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1 **Acoustic analysis of the effect of Personal Protective Equipment on speech** 2 **understanding: Lessons for clinical environments**

3
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14 15 **Abstract**

16 17 **Objective**

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

22 23 **Design**

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

28 29 **Study Sample**

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

32 33 **Results**

34 The Type IIR mask had the smallest impact on SNR (2.6 dB with visor). Most FFP3s with an
35 addition of a visor (if not already face covering) impacted SNR by approximately 6 dB. The
36 3M 6000 was significantly worse (15.8 dB).

37 38 **Conclusions**

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

44 **Introduction**

45
46 Covering the face with a mask can impair communication in two ways, acoustic and
47 visual. The acoustic power of the voice is attenuated by the material of the mask
48 which reflects and/or absorbs some of the sound, preventing it from being projected
49 to the listener. At the same time, most masks are opaque and therefore obscure lip
50 movements. In a totally quiet environment, neither of these things may matter unless
51 the voice becomes so faint that vital parts of speech fall below the listener's
52 detection threshold. However, anaesthetic, theatre and intensive care environments
53 contain varying levels of background noise with Leq varying between 52.9 to 75.1 dB
54 (Stringer et al, 2008; see also Hasfeldt et al, 2010; Willett, 1991; Nott & West, 2003).
55 The primary cause for the background noise varies but common sources include
56 anaesthetic machines, suction devices and other communication within the same
57 environment. Wearing a facemask could then attenuate the voice towards or below
58 its masked intelligibility threshold, resulting in potential misunderstanding or poorer
59 performance. This attenuation can be compensated up to a point by increasing voice
60 volume. However performance of tasks with potentially high cognitive load such as
61 intubation or surgery could be negatively impacted (Way et al, 2013; Füllgrabe,
62 2020). It is therefore important that acoustic attenuation of frequencies crucial for
63 speech perception be minimised (Mendel et al, 2008).

64

65 Face masks such as fluid resistant surgical masks (FRSM Type IIR) have been
66 commonplace in theatre environments for decades. These masks are splash
67 resistant to protect against bodily fluids but are tested on exhalation in order to test
68 the efficiency of the mask to prevent the wearer from transmitting infection. During
69 the Covid-19 pandemic, it has become necessary in many theatre and anaesthetic

70 environments, and indeed in all situations where aerosol generating procedures
71 (AGPs) are carried out, to instead use filtering facepiece masks. FFP2 and FFP3
72 masks are tested on inspiration (to protect the wearer) and filter 94% or 99% of
73 suspended particles, respectively. In addition, they must permit a maximum leakage
74 of 8% or 2%, respectively. Clear plastic visors are also commonly worn in addition,
75 with the purpose of adding further splash protection.

76

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

81

82 Previous studies have investigated the attenuation properties of various masks
83 including medical masks and respirators (Corey et al, 2020; Goldin et al, 2020;
84 Mendel et al, 2008; Radonovich et al, 2010). Some have also assessed speech
85 reception in background noise (Palmiero et al, 2016). Homans & Vroegop. (2021)
86 investigated the impact on speech understanding of a surgical mask and a face
87 shield in those with moderate to severe hearing loss or cochlear implant users.

88 Within this study speech perception even in quiet conditions were effected by both
89 mask and face shield. Toscano & Toscano (2021) highlighted that differences in
90 speech understanding between masks were only exhibited at high signal-to-noise
91 ratios (SNR). Brown et al. (2021) also examined the impact of speech intelligibility
92 (SI) and listening effort without visual clues due to masks. It found that finding that
93 intelligibility and and listening effort was negatively affected in noise and particularly
94 in older adults. Within our study we evaluate the acoustic properties of personal

95 protective equipment in the form of commonly used FFP3 masks and additional face
96 protection (visors) in order to predict the impact on communication in theatre and
97 anaesthetic environments. This would allow us to discern what strategies or assistive
98 technologies may assist health professionals in their clinical communication within
99 such settings.

100

101 **Methods**

102

103 Recordings were performed in a 1201-A (Industrial Acoustics) booth. Measurements
104 of the acoustic attenuation produced by different face masks were collected using an
105 acoustic manikin (Brüel & Kjaer, Head and Torso Simulator, type 4128-D) which has
106 a built-in mouth simulator. This acoustic manikin is designed to reproducibly
107 generate a realistic sound field emanating from the human mouth and is used to
108 assess electroacoustic devices such as headsets, telephones, audio conference
109 devices and hearing aids (Brüel & Kjær, 1985; Huang et al, 2012; Lavandier et al,
110 2012; ANSI, 1997). Data collection and analysis was performed using Matlab 2020a.

111

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

122

123 This measurement was performed for a variety of PPE appropriately fitted to the
124 mannequin's face including: Surgical mask (Dishang FRSM Type IIR), FFP3 masks
125 covering nose and mouth (3M 1863, 3M 1873, 3M 8833, ArmourUp) (3M, 2020a;
126 Medino, 2020), FFP3 masks covering the full face (3M 6000, Tecman Hood TM-H2)
127 (3M, 2020b; Tecmen, 2020) as shown in Figure 1. The 3M 6000 comprises of a
128 reusable mask with 2 changeable filters whilst the Tecman Hood TM-H2 is a
129 Powered Air-Purifying Respirator (PAPR). The latter produces a positive pressure
130 within the headpiece (which isn't sealed), so expired air is free to escape from the
131 base of the hood. Each condition was repeated with and without visor (Royal Mint
132 face visor) where appropriate. The transparent visor was made from 1 mm PET and
133 covered the mannequin's face, nose and mouth.

134

135 In order to visualise the perceptual effect of PPE, the differences in transfer function
136 were smoothed in the fashion of cochlear excitation patterns (Moore & Glasberg,
137 1983). This converts the difference in sound transmission with and without PPE into
138 the change would be perceived by a listener as a function of frequency. The overall
139 practical effect of the attenuation was evaluated using a weighting function from the
140 articulation index (ANSI, 1997, Table 1). This function weights each frequency band
141 according to its importance in speech perception to produce a predicted reduction in
142 the effective signal level for speech reception caused by the mask. When listening in
143 noise there will, therefore, be a corresponding reduction in effective signal-to-noise
144 ratio. For this purpose, these weightings were redistributed onto ERB-spaced
145 frequency bands (Table I) using Moore and Glasberg's (1983) Eq. 5. It provided an
146 objective and comparable measurement converting acoustic transmission into the

147 perceived effect of the difference in sound transmission on listener experience,
148 establishing the likely practical effect on verbal communication.

149

150 **Results**

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

160

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

165

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

173 differences attributable to differences between the respective mouth-and-nose
174 covering masks.

175

176 The surgical mask (Type IIR) showed the lowest speech-weighted reduction in
177 speech transmission (shown in Figure 3). However, this mask doesn't have the same
178 aerosol filtration abilities as the others illustrated. This is due to its certification
179 primarily being related to filtering expired air from the wearer rather than protecting
180 the user. Thus, currently it is not permitted for use in many theatre and anaesthetic
181 environments, or in any clinical environments where aerosol generating procedures
182 are taking place. All of the other masks have comparable aerosol filtration abilities.

183 The 5 FFP3 mouth-and-nose covering masks all had similar speech-weighted
184 reductions in SNR. Although the 3M 1863 caused the least attenuation of the FFP3
185 masks, this is still double that of the IIR surgical mask (5.3 dB compared to 2.6 dB
186 for IIR surgical mask).

187 While many masks had a similar effect on speech, there are some clear outliers. The
188 3M 6000 reusable full-face mask produced an attenuation 9.2 dB greater than that of
189 any other mask from the test set. Additionally, these results show that the addition of
190 a visor consistently adds about 1.7 dB of attenuation to a speech signal.

191

192 **Discussion**

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

198

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

210

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

221

222 In addition to the attenuation spectra, another important feature which will have an
223 impact on understand is the ability to support lipreading (Macleod & Summerfield,
224 1987). The only mask which we tested in this study which allowed the possibility of
225 lipreading within our cohort was the Tecmen TM-H2. (Atcherson et al, 2017;
226 Atcherson et al, 2020; Brown et al, 2021) has also highlighted the importance of
227 visual input from transparent facemasks over those that do not allow for lipreading
228 clues. Ideal designs for the future should allow the possibility of lipreading. This has
229 been shown to greatly improve speech-reception thresholds when available
230 (approximately 11 dB) (Macleod & Summerfield, 1987). The use and integration of
231 additional communication strategies may also be necessary (e.g. assistive mobile
232 communication) or options that enable the issue here to be bypassed (e.g. non-
233 verbal aids). Where possible ambient noise should be reduced in clinical areas
234 where FFP3 masks are used in order to reduce the SNR. Previous studies
235 demonstrating the benefits of the sterile cockpit in reducing communication errors in
236 anaesthetic and surgical settings (Broom et al, 2011; Statement, 2014; Way et al,
237 2013). How and when these should be employed requires further research in a
238 clinical setting.

239

240 Limitations of the work include not being able to account for a possible increase in
241 speech level that is expected to aid communication when using such devices.

242 Additionally, the use of glasses or goggles were not assessed as a comparator.

243

244 Where overall equivalence in protective qualities is shown, acoustic properties may
245 influence correct compliance along with wearer comfort and other considerations.

246 The information obtained from this work is useful clinically as it allows us to clarify

247 why different FFP3 masks may result in perceptually different levels of speech
248 understanding between individuals. In addition, it also demonstrates the summative
249 effect of a visor used in combination with a FFP3 face and mouth covering.

250

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

255

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259

260 **Competing interests**

261 None declared.

262

263 **Data availability statement**

264 Data are available upon reasonable request

265

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- 373
- 374

375
376**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

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

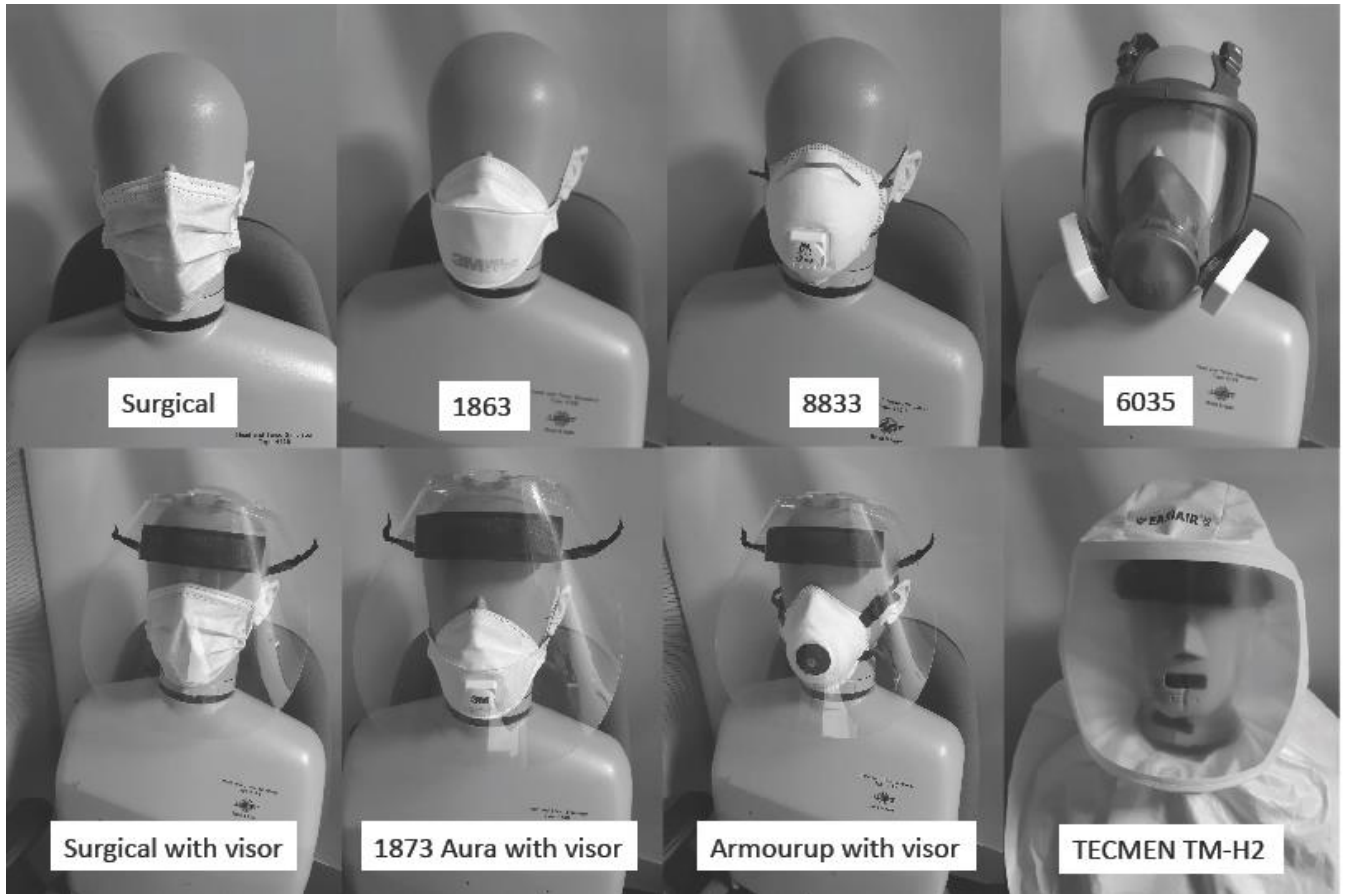
Figure Legends

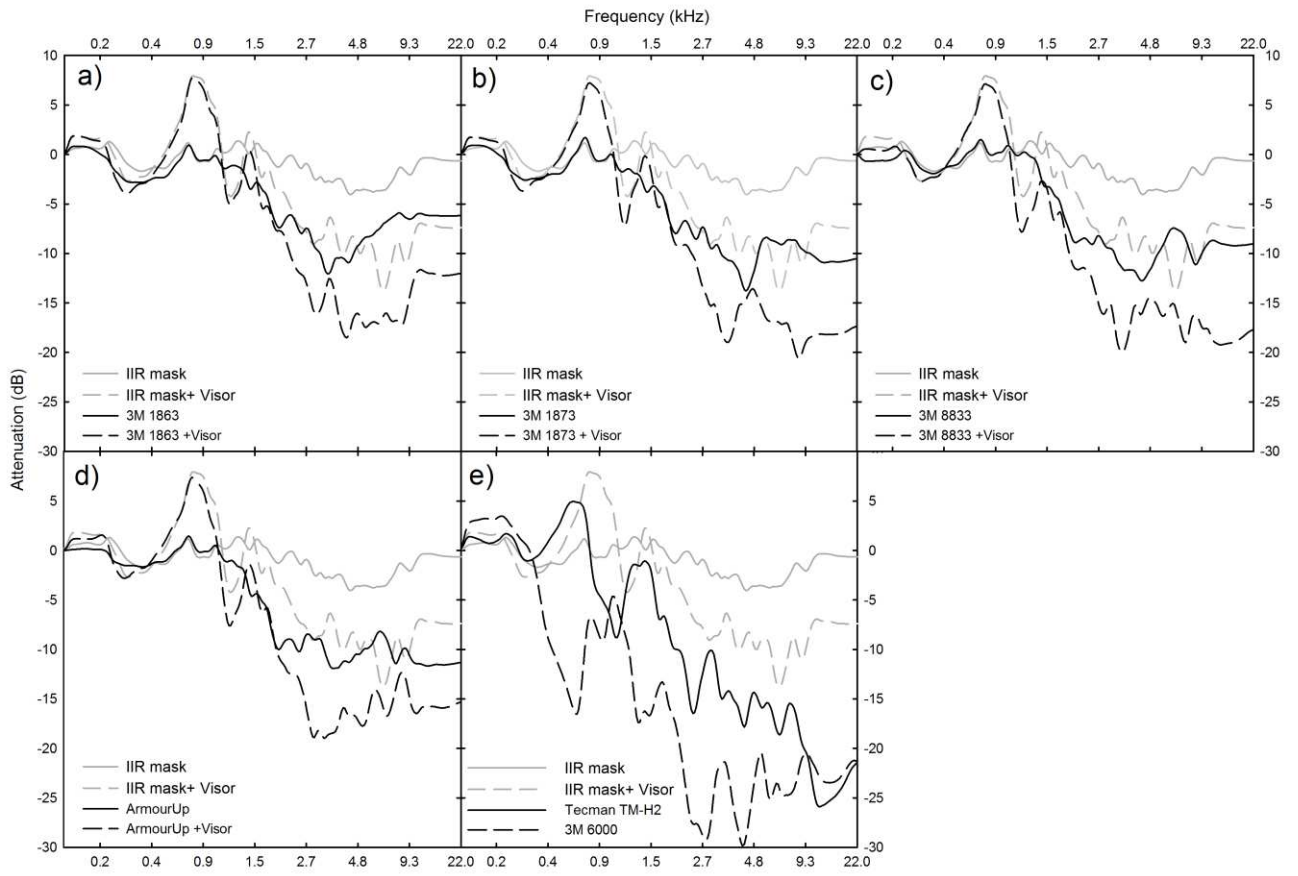
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Figure 1. Photographs of the manikin fitted with various types and combinations of PPE used in the study.

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).





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