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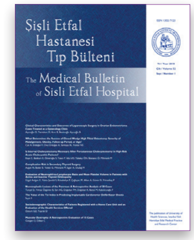

Original Research

Effects of Personal Protective Equipment on Speech Acoustics

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ABSTRACT

Objectives: The transmission of severe acute respiratory syndrome coronavirus-2 occurs primarily through droplets, which highlights the importance of protecting the oral, nasal, and conjunctival mucosas using personal protective equipment (PPE). The use of PPE can lead to communication difficulties between healthcare workers and patients. This study aimed to investigate changes in the acoustic parameters of speech sounds when different types of PPE are used.

Methods: A cross-sectional study was conducted, enrolling 18 healthy male and female participants. They were instructed to produce a sustained [ɑː] vowel for at least 3 s to estimate voice quality. In addition, all Turkish vowels were produced for a minimum of 200 ms. Finally, three Turkish fricative consonants ([f], [s], and [ʃ]) were produced in a consonant/vowel/consonant format with different vowel contexts within a carrier sentence. Recordings were repeated under the following conditions: no PPE, surgical mask, N99 mask, face shield, surgical mask + face shield, and N99 mask + face shield. All recordings were subjected to analysis.

Results: Frequency perturbation parameters did not show significant differences. However, in males, all vowels except [u] in the first formant (F1), except [ɔ] and [u] in the second formant (F2), except [ɛ] and [ɔ] in the third formant (F3), and only [i] in the fourth formant (F4) were significant. In females, all vowels except [i] in F1, except [u] in F2, all vowels in F3, and except [u] and [ɯ] in F4 were significant. Spectral moment values exhibited significance in both groups.

Conclusion: The use of different types of PPE resulted in variations in speech acoustic features. These findings may be attributed to the filtering effects of PPE on specific frequencies and the potential chamber effect in front of the face. Understanding the impact of PPE on speech acoustics contributes to addressing communication challenges in healthcare settings.

Keywords: Communication disorder, COVID-19, personal protective equipment, phonetics, speech

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Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is a novel virus known to be easily transmitted through respiratory droplets. Infection primarily occurs through the oral and nasal mucosa, as well as the conjunctival membranes. The transmission pattern and contagiousness of this virus have been extensively studied, with simulations demonstrating its rapid spread.[1] To mitigate the risk of infection during the pandemic, the proper use of personal protective equipment (PPE), such as face masks, transparent face shields, and goggles, is strongly recommended.

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Face masks, which typically cover both the nose and mouth, serve as a means of particle filtration. Conventional surgical masks, consisting of two or three layers of fabric, are designed to reduce the production of aerosols. Although surgical masks have a relatively thin texture, they still provide some level of particle filtration. In European standards, particle filtration is categorized as FFP1, FFP2, and FFP3 based on the number of particles filtered. FFP2 and FFP3 masks, with their tighter structures, filter at least 94% and 99% of particles, respectively. These masks are highly recommended in critical settings such as COVID-19 intensive care units and operating rooms, where more effective filtration is required. Transparent face shields and goggles are suggested to protect against conjunctival or mucosal contamination. Goggles do not cover the nose or mouth but provide eye protection, while transparent face shields cover the entire face and create a barrier against particles and aerosols.

Before the COVID-19 pandemic, research focused on examining the acoustic effects of various fabrics for judicial purposes.[2] However, with the global spread of COVID-19, the use of PPE has become widespread, leading to observed effects on communication. For example, a study has reported voice radiation distortion,[3] and recent reports highlight communication challenges between health-care workers and patients due to the use of PPE. Bandaru et al.[4] found impaired speech intelligibility scores when using different face masks, and Poostchi noted the significant impact on patients with hearing loss who rely on lip reading.[5]

Even as the COVID-19 pandemic gradually subsides, the importance of PPE remains crucial. While its initial implementation aimed to mitigate the spread of the virus, the enduring significance of PPE in various settings should not be underestimated. Lessons learned during this challenging period have underscored the critical role of PPE in protecting individuals and minimizing potential risks. Considering these factors and the aforementioned effects of PPE on communication, our objective was to investigate the impact of different PPEs on speech acoustic parameters, hypothesizing that PPE may contribute to communication disorders.

Materials and Methods

This cross-sectional study was conducted at the otorhinolaryngology department of Prof. Dr. Süleyman Yalçın City Hospital from November 2020 to December 2020. The study included 18 healthy male and 18 healthy female volunteers. All participants were healthcare providers (doctors and nurses) who were native Turkish speakers and had normal hearing. They had no history of acute respiratory system infections or vocal fold surgery. Individuals with a history of recent acute respiratory infections, voice abuse or fatigue, or surgery were excluded from the study.

Speech Material

The acoustic features of Turkish speech sounds were analyzed using various speech materials. Three types of speech stimuli were used: (1) sustained production of the [ɑː] vowel for a minimum duration of 3 s; (2) production of all Turkish vowels ([ɑ], [ɛ], [ɯ], [i], [ɔ], [œ], [u], and [y]) for at least 200 ms, along with recordings of the primary phonetic realizations of these vowels; and (3) 18 sentences containing specific words. The chosen words focused on Turkish fricative consonants ([f], [s], and [ʃ]) and utilized consonants at the beginning and end of monosyllabic words with different vowel contexts ([ɑ], [i], and [u]). The remaining words in the sentences were carefully selected to minimize the influence of adjacent formants. The speech material can be accessed as an online supplemental file 1.

Recordings and Analysis

Recordings were performed in a quiet and anechoic chamber with a background noise level below 30 dB A and a reverberation time of 0.1 s. A stand holding an MXL USB.006 cardioid condenser microphone (MXL®, CA, USA) with a pop filter was positioned in front of the participants and adjusted to their height. The distance between the mouth and the microphone was approximately 15 cm. All recordings were captured using Audacity v.2.4.2 for Mac.[6]

The participants produced speech material under six different conditions: no PPE, surgical mask (Evony®, Hayat, Kocaeli, Türkiye), N99 mask (MFA®, Zonguldak, Türkiye), face shield (Wotex®, Istanbul, Türkiye), surgical mask with face shield, and N99 mask with face shield (Fig. 1). The selection of PPE types was based on recommendations from previous publications[1] and their widespread use among healthcare providers. N99 masks were chosen instead of N95 masks due to their higher density, which may better demonstrate any differences. Recordings were conducted in a random order to prevent bias related to voice fatigue, ensuring an equal number of conditions for each row. The random order table is provided as an online supplemental file 2.

The recorded speech data were segmented according to the speech material and saved in 44,100 Hz/16-bit PCM WAV format. Each segmented file was analyzed using Praat software and relevant scripts.[7] Firstly, voice quality parameters were estimated on sustained [ɑː] vowels using the "Voice report" command in the View and Edit window of Praat software. Secondly, the mean values of the first, second, third, and fourth formant frequencies (F1, F2, F3, and F4) and formant bandwidth frequency values (B1, B2, B3,

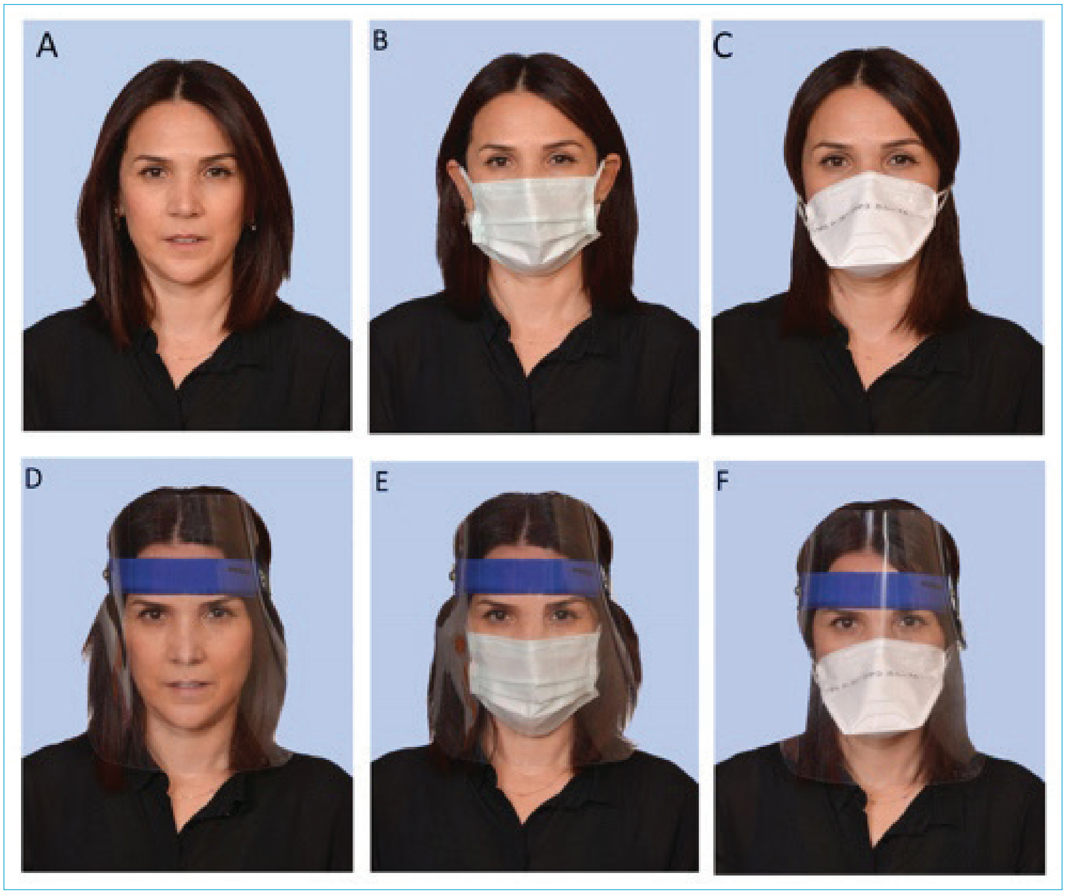

Figure 1. (a): No personal protective equipment, (b): Surgical mask, (c): N99 mask, (d): Face shield, (e): Surgical mask+ face shield, (f): N99+ face shield.

and B4) at the midpoints of the analyzed vowel segments were measured. Finally, the spectral moments of the consonants were measured. The formant and spectral moment measurements were conducted using Praat scripts initially developed by Henning Reetz and subsequently modified by the second author.[8,9]

Statistical Analysis

The obtained data included the mean, median, minimum, and maximum values, as well as the 25th and 75th percentiles. To assess normality, the Shapiro-Wilk test was conducted. Group comparisons and pairwise comparisons were analyzed using the Friedman test and Friedman *post-hoc* tests. A significance level of $p<0.05$ was considered statistically significant, with adjustments made for multiple comparisons. All statistical analyses were performed using SPSS v.20 for MAC (IBM® Corp., Armonk, NY, USA).

Ethical Statement

This study was approved by the local ethics committee of Göztepe Prof. Dr. Süleyman Yalçın City Hospital (No. 2020/0743 and the principles of the Helsinki declaration were strictly followed.

Results

The results were categorized into two subgroups: male and female. The average age for the male group was 33.6±6.2 years (minimum 25, maximum 47), while the average age for the female group was 35±9.1 years (minimum 23, maximum 50). Detailed descriptive data can be found in the online supplemental material (Online supplemental file 3).

Regarding voice quality estimates, we observed no changes in F0 and jitter parameters across the conditions. However, significant differences were found in certain shimmer parameters and the mean harmonic-to-noise (HNR) parameter in the female group. Specifically, shimmer local ($p=0.041$), shimmer local-abs ($p=0.023$), and mean HNR ($p<0.001$) showed statistically significant changes. In the male group, shimmer apq5 ($p=0.029$), shimmer apq11 ($p=0.003$), shimmer local ($p=0.034$), shimmer local-abs ($p=0.015$), and HNR ($p=0.014$) parameters were found to be significantly different. For detailed statistical results and *post-hoc* tests, please refer to Table 1.

The acoustics of vowel formants were evaluated, specifically focusing on different vowel sounds. In females,

Table 1. Perturbation parameters of [ɑː] vowel. p<0.05

Parameters	Female		Male	
	p	*Post-hoc* test	p	*Post-hoc* test
F0 median	0.620		0.845	
F0 mean	0.771		0.794	
Jitter (local)	0.137		0.360	
Jitter (local, abs)	0.195		0.340	
Jitter (rap)	0.583		0.174	
Jitter (ppq5)	0.424		0.517	
Shimmer (local)	0.041	C–D	0.034	C–D
Shimmer (local, dB)	0.023	C–D	0.015	C–D
Shimmer (apq3)	0.083		0.158	
Shimmer(apq5)	0.107		0.029	C–D
Shimmer (apq11)	0.090		0.003	A–D
Mean autocorrelation	0.008	–	0.826	
NHR	0.018	–	0.782	
HNR	<0.001	A–C, A–E, A–F	0.014	A–F, D–F

*Friedman test; **pairwise comparison of groups (Friedman *post hoc* test); F0: Fundamental frequency; NHR: Mean Noise-to-Harmonics Ratio; HNR: Mean Harmonics-to-Noise Ratio; A: No personal protective equipment; B: Surgical mask; C: N99 mask; D: Face shield; E: Surgical mask+face shield; F: N99+face shield.

Table 2. p-values of [ɑ], [ɛ], [ɯ], [i], [ɔ], [œ], [u], [y] vowels's production without faceshield (no PPE + only surgical mask+ only N99 mask) and with faceshield (only faceshield+ surgical mask with face shield + N99 with face shield)

	Female				Male			
	*f*1	*f*2	*f*3	*f*4	*f*1	*f*2	*f*3	*f*4
[ɑ]	0.05	<0.001	<0.001	0.006	0.003	<0.001	<0.001	0.025
[ɛ]	0.009	<0.001	<0.001	<0.001	<0.001	<0.001	0.007	0.108
[ɯ]	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.255
[i]	0.079	<0.001	<0.001	<0.001	<0.001	<0.001	0.614	<0.001
[ɔ]	<0.001	0.038	0.005	0.013	<0.001	0.483	0.058	0.040
[œ]	<0.001	<0.001	<0.001	0.004	<0.001	<0.001	<0.001	0.112
[u]	<0.001	0.104	0.295	0.681	0.019	0.346	0.002	0.401
[y]	<0.001	<0.001	<0.001	0.113	<0.001	<0.001	0.001	0.007

*f*1: Comparison of first formants with and without faceshield; *f*2: Comparison of second formants with and without faceshield; *f*3: Comparison of third formants with and without faceshield; *f*4: Comparison of forth formants with and without faceshield. (Wilcoxon test, p<0.05).

statistically significant differences were found in all formants of [ɑ], [ɛ], [ɯ], [ɔ], and [œ]. The formants F2, F3, and F4 of [i], F1 and F3 of [u], and F1, F2, and F3 of [y] were also found to be significant. In males, all formants of [i] showed statistical significance. In addition, the formants F1, F2, and F3 of [ɑ], [ɯ], [œ], and [y] showed significant differences. The formants F1 and F2 of [ɛ], F1 of [ɔ], and F3 of [u] were also statistically significant. The other formant values were changed but show no statistical importance. The p-values for group comparisons and pairwise comparisons can be found in the supplementary data (Online supplemental file 4). Measurements were also analyzed in combination with and without a face shield, as shown in Table 2.

Regarding consonant acoustics, the change in all comparisons was significant, except for the skewness value of [s] in the male group (Online supplemental file 5).

Discussion

The SARS-CoV-2 virus, the causative agent of COVID-19, is highly contagious and primarily spreads through aerosols and droplets. Social distancing is strongly recommended to limit the transmission of the infection; however, health-care professionals face an increased risk and must continue working. Even as the COVID-19 pandemic subsides, the importance of PPE remains paramount. While its initial implementation was primarily driven by the need to curb the spread of the virus, the enduring value of PPE in various settings cannot be overlooked. Other viral infections or future pandemics may pose similar risks, making the consistent use of PPE crucial for the protection of health-care workers and the general public. As such, health-care institutions and individuals should maintain vigilance and prioritize the proper use of PPE, ensuring their readiness for any potential health crisis. For this reason, different facemasks and face protection shields are commonly used.

The use of PPE raises concerns regarding "communication difficulties," which can be discussed from two perspectives. Firstly, patients with hearing impairments who rely on lip-reading may face challenges as face-covering masks hinder direct visibility of the lips and mouth.[5] Secondly, individuals themselves may encounter difficulties due to PPE use. Bandaru et al. demonstrated how the use of N99 masks and face shields can alter speech discrimination scores.[4] Ribeiro et al. also noted vocal fatigue and discomfort associated with the use of face masks.[10]

Several studies have conducted objective measurements to detect amplitude changes resulting from the use of different types of face masks, employing artificial head and mouth simulators. Goldin et al. utilized white noise to assess the acoustic effects of various masks (no mask, simple mask, N99 without ventilation, and N99 with ventilation). They observed a low-pass filter effect, resulting in an attenuation of 4–12 dB (from simple mask to N99 mask) in the middle and high frequencies (2000–7000 Hz).[11] Corey et al. compared plastic face shields with other masks and reported that face shields exhibited very poor acoustic performance, particularly in the high-frequency range, indicating inferiority compared to other masks.[12] The front-facing PPE demonstrated the lowest acoustic properties, likely due to sound wave deflection caused by the acoustic characteristics of such equipment.[12] Cavallaro et al. tested surgical masks by enunciating a sustained [ɑː] vowel using real human voices and found no significant difference in fundamental frequency, jitter, or shimmer between wearing a surgical mask and not wearing one.[13]

Our study consisted of three parts, with the first part focusing on perturbation analyses of the sustained [ɑː] vowel. We found that neither F0 nor jitter parameters were distorted when using face masks or combinations of PPE. However, some shimmer parameters showed significant effects. Previous literature also suggested no differences in F0 and jitter parameters.[14-16] Interestingly, the N99 mask consistently decreased shimmer levels in most experiments, which could be attributed to the clipping of fluctuating wave peaks. In our study, we speculate that face shields act as resonant chambers in front of the face, potentially causing a resonator effect. This finding aligns with recent literature. We also observed a significant change in mean HNR values, which is consistent with existing literature. This change is likely related to mask use, as mask users may unconsciously increase the projection of their voice.[14]

Joshi et al. conducted a study examining the formants of /ɑ/ and /i/ and observed changes in F2 and F1.[16] In our study, we investigated the formant properties of all Turkish vowels. We calculated formant frequency bandwidths by selecting the midpoint of the relevant segment, but since the results were not descriptive, we did not discuss the bandwidth measurements. However, we did observe changes in formants due to the conditions. Specifically, we found that the mean values of formants below 1000 Hz slightly increased to approximately 1000 Hz, while formants above the 1000 Hz middle or high frequency decreased to 1000 Hz when a face shield was used as a resonator effect. These findings align with the current literature. Gama et al. noted that frequencies below 3000 Hz were less affected, with the main distortion occurring at higher frequencies.[14] In our study, we observed a filtering effect when using a face mask, and this effect may become more apparent with increased material density. Additionally, various factors such as the length of the vocal tract, lip closure pattern, tongue volume and position, and mandible position can influence the formants.[14,17] The elastic straps, nose clips or wires, material, and shape of the mask may also contribute to these effects.

In the third part of our study, we examined the impact of PPE use on consonant acoustics, focusing on middle and high frequencies. We selected specific consonants known for their acoustic characteristics. The center of gravity (COG) for [f] was found to be located at 7152±2203 Hz, for [s] at 9304±1029 Hz, and for [ʃ] at 4777±1060 Hz.[18] In our current study, we observed a significant decrease in COG levels for the related consonants when face masks and face shields were utilized. Particularly, the use of face shields had a pronounced effect on the results.

Limitation of the study

First, unlike previous studies that measured changes in sound pressure level, we focused on analyzing changes in the frequency spectrum in our study. Second, the use of face masks can potentially affect speech physiology. Different types of face masks and face shields may impede the movement of the mouth and lips, especially when tight straps are involved, resulting in muffled speech. Third, the use of tight-fitting straps and narrow spaces can be uncomfortable, potentially affecting speech performance due to psychological factors. Another limitation of our study is the lack of validation for the sentences used to analyze the formants. These particular sentences are not established in the literature, and it is recommended to develop more standardized sentences for this purpose. Finally, our study focused solely on the Turkish language, and we encourage replication of this study in other languages to further validate the findings.

Conclusion

The use of PPE can cause speech distortion and negatively impact communication. This distortion may be attributed to the low-pass filter characteristics of the PPE. In particular, face shields can create a cavity effect, which acts as a resonator and further exacerbates the distortion. It is important to assess speech discrimination scores in both individuals with normal hearing and those with hearing impairments when using different types of PPE.

Disclosures

Online Supplementary Files: https://jag.journalagent.com/sislietfaltip/abs_files/SETB-22556/SETB-22556_(0)_SETB-2023-04-052_online_supplemental_files_1-5.pdf

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Ethics Committee Approval: The study was approved by the Ethics Committee of Istanbul Göztepe Prof. Dr. Süleyman Yalçın City Hospital (No: 2020/0743, dated 16.12.2020).

Consent to Participate: Informed consent was obtained from all individual participants included in the study.

Peer-review: Externally peer-reviewed.

Conflict of Interest: None declared.

Authorship Contributions: Concept – A.M., S.C.; Design – A.M., M.A.K.; Supervision – A.M., S.C.; Fundings – A.M., M.A.K.; Materials – A.M., S.C.; Data collection and/or processing – A.M., M.A.K.; Analysis and/or interpretation – A.M., M.A.K.; Literature review – A.M., M.A.K.; Writing – A.M., M.A.K.; Critical review – S.C., M.A.K.

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