Acoustic analysis of the effect of Personal Protective Equipment on speech understanding: Lessons for clinical environments

Robert WJ Mcleod[1], Maria Gallagher[1], Andy Hall[2] , Sarah P Bant[3], John F Culling [1].

1. School of Psychology, Cardiff University, Tower Building, Park Place, Cardiff CF10 3AT, United Kingdom
2. ENT Department, University Hospital of Wales, Cardiff, CF14 4XW
3. Audiology department, Betsi Cadwaladr University Health Board, Bangor, LL57 2PW

Corresponding Author
Robert Mcleod
Email: mcleodrwj@googlemail.com

Abstract

Objective

The use of various types of filtering facepiece class 3 (FFP3) mask have become commonplace since the COVID-19 outbreak. These have been evaluated in terms of efficacy regarding aerosol filtration but less emphasis has been placed on the acoustic effects of such masks and their consequences for clinical communication.

Design

A microphone 65cm from a sound-producing Head and Torso Simulator (wearing the masks) was used to measure attenuation via a tone sweep. Predicted impact on speech reception in noise was assessed by weighting the attenuations of cochlear excitation patterns by the frequency importance function of the Speech Intelligibility Index.

Study Sample

We evaluated acoustic attenuation properties of 7 FFP3 masks and a Type IIR surgical mask (as a comparator).

Results

The Type IIR mask had the smallest impact on SNR (2.6 dB with visor). Most FFP3s with an addition of a visor (if not already face covering) impacted SNR by approximately 6 dB. The 3M 6000 was significantly worse (15.8 dB).

Conclusions

Mouth and nose covering FFP3s masks had similar effects on SNR (≈6.2 dB with visor). The Tecmen TM-H2 had several advantages over other masks evaluated. It was reusable, allowed lipreading clues and the attenuation was similar to other FFP3s.

Introduction

Covering the face with a mask can impair communication in two ways, acoustic and visual. The acoustic power of the voice is attenuated by the material of the mask which reflects and/or absorbs some of the sound, preventing it from being projected to the listener. At the same time, most masks are opaque and therefore obscure lip movements. In a totally quiet environment, neither of these things may matter unless the voice becomes so faint that vital parts of speech fall below the listener's detection threshold. However, anaesthetic, theatre and intensive care environments contain varying levels of background noise with Leq varying between 52.9 to 75.1 dB (Stringer et al, 2008; see also Hasfeldt et al, 2010; Willett, 1991; Nott & West, 2003). The primary cause for the background noise varies but common sources include anaesthetic machines, suction devices and other communication within the same environment. Wearing a facemask could then attenuate the voice towards or below its masked intelligibility threshold, resulting in potential misunderstanding or poorer performance. This attenuation can be compensated up to a point by increasing voice volume. However performance of tasks with potentially high cognitive load such as intubation or surgery could be negatively impacted (Way et al, 2013; Füllgrabe, 2020). It is therefore important that acoustic attenuation of frequencies crucial for speech perception be minimised (Mendel et al, 2008).

Face masks such as fluid resistant surgical masks (FRSM Type IIR) have been commonplace in theatre environments for decades. These masks are splash resistant to protect against bodily fluids but are tested on exhalation in order to test the efficiency of the mask to prevent the wearer from transmitting infection. During the Covid-19 pandemic, it has become necessary in many theatre and anaesthetic environments, and indeed in all situations where aerosol generating procedures (AGPs) are carried out, to instead use filtering facepiece masks. FFP2 and FFP3 masks are tested on inspiration (to protect the wearer) and filter 94% or 99% of suspended particles, respectively. In addition, they must permit a maximum leakage of 8% or 2%, respectively. Clear plastic visors are also commonly worn in addition, with the purpose of adding further splash protection.

Understandably, the differing requirements of the mask classes are likely to have consequences for their underlying acoustic properties. For those that have been using FFP3 masks regularly in the COVID-19 pandemic the impairment to communication has been subjectively highlighted (Frauenfelder et al, 2020).

Previous studies have investigated the attenuation properties of various masks including medical masks and respirators (Corey et al, 2020; Goldin et al, 2020; Mendel et al, 2008; Radonovich et al, 2010). Some have also assessed speech reception in background noise (Palmiero et al, 2016). Homans & Vroegop. (2021) investigated the impact on speech understanding of a surgical mask and a face shield in those with moderate to severe hearing loss or cochlear implant users. Within this study speech perception even in quiet conditions were effected by both mask and face shield. Toscano & Toscano (2021) highlighted that differences in speech understanding between masks were only exhibited at high signal-to-noise ratios (SNR). Brown et al. (2021) also examined the impact of speech intelligibility (SI) and listening effort without visual clues due to masks. It found that finding that intelligibility and and listening effort was negatively affected in noise and particularly in older adults. Within our study we evaluate the acoustic properties of personal protective equipment in the form of commonly used FFP3 masks and additional face protection (visors) in order to predict the impact on communication in theatre and anaesthetic environments. This would allow us to discern what strategies or assistive technologies may assist health professionals in their clinical communication within such settings.

Methods

Recordings were performed in a 1201-A (Industrial Acoustics) booth. Measurements of the acoustic attenuation produced by different face masks were collected using an acoustic manikin (Bruel & Kjaer, Head and Torso Simulator, type 4128-D) which has a built-in mouth simulator. This acoustic manikin is designed to reproducibly generate a realistic sound field emanating from the human mouth and is used to assess electroacoustic devices such as headsets, telephones, audio conference devices and hearing aids (Brüel & Kjær, 1985; Huang et al, 2012; Lavandier et al, 2012; ANSI, 1997). Data collection and analysis was performed using Matlab 2020a.

Being anthropomorphic, the manikin can also provide a realistic fit for head-worn personal protective equipment (PPE). The acoustic attenuation through a particular piece of, or combination of, PPE was derived by measuring transfer functions between the manikin and a microphone (Sennsheiser K6) 65cm in front of the manikin. Power spectra with and without PPE were subtracted to obtain the attenuation. This negated any effect of the presentation level and subtraction also cancelled any residual effect of reverberation within the booth. Transfer functions were measured using the tone-sweep method (Müller & Massarani, 2001). This method plays a rising frequency sweep (0.1-22 kHz) from the mouth of the acoustic manikin and the transmission is recorded by microphone.

This measurement was performed for a variety of PPE appropriately fitted to the mannequin’s face including: Surgical mask (Dishang FRSM Type IIR), FFP3 masks covering nose and mouth (3M 1863, 3M 1873, 3M 8833, ArmourUp) (3M, 2020a; Medino, 2020), FFP3 masks covering the full face (3M 6000, Tecman Hood TM-H2) (3M, 2020b; Tecmen, 2020) as shown in Figure 1. The 3M 6000 comprises of a reusable mask with 2 changeable filters whilst the Tecman Hood TM-H2 is a Powered Air-Purifying Respirator (PAPR). The latter produces a positive pressure within the headpiece (which isn’t sealed), so expired air is free to escape from the base of the hood. Each condition was repeated with and without visor (Royal Mint face visor) where appropriate. The transparent visor was made from 1 mm PET and covered the mannequin’s face, nose and mouth.

In order to visualise the perceptual effect of PPE, the differences in transfer function were smoothed in the fashion of cochlear excitation patterns (Moore & Glasberg, 1983). This converts the difference in sound transmission with and without PPE into the change would be perceived by a listener as a function of frequency. The overall practical effect of the attenuation was evaluated using a weighting function from the articulation index (ANSI, 1997, Table 1). This function weights each frequency band according to its importance in speech perception to produce a predicted reduction in the effective signal level for speech reception caused by the mask. When listening in noise there will, therefore, be a corresponding reduction in effective signal-to-noise ratio. For this purpose, these weightings were redistributed onto ERB-spaced frequency bands (Table I) using Moore and Glasberg’s (1983) Eq. 5. It provided an objective and comparable measurement converting acoustic transmission into the perceived effect of the difference in sound transmission on listener experience, establishing the likely practical effect on verbal communication.

Results

Figure 2 shows the acoustic attenuation spectra as a function of frequency for a variety of masks from 0.1-22 kHz. The frequency axis is scaled in equivalent rectangular bandwidths (ERBs) (Moore & Glasberg, 1983) The Figure 2a-d shows the attenuation spectra for FFP3 masks covering the nose and mouth with and without a visor. A Type IIR surgical mask with and without a visor is also plotted as a useful baseline for comparison. The type IIR surgical mask produces the smallest attenuation of all the masks but is also the only non=FFP3 tested. Although there are differences between the masks, these are generally most pronounced at high frequencies (>10 kHz).

Figure 2e shows mouth-and-nose covering masks. In general, mouth-and-nose covering masks produced a more marked attenuation (10-15 dB) of frequencies above about 1.5 kHz. The one exception is the 3M 6000, this mask produced marked attenuation at most frequencies, extending up to nearly 30 dB.

The Tecmen TM-H2 also differs from the other masks tested in having full head covering with integral visor. This mask produced a degree of resonance at about 700 Hz, but then more substantial attenuation (25 dB maximal at 11 kHz) than the mouth-and-nose masks at higher frequencies. The addition of visors to the various mouth-and-noise covering FFP3 masks produced an overall effect rather similar to the Tecmen TM-H2. The resonance is greater in magnitude (~8 dB) and little higher in frequency at nearly 900 Hz, but otherwise the spectra are all quite similar, with any differences attributable to differences between the respective mouth-and-nose covering masks.

The surgical mask (Type IIR) showed the lowest speech-weighted reduction in speech transmission (shown in Figure 3). However, this mask doesn't have the same aerosol filtration abilities as the others illustrated. This is due to its certification primarily being related to filtering expired air from the wearer rather than protecting the user. Thus, currently it is not permitted for use in many theatre and anaesthetic environments, or in any clinical environments where aerosol generating procedures are taking place. All of the other masks have comparable aerosol filtration abilities. The 5 FFP3 mouth-and-nose covering masks all had similar speech-weighted reductions in SNR. Although the 3M 1863 caused the least attenuation of the FFP3 masks, this is still double that of the IIR surgical mask (5.3 dB compared to 2.6 dB for IIR surgical mask).

While many masks had a similar effect on speech, there are some clear outliers. The 3M 6000 reusable full-face mask produced an attenuation 9.2 dB greater than that of any other mask from the test set. Additionally, these results show that the addition of a visor consistently adds about 1.7 dB of attenuation to a speech signal.

Discussion

These results demonstrate the impact of FFP3 masks on both acoustic attenuation and speech-weighted attenuation in comparison to standard surgical masks. There was an average of 4.5 dB and 6.2 dB speech-weighted attenuation (without and with visors) for all mouth and nose covering FFP3 versus 1.2 dB and 1.4 dB for an IIR surgical mask.

The two main features that are observed in the attenuation spectra are high frequency attenuation and low frequency resonance. The high-frequency attenuation will make the speech susceptible to background noise in that frequency region. The masks vary in the degree to which they produce this attenuation with an IIR surgical mask being the least obstructive and the 3M 6000 by far the most. The very high attenuation produced by the 3M 6000 may make it unsuitable for situations in which verbal communication is necessary. Palmiero et al, (2016) study into various protective facemasks used in healthcare settings also employed an acoustic manikin. They also found air-purifying respirators had the biggest impact of SI and surgical masks the least. However, they did not investigate the impact of visors on SI.

Marked attenuation was seen for mouth-and-nose covering masks (10-15 dB) for frequencies above 1.5 kHz. The low frequency resonance increases the received speech energy and so potentially *improves* intelligibility in noise. This resonance appears to occur whenever there is a flat plastic window in front of the mouth. It may occur as a result of reflected sound from the mask resonating in the enclosed space. In most cases, however, the resonant frequency is too low to substantially benefit speech and is outweighed in the overall effect of the mask by the high-frequency attenuation. Corey et al. (2020) tested various face masks, including, type IIR, cotton and N95. Similar low frequency attenuation as well as resonance at 900 Hz was also identified.

In addition to the attenuation spectra, another important feature which will have an impact on understand is the ability to support lipreading (Macleod & Summerfield, 1987). The only mask which we tested in this study which allowed the possibility of lipreading within our cohort was the Tecmen TM-H2. (Atcherson et al, 2017; Atcherson et al, 2020; Brown et al, 2021) has also highlighted the importance of visual input from transparent facemasks over those that do not allow for lipreading clues. Ideal designs for the future should allow the possibility of lipreading. This has been shown to greatly improve speech-reception thresholds when available (approximately 11 dB) (Macleod & Summerfield, 1987). The use and integration of additional communication strategies may also be necessary (e.g. assistive mobile communication) or options that enable the issue here to be bypassed (e.g. non-verbal aids). Where possible ambient noise should be reduced in clinical areas where FFP3 masks are used in order to reduce the SNR. Previous studies demonstrating the benefits of the sterile cockpit in reducing communication errors in anaesthetic and surgical settings (Broom et al, 2011; Statement, 2014; Way et al, 2013). How and when these should be employed requires further research in a clinical setting.

Limitations of the work include not being able to account for a possible increase in speech level that is expected to aid communication when using such devices. Additionally, the use of glasses or goggles were not assessed as a comparator.

Where overall equivalence in protective qualities is shown, acoustic properties may influence correct compliance along with wearer comfort and other considerations. The information obtained from this work is useful clinically as it allows us to clarify why different FFP3 masks may result in perceptually different levels of speech understanding between individuals. In addition, it also demonstrates the summative effect of a visor used in combination with a FFP3 face and mouth covering.

The COVID-19 pandemic has led to a prominent focus on personal protection, yet for the protection of patients themselves it is important we recognise the challenges in communication that this equipment causes and find strategies to minimise these effects.

Funding

The authors have not declared a specific grant for this research from any funding agency in the public, commercial or not- for- profit sectors.

Competing interests

None declared.

Data availability statement

Data are available upon reasonable request

References

3M, 2020a. 3M Products for Worker Health & Safety. Available at: https://www.3m.co.uk/3M/en_GB/company-uk/3m-products/~/All-3M-Products/Health-Care/Worker-Health-Safety/Disposable-Respirators/?N=5002385+8707795+8710997+8711405&rt=r3 [Accessed February 28, 2021].

3M, 2020b. 3M™ Reusable Full Face Mask 6000 Series. Available at: https://www.3m.co.uk/3M/en_GB/company-uk/3m-products/~/All-3M-Products/?N=5002385+8709394+8709962+3291100252&preselect=8711017+8720539+8720550+3294278275&rt=rud [Accessed February 28, 2021].

ANSI, 1997. Methods for Calculation of the Speech Intelligibility Index. *Am. Natl. Stand.* Available at: https://webstore.ansi.org/standards/asa/ansiasas31997r2017 [Accessed

October 13, 2020].

Atcherson, S.R., Finley, E.T., McDowell, B.R., 2020. More Speech Degradations and Considerations in the Search for Transparent Face Coverings During the COVID-19 Pandemic. *Audiol. Today*, (November/December). Available at: https://www.audiology.org/audiology-today-novemberdecember-2020/more-speech-degradations-and-considerations-search-transparent [Accessed February 28, 2021].

Atcherson, S.R., Mendel, L.L., Baltimore, W.J., Patro, C., Lee, S., et al, 2017. The effect of conventional and transparent surgical masks on speech understanding in individuals with and without hearing loss. *J. Am. Acad. Audiol.*, 28(1), p.58–67.

Broom, M.A., Capek, A.L., Carachi, P., Akeroyd, M.A., Hilditch, G., 2011. Critical phase distractions in anaesthesia and the sterile cockpit concept. *Anaesthesia*, 66(3), p.175–179. Available at: https://pubmed.ncbi.nlm.nih.gov/21320085/ [Accessed October 6, 2020].

Brown, V.A., Van Engen, K.J., Peelle, J.E., 2021. Face mask type affects audiovisual speech intelligibility and subjective listening effort in young and older adults. *Cogn. Res. Princ. Implic.*, 6(1). Available at: https://doi.org/10.1186/s41235-021-00314-0.

Brüel & Kjær, 1985. Head and Torso Simulator Type 4128. Available at: https://www.bksv.com/en/products/transducers/ear-simulators/head-and-torso/hats-type-4128c?gclid=Cj0KCQiA48j9BRC-ARIsAMQu3WQytjQfQG7CeLChlp43KrYhTLfyZWBwzQf6u4tm6_CucFLGcufRMnsaAt5mEALw_wcB [Accessed November 16, 2020].

Corey, R.M., Jones, U., Singer, A.C., 2020. Acoustic effects of medical, cloth, and transparent face masks on speech signals. *J. Acoust. Soc. Am.*, 148(4), p.2371–2375.

Frauenfelder, C., Butler, C., Hartley, B., Cochrane, L., Jephson, C., et al, 2020. Practical insights for paediatric otolaryngology surgical cases and performing microlaryngobronchoscopy during the COVID-19 pandemic. *Int. J. Pediatr. Otorhinolaryngol.*, 134(January).

Füllgrabe, C., 2020. On the Possible Overestimation of Cognitive Decline: The Impact of Age-Related Hearing Loss on Cognitive-Test Performance. *Front. Neurosci.*, 14(June).

Goldin, A., Weinstein, B., Shiman, N., 2020. How Do Medical Masks Degrade Speech Reception? - Hearing Review. Available at: https://www.hearingreview.com/hearing-loss/health-wellness/how-do-medical-masks-degrade-speech-reception [Accessed February 28, 2021].

Hasfeldt, D., Laerkner, E., Birkelund, R., 2010. Noise in the Operating Room-What Do We Know? A Review of the Literature. *J. Perianesthesia Nurs.*, 25(6), p.380–386. Available at: http://dx.doi.org/10.1016/j.jopan.2010.10.001.

Homans, N.C., Vroegop, J.L., 2021. The impact of face masks on the communication of adults with hearing loss during COVID-19 in a clinical setting. *Int. J. Audiol.*, 0(0), p.1–6. Available at: https://doi.org/10.1080/14992027.2021.1952490.

Huang, C.H., Pawar, S.J., Hong, Z.J., Huang, J.H., 2012. Earbud-type earphone modeling and measurement by head and torso simulator. *Appl. Acoust.*, 73(5), p.461–469.

Lavandier, M., Jelfs, S., Culling, J.F., Watkins, A.J., Raimond, A.P., et al, 2012. Binaural prediction of speech intelligibility in reverberant rooms with multiple noise sources. *J. Acoust. Soc. Am.*, 131(1), p.218–31. Available at:

http://www.ncbi.nlm.nih.gov/pubmed/22280586 [Accessed September 21, 2013].
Macleod, A., Summerfield, Q., 1987. Quantifying the contribution of vision to speech perception in noise. *Br. J. Audiol.*, 21(2), p.131–141. Available at: http://informahealthcare.com/doi/abs/10.3109/03005368709077786 [Accessed October 13, 2020].
Medino, 2020. Armour Up. Available at: https://www.medino.com/product/armour-up-moulded-cup-respirator-with-valve-5-masks [Accessed February 28, 2021].
Mendel, L.L., Gardino, J.A., Atcherson, S.R., 2008. Speech understanding using surgical masks: A problem in health care? *J. Am. Acad. Audiol.*, 19(9), p.686–695.
Moore, B.C.J., Glasberg, B.R., 1983. Suggested formulae for calculating auditory-filter bandwidths and excitation patterns. *J. Acoust. Soc. Am.*, 74(September), p.750–753.
Müller, S., Massarani, P., 2001. Transfer-function measurement with sweeps. *J. Audio Eng. Soc.*, 49, p.443–471. Available at: http://www.aes.org/e-lib/online/browse.cfm?elib=10189.
Nott, M.R., West, P.D.B., 2003. Orthopaedic theatre noise: A potential hazard to patients. *Anaesthesia*, 58(8), p.784–787. Available at: https://pubmed.ncbi.nlm.nih.gov/12859472/ [Accessed October 6, 2020].
Palmiero, A.J., Symons, D., Morgan, J.W., Shaffer, R.E., 2016. Speech intelligibility assessment of protective facemasks and air-purifying respirators. *J. Occup. Environ. Hyg.*, 13(12), p.960–968. Available at: http://dx.doi.org/10.1080/15459624.2016.1200723.
Radonovich, L.J., Yanke, R., Cheng, J., Bender, B., 2010. Diminished speech intelligibility associated with certain types of respirators worn by healthcare workers. *J. Occup. Environ. Hyg.*, 7(1), p.63–70.
Ritter, E., Miller, C., Morse, J., Onuorah, P., Zeaton, A., et al, 2021. Impact of Masks on Speech Recognition in Adult Patients with and without Hearing Loss. *Orl*.
Statement, P., 2014. AORN Position Statement on Managing Distractions and Noise During Perioperative Patient Care. *AORN J.*, 99(1), p.22–26.
Stringer, B., Haines, T.A., Oudyk, J.D., 2008. Noisiness in operating theatres: nurses' perceptions and potential difficulty communicating. *J. Perioper. Pract.*, 18(9), p.384, 386–91. Available at: https://pubmed.ncbi.nlm.nih.gov/18828453/ [Accessed October 6, 2020].
Tecmen, 2020. Tecmen TM-H2. Available at: https://www.tecmen.com/products_cont2.html?id=24 [Accessed February 28, 2021].
Toscano, J.C., Toscano, C.M., 2021. Effects of face masks on speech recognition in multi-talker babble noise. *PLoS One*, 16(2 February), p.1–12.
Way, T.J., Long, A., Weihing, J., Ritchie, R., Jones, R., et al, 2013. Effect of noise on auditory processing in the operating room. *J. Am. Coll. Surg.*, 216(5), p.933–938.
Willett, K.M., 1991. Noise-induced hearing loss in orthopaedic staff. *J. Bone Jt. Surg. - Ser. B*, 73(1), p.113–115.

Table

Lower bound (Hz)	Upper bound (Hz)	Weighting
15	46	0.0000
46	81	0.0000
81	119	0.0020
119	161	0.0043
161	206	0.0056
206	257	0.0133
257	312	0.0163
312	374	0.0260
374	441	0.0324
441	516	0.0391
516	598	0.0394
598	690	0.0401
690	791	0.0410
791	903	0.0431
903	1027	0.0451
1027	1165	0.0449
1165	1319	0.0454
1319	1491	0.0469
1491	1684	0.0464
1684	1899	0.0455
1899	2142	0.0464
2142	2415	0.0465
2415	2724	0.0464
2724	3076	0.0451
3076	3477	0.0438
3477	3937	0.0429
3937	4467	0.0416
4467	5083	0.0315
5083	5803	0.0268
5803	6654	0.0230
6654	7668	0.0176
7668	8895	0.0079
8895	10400	0.0037

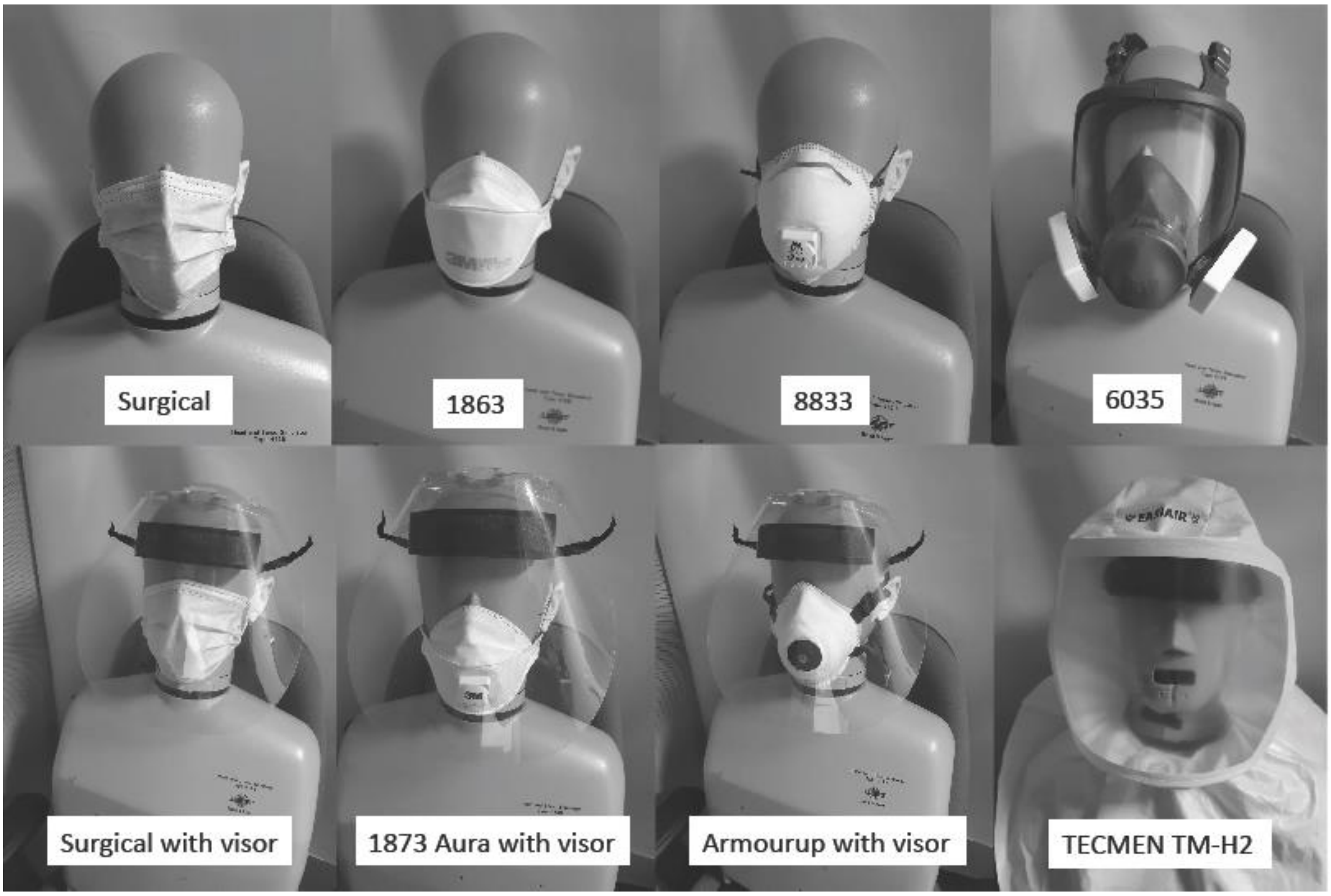
Table 1. Speech-intelligibility index weightings (ANSI, 1997, Table I) redistributed over 1-ERB bands.

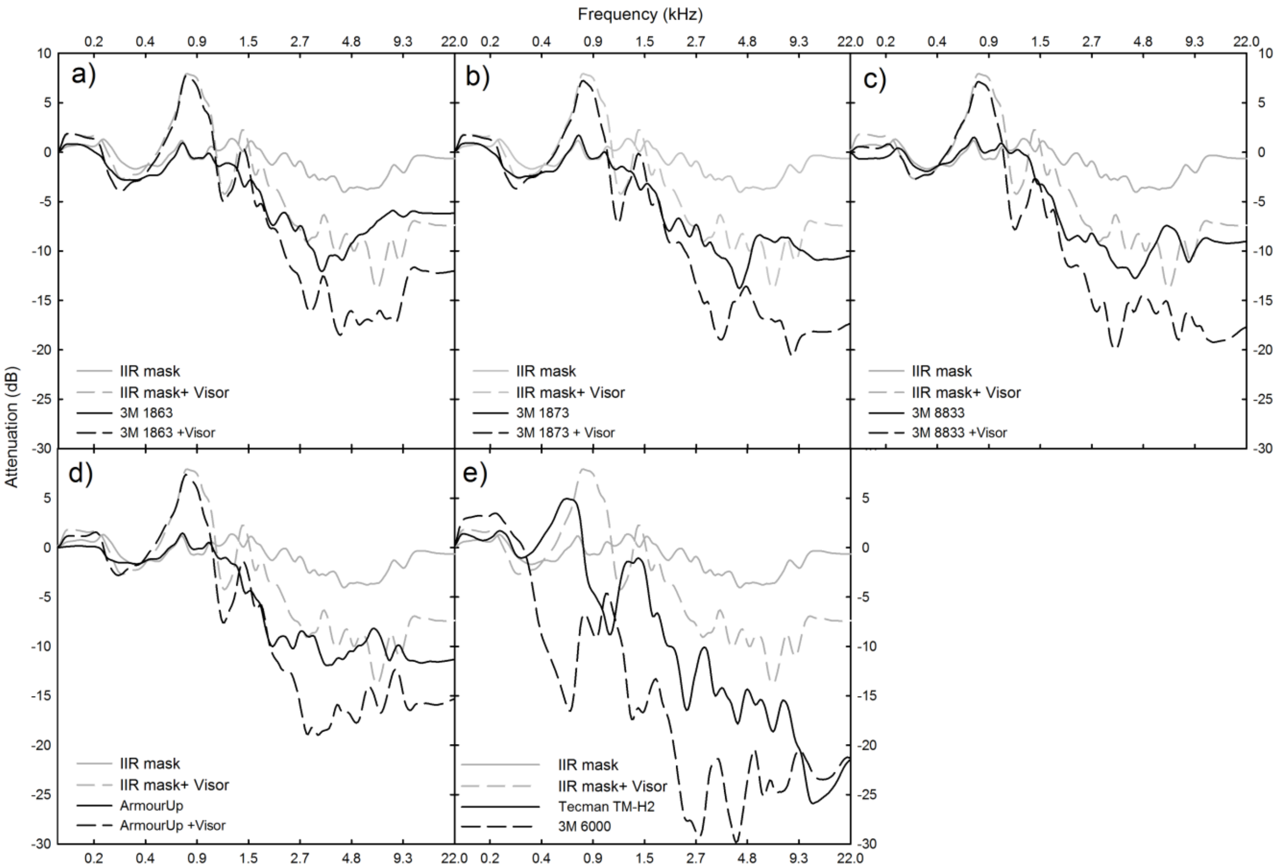
Figure Legends

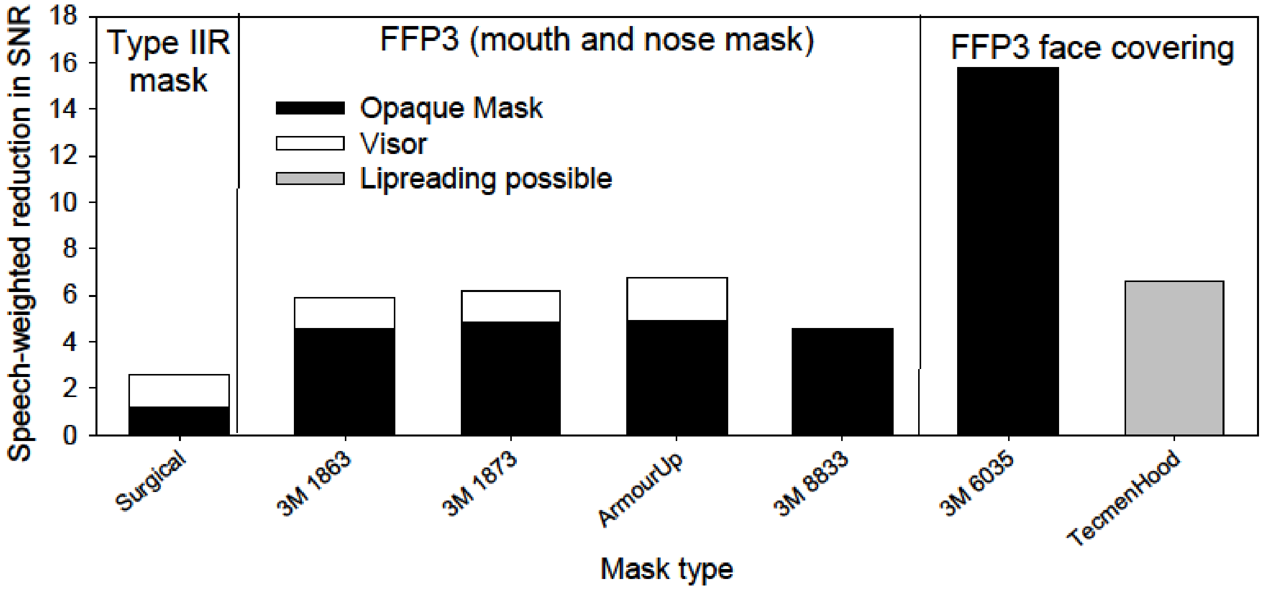
Figure 1. Photographs of the manikin fitted with various types and combinations of PPE used in the study.

Figure 2. Acoustic attenuation spectra between 10 Hz and 22 kHz for various masks. The impact on the addition of a visor is also shown where appropriate. Frequency axis is scaled in equivalent rectangular bandwidths (ERBs).

Figure 3: Speech-weighted reduction in signal to noise ratio in selected masks (with and without the addition of a visor, where applicable).


Surgical
1863
8833
6035
Surgical with visor
1873 Aura with visor
Armourup with visor
TECMEN TM-H2


Frequency (kHz)
Attenuation (dB)
a)
b)
c)
d)
e)
0.2
0.4
0.9
1.5
2.7
4.8
9.3
22.0
10
5
0
-5
-10
-15
-20
-25
-30
IIR mask
IIR mask+ Visor
3M 1863
3M 1863 +Visor
3M 1873
3M 1873 + Visor
3M 8833
3M 8833 +Visor
ArmourUp
ArmourUp +Visor
Tecman TM-H2
3M 6000


Speech-weighted reduction in SNR
18
16
14
12
10
8
6
4
2
0
Type IIR mask
FFP3 (mouth and nose mask)
FFP3 face covering
Opaque Mask
Visor
Lipreading possible
Surgical
3M 1863
3M 1873
ArmourUp
3M 8833
3M 6035
TecmenHood
Mask type

398