

Impact of Face Masks on Audiovisual Word Recognition in Young Children with Hearing Loss During the Covid-19 Pandemic

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Abstract

Objective: To investigate effects of surgical and transparent face masks on audiovisual speech recognition of words for deaf and hard of hearing children.

Design: Recorded Word Intelligibility by Picture Identification test (WIPI) was presented via a computer monitor to children in a quiet test room. The acoustic power spectra of each mask type was compared to the baseline no mask condition. Percent correct word recognition was recorded for four mask conditions (no mask, surgical mask, transparent apron mask, and ClearMask) in counterbalanced order. Repeated measures ANOVA was used to test for significant differences in word recognition scores across mask types.

Study Sample: Thirteen children (3 to 7 years) in a private auditory oral school wearing hearing aids, bone-anchored hearing aids, or cochlear implants. Children were excluded if English was not their primary language or if they had a severe speech-language delay, uncorrected vision loss, or developmental disorder that would affect the results. No children had been exposed to or had contracted the Covid-19 virus.

Results: Acoustic spectra showed a decrease in the 2000–8000 Hz region for the transparent apron mask. The surgical mask and ClearMask showed fewer acoustic effects. Children with hearing aids performed similarly to children with cochlear implants. Word recognition was significantly poorer for surgical masks and transparent apron masks. The ClearMask condition was not significantly worse than the no mask condition for words in quiet.

Conclusions: Standard surgical and custom apron shield masks significantly hampered word recognition, even in quiet conditions. The commercially available ClearMask did not significantly affect scores in quiet for young deaf and hard of hearing children, but scores were highly variable.

Keywords: Covid-19, speech perception, hearing loss, deafness, face mask

Acronyms: BAHA = bone anchored hearing aids; BKB-SiN = Bamford-Kowal-Bench Speech-in-Noise Test; CI = cochlear implants; DHH = deaf or hard of hearing; HA = hearing aids; WIPI = Word Intelligibility by Picture Identification test

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The Covid-19 pandemic has unleashed a plethora of new and difficult situations to manage; among these are the communication difficulties imposed by mask wearing. For infants and young children who are learning communication skills, mask wearing by their parents, teachers, and peers presents both a visual and an auditory barrier to spoken communication and emotional cues. Children who are deaf or hard of hearing (DHH) are

especially vulnerable, as they have developing auditory and language skills, and are more reliant upon visual information. Speech perception is inherently a multimodal task that integrates visual and auditory information to aid understanding, especially in noisy environments, where visual cues become more important as the signal-to-noise ratio decreases (von Kriegstein, 2012). Adults use visual timing cues to process and recall speech in noisy

environments with greater accuracy than in auditory-only conditions (Lalonde & Holt, 2016). Normal hearing adults process lip movements by first modulating neuronal activity in the visual cortices at frequencies that match articulatory lip movements. Slower features of lip movements are then mapped onto the corresponding speech sound features and delivered to auditory areas, facilitating speech sound mapping. Visual timing thus facilitates auditory comprehension with cues that are specific to speech sounds (Bourguignon et al., 2020).

Noise is well recognized as a barrier to communication for children learning in classrooms and other acoustically challenging environments, but many other factors are important, including development, language proficiency, hearing status, and auditory experience (Leibold, 2017). As a result, children require a better signal-to-noise ratio to understand speech as well as adults do. When processing speech in low signal-to-noise environments, infants benefit from visual cues timed to the onset and offset of auditory speech, but they are not mature in their use of full visual speech cues, compared to adults (Lalonde & Werner, 2019). Preschool children increase their use of visual cues to support speech perception between 3 and 4 years of age, an important developmental shift (Lalonde and Holt, 2015). As young as 4 years of age, children with typical hearing are able to use knowledge of phonetic cues to aid speech perception in noise (Lalonde & Holt, 2015). Older children (6–8 yrs.) and adults demonstrate advantages in auditory speech detection, discrimination, and recognition when visual speech is available, although adults show more benefit for speech recognition, compared to simpler detection and discrimination tasks (Lalonde & Holt, 2016). Children who are DHH also benefit from audiovisual cues. Interestingly, children who are DHH are better than children with normal hearing at extracting phonetic information from audiovisual signals (Lalonde & McCreery, 2020).

Children who are DHH may be more impacted by the loss of visual cues due to the introduction of personal protective equipment such as masks and shields in the school setting. Solid facial coverings, such as cloth and surgical masks that cover the lips and lower part of the face, inhibit listeners from using the visual cues that facilitate greater accuracy in speech recognition, and masks also decrease auditory cues (Atcherson et al., 2017). In quiet, surgical masks do not appear to negatively impact speech understanding for adults with normal hearing or hearing loss, but in noise, there is a deleterious effect (Mendel et al., 2008). Significant negative impacts on speech perception in noise have been demonstrated with speakers wearing surgical masks (Atcherson et al., 2017; Hampton et al., 2020; Thibodeau et al., 2021). The study by Atcherson et al. (2017) included 30 adults, with 10 in each of three groups (normal hearing, moderate hearing loss, and severe-profound hearing loss) and three mask conditions (no mask, standard paper surgical mask, and transparent surgical mask). A connected speech test, the Bamford-Kowal-Bench Speech-in-Noise Test (BKB-SiN) with background speech babble showed that both groups of DHH adults had better scores in the transparent surgical

mask condition, with the greatest improvement among the profound hearing loss group. The study by Thibodeau et al. (2021) evaluated audiovisual recognition of sentences recorded in background noise with custom made 2-layer cloth masks, with a transparent window that was covered to create an opaque condition. Their study showed that performance was higher for the transparent masks, with subjective ratings of confidence and concentration also better for transparent masks. Acoustic recordings of auditory-only presentation suggested that the benefits were not attributable to an acoustic advantage, but rather to the addition of visual cues. In fact, performance in the auditory-only mode was lower with the transparent mask than with an opaque mask, likely due to decreased sound transmission with the plastic window. Bottalico et al. (2020) studied the effects of wearing face masks on classroom communication in college students and found that fabric masks yielded a significantly greater reduction in speech intelligibility in noise compared to surgical or N95 masks, likely due to greater loss of acoustic cues. Therefore, they recommended the use of medical grade masks in teaching environments. Transparent masks were not examined in that study. Other recent studies found that all masks attenuate frequencies above 1000 Hz to 3000 Hz (Corey et al., 2020; Magee et al., 2020) with higher levels of attenuation observed for masks with plastic barriers (Vos et al., 2021). Acoustic attenuation caused by reflection from hard barriers, such as transparent masks, reduces low frequency transmission less than high frequencies, so is especially problematic for individuals with hearing loss, who tend to have poorer audibility and spectral resolution in the high frequencies.

Understanding the impact of mask type on audiovisual perception is important, as the National Association of the Deaf (NAD) and opinion pieces have recommended use of transparent face masks to allow access of visual cues during both spoken and manual communication (Campagne, 2021; NAD, 2020). The clear mask manufactured by ClearMask™ (ClearMask LLC, Baltimore, MD, U.S.A.) was approved by the FDA in August 2020 for use during the COVID-19 pandemic to improve visual cues in the medical environment, but is more expensive than standard surgical masks. An alternative reusable mask that combines a face shield and washable fabric cover to prevent discomfort around the ears and movement problems is the “apron mask”. It is intended to prevent virus transmission that can occur around clear face shields that are worn alone without masks.

We designed this study to determine if young children who are DHH benefit from visual cues provided by transparent masks (ClearMask and transparent apron mask), compared to no masks or standard surgical masks. We hypothesized that all face masks would significantly degrade acoustic quality and word recognition in young listeners, thus a no mask condition would present the highest level of accuracy understanding speech in noise. The ClearMask and a custom transparent apron mask, which provide the added benefit of visual cues, were expected to present a higher percentage of accuracy

than the surgical mask condition. Because young children who are DHH rely more on visual cues than their peers with lesser degrees of hearing impairment, they may demonstrate greater accuracy on the ClearMask and transparent apron mask conditions, and poorer accuracy in the surgical mask condition.

Method

Children aged 3 to 7 years, with varying degrees of hearing loss, who attend school in a private auditory oral program were included in the study. All participants are oral language users of hearing aids (HA), bone anchored hearing aids (BAHA), or cochlear implants (CI). All receive daily intensive speech and language intervention using the Listening and Spoken Language approach. Children were assigned to groups based on the degree of hearing loss in the better ear (*profound* using CI versus *severe or less* using HA or BAHA), detailed in Table 1. Children were excluded if they did not use English as their primary

language, had visual impairment not remedied by corrective lenses, or had severe speech-language or developmental delay that precluded their ability to respond verbally to the word recognition task. All children included in the study had routine speech-language and hearing assessments at the school, and data logging of their amplification devices to ensure regular device use. The study was reviewed and approved by the research committee and executive director at the school, and an approved written consent form was sent to parents, who provided informed consent. The Institutional Review Board at Cincinnati Children's was consulted, and the study was not required to be externally reviewed, as research conducted in accepted educational settings, that involves normal educational practices, including most research on special education instruction strategies are exempt according to 45 CFR 46.104. All data were de-identified using a unique numerical identifier prior to statistical analysis.

Table 1
Demographic and Clinical Data for Children Included in the Study

Group		Age at HA or CI (years)	Age at Enrollment (years)	Age at Test (years)	Aided Avg dB HL (.25-8 kHz)
HA or BAHA	Mean	1.64	2.83	5.16	20.50
	Std Dev	1.15	1.42	1.07	9.27
CI	Mean	1.34	1.43	4.47	27.43
	Std Dev	0.56	0.78	0.78	3.80
Student t-test (2 sample, heteroscedastic)	p-value	0.6473	0.0852	0.2719	0.1697

Note. BAHA = Bone-anchored hearing aid; CI = cochlear implant; HA = Hearing aid; HL = hearing level.

Procedures

The Word Intelligibility by Picture Identification (WIPI) test (Ross & Lerman, 1970) was selected for word recognition testing. Although it has a specified language age between five and eleven years, it has been used routinely at the school with younger children. It is a closed set format and has multiple test lists equalized for difficulty. The WIPI is effective in evaluating ability to identify words on the basis of their spectral characteristics in young children with congenital deafness (Schindler et al., 2003). In this test, the listener hears the phrase "point to," followed by a target word. A set of six pictures is shown, and the listener is asked to identify the picture corresponding to the target word. We adapted and recorded the WIPI test for audiovisual presentation via computer, with pictures displayed on the standard test book. Four 25-item lists, one per mask condition were spoken by a female adult native, Midwestern English speaker (Erin Lipps, educational audiologist). The outcome variable was percent correct recognition of words in quiet for three face mask conditions as shown

in Figure 1, in counterbalanced order with the no mask condition as the control. The apron mask was custom designed by the school, while the other masks were purchased from commercial suppliers.

The WIPI lists were audio-visually recorded on an iPad with an internal camera and an external Blue-Yeti microphone in a double-walled sound booth (Industrial Acoustics Company, Inc. Model 120A). The video recording was focused on the speaker's face showing her entire head and shoulders while wearing the different masks, and the speaker was facing the video camera. A Larson-Davis system 824 sound level meter (Depew, New York) with a Brüel & Kjær half-inch free field microphone (type 4189, Nærum, Denmark) was used to ensure the long-term average level was at 65 dBA ± 2 dB sound pressure level (SPL) for all conditions. The speaker was seated three feet from the microphone and instructed to speak each word with a constant effort across the mask conditions. The words were spoken with a 10 second inter-word interval to provide time for responses.

Figure 1
Masks Used in the Study



In the test setting, the child participant sat at a table in a quiet office, with the educational audiologist as the tester. The word lists and mask conditions were presented in a pre-set, counterbalanced order across the participants, to avoid order effects for both word list and mask condition. The simultaneous audio- and video-recorded word lists were presented via a desktop computer and external monitor in a quiet room in the school setting. The computer speaker volume was set at 85% and the video player volume was set at 100%. Using these settings, the stimuli were measured using a Larson-Davis sound level meter (System 824) with a Brüel & Kjær half inch free field microphone (Type 4189). The equivalent continuous sound level (Leq) was 55 dB SPL, ranging from 51 to 60 dB SPL. Peak SPL was 85 dB, ranging from 63 to 90 dB SPL.

The child was instructed to watch the computer monitor that showed the presenter, with or without a mask, and listen to the word lists spoken by the presenter at face level, at a standard distance of three feet, presented binaurally through the computer speaker. The tester showed the participant the standard WIPI test book of six pictures on each page, and the participant chose the picture that matched the word they heard and scored the response on the corresponding word list. Having one person administering and scoring the assessments minimized the effects of interrater reliability, but the scorer was not blinded to the degree of hearing loss or type of amplification device. The percent of correct words identified for each condition and each group (HA vs. CI) was analyzed for significance using a two-way Repeated Measures Analysis of Variance (RMANOVA; mask

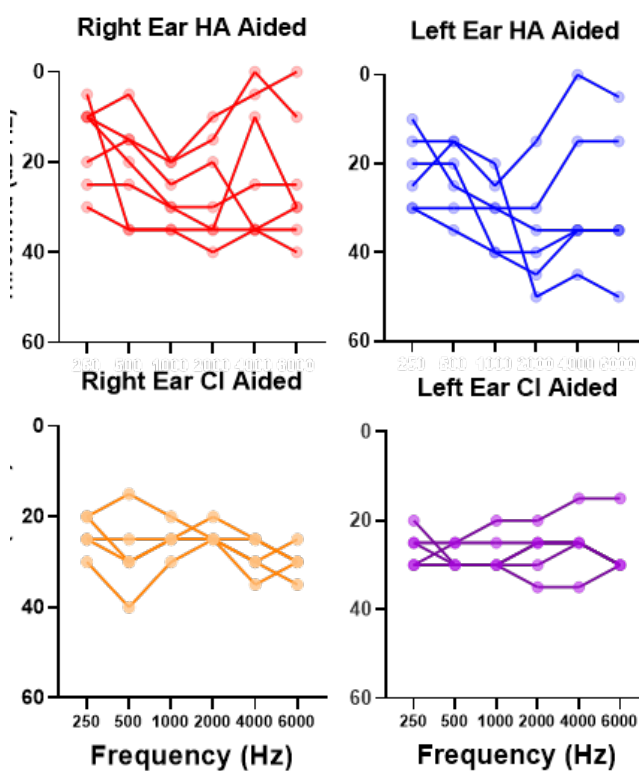
condition as the repeated measure). Post-hoc tests were performed if the RMANOVA was significant for each pair of mask conditions.

Results

Children who enrolled and completed testing ($N = 14$) were divided into two groups based on the degree of hearing loss in the better hearing ear and device type. One child with HAs had highly irregular scores across conditions and appeared to have variable attention. That child was subsequently diagnosed with autism, so was excluded from the final analysis. The remaining sample of 13 children included: (a) Bilateral HA or BAHA group ($n = 6$; 5 males and 1 female; 4.0 to 6.9 years) with normal sloping to profound sensorineural or conductive hearing loss, and (b) Bilateral CI group ($n = 7$, 3 males and 4 females; 3.3 to 5.7 years). Children were tested using their devices set to their typical settings. Table 1 provides comparisons for clinical data for both groups. The sample was 79% Caucasian, 14% African American, and 7% Asian. Most of the etiologies were congenital cytomegalovirus (CMV, 38%) or unknown (38%); of the others, 15% had craniofacial anomalies, and 8% had Usher syndrome.

Real ear validation was completed on every child with a hearing aid. Additionally, every child received LING 6 checks twice daily to ensure they had access to the full speech spectrum. Individual aided audiograms are shown in Figure 2 for the left and right ears, and for HA and CI users separately. One child with a BAHA is not included in the aided audiogram figure since the mode

Figure 2
Individual Aided Audiograms for Right and Left ears, for Hearing Aid (HA) and Cochlear Implant (CI) Users

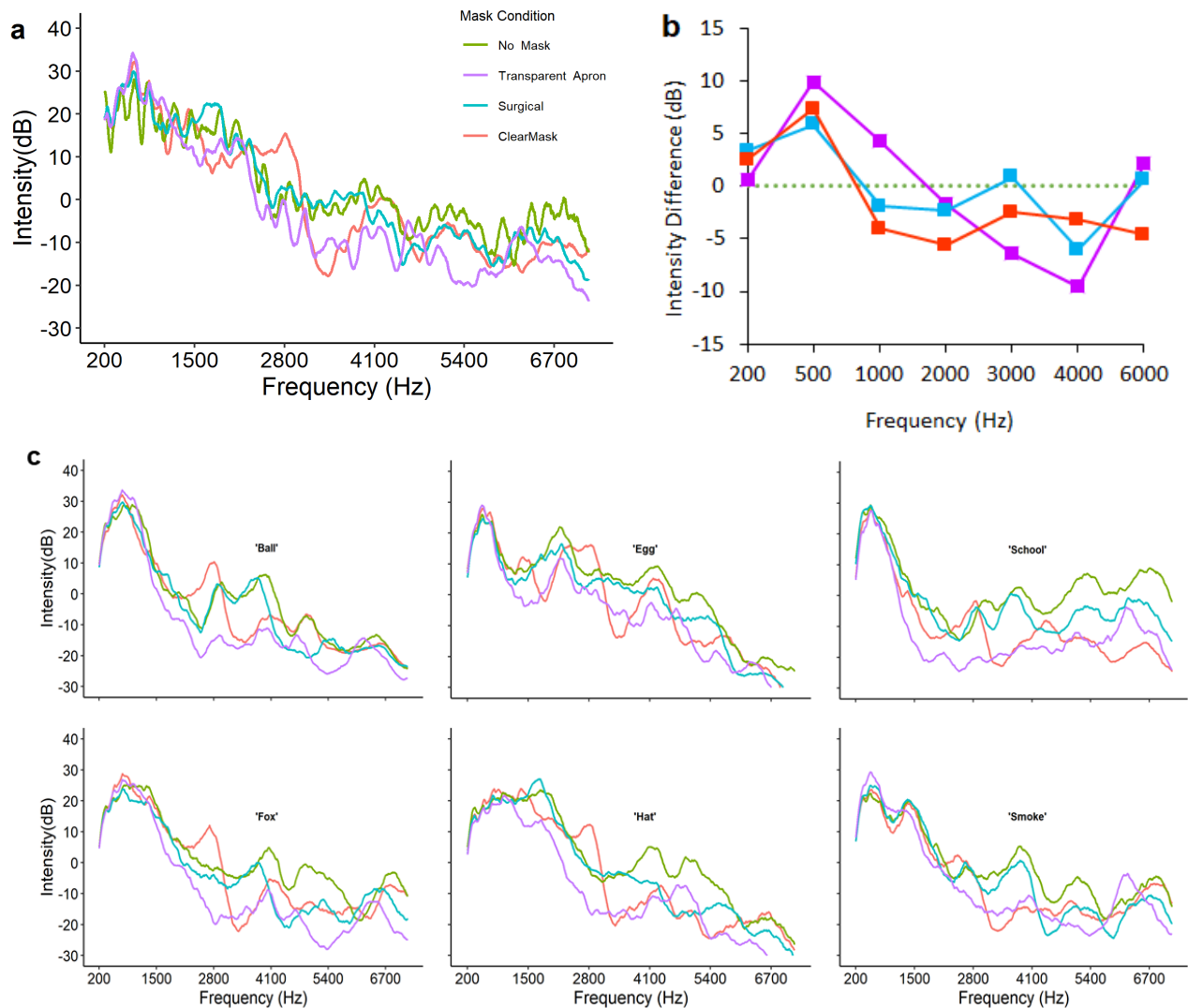


was vibrotactile, and therefore the ear stimulated is unknown. These figures illustrate variability in access to sound, especially for children wearing HAs in the high frequencies. Average aided thresholds for children wearing HAs fell into the 8 to 35 dB HL (hearing level) range, while aided thresholds for children wearing CIs fell in the 21 to 35 dB HL range.

The first 10 words from the WIPI word list were recorded and analyzed for spectral content across the four mask conditions, spoken by the same speaker. Figure 3a shows the spectrograms for the 10 words averaged across each mask condition. The average spectrograms showed that, compared to the no mask condition, the surgical mask had the smallest reduction in high frequencies (> 2 kHz). The ClearMask had a resonant enhancement at 2800 Hz, but slightly less energy overall in the higher frequency range, especially between 3000–4000 Hz. The apron mask had

the largest overall attenuation, especially from 2000 to 8000 Hz. The average difference in band energy between the no mask condition (baseline) compared to the face mask conditions across the 10 words is shown in Figure 3b. All three mask conditions showed an enhanced level of 6–10 dB, relative to no mask, at 500 Hz (Figure 3b), but variable decreases at higher frequencies. Overall, the surgical mask had the least effect, the ClearMask was attenuated uniformly at 1000 Hz and above, and the Apron mask had the largest enhancement at 500–1000 Hz, and the largest decrease above 2000 Hz. Figure 3c shows the spectrograms for six words selected across the range of lower and higher frequency initial consonants, and for different vowels (ball, egg, school, fox, hat, and smoke). These spectrograms demonstrate a similar pattern as the overall patterns for each mask type, indicating that the effects were due to mask differences rather than differences among the words between lists.

Figure 3
Recording and Analysis of Words for Spectral Content



Note. (a) Power spectra of the 10 words averaged across each mask type. (b) Difference in band energy between the three mask conditions in reference to the no mask condition. (c) Power spectra of six example words selected across the range of lower and higher frequency consonants, and different vowels (ball, egg, fox, hat, school, and smoke).

Individual children's performance across the four mask conditions is shown in Figure 4 for HA and CI groups separately. There was substantial variability in each condition in both groups, and the HA group overlapped the scores of the CI group. There were no ceiling or floor effects in the word recognition scores, so the WIPI test was well suited to the children's language ages and their aided speech perception skills. The two-way RMANOVA (Table 2) showed no overall difference in the scores of the HA group compared to the CI group. Since there was not a significant group difference, combined data for both groups across the conditions is shown in violin plots (Figure 5). There was a significant main effect of mask type on word recognition ($p < 0.004$). Post-hoc pairwise comparisons (Holm-Šidák correction) showed that the no mask condition was significantly better compared to the apron mask ($p = 0.017$) and the surgical mask ($p = 0.004$), but the ClearMask was not significantly different from the no mask condition ($p = 0.178$). The range of scores was smaller and generally poorer for the surgical mask, which suggested that loss of visual cues was important, but there was not a statistically significant difference between the mask types.

Discussion and Conclusions

In this sample of children enrolled in an oral school setting, we found that both the standard surgical and transparent apron mask presented a significant barrier to audiovisual communication in young children who are DHH. The spectral analysis showed that the surgical mask had a small effect on the acoustics of speech, thus the observed decrease in word recognition is likely due to loss of visual cues. The ClearMask had an interesting effect on the acoustics of the speech signal, with an apparent increase, or resonance in the frequency range around 2800 Hz that may partially offset the loss of cues at higher frequency regions, but a decrease in the range just above 3000 Hz. Even though the surgical and ClearMask had relatively similar impacts on acoustics, the ClearMask was not significantly poorer than the no mask condition on recognition of words in quiet. This may be due to visual cues preserved by the ClearMask compared to the surgical mask. The ClearMask produced the most variable scores, although 9 of 13 children maintained similar scores in this condition, compared to their unmasked performance. The transparent apron mask had a greater impact on acoustics of speech. The size and placement of the apron mask on the face also appears to obscure some visual cues due to greater glaring, and adversely affects transmission of acoustic energy. All three types of mask had a resonant peak at about 500 Hz compared to the no mask condition. This increased level at low frequencies could make speech sounds muffled and less intelligible. Consistent with this finding, studies in adults have consistently found negative effects on speech communication with surgical masks in quiet (Bandaru et al., 2020) and for words and sentences in noise (Atcherson et al., 2017; Bottalico et al., 2020; Hampton et al., 2020; Toscano & Toscano, 2021; Wittum et al., 2013). Studies in adults have found a benefit of transparent masks, especially in noisy backgrounds, even in adults with normal hearing (Atcherson et al., 2017; Thibodeau et al., 2021). A recent study in adults with cochlear implants showed the greatest attenuation of high frequency acoustics and sentence perception in noise with an N95 mask plus a face shield, compared to an N95 mask or no mask (Vos et al., 2021). A survey of impacts on communication with mask wearing in adults reported that face coverings negatively impact hearing, understanding, engagement, and feelings of connection with the speaker, especially when communicating in medical situations (Saunders et al., 2020). People with hearing loss were more impacted than those without hearing loss.

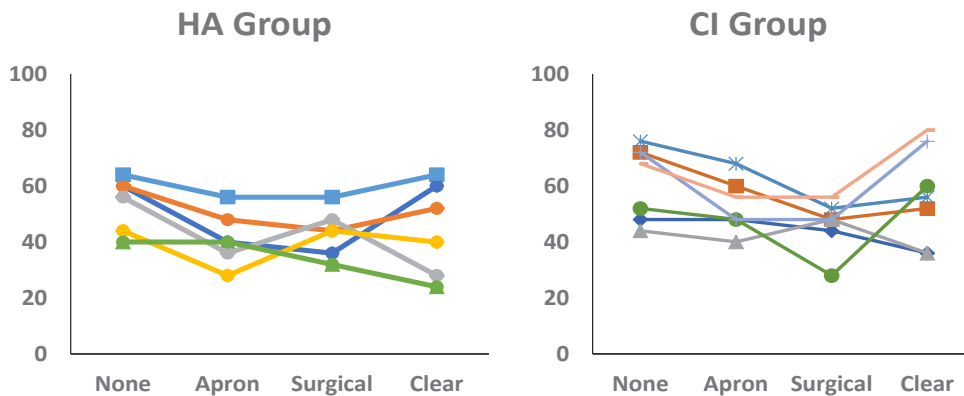
The only other study on communication with masks we are aware of in children who are DHH was recently reported by Lalonde et al. (2021). That study compared auditory alone and audiovisual speech perception of consonant-vowel phonemes in speech-spectrum noise in children who are DHH aged 7–18 years to their siblings with normal hearing and to parents with normal hearing. The no mask condition was compared to a surgical mask, cloth mask, ClearMask, and transparent Communicator brand mask. Similar to our findings, the ClearMask had greater attenuation in the high frequencies than the surgical mask. Results showed

Table 2
Two-way Repeated Measures ANOVA Results

Within Subjects Effects					
Cases		df	F		<i>p</i>
Mask Condition		3	5.458		*0.004
Mask Condition * Group		3	0.700		0.559
Between Subjects Effects					
		df	F		<i>p</i>
Group		1	2.543		0.139
<i>Note.</i> Type III Sum of Squares					
Post Hoc Comparisons - RM Factor 1					
Comparison		Mean Difference	SE	<i>t</i>	<i>p</i> _{holm}
None v.	Apron	10.905	3.466	3.146	*0.017
	Surgical	13.048	3.466	3.765	*0.004
	Clear	7.238	3.466	2.088	0.178
Apron v.	Surgical	2.143	3.466	0.618	0.596
	Clear	-3.667	3.466	-1.058	0.596
Surgical v.	Clear	-5.810	3.466	-1.676	0.309

Note. *p*-value adjusted for comparing a family of 6 using Holm-Šidák method. Results are averaged over the levels of Group. Significant comparisons are noted with an asterisk ($p < 0.05$).

Figure 4
Individual Percent Correct for Each Mask Condition by Group



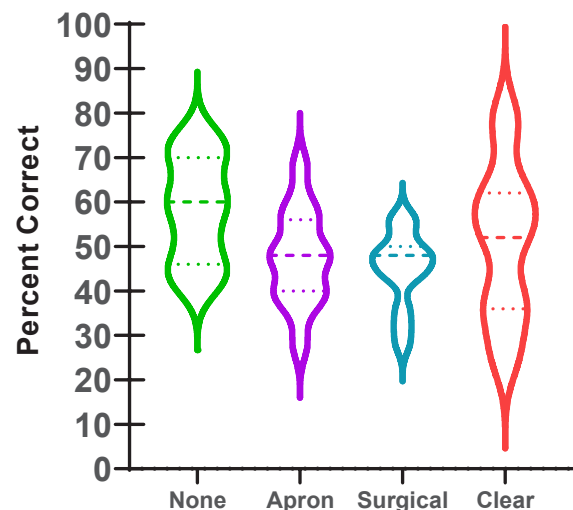
Note. Left panel: Cases with normal-severe hearing loss using hearing aids (HA) or bone anchored hearing aids (BAHA). Right panel: Cases with profound hearing loss using cochlear implants (CI).

that children with hearing loss performed worse than normal hearing adults or siblings. Children who are DHH benefitted more from visual cues with clear masks, and audiovisual speech perception was the least affected by transparent masks.

Limitations of the current study are a relatively small and restricted sample size at one oral school with a single familiar speaker, and performance on a single monosyllabic word recognition task in quiet. Impacts of noise in the classroom and effects of less familiar speakers or rapid running speech would undoubtedly exacerbate the effects shown here, but were not assessed in this study. We may have had insufficient power to detect small differences among the mask conditions, especially with the large variability among mask types. Strengths of the study include the diversity of hearing loss type, range, and type of devices, as well as etiologies of congenital hearing loss. Because the children were in an auditory-oral educational setting, they rely heavily on acoustic as well as visual cues for communication. Normal hearing children, or children educated with sign language may have different results.

Benefits of the transparent apron or ClearMask may include emotional connections and ability to see facial expressions, in addition to speech reading cues. Facial recognition is an important social and psychological input for children and for adults (Freire & Lee, 2001). Facial cues are important for sign language users, thus non-transparent face masks would be expected to impact their communication accessibility (Campagne, 2021). Additionally, face masks obscure reading of emotion, an important skill for communication development in young children (Carbon, 2020). Facial recognition may also provide a greater advantage in noisy classroom conditions that we were not able to study in the classroom environment due to pandemic restrictions. This would be a valuable area to study in the future since mask wearing may become routine in school settings with continued Covid-19 restrictions or new infectious outbreaks.

Figure 5
Violin Plots for Each Mask Condition for Both Groups Combined



Note. Mean scores are shown by the middle dashed line, dotted lines represent interquartile intervals, and stems show ranges.

Educators using the transparent apron mask at this school reported improvement in ease of communication with children who use visual cues for speech understanding. They reported that the transparent apron mask is particularly useful during speech tasks which require the child to see the educator's mouth for visual cues. They were not using the ClearMask in the classroom, so we do not know how it works in practice in the classroom. Educators did report that the ClearMask was not preferred due to fit issues and shifting around the face when talking. There was concern that this led to increased touching of the face and potential for increased risk of viral transmission. Additionally, the disposable nature of the ClearMask makes it a more expensive option. However, based on speech perception benefits demonstrated in this study, it is a viable, commercially available choice to provide audiovisual cues whenever

audiovisual communication is important and thus deserves further study.

Another option that is readily available in schools for children who are DHH are remote microphone technologies to overcome acoustic degradation, especially in noise. Corey et al. (2020) found that masks have little effect on lapel microphones, suggesting that existing sound reinforcement and assistive listening systems may be effective for verbal communication with masks. Thus, use of existing remote microphone technologies with children who are DHH in combination with transparent masks would allow both auditory and visual cues to be maximized, and provide the emotional connection that children need, especially during stressful times as children and their families experienced during the Covid-19 pandemic. This combined option would be the best choice if masks must continue to be worn by teachers and other personnel in classrooms settings in the future.

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EHDInfo

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Early Hearing Detection and Intervention (EHD) Frequently Asked Question (FAQ) Guide for Pediatricians

The EHD FAQ Guide, developed by the American Academy of Pediatrics (AAP) EHD program, is an introductory resource for pediatricians serving families with children who are deaf or hard of hearing (D/HH). This resource provides important resources about the EHD program in states, discusses how best to partner with families, and offers tips for billing and coding.



 Early Hearing
Detection & Intervention
a program of the American Academy of Pediatrics