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Listening Effort and Speech Perception Performance Using Different Facemasks

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ABSTRACT

Purpose: The aim of this study was to assess the effect of eight different facemasks on speech perception and listening effort in listeners with normal hearing (NH) and hearing loss by manipulating both mask type and background noise levels.
Method: Forty adults listened to Quick Speech-in-Noise Test sentences recorded by a female talker through eight different facemasks including a baseline condition with no mask. Listeners were tested in the sound field positioned 6 ft from the loudspeaker. Signal-to-noise ratio (SNR) loss and listening effort were measured.
Results: Listeners with NH exhibited a mild SNR loss, whereas those with hearing loss experienced a moderate SNR loss. Scores for the mild hearing loss group were significantly poorer (higher) than those with slight hearing loss. Speech perception performance was best in the no mask, KN95, and surgical mask conditions and poorest in the cloth mask and cloth mask plus face shield conditions for all groups. As listening effort decreased, speech perception increased for all groups.
Conclusions: The impact of different types of facemasks on speech perception in noise was demonstrated in this study indicating that as the SNR was reduced, listening effort increased and speech perception performance decreased for listeners with NH and slight/mild hearing loss. No mask, KN95, and surgical masks had the least impact on performance, whereas cloth masks posed a significant detriment to communication. If communication is to occur in a background of noise while wearing masks, a KN95 mask and an SNR of at least +15 dB is recommended regardless of hearing status.

The COVID-19 pandemic brought unprecedented changes to everyday life, including the creation of nationwide facemask recommendations and mandates. Universal mask-wearing mandates were implemented to slow down and prevent the widespread transmission of SARS-CoV-2, the novel coronavirus commonly referred to as COVID-19 (Brooks et al., 2020). During the pandemic, facemasks became an essential addition to personal protective equipment (PPE) for health care workers and the general population. Facemasks can be generally categorized as respirators (N95), medical masks (surgical masks [SMs]), and woven cloth masks (Nguyen et al., 2021). Facemasks are designed to protect against droplet-spread infectious diseases, such as COVID-19 (Gralton & McLaws, 2010). However, some masks are less effective at providing adequate protection from disease than others. Medical masks, such as N95 and KN95, provide the best protection, whereas cloth masks have been shown to be less effective (Chughtai et al., 2020).

Properly fit facemasks cover a significant portion of a person's face, including the lips and mouth, which can negatively impact social interaction and introduce difficulties in understanding spoken language. Carbon (2020) examined the effects of facemasks on one's ability to recognize facial expressions and found the presence of facemasks significantly affected one's ability to correctly

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identify facial expressions. Giovanelli et al. (2021) examined the effects of facemasks on listening in noise when visual cues (such as covering the speaker's lips with a facemask and presenting an audio track through a video call with a black screen) were reduced. They also found that limiting access to visual information with facemasks led to poorer speech perception performance, lower listening confidence, and increased listening effort (Giovanelli et al., 2021). Participants reported having to concentrate less when listening to and watching a speaker wearing a transparent mask. Maintaining audiovisual cues with transparent facemasks facilitates the ability to decipher and comprehend speech in the presence of noise (Giovanelli et al., 2021; Thibodeau et al., 2021; Yi et al., 2021).

Unfortunately, many facemasks do not allow for visual cues, and several studies have investigated the acoustic effects of facemasks on speech signals (Atcherson et al., 2017; Corey et al., 2020; Cox et al., 2022; Magee et al., 2020; Maryn et al., 2021; Mendel et al., 2008; Nguyen et al., 2021, 2022). These studies found that various types of masks decrease the intensity of the vocal signal by 2–12 dB depending on mask type. Nguyen et al. (2021) found that speech produced through surgical or KN95 masks was associated with decreased fricative amplitude and poorer speech clarity. Corey et al. (2020) examined the acoustic effects of different types of facemasks including medical-grade SMs, KN95 and N95 respirators, six different cloth masks of varying thickness, and transparent masks. They found most masks attenuated higher frequency signals but had little effect on frequencies below 1 kHz. Magee et al. (2020) found similar results, showing a detrimental effect of spectral information for the N95 respirator above 3 kHz and for the surgical and cloth masks above 5 kHz. Additionally, Nguyen et al. (2021) found a decrease in the spectral levels of connected speech between 1 and 8 kHz for both surgical and KN95 masks.

These results are consistent with a previous study by Goldin et al. (2020), who found that masks act as low-pass filters that attenuate high-frequency signals, specifically those between 2 and 7 kHz by 3–12 dB. This attenuation pattern has been compared to a "pseudo hearing impairment," as it mimics the effects of a slight high-frequency hearing loss. As such, it has been suggested that using hearing-assistive technologies or low-gain hearing aids may help those with normal hearing (NH) and slight hearing loss (SHL) overcome the negative acoustic effects of facemasks (Rahne et al., 2021).

Much of the primary literature examining the effects of facemasks on acoustic information and speech perception focused on speech understanding abilities using stimuli presented in quiet or with fixed background noise. Brown et al. (2021) highlighted the inconsistencies in the present literature, specifically noting several studies that only used a single type of facemask, a single signal-to-noise ratio (SNR), or only presented speech in quiet. Recently, however, a few studies have investigated the effects of speech perception with facemasks using noise with varying background levels, which could provide a better indication of an individual's real-world speech understanding abilities (Bandaru et al., 2020; Rahne et al., 2021; Toscano & Toscano, 2021). Rahne et al. (2021) examined the effects of surgical and N95 masks on speech perception and listening effort in noise. Measuring speech recognition threshold (SRT) with varying background noise levels, they found that speech perception abilities were significantly reduced because individuals with NH had a higher SRT in both mask conditions. However, there was not a noticeable effect of mask type on listening effort. Bandaru et al. (2020) examined the effect of speech perception on health care workers and observed an increase in SRT ranging from 5 to 40 dB without PPE and from 15 to 50 dB with the addition of an N95 mask and face shield, resulting in an average increase in SRT of 12.4 dB.

Despite the increase in the number of studies examining the impact of varying levels of background noise on speech understanding with facemasks, there remains a paucity of research regarding listening effort associated with facemask use. Listening effort refers to the amount of mental exertion required to attend to and understand an auditory message (Picou et al., 2019). Speech understanding is a complex task that requires sufficient peripheral hearing sensitivity and higher level auditory and cognitive functions, such as auditory attention and working memory (Davis, 1964; Johnson et al., 2015; Marslen-Wilson, 1987). Listening effort emerged as the primary behavioral correlate representing the mental exertion used to aid speech understanding in difficult listening conditions (McGarrigle et al., 2014). Measuring listening effort provides added information regarding the specific difficulty of understanding the acoustic signal beyond speech intelligibility scores.

Brown et al. (2021) investigated the degree to which different types of facemasks and noise levels affected speech understanding in young and older listeners with self-reported NH and found that listening effort increased in noise. Measuring listening effort in this way showed that a clear differentiation between the specific mask conditions existed. Notably, speech perception with the transparent mask was poor, and listening effort was rated the highest for both young and older adults. This inverse relationship suggests that, in the absence of visual cues from the speaker, transparent masks significantly inhibited speech understanding. To overcome this, Brown et al. emphasized the importance of providing visual cues when using a transparent facemask for individuals with hearing loss.

Much of the research that has been conducted looking at the effects of facemasks on speech understanding was performed on individuals with NH and is limited in its generalizability to those with hearing loss. Only a few studies have examined the effects of listening effort and speech perception in background noise for individuals with hearing loss (Homans & Vroegop, 2022; Picou et al., 2011). This research showed that hearing loss itself creates additional cognitive demands and thus impairs speech perception ability and increases listening effort. Homans and Vroegop (2022) measured the effects of SMs and face shields on speech perception for individuals with moderate-to-severe hearing loss, cochlear implant users, and hearing aid users. They found that as hearing loss worsened, there was a greater consequence on speech understanding. Furthermore, speech perception was better in the face shield condition compared to the SM condition, likely due to the addition of visual facial cues from the speaker. These results contrast with that of Vos et al. (2021), who found speech perception was worse in the face shield condition compared to the SM condition. Brown et al. (2021) and Yi et al. (2021) highlight the importance of allowing access to visual cues for individuals with hearing loss whenever possible while speaking with a facemask.

The aim of this study was to build upon current literature by investigating the relationship between speech perception and listening effort under different SNRs and eight different mask conditions for listeners with NH and hearing loss. The goal was to address the disparities in previous studies, such as use of a single facemask, fixed SNR, and the absence of listening effort scores, by manipulating both mask type and background noise levels as well as examining listening effort to obtain a more complete picture of the effects of facemasks on speech perception. Speech-in-noise ability was quantified by measuring SNR loss, which is the decibel increase in SNR required by an individual with hearing loss to understand speech in noise compared to someone with NH ability (Killion et al., 2004). It was hypothesized that as listening conditions worsened, either through poor SNRs or due to the degraded acoustic effects of the facemasks, speech perception performance would be reduced, and listening effort would be greater, resulting in the need for a better SNR for certain masked conditions. In addition, those with NH were expected to function as if they had hearing loss, and performance for those with hearing loss was expected to be worse than those with NH.

Method

Participants

A total of 40 adults with NH and hearing loss participated in this study. The participants with NH (10 women, eight men; M_{age} = 37 years) had a pure-tone average (PTA) better than or equal to 15 dB and audiometric thresholds better than 20 dB HL at 500, 1000, 2000, and 4000 Hz in both ears (n = 18). The adults with hearing loss (n = 22) were divided into two groups based on their PTAs: The SHL group (five women, six men; M_{age} = 52 years) had PTAs between 16 and 25 dB in both ears (n = 11), whereas the mild hearing loss (MHL) group (six women, five men; M_{age} = 48 years) had PTAs greater than 25 dB in at least one ear (n = 11). All participants were native English speakers, had normal middle ear functioning as evidenced by a Type A tympanogram in both ears, and normal cognitive function based on the Mini-Mental State Examination (MMSE; Folstein et al., 1975). All participants were reportedly physically and mentally healthy.

Stimuli

The Quick Speech-in-Noise Test (QuickSIN; Killion et al., 2004) was used in this study because its sentences have limited contextual cues, making them not easily predictable by the listener. The QuickSIN consists of Institute of Electrical and Electronics Engineers (1969) sentences presented in four-talker babble. QuickSIN lists are composed of six sentences, with each sentence containing five key words that must be accurately repeated by the listener. Sentence presentation level is fixed as the four-talker babble gradually decreases in 5-dB steps from an SNR of +25–0 dB. The formula for calculating SNR loss is derived from measuring SNR-50, which is the SNR required for the individual to repeat 50% of the words correctly. Each key word is worth 1 point; after completing six sentences in a list, SNR loss is computed by adding all the correct words that were repeated and subtracting them from 25.5 (Etymotic Research, 2001).

All sentences were spoken by a native English–speaking female, aged 25 years, wearing different facemasks. The speaker had a general American dialect, no diagnosed voice disorders, and no speech production errors. She was instructed to speak naturally at a typical rate keeping inflection at a natural level. Eight different facemask conditions were used: (a) SM, (b) KN95, (c) N95, (d) cloth mask with two layers (CM2), (e) cloth mask with three layers (CM3), (f) transparent mask with a small visual opening (TM1), (g) transparent mask with a large visual opening (TM2), and (h) face shield + cloth mask with three layers (SHCM3). Two equivalent lists of six sentences each were recorded for each mask condition and a baseline condition with no mask (NM). All sentences were recorded using a Blue Yeti USB microphone using Adobe Audition (Version 13.0) software. The recorded sentences were digitized to a 16-bit resolution and sampled at 44,100 Hz. All recordings took place in a quiet room with an ambient noise level of approximately

42 dBA. The microphone setting was set to a cardioid polar pattern and calibrated in dB SPL. The frequency response of the microphone was characterized by a low-frequency roll-off at 120 Hz, a relatively uniform response between 120 and 2 kHz, and a treble increase between 3 and 6 kHz.

The female speaker wore the masks according to the World Health Organization (2020) guidelines, with the recording microphone placed 16 in. away from her mouth for all conditions. The face shield in the SHCM3 condition was positioned 2 in. away from the mask. Appendix A includes photographs of the female speaker wearing the masks in the different conditions. Appendix B provides specific details about the masks used in this study.

This study also measured listening effort in the different facemask conditions using a modified listening effort rating scale (Johnson et al., 2015) as shown in Table 1. Listeners were asked to rate how effortful the listening task was on a 7-point scale. Effort was rated from 1, where no extra effort was involved in hearing the sentence, to 7, where listening effort was perceived to be maximal. This method of measuring listening effort has been shown to be efficient and has good face validity (Johnson et al., 2015; McGarrigle et al., 2014).

Procedure

Participants were instructed to sign an informed consent and a COVID-19 contact tracing form in accordance with the University of Memphis Institutional Review Board guidelines. After signing the paperwork, all participants completed an audiological evaluation that included otoscopic examination, tympanometry (Maico- MI34), air-conduction thresholds (GSI-61), and a cognitive screening using the MMSE. The MMSE is a very simple and quick cognitive screening tool that screens for mild cognitive impairment. It consists of seven different domains, including registration (repeating named prompts), attention, calculation, recall, language, ability to follow simple commands, and orientation (Folstein et al., 1975).

All participants sat 6 ft away from the loudspeaker in an air-conditioned sound-treated double-walled room meeting ANSI S3.1-1999 (R2008) specifications (American National Standards Institute, 2008). The speech and noise stimuli were presented through a loudspeaker placed at 0^{o} azimuth from the participants. The stimuli were presented auditory only; no visual cues were available. The test materials were presented using compact disks (CDs) through a SONY, RCD-W500C CD player, which was routed through an audiometer (GSI 61) to the loudspeaker in the sound booth. The facemask conditions were randomly presented, and two lists of six sentences each were presented per condition. No participant heard the same sentence more than once to minimize any learning and practice effects. The presentation level of the speech was kept constant at 50 dB HL, whereas the level of the noise varied from +25 to 0 dB SNR in 5-dB steps. After each sentence, participants were instructed to repeat what they heard, and guessing was allowed. After each sentence was presented, participants were asked to rate the effort they used to hear the sentence using the modified effort rating scale (see Table 1). Presentation of the stimulus was stopped after each sentence to allow participants time to repeat what they heard and rate their listening effort.

Table 1. Modified listening effort scale used in this study.

Rating	Effort
1	No effort
2	Very little effort
3	Little effort
4	Moderate effort
5	Considerable effort
6	Much effort
7	Extreme effort

Spectral Analysis

In addition to speech perception performance and listening effort, the study also investigated the spectral attributes of the speech materials presented through each mask condition. Praat software was used to extract acoustical energy at each frequency for each condition (Boersma, 2011). All signals had the same sampling rate and duration, and 1,048,577 positive frequency bins were retrieved from each mask condition. The positive bins were imported into R, and the spectra were created using custom-written code.

Data Analysis

SNR loss was calculated using the formula 25.5 − total words correct (Etymotic Research, 2001). To ensure accuracy in scoring the QuickSIN, the talk-back responses from the participants were recorded using a Marantz Professional HD/CD Digital Recorder (PMD660) and rescored by the experimenters off-line. One of the researchers who collected the data performed interjudge scoring reliability on data that were collected by a different researcher. Interjudge scoring reliability was conducted on 30% of the data, using the following formula: [agreements / (agreements + disagreements)] × 100%, and interjudge scoring reliability was 98%. Scoring was conducted in a quiet listening environment with levels set to a comfortable listening level in a sound field utilizing laptop speakers.

Because the data were not normally distributed, nonparametric statistics were conducted. The average SNR loss scores were then subjected to two separate

Kruskal–Wallis one-way analyses of variance (ANOVAs) on ranks to determine if there were significant differences among the groups and the mask conditions. In addition, three separate Kruskal–Wallis one-way ANOVAs on ranks were conducted for the listening effort scores to determine if significant differences were found among the groups, mask conditions, and SNRs.

Results

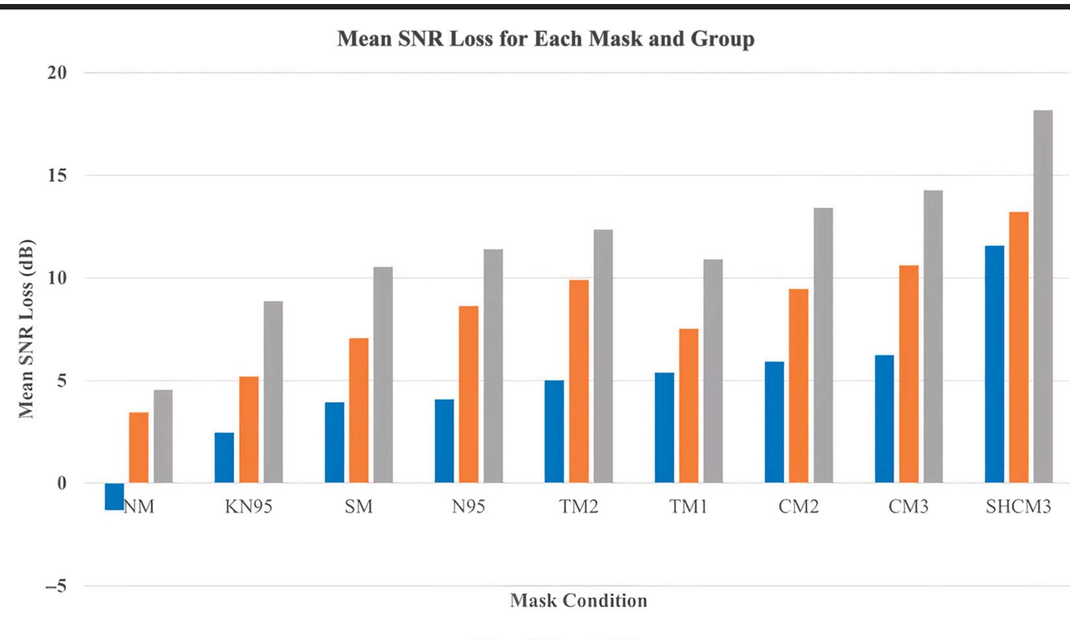
Speech Perception

The mean SNR loss was 5.05 dB for the NH group and 8.09 and 11.60 dB for the SHL and MHL groups, respectively. The Kruskal–Wallis revealed a statistically significant difference between the groups, $H(2) = 62.91$, $p < .001$. Post hoc all pairwise multiple comparisons using Dunn's method revealed that the NH group was significantly different from both hearing loss groups ($p < .001$) and that the SHL and MHL groups were significantly different from each other ($p = .004$), indicating greater SNR loss for the participants with more hearing loss.

Figure 1 shows the mean SNR loss for the three groups of participants across mask conditions. A statistically significant difference was found across the mask conditions, $H(8) = 129.05$, $p < .001$, with post hoc Dunn's comparisons revealing less SNR loss for the NH group (blue bars) followed by the SHL (orange) and MHL (gray) groups, respectively, for all mask conditions. Speech perception performance was best in the NM, KN95, and SM conditions and poorest in the CM3 and SHCM3 conditions for all groups ($p < .05$). Figure 1 shows best to worst performance with all three groups combined in the following conditions: NM, KN95, SM, N95, TM2, TM1, CM2, CM3, and SHCM3. Within the NH and SHL groups, the order of performance followed this pattern except that TM1 was better than TM2 for those with SHL. The order of performance for the MHL group was different with best to worst performance in the following order: NM, KN95, SM, TM1, N95, TM2, CM3, CM2, and SHCM3.

Within each group, performance in the different mask conditions varied. For all groups, performance in the SHCM3 mask condition was significantly poorer than the NM and KN95 conditions ($p < .001$), and for the NH group, performance in the SHCM3 mask condition was significantly poorer than all other mask conditions except the CM3 condition, $H(8) = 106.71$, $p < .001$. However, for the SHL and MHL groups, performance was not significantly different across most of the mask conditions. For the SHL group, significant differences were only seen between the NM condition and TM2, CM3, and SHCM3, respectively, and between the KN95 and SHCM3 conditions, $H(8) = 37.99$, $p < .001$. The only significant

Figure 1. Mean signal-to-noise ratio (SNR) loss for each group (normal hearing [NH], slight hearing loss [SHL], and mild hearing loss [MHL]) for each mask condition. Performance in the NM, KN95, and SM conditions was significantly better than in the CM3 and SHCM3 conditions for all groups ($p < .05$). NM = no mask; SM = surgical mask; TM2 = transparent mask with a large visual opening; TM1 = transparent mask with a small visual opening; CM2 = cloth mask with two layers; CM3 = cloth mask with three layers; SHCM3 = face shield + cloth mask with three layers.



differences found for the MHL group were between SHCM3 and KN95 and between SHCM3 and NM, $H(8) = 25.03$, $p < .001$.

Listening Effort

Three separate Kruskal–Wallis one-way ANOVAs on ranks were conducted to determine significant differences for listening effort across groups, mask conditions, and SNRs.

Effect of Group

For group, a statistically significant difference was found between the groups, $H(2) = 97.52$, $p < .001$. Post hoc all pairwise multiple comparisons using Dunn's method revealed effort scores for the NH group were significantly different from both hearing loss groups ($p < .001$), and the SHL and MHL groups were significantly different from each other ($p < .001$).

Effect of Mask

Table 2 shows the mean listening effort scores per group across mask condition showing that lower scores indicated less listening effort was exhibited in the easier mask conditions whereas higher scores reflected considerable listening effort in the more difficult mask conditions. Table 2 ranks the mask conditions from least to most effort based on listening effort, showing the same order of mask conditions for the NH and MHL groups. The order differed marginally for the SHL group.

With all groups combined, statistically significant differences were found between mask conditions, $H(8) = 167.18$, $p < .001$. Post hoc Dunn's comparisons revealed effort scores were significantly different for all groups between the SHCM3 condition and all other conditions except CM3, whereas CM3 was significantly different from all other conditions except TM2 and CM2. Listening effort was found to be significantly different between all mask conditions and the NM condition ($p < .001$). Within the NH group, significant differences in listening effort, $H(8) = 77.74$, $p < .001$, were found between SHCM3 and all other mask conditions except CM3, between CM3 and KN95 and NM, and between CM2 and NM. No other significant differences were found. For the hearing loss groups, significant differences were also found between masks: SHL, $H(8) = 44.37$, $p < .001$; MHL, $H(8) = 59.76$, $p < .001$. For the SHL group, significant differences were found between SHCM3 and NM, KN95, SM, and TM1 and between NM and CM3, CM2, and TM2. Similar findings were seen for the MHL group, with the exception of an additional difference between SHCM3 and TM2.

Table 2. Mean listening effort scores per group and mask condition.

Mask condition	NH	SHL	MHL
NM	2.77	3.45	3.78
KN95	3.33	3.89	4.60
SM	3.64	4.10	4.74
N95	3.67	***4.47***	4.80
TM1	3.75	***4.13***	4.83
TM2	3.77	***4.69***	4.87
CM2	3.93	***4.61***	5.25
CM3	4.56	4.80	5.57
SHCM3	5.12	5.63	6.08

Note. A rating of 1 indicated no listening effort, and a rating of 7 suggested extreme listening effort. Groups: normal hearing (NH), slight hearing loss (SHL), and mild hearing loss (MHL). Listening effort ratings are listed from least to most effort and are in the same order for each mask condition for the NH and MHL groups. The ratings highlighted in italics and bold in the SHL column show where the order differs for that group compared to the others. Mask conditions: no mask (NM), KN95, surgical mask (SM), N95, transparent mask with one layer (TM1), transparent mask with two layers (TM2), cloth mask with two layers (CM2), cloth mask with three layers (CM3), face shield + cloth mask with three layers (SHCM3).

Effect of SNR

Table 3 shows the mean listening effort scores per group as a function of SNR, revealing less listening effort was exhibited at the more favorable SNRs whereas greater effort was seen at the poorer SNRs. Listening effort for all groups was the greatest for the 0 dB SNR condition (6.80, 6.85, and 6.90 out of 7) for the NH, SHL, and MHL groups, respectively. With all groups combined, $H(5) = 1365.62$, $p < .001$, and within the NH group, $H(5) = 697.29$, $p < .001$, statistically significant differences in listening effort were found between all SNRs except +20/+15 dB SNR and +20/+25 dB SNR. For the SHL group, the only comparisons where no significant difference was found were between +15/+20, +15/+25, +20/+25 dB SNR, $H(5) = 327.15$, $p < .001$, and for the MHL group, the only comparisons where no significant difference was found were between +15/+20 and +20/+25 dB SNR, $H(5) = 3.96.26$, $p < .001$.

Figure 2 depicts the listening effort scores for each of the three groups for each mask condition at each SNR.

Table 3. Mean listening effort scores with all masks combined per group as a function of signal-to-noise ratio (SNR).

SNR	NH	SHL	MHL
+25	1.59	2.30	3.31
+20	2.06	2.74	3.75
+15	2.56	3.24	4.05
+10	4.30	5.11	4.40
+5	5.73	6.28	6.27
0	6.80	6.85	6.90

Note. A rating of 1 indicated no listening effort, and a rating of 7 suggested extreme listening effort. Groups: normal hearing (NH), slight hearing loss (SHL), and mild hearing loss (MHL).

Figure 2. Mean listening effort scores for the mask conditions (no mask [NM], KN95, surgical mask [SM], N95, transparent mask with one layer [TM1], transparent mask with two layers [TM2], cloth mask with two layers [CM2], cloth mask with three layers [CM3], face shield + cloth mask with three layers [SHCM3]) as a function of signal-to-noise ratio (SNR) for the three groups. (a) Results for the normal hearing (NH) group. (b) Results for the slight hearing loss (SHL) group. (c) Results for the mild hearing loss (MHL) group.

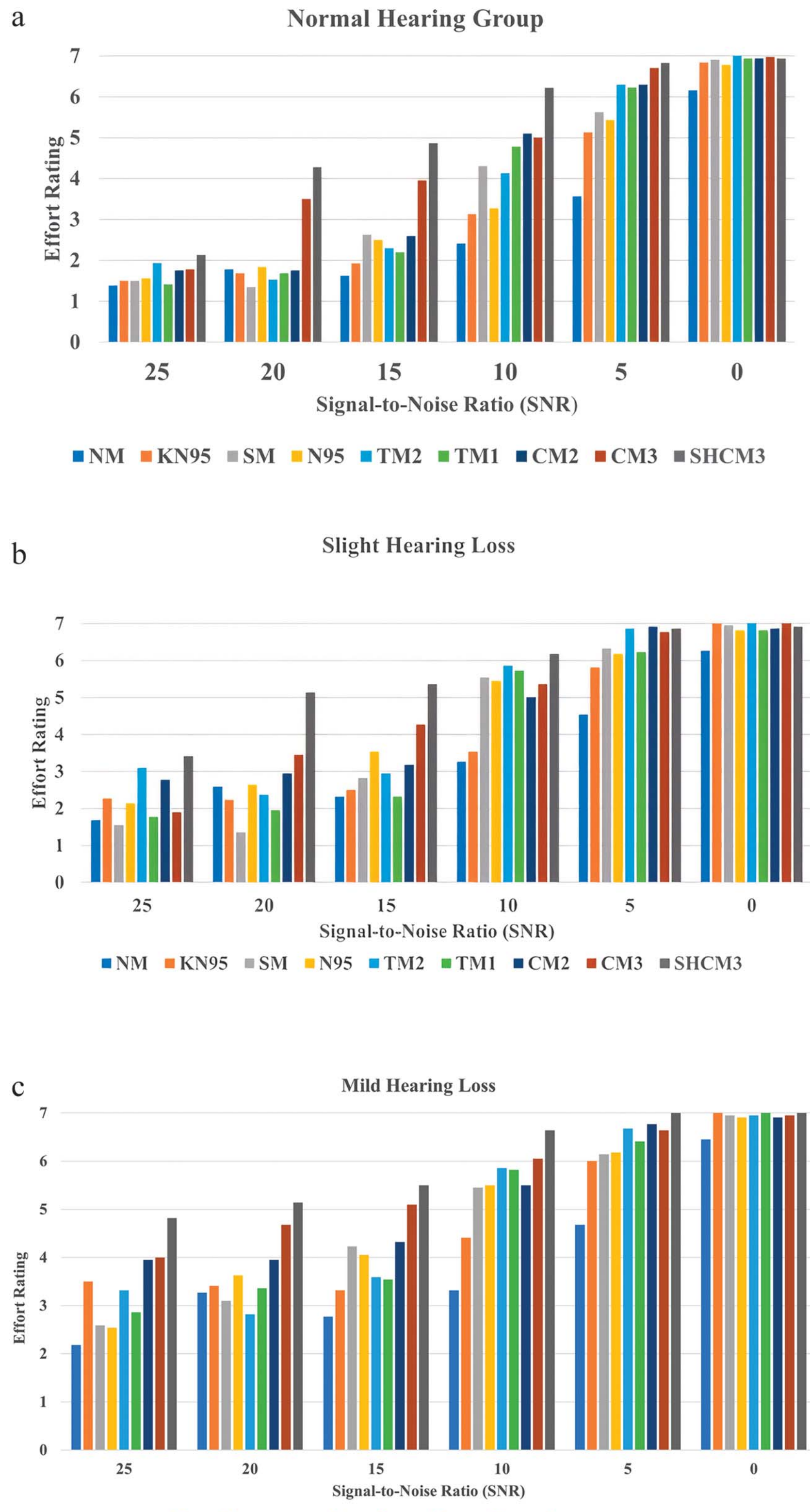


Table 4. Spearman rank-order correlations between the mean number of words correct obtained per sentence and the mean listening effort rating at each signal-to-noise ratio (SNR) collapsed across mask conditions for each group.

	NH		SHL		MHL	
SNR	**Correlation**	***p***	**Correlation**	***p***	**Correlation**	***p***
+25 dB	−.15	.68	−.70	.03	−.82	< .001
+20 dB	−.90	< .001	−.94	< .001	−.88	< .001
+15 dB	−.86	< .001	−.99	< .001	−.95	< .001
+10 dB	−.82	.004	−.88	< .001	−.95	< .001
+5 dB	−.99	< .001	−.095	< .001	−.98	< .001
0 dB	−.81	< .004	−.47	.19	−.51	.14

Note. All correlations were statistically significant at $p < .05$ except at +25 dB for the NH group and 0 dB for the SHL and MHL groups. Groups: normal hearing (NH), slight hearing loss (SHL), and mild hearing loss (MHL).

Overall, as SNR got worse, listening effort scores increased. The 0 dB SNR condition was clearly the most difficult for all groups in all mask conditions even if NM was used because listening effort scores approached ceiling (rating of 7) at this SNR. Similarly, high effort scores were seen at +5 dB SNR, with slightly lower scores for the NM condition compared to the others. For the NH group (see Figure 2a), effort ratings at +25, +20, and +15 dB SNR were very low for all mask conditions except at +20 and +15 dB SNR for the CM3 and SHCM3 mask conditions, which showed higher levels of effort just at those SNRs. A similar trend was seen for the SHL (see Figure 2b) and MHL (see Figure 2c) groups, but the amount of effort was higher overall for both hearing loss groups at these SNRs. Effort scores not at the extreme SNRs (e.g., +10 dB SNR) showed the most variability across groups. However, for the SHL and MHL groups, even that SNR showed difficulty regardless of mask condition.

Speech Perception and Listening Effort

Spearman rank-order correlations were calculated between the mean number of words correct and the mean listening effort rating obtained per sentence at each SNR for each participant in all three groups across mask conditions. Table 4 shows significant negative correlations ($p < .05$) except at +25 dB for the NH group and at 0 dB for the SHL and MHL groups. As listening effort scores decreased, speech perception scores increased. Table 5 shows similar correlations between speech perception scores and listening effort, but this time as a function of mask condition for all three groups with SNRs collapsed. Significant negative correlations ($p < .05$) were observed for all groups and all mask conditions except for SHCM3 for the NH and MHL groups and the NM condition for the NH group. These findings indicate a common and expected trend showing that better speech perception scores were negatively correlated with low effort.

Table 5. Spearman rank-order correlations between the mean number of words correct obtained per sentence and the mean listening effort rating for each mask condition (no mask [NM], KN95, surgical mask [SM], N95, transparent mask with one layer [TM1], transparent mask with two layers [TM2], cloth mask with two layers [CM2], cloth mask with three layers [CM3], face shield + cloth mask with three layers [SHCM3]) collapsed across signal-to-noise ratio for each group.

	NH group		SHL group		MHL group	
Mask	**Correlation**	***p***	**Correlation**	***p***	**Correlation**	***p***
NM	−.43	.41	−.94	.01	−.88	< .03
KN95	−.83	.05	−.77	.10	−.83	< .05
SM	−1.00	< .003	−1.00	< .003	−1.00	< .002
N95	−.93	.02	−.94	.02	−1.00	< .002
TM2	−.90	.02	−1.00	< .003	−.94	< .01
TM1	−.94	.02	−1.00	< .002	−.83	< .06
CM2	−.99	< .002	−.89	.03	−1.00	< .002
CM3	−1.00	< .002	−.94	.02	−.94	< .02
SHCM3	−.94	.01	−.94	< .02	−.75	1.0

Note. All correlations were statistically significant at $p < .05$ except for SHCM3 for the NH and MHL groups and NM for the NH group. Groups: normal hearing (NH), slight hearing loss (SHL), and mild hearing loss (MHL).

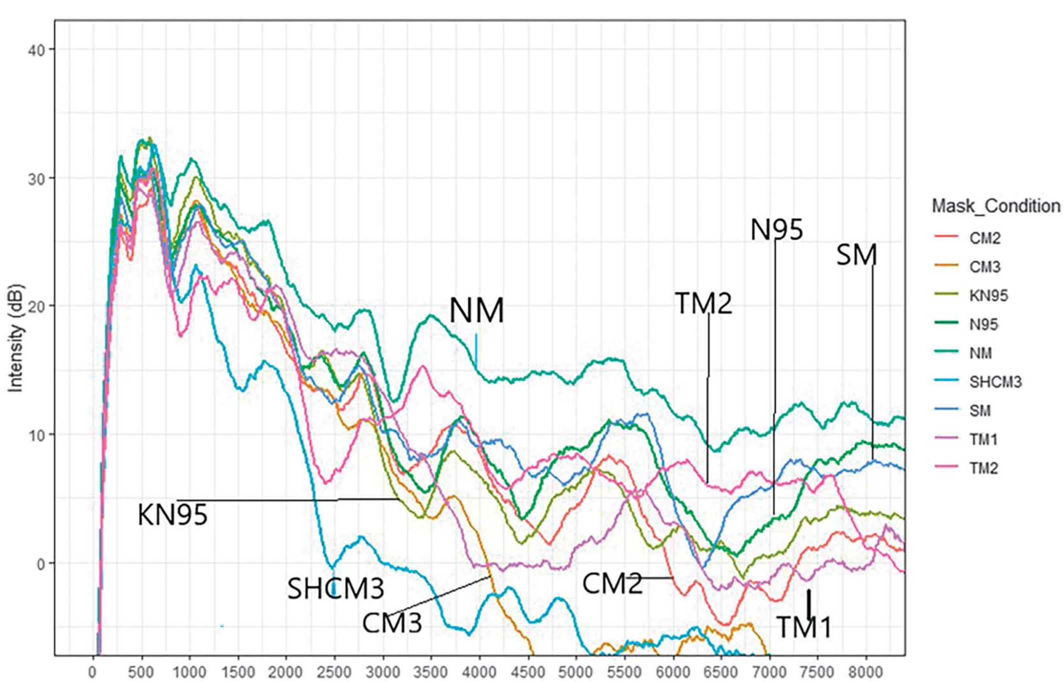
Discussion

This study investigated listening effort and speech perception performance in noise in listeners with NH and hearing loss using eight different masks, including a baseline NM condition. Speech-in-noise ability was quantified by measuring SNR loss, which is the increase in SNR required by a listener to obtain 50% correct performance compared to a listener with NH. A typical SNR loss value for listeners with NH is 2 dB, meaning the listener achieves 50% correct when the signal is 2 dB above the noise. Listeners with hearing loss typically have SNR losses higher than 2 dB (Killion et al., 2004).

When mask conditions were collapsed, listeners with NH experienced a measurable SNR loss averaging about 5 dB, which is higher than would be expected for this population. Even though speech perception performance was better for the NH group compared to the SHL and MHL groups, their SNR loss suggested that despite having hearing within a normal limit, the use of a mask without visual cues while listening to speech in noise resulted in those listeners functioning as if they had a hearing loss. This finding is most likely due to two factors: (a) the degraded acoustic information measured through the mask conditions as evidenced by the acoustic transformation presented in Figure 3 and (b) the lack of visual cues available to assist in performing closure when acoustic information is missing. An SNR loss of 5 dB is a mild SNR loss (Etymotic Research, 2001). This finding is in agreement with that of Rahne et al. (2021), who suggested that listeners with typical hearing can exhibit a pseudo hearing loss under these degraded conditions. Furthermore, the participants in the SHL and MHL groups demonstrated SNR losses of 8 and 11 dB, respectively, suggesting a moderate SNR loss for those groups (Etymotic Research, 2001). These findings reinforce the fact that when a mask is used, speech perception performance in noise can be greatly hindered regardless of the type of mask.

No SNR loss was measured in the NM condition for the NH group, and best performance for all groups was found when NM was present and when the KN95 or SM was used. It was expected that performance would be best in the NM condition given that there is neither obstruction of the signal nor any possible interference between the articulators and the mask that could negatively affect speech production and subsequently speech perception. The reduced thickness of the SM compared to the other masks is likely the reason that the SM condition did not have a significant negative effect on speech perception performance. Appendix B shows that the three thinnest masks were the SM, TM1, and TM2 masks, yet we did not see adequate speech perception performance

Figure 3. Frequency spectrum for each mask condition. The *y*-axis represents relative intensity in decibel (dB), and the *x*-axis represents frequency in Hertz (Hz). NM = no mask; SM = surgical mask; TM2 = transparent mask with a large visual opening; TM1 = transparent mask with a small visual opening; CM2 = cloth mask with two layers; CM3 = cloth mask with three layers; SHCM3 = face shield + cloth mask with three layers.



with the TM1 and TM2 conditions compared to the SM. This is likely due to the difference in material (plastic) for the transparent masks compared to the woven fabric in the SM. The greater thickness of the plastic compared to the fabric resulted in a more degraded signal that negatively affected the acoustics as shown in Figure 3, which is also consistent with results reported by several researchers (Corey et al., 2020; Cox et al., 2022; Goldin et al., 2020; Maryn et al., 2021). Even though a clear mask would be beneficial regarding access to visual cues, the results of this study indicated that TM1 and TM2 had a greater negative impact on acoustic cues than some of the other masks that were not transparent, which is consistent with the findings reported by several researchers (Atcherson et al., 2017; Cox et al., 2022; Maryn et al., 2021). Both Maryn et al. (2021) and Cox et al. (2022) found that transparent masks have the most negative impact on the acoustic spectrum of speech. Furthermore, Cox et al. found that lowering the mass of the plastic inserts used in transparent masks not only preserves visual cues but also reduces potential negative attenuation effects.

It is unclear why the KN95 mask had less of a negative impact on speech perception. It is possible the mask's position relative to the face and the articulators could have affected the resonance within the KN95 mask in some way. Future research should investigate such an assumption. In comparison, the thickest masks with the most layers (CM3 and SHCM3) produced the worst speech perception performance and were consistently the most difficult conditions for participants in all groups. Given the findings reported here and evidence from Chughtai et al. (2020), the use of cloth masks is not recommended as they do not provide great protection from air-borne disease and they have the greatest negative impact on speech perception and listening effort.

To further pursue the impact of each mask's physical characteristics on speech perception, the spectral attributes of the speech materials presented through each mask condition were analyzed. The spectral analysis shown in Figure 3 indicated that all the mask conditions had similar spectral energy below approximately 700 Hz, followed by a sharp drop in amplitude. Overall, the NM condition had the most energy across all frequencies, whereas the SHCM3 condition had the least, showing the most rapid decline in amplitude beginning at a much lower frequency (approximately 1000 Hz) than the other mask conditions. These results are in agreement with the findings reported by other researchers (Corey et al., 2020; Cox et al., 2022; Goldin et al., 2020; Maryn et al., 2021) indicating that masks act as low-pass filters reducing the intensity of the signal especially in the high frequencies. Speech perception performance is highly dependent on high-frequency information as audibility of high-frequency consonants is critical to the clarity of speech (Schow & Nerbonne, 2007). As high-frequency energy decreased in the more difficult mask conditions, speech perception performance also decreased. Speech perception performance in this study was best for the NM condition and worst for the SHCM3 conditions for all groups, which is consistent with these findings.

Performance was clearly better for the NH group in all mask conditions compared to the SHL and MHL groups, indicating that even a minimal amount of hearing loss had a definite impact on speech perception and listening effort regardless of type of mask. However, even those with NH functioned as if they had a hearing loss in some mask conditions. Although specific comparisons between masks within groups showed some variability in the pattern of performance, masks such as the CM3 and SHCM3 were undoubtedly detrimental to speech understanding regardless of hearing status.

It was not surprising that less listening effort was exhibited in the easier mask conditions and favorable SNRs, whereas considerably more listening effort was demonstrated in the more difficult mask conditions and poorer SNRs. At 0 dB SNR, no differences were seen across mask conditions, emphasizing that such an unfavorable SNR negatively affected speech perception regardless of mask condition and hearing status. The fact that the 0, +5, and +10 dB SNRs were extremely difficult for all participants regardless of hearing ability or type of mask suggests that in order for speech perception to be understandable in noise while using a mask, the SNR should be at least +15 dB, if not higher. It is recommended that children with hearing loss have at least a +15 dB SNR in the classroom (Larsen & Blair, 2008). The results of this study suggest a similar recommendation for all individuals communicating with a mask in a background of noise, and it should probably be an even better SNR for those with hearing loss.

For those with NH, type of mask did not have an effect at +25 dB, but once the SNR was reduced to +20 dB, the CM3 or SHCM3 mask conditions already had a negative impact on performance. This is a significant finding given that +20 dB is generally considered to be a favorable SNR. Those with SHL and MHL had even greater difficulty at +20 dB, and by the time the SNR reached +15 or lower, effort was very high, and performance was negatively affected. Though the difference in hearing sensitivity was not very large between the two hearing loss groups, the effect of the mask and SNR was apparent.

Conclusions

The impact of different types of facemasks on speech perception in noise was demonstrated in this study, indicating that as the SNR was reduced, listening effort increased and speech perception performance decreased when listeners with NH or SHL/MHL listened to stimuli presented through facemasks. NM, KN95, and SMs had the least impact on performance, whereas cloth masks, especially those with two or three layers and a face shield (CM2, CM3, and SHCM3), posed a significant detriment to communication. Even listeners with NH demonstrated an SNR loss when masks were used. Although the N95 mask is highly recommended for protection from disease, our results suggest that speech perception in noise and listening effort will be impacted with this mask, especially if the listener has a hearing loss.

Because most facemasks impose a barrier that makes speechreading impossible and facial expressions nonexistent, it would be beneficial to communication if a clear mask can be used. Atcherson et al. (2017) found that listeners with NH and hearing loss benefited from using a transparent mask that provided visual input when listening to speech in noise, and the magnitude of improvement in speech perception was greater for those with the most hearing loss. Although a transparent mask may help with visual cues, the results of this study and others (Atcherson et al., 2017; Cox et al., 2022; Maryn et al., 2021) suggested that the acoustic signal through transparent masks was worse than some of the other masks studied. Thus, the use of transparent masks should be considered while weighing the balance between access to visual cues and the reduction of acoustic cues. If a transparent mask with thin plastic inserts can be used, fewer attenuation effects may be present (Cox et al., 2022).

Regardless of which facemask type is used, it is critical that people use specific strategies to enhance communication, especially with those who have even a slight degree of hearing loss. Well-known communication strategies include using natural, clear speech by speaking slowly; using simplified messages; getting the listener's attention; reducing background noise; and so forth. Amplification systems could also be of benefit. In addition, if communication is to occur in a background of noise while wearing masks, an SNR of at least +15 dB is recommended.

Author Contributions

Lisa Lucks Mendel: Conceptualization, Formal analysis, Writing – original draft. **Monique A. Pousson:** Conceptualization, Data curation, Formal analysis, Writing – review & editing. **Bhanu Shukla:** Conceptualization, Data curation, Formal analysis, Writing – original draft. **Kara Sander:** Conceptualization, Data curation, Formal analysis, Writing – original draft. **Brooke Larson:** Data curation, Formal analysis, Writing – review & editing.

Data Availability Statement

Data are available from the authors at https://www.memphis.edu/spal/index.php. The data that support the findings of this study are available from the corresponding author, L.L.M., upon reasonable request.

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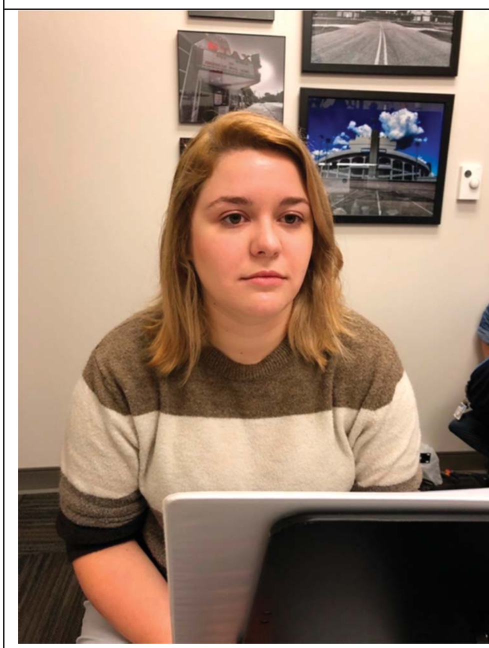
Appendix A (p. 1 of 2)

Mask Conditions

No Mask	Surgical Mask
	
KN95	**N95**
	

Appendix A (p. 2 of 2)

Mask Conditions

CM (2 & 3)	TM1
	
TM2	**SHCM3**
	

Note. Printed with permission.

Appendix B

Facemask Specifications

Part 1. Specific details for each mask including material, shape, number of layers and the presence or absence of a noise piece. Information obtained from product packaging and respective websites.

Mask	Company	Material	Shape	Layers	Nosepiece
SM	Bodyguard Safety Gear	70% nonwoven fabric; 30% melt-blown fabric	Straight rectangle	3	Yes
KN95	Bi-Wei-Kang	Leak proof nonwoven fabric; ethylene propylene side by side; high-density filter layer; direct skin contact layer (melt-blown nonwoven fabric)	Triangular cup	5	Yes
N95	3M	Straps: polyisoprene Staples: steel Nosefoam: polyester Nose clip: aluminum Filter: polypropylene	Oval cup	2	Yes
CM3 (CM2 with filter)	Carbon PM 2.5	Outer layer: 100% cotton Inner layer: 100% rayon Middle layer: filter	Rounded rectangle	3	No
CM2	Wedding Star	Outer layer: 100% cotton Inner layer: 100% rayon	Rounded rectangle	2	Yes
TM1	Clear Mask	Clear plastic; foam	Straight rectangle	1	No
TM2	The Communicator	Clear plastic; cloth	Rounded rectangle	1	Yes
Face shield	N/A	Clear plastic	N/A	1	No
Filter	PM 2.5	Outer layer: 60% nonwoven fiber Inner layer: 40% melt-blown fabric	Rounded rectangle	5	No

Note. SM = surgical mask; CM3 = cloth mask with three layers; CM2 = cloth mask with two layers; TM1 = transparent mask with a small visual opening; TM2 = transparent mask with a large visual opening.

Part 2. Specific details for each mask including length, width, weight, and thickness.

Mask	Length (cm), side to side	Width (cm), top to bottom	Weight (g/oz)	Thickness (mm)
SM	17.6	9.5	3.27 g	0.36
KN95	15.24	11.43	5.62 g	0.81
N95	12.065	12.7	6.97 g	1.05
CM3 (CM2 with filter)	17.145	13.335	12.06 g	1.25
CM2	17.145	13.335	10.16 g	0.48
TM1	19.1	10.9 (from center)	9.68 g	0.23
TM2	19.05	10.795	5.80 g	0.17
Face shield	21.9 (top to bottom center)	24.5 (at widest point)	66.59 g (2.34 oz)	0.70
Filter	12	8	1.91 g	0.77

Note. Information obtained from product packaging and respective websites. SM = surgical mask; CM3 = cloth mask with three layers; CM2 = cloth mask with two layers; TM1 = transparent mask with a small visual opening; TM2 = transparent mask with a large visual opening.