can be put in context by relating this to the gains of speech-reading, which is what a transparent face mask or shield enables. MacLeod and Summerfield[41] quantified the benefit of visual cues across a range of SNRs for simple sentence-length material when testing young participants with normal hearing. They found the SNR benefit varied between 6 and 15 dB with an average of 11 dB. Note, MacLeod and Summerfield considered white noise as an interferer, whereas the SII calculation above used a more common speech-spectrum-shaped noise interferer. Even allowing for this difference, the results show that the provision of speech-reading provides a larger benefit than the improvement in acoustic SNR achieved by the new designs with a lower insertion loss. Finally, the differences in the attenuations of the masks would be expected to influence listening effort, which is something that is not well measured by a metric such as the SII.[42,43]

V. CONCLUSIONS

A series of experiments have quantified the insertion losses from face masks and shields with clear plastic panels that allow speech-reading. These have then been related to the effects of speech perception through calculations of the SII.

One focus of the research was to try and improve the experimental methods. While a number of papers had published measurements on masks, the techniques varied in quality, which makes it hard to synthesize previous findings in the literature. This motivated an examination of the experimental uncertainties, something that is lacking in previous work. The tests showed that measurements on a head and torso with a mouth simulator could replicate the average results from four human talkers within experimental errors. They also showed that manufacturing variability of cloth masks and the inconsistencies of human talkers were a greater source of experimental error than fitting differences on a single mannikin. It is recommended that future studies on masks should fully quantify and publish the material properties and geometry of the masks and shields tested. Alongside more robust measurement protocols, like those detailed in this paper, the results across studies could then be meaningfully compared.

The second focus of the work was to produce an open-source design for a transparent mask that had a better acoustic performance. While shields and face masks with clear panels can aid speech-reading, without careful design, communication can be harmed through additional sound attenuation at mid-high frequencies. By considering a simple model of sound transmission, the experiments demonstrated that face masks and shields could be made less attenuating by reducing the acoustic mass of the plastic. This improves the SSI, although to put this in context, the benefits are smaller than those obtained from allowing speech-reading through the clear plastic. Finally, a new mask using a thin TPU insert was designed that had lower sound attenuation than the previous designs. The instructions on how to make this are included in the supplementary material.[35]

ACKNOWLEDGMENTS

This work was funded by UK Research and Innovation under Grant No. EP/V051571/1. Thanks to Mark Miodownik from University College London and Andy Ogden from English Fine Cottons for their advice on the materials. Thanks to Ryan M. Corey, University of Illinois, and Samuel R. Atcherson, University of Arkansas for Medical Sciences, for providing their data.

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