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Effect of wearing personal protective equipment on acoustic characteristics and speech perception during COVID-19

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ABSTRACT

With the COVID-19 pandemic, the usage of personal protective equipment (PPE) has become ‘the new normal’. Both surgical masks and N95 masks with a face shield are widely used in healthcare settings to reduce virus transmission, but the use of these masks has a negative impact on speech perception. Therefore, transparent masks are recommended to solve this dilemma. However, there is a lack of quantitative studies regarding the effect of PPE on speech perception. This study aims to compare the effect on speech perception of different types of PPE (surgical masks, N95 masks with face shield and transparent masks) in healthcare settings, for listeners with normal hearing in the audiovisual or auditory-only modality. The Bamford–Kowal–Bench (BKB)-like Mandarin speech stimuli were digitally recorded by a G.R.A.S KEMAR manikin without and with masks (surgical masks, N95 masks with face shield and transparent masks). Two variants of video display were created (with or without visual cues) and tagged to the corresponding audio recordings. The speech recording and video were presented to listeners simultaneously in each of four conditions: unattenuated speech with visual cues (no mask); surgical mask attenuated speech without visual cues; N95 mask with face shield attenuated speech without visual cues; and transparent mask attenuated speech with visual cues. The signal-to-noise ratio for 50% correct scores (SNR50) threshold in noise was measured for each condition in the presence of four-talker babble. Twenty-four subjects completed the experiment. Acoustic spectra obtained from all types of masks were primarily attenuated at high frequencies, beyond 3 kHz, but to different extents. The mean SNR50 thresholds of the two auditory-only conditions (surgical mask and N95 mask with face shield) were higher than those of the audiovisual conditions (no mask and transparent mask). SNR50 thresholds in the surgical-mask conditions were significantly lower than those for the N95 masks with face shield. No significant difference was observed between the two audiovisual conditions. The results confirm that wearing a surgical mask or an N95 mask with face shield has a negative impact on speech perception. However, wearing a transparent mask improved speech perception to a similar level as unmasked condition for young normal-hearing listeners.

1. Introduction

Effective communication between doctors and patients is central to the provision of medical care [1,2]. Owing to the COVID-19 pandemic, the use of different types of personal protective equipment (PPE) is mandatory to prevent the spread of the virus [3,4]. In healthcare settings, it is common that patients wear surgical masks and healthcare workers wear N95 masks with a face shield for additional eye protection. However, the use of PPE reduces the ability of healthcare personnel to effectively communicate with patients and co-workers, exerting a negative impact on the effectiveness, efficiency and safety in the treatment of diseases [5].

The muffled sound and the lack of visual cues caused by wearing PPE contribute to the decreased performance of speech perception. To address this issue, transparent masks are recommended as an alternative, to provide extra visual information, which results in better communications, more empathy and greater trust [6].

Several studies have examined the adverse impact of different types of PPE on speech perception. In some studies, there was no significant difference between results with and without a surgical mask [7–12], whereas Bottalico et al. found that speech intelligibility was reduced by 12 percent with surgical masks as compared to unmasked condition [13]. In a study conducted by Bandaru et al.
As for the signal-to-noise ratio for 50% correct scores (SNR50), thresholds showed an average increase of 12.4 dB and the speech recognition scores (SRS) a mean decrease of 7 percent when presented with an N95 mask with face shield. The study by Atcherson et al. [11] revealed that wearing a transparent mask had little or no effect for individuals with normal hearing or moderate hearing loss, but significantly increased the speech perception for individuals with severe to profound hearing loss with the presence of visual cues.

It is important to note that, these previous studies suffered from three limitations. First, the majority of these studies neglected the influence of visual cues; this is a limitation because the additional visual information has been shown to have a positive effect on speech perception [15,16] and most healthcare interactions are based on face-to-face communication between clinician and patient. Second, given that the speech stimuli were recorded by a human talker wearing different types of PPE, the heterogeneity of the experimental conditions caused by the talker’s speech characteristics (e.g., speed, intensity, pauses, quality) cannot be ignored. Third, the ceiling effects in these studies, due to the low level or absence of background noise, obscured the inherent differences between different test conditions. The normal-hearing listeners scored nearly 100% both in the no-mask and transparent-mask condition, and no significant difference was noted although they felt the task was easier in the transparent-mask condition [11].

The purpose of this study was to quantitatively analyze the effects of three different types of PPE (surgical mask, N95 mask with face shield and transparent mask) on speech perception in healthcare settings. Our study was designed to reflect realistic clinical settings. In this study, (1) all participants were presented with either audiovisual or audio-only stimuli, as they simultaneously listened to Bamford–Kowal–Bench (BKB)-like Mandarin speech stimuli recorded under four conditions, and watched the corresponding video with or without visual cues; (2) all the speech stimuli, with or without attenuation by PPE, were recorded by a G.R.A.S KEMAR manikin rather than a human talker, to maintain comparability of the groups; and (3) the SNR50 thresholds were measured to avoid ceiling and floor effects.

2. Material and methods

2.1. Participants

Twenty-four healthy participants, aged 20 to 23 years old, were recruited for this study. All participants were female and nurses of the Chinese PLA General Hospital. This study has specifically targeted female nurses as nurses are heavily involved in patient care and the nursing department in the hospital is predominantly made up of females. All subjects were screened with otoscopy, pure-tone audiometry and tympanometry. Otoscopy was performed on all subjects after the removal of the cerumen, to confirm a clear external auditory canal and an intact tympanic membrane. Pure-tone hearing thresholds of all subjects were evaluated with a GSI-61 audiometer in a soundproof room according to the standard audiometric procedures. All participants had normal bilateral hearing thresholds (<25 dB HL) at octave frequencies from 0.25 to 4 kHz. Tympanometry was conducted with a GSI Tymstar middle ear analyzer using 226-Hz probe tones, and all listeners had normal type-A tympanograms. No subjects had a history of otological disease, and all had good visual acuity with or without glasses to ensure audio-visual integration was not affected by vision issue.

2.2. Stimuli

A set of validated BKB-like Mandarin sentences that match the international long-term average speech spectrum [17], each with a paired four-talker babble noise and a synchronous video, were adopted to assess speech recognition. The speech material consists of 14 lists of BKB-like sentences for measuring SNR50 thresholds in noise, and every list contained 20 sentences with 4 to 6 keywords each. The paired babble noise was a four-talker babble recorded by four Chinese talkers (two male and two female) reading random sentences. The corresponding video of a male speaker for every sentence was displayed synchronously on the screen. The SNR50 threshold in noise is the signal-to-noise ratio (SNR) at which the subject understands 50% of the whole sentences correctly. It was measured by a custom-made software in an adaptive testing procedure, as follows. The speech intensity level was fixed but the noise intensity level of each test sentence was varied in steps depending on the result of the previous sentence, which was scored as the number of keywords correctly repeated, and the final SNR50 threshold in noise was the mean value of the last several SNRs, which fluctuated in a small range.

The G.R.A.S KEMAR manikin wearing three different types of PPE (surgical mask, N95 mask with face shield and transparent mask, Table 1), or no mask, was used to mimic real-world conversation scenarios (Fig. 1). In the four conditions mentioned above, the BKB-like Mandarin sentences were played through the KEMAR manikin’s mouth, which can be equalized to emit a sound signal from 100 Hz to 10 kHz, up to a level of minimum 100 dB SPL at the mouth reference point – the point on the reference axis 25 mm in front of the lip plane. A microphone (B&K 4190), with a height levelling the mouthpiece of the KEMAR manikin, was positioned at 1 m from it for audio recording. All sentences were recorded in an anechoic room at the National Institute of Metrology of China. Audio recording for the four conditions was kept in the same configuration to ensure consistency in the recorded speech stimuli. The stimuli speech were then analyzed and edited with Audition CC 2020 software (Adobe, San Jose, CA, USA). The four-talker babble noise was unmodified.

To remove the visual cues, masked versions of the corresponding videos were processed by adding an image of a surgical mask to occlude the face below the eyes (Fig. 2). Therefore, lipreading and some nonverbal cues were unavailable for the participants in the two auditory-only conditions (surgical mask and N95 mask with face shield). The original unmasked videos were used in the other two audiovisual conditions (no mask and transparent mask).

The speech and video material were arranged for the following four test conditions:

- Condition 1: Unattenuated speech with visual cues (NoMask).
- Condition 2: Surgical mask attenuated speech without visual cues (S-Mask).
- Condition 3: N95 mask and face shield attenuated speech without visual cues (N95wFS).
- Condition 4: Transparent mask attenuated speech with visual cues (T-mask).

2.3. Procedures

All participants were informed that this research’s aim was to evaluate speech perception under different PPE conditions, and all participants were compensated for their involvement in the study. All participants were well-rested to avoid fatigue or poor concentration. A written informed consent form was signed by each participant before the test.
Digital-to-analog conversion of the audio signals (i.e., BKB sentences and babble noise) were conducted using custom-made software running on a Lenovo ThinkPad X230 laptop outside the soundproof room connected to an audio interface (TASCAM US-366) and a power amplifier (JBL CSA-2120). The final analog output was presented through the speaker (JBL Control 1 Pro) inside the room. The videos were presented on a 19-inch Dell monitor, which was connected to the laptop and located above the JBL speaker. The speech and four-talker babble noise were presented through the same loudspeaker at zero-degree azimuth and 1-m distance from the listeners. Listeners’ responses to the stimuli were heard through a microphone in the room and the score for every sentence was calculated as percent correct (total words understood correctly/total words presented). The final results of the SNR 50 thresholds in noise were recorded on the custom-made software.

At the beginning, participants were told about the content of the test, and two practice trials with unmasked videos (list N) or masked videos (list M) were completed sequentially to familiarize listeners with the procedure. The material lists (A–H) and test conditions were randomized for all participants to eliminate order effects. SNR 50 thresholds in noise for all participants were measured twice for each test condition. For example, listener 1 was tested successively in an order of NoMask (lists A and B), S-Mask (lists C and D), N95wFS (lists E and F) and T-mask (lists G and H), whereas listener 2 was tested successively in an order of S-Mask (lists F and H), NoMask (lists B and G), T-mask (lists A and C) and N95wFS (lists D and E). The average SNR 50 threshold in noise for each test condition was used in the final analysis.

2.4. Data analysis

Audition CC 2020 software was used to remove all the pause between sentences in each condition. For each test condition, the

| S-Mask | Medical surgical mask | Naton | Polypropylene (PP) spun bonded non-woven fabric + melt blown + spun bonded non-woven fabric | 3 | Ear hanging |
|-------|------------------------|-------|------------------------------------------------------------------------------------------------|---|-------------|
| T-mask | Transparent mask | Unknown | Fabric face mask with a clear plastic | 1 | Ear hanging |
| N95wFS | N95 mask | 3 M 9010 | Spun bond PP + Melt blown + Electrostatic cotton + Melt blown + Spun bond PP | 5 | Two elastic head straps |
| Face shield | GUARDIAN | Polycarbonate | | 1 | An elastic band |

Abbreviations: S-Mask: surgical mask. T-Mask: transparent mask. N95wFS: N95 mask with face shield. PP: polypropylene.
sound intensity values were obtained as the average of the fourteen lists. The frequency analysis of each audio file was performed in Audition CC 2020 software using an FFT with a window size of 512 points and a Blackman–Harris window function. The intensity values were obtained at a rate of 128 Hz for each condition. Then, the relative intensity values were calculated by subtracting the intensity values of each mask condition from the NoMask condition respectively. The line graph was drawn using ggplot2 (https://ggplot2.tidyverse.org/) in RStudio.

The SNR50 thresholds in noise were expressed as the mean ± standard deviation and analyzed with SPSS (version 24; SPSS, Chicago, IL, USA). Wilcoxon matched-pairs signed-rank test (n < 30) was used for comparisons between the NoMask and T-mask conditions (both with visual cues), and between the N95wFS and S-mask conditions (both without visual cues). A two-tailed P-value of <0.05 was considered statistically significant.

3. Results

3.1. Spectral analysis of speech stimuli

Fig. 3 was plotted based on relative intensity values. Surgical masks attenuated high frequencies by about 4 dB. Transparent masks blocked about 8–20 dB and N95 masks with face shield caused the most-severe attenuation of around 10 dB at high frequencies. The results are consistent with findings by others [18,19].

3.2. Speech perception results

For each participant, the mean SNR50 thresholds of the two measurements for each test condition were used in the final analysis. The SNR50 values for the four test conditions were: NoMask = – 10.5 ± 1.1 dB SNR; N95wFS = – 1.9 ± 1.0 dB SNR; S-Mask = – 3.5 ± 0.9 dB SNR; and T-Mask = – 10.4 ± 2.7 dB SNR. There was a significant difference in the SNR50 thresholds between the two auditory-only conditions (N95wFS vs S-Mask; P < 0.001, paired Wilcoxon signed-rank test). No significant difference was observed between the two audiovisual conditions (NoMask vs T-Mask; P = 0.617, paired Wilcoxon signed-rank test). These results are plotted in Table 2 and Fig. 4.

4. Discussion

The objective of this study was to quantitatively evaluate the effect of different types of PPE (surgical mask, N95 mask with face shield and transparent mask) on speech perception. Twenty-four normal-hearing subjects participated in this study. To simulate real-world conversations, each participant listened to simulated speech attenuated by several types of PPE and simultaneously watched the speaker’s videos with or without visual cues. The SNR50 thresholds in noise of the four test conditions (no mask and three masked conditions) were measured. The results demonstrated that wearing either a surgical mask or an N95 mask with face shield decreased the performance of speech perception relative to wearing no mask. It is worth noting that speech perception with the transparent mask was comparable to the unmasked condition.

### Table 2

| Condition        | SNR50 thresholds (dB) | P-value* |
|------------------|-----------------------|----------|
|                  | Mean | SD  |                  |
| Audio-only conditions |     |     | 0.000***       |
| S-Mask           | –3.5 | 0.9 |                  |
| N95wFS           | –1.9 | 1   |                  |
| Audiovisual conditions |     |     | 0.617      |
| NoMask           | –10.5 | 1.1 |                  |
| T-Mask           | –10.4 | 2.7 |                  |

The SNR50 thresholds for speech perception in noise with different types of PPE. Significances were calculated with Wilcoxon matched-pairs signed-rank tests (**P < 0.001; SD: standard deviation; N95wFS: N95 mask with face shield; NoMask: no mask; S-Mask: surgical mask; T-Mask: transparent mask). *Wilcoxon matched-pairs signed-rank test.

**Fig. 3. Sound levels under four conditions.** Sound levels for three types of PPE, compared with that with no mask. The X-axis indicates the sound level for NoMask. Abbreviations: N95wFS: N95 mask with face shield. NoMask: no mask. S-Mask: surgical mask. T-Mask: transparent mask.

**Fig. 4. SNR50 thresholds in the four conditions.** **P < 0.001; NS: not significant (P > 0.05).** Abbreviations: NoMask: no mask. N95wFS: N95 mask with face shield. S-Mask: surgical mask. T-Mask: transparent mask.
Results revealed that different types of PPE affect speech perception performance by varying extent. Because there were two independent variables (i.e., type of masking condition and presence/absence of visual cues) in this study, it was not possible to directly compare the SNR50 thresholds among the four conditions. The two auditory-only conditions (surgical mask and N95 mask with face shield) markedly reduced speech understanding in noise, as they both had a much higher SNR50 threshold in noise compared with results in the NoMask condition despite the lack of a statistical comparison (Fig. 4). This reduction was mainly attributed to the attenuation of speech stimuli and the lack of visual cues. The presence of masks attenuated sounds mainly in the high frequencies (Fig. 3) and, therefore, the participants felt that the sentences were muffled. This agrees with the results of a study by Bandaru et al. [14], which showed that speech perception significantly deteriorated when the audiologist wore an N95 mask with face shield. Visual cues were eliminated by covering the speaker’s face below the eyes in these two auditory-only conditions. Visual cues have been shown to be important in speech comprehension [20] and the lack of visual cues made it more difficult for the subjects to understand speech in noise. Instead, normal-hearing subjects were more confident in the speech test with visual cues in a previous study [11]. Therefore, the auditory and visual factors both contributed to the deterioration in speech perception.

We found that the surgical mask condition had a significantly lower SNR50 than did the N95 mask with face shield. This trend is consistent with the results of other studies [14,21] in which N95 masks caused worse performance in speech perception than did surgical masks. This difference could be related to the degree of the attenuation of sound: the speech sound was more attenuated by the N95 mask than the surgical mask, as shown in Fig. 3.

Surprisingly, the transparent mask clearly demonstrated an improved performance on speech perception compared with the other two types of PPE. There was no significant difference in SNR50 thresholds in noise between no mask and the transparent mask, although a slightly higher SNR50 threshold in noise was predicted for the transparent mask because of its attenuation of sound. This finding suggests that visual cues improve speech perception performance close to normal level, despite the negative impact of masks on the high-frequency components of speech. Although the sound was muffled, listeners could still understand words in sentences, as in the unmasked condition, by integrating auditory and visual speech information. Visual cues can compensate for the deterioration in speech perception due to a mask. Previous studies pointed out that visual cues can provide additional temporal information such as the onset of speech, and phonetic information associated with phonemes, syllables and words in the audiovisual condition [22].

It is worth noting that the standard deviation observed in the transparent mask with visual cues condition was markedly larger than in the other conditions. We speculate that the major reason was the difference in audiovisual integration ability between subjects, as the hearing abilities appeared stable across test conditions and the visual cues were already counterbalanced between the two audiovisual conditions. Participants with stronger audiovisual integration obtained more temporal and phonetic information of the incoming acoustic signal, resulting in lower SNRs. Additionally, the excellent ability to learn to use visual cues was considered to be the main reason for the two outlier subjects in the transparent mask condition, as they both completed the NoMask condition before the transparent-mask condition.

These results clearly suggest that a transparent mask is a valid tool for improving speech perception in healthcare settings, where it is inevitable for individuals to be disturbed by various noise sources, such as staff and patient conversations, monitoring devices with sound alarms, computer printers, and telephones [23]. Although raising voice can improve speech understanding [24], it could easily result in fatigue, which leads to an elevated risk of medical mistakes [25]. However, wearing a transparent mask makes communication as easy as not wearing a mask, with the help of visual cues. Apart from better communication, more empathy and greater trust are also brought about by wearing a transparent mask rather than an opaque mask [6]. These advantages of transparent masks make them worthy of clinical promotion and application.

Unlike previous studies, precise quantitative speech material was adopted and SNR50 thresholds in noise were measured for subjects in this study. The speech stimuli were recorded by a G.R.A.S KEMAR manikin wearing different masks, to mimic sound attenuation by various types of PPE, rather than recorded by a human. Thus, the differences in sound with different types of PPE are fully attributed to sound attenuation, and other factors such as fluctuations of the human talker’s speech characteristics (e.g., speed, intensity, quality) presented in previous studies, were completely ruled out, improving the credibility and precision of the results. Measurement of SNR50 thresholds in noise, rather than SRS in a fixed SNR, was applied to avoiding the “ceiling effect” in previous studies: in those, all normal-hearing subjects scored nearly 100 % on SRS whether PPE was used or not. The ceiling effect may not reflect the real difference between different test conditions, as some participants felt that the presence of visual cues helped with speech perception but they had similar scores [11]. In this study, the final SNR value was adjusted to a specific value for every participant in an adaptive method, to obtain a 50 % SRS, so that the test would not be too easy or too difficult for them. Therefore, the results measured by SNR50 thresholds in noise were easier and more objective to interpret.

This study had several limitations. First, two more test conditions that were originally planned (unattenuated speech without visual cues and transparent mask attenuated speech without visual cues) were not tested, because completing all six test conditions in a single session was time-consuming and involved sustained attention, which led to poor subject cooperation due to fatigue and impatience in the late stages. The four test conditions we adopted in this study mimic the real clinic condition, helping this study provide practical significance and reference for real-world scenarios. Second, the transparent mask used in this study was not a medical one, as medical transparent masks approved by the FDA were not available at the experimental site. Considering that medical and non-medical transparent masks are both mainly composed of a transparent plastic panel and other fabric components, it is reasonable to assume that they have similar degree on sound attenuation and visibility of visual cues, and, therefore, a similar effect on speech perception. Third, the speech stimuli were recorded by a male speaker, whose fundamental frequency is different from a female speaker. Further research could be conducted to determine whether there is a similar effect on speech understanding with different types of PPE for a recording with a female voice.

5. Conclusions

In this study, the effects of different types of PPE (surgical mask, N95 mask with face shield and transparent mask) on speech perception in health settings were quantitatively analyzed by measurement of SNR50 thresholds in noise. The speech stimuli we adopted were recorded by a G.R.A.S KEMAR manikin rather than a real human, which improves the consistency and credibility of the findings. The results suggested that wearing a surgical mask or an N95 mask with face shield significantly hampered communication, whereas speech perception for the young normal-hearing listeners reached, surprisingly, to a normal level with the wearing of a trans-
parent mask. The study provides strong evidence that transparent medical masks should be provided to healthcare staff or patients who feel difficulty in communication, to contribute to a better patient-physician relationship and better treatment outcome.

CRediT authorship contribution statement

Peng Zhou: Methodology, Formal analysis, Writing – original draft, Visualization. Shinmin Zong: Writing – review & editing. Xin Xi: Resources, Conceptualization, Supervision, Project administration. Hongjun Xiao: Conceptualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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