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Challenges for Children with Cochlear Implants in Everyday Listening Scenarios: The Competitive Effect of Noise and Face Masks on Speech Intelligibility

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Abstract: Speech intelligibility (SI) tests under realistic acoustic scenarios are complex tasks to perform. Optimal acoustics, in terms of reverberation and noise, are thus needed. This is particularly true in the presence of young hard-of-hearing (HoH) children equipped with cochlear implants who need speech to be highly intelligible to learn. During the COVID-19 pandemic starting in early 2020, wearing face masks became common to avoid the spread of infection, mainly impacting the increasingly challenging task of listening for HoH listeners. This study investigated the influence of different types of face masks on speech intelligibility and listening difficulty under competitive noise scenarios. Fourteen children with cochlear implants were involved, as well as six children with typical hearing. Three types of face masks with different acoustic, filtration, and breathability characteristics were considered; three signal-to-noise ratios (SNR) of +10 dB, +5 dB, and 0 dB were used. As expected, lower SNRs corresponded to lower speech intelligibility, and SI without a mask was similar to that obtained with a mask at the lowest acoustic attenuation, albeit with a low filtration efficiency. These preliminary outcomes help improve speech communication strategies in classrooms to support optimal listening conditions.

Keywords: face masks; speech intelligibility; listening difficulty; cochlear implant; children; noise

Citation: Puglisi, G.E.; Di Iulio, M.; Bottalico, P.; Murgia, S.; Consolino, P.; Bisetti, M.S.; Pittà, G.; Shtrepi, L.; Astolfi, A. Challenges for Children with Cochlear Implants in Everyday Listening Scenarios: The Competitive Effect of Noise and Face Masks on Speech Intelligibility. *Appl. Sci.* **2023**, *13*, 8715. https://doi.org/10.3390/app13158715

Academic Editor: José A. González-López

Received: 30 January 2023
Revised: 10 March 2023
Accepted: 28 April 2023
Published: 28 July 2023

1. Introduction

When the COVID-19 pandemic emerged in early 2020, people changed their habits and lifestyles to restrain contagions. Airborne spread and physical contact are the two main ways for the SARS-CoV-2 virus to be transmitted; therefore, preventive measures were identified by health and government authorities [1]. When possible, physical distancing was encouraged; however, in enclosed environments as well as in open-air crowded settings, mandatory advice was given to wear face masks. Based on the recent outcomes on this topic, in Italy, the most commonly used face masks are non-transparent. They can be clustered depending on their characteristics in terms of material, breathing resistance, and filtration efficiency [2]. First, filtering face masks such as N95 and FFP masks; second, surgical face masks; third, nonmedical face masks typically made of cloth. As reported, thanks to the use of face masks in everyday settings, it was possible to reduce infections and preserve health. However, regardless of their material and technical characteristics, they constitute an obstacle to effective speech and empathetic communication as well as for speech understanding for the following main reasons:

- They act as filters that alter the speech signal in terms of amplitude frequency responses [3];
- They lead to excessive vocal effort for the talker and increased listening effort for the listener [4,5];
- The physical presence of masks limits the secondary communication strategies for hard-of-hearing (HoH) listeners, who usually benefit from lip-reading and who are further hampered from an emotional point of view [6–8];
- The signal degradation implies a reduction in speech intelligibility, and it is further worsened in the case of dysphonic voices [9];
- Speech is intrinsically variable due to communication intent, e.g., spontaneous or clear [8,10,11], as well as by the use of a voice-amplification system [12], by the activity carried out [13], and therefore the presence of a face mask can alter its characteristics;
- The degree of speech understanding under competitive conditions, such as in the presence of face masks, can be decreased in non-native listeners [14].

Face masks represent a barrier to communication. Their negative effects are emphasized for a vulnerable population of listeners who are HoH and wear hearing aids (HAs) or have cochlear implants (CIs). The effects are both on their performance and their mental well-being. Homans and Vroegop [15] delivered an online questionnaire about the effects of face masks on the speech communication process of adults wearing CIs. The main outcome of the study consisted of evidence that up to 80% of the people who answered the questionnaire reported considerable problems, which turned into psychological distress, such as an increased feeling of loneliness.

From an objective point of view, when the degrading effect of face masks on speech is combined with a poor acoustic environment in terms of a high level of reverberation and noise, the speech communication process, which implies the quality of speech understanding, too, can be also strongly degraded. This is a major problem in environments where communication plays an essential role such as school and for younger listeners who should be supported in the learning process [16,17]. Accounting for the presence of HoH listeners, when a CI or a HA is well fitted, young listeners may achieve in quiet conditions high speech intelligibility levels similar to their peers with typical hearing (TH); vice versa, the presence of noise and reverberation does not enable them to reach comparable performances [18,19]. Furthermore, face masks behave as low-pass filters that reduce speech intensity at the frequencies that are fundamental for speech comprehension, i.e., mid-to-high [20–22]. Bottalico et al. [4] investigated the effects of different types of face masks on speech communication in auralized classrooms with different reverberation conditions. They showed that surgical and N95 masks should be used rather than cloth masks to minimize the decrease in speech intelligibility (SI) and the increase in listening effort (LE). Lipps et al. [23] showed that the use of surgical masks and of face shields significantly hampered SI for HoH children from 3 to 7 years of age, compared to the use of a clear mask, which consisted of a mask made of a transparent layer positioned in front of the nose and mouth to enable visual cues. Additionally, Zhou et al. [24] suggested that wearing a transparent mask improves SI to that of unmasked conditions with respect to surgical or N95 face masks, at least as far as young listeners with typical hearing are concerned. However, these studies highlight that the use of transparent masks is not always possible due to costs and to the still highly variable results.

Although wearing masks with transparent sections would better enable HoH listeners to benefit from lip-reading, it is not always possible to acquire them for extensive use in everyday life settings (such as for teaching activities in classrooms) due to their higher costs and for hygienic reasons, as it is not possible to clean them continuously for reuse. Therefore, to the aim of the present study, no transparent face masks were selected, but only masks that are largely available and that are delivered by the non-profit organization "C.I.A.O Ci Sentiamo", which is involved in the project, because common uses were considered. The aim of this study can be summarized as the investigation of the combined effect of ecological acoustic scenarios, i.e., different noise conditions in terms of signal-to-noise ratios

(SNRs), and of the use of face masks with different acoustic properties. Professionals and experts in the field should take advantage of the outcomes to implement specific design and operative strategies to account for acoustic needs in everyday listening scenarios. In particular, such an investigation involves HoH young listeners who wear CI, since the effect of competitive ecological acoustic conditions degrades speech intelligibility towards them to a greater extent than with respect to their peers with typical hearing.

2. Methodology

2.1. Participants

Twenty children were enrolled in the study voluntarily. Their ages ranged between 7 years and 15 years (mean age, M, equal to 10.05 years; standard deviation, SD, equal to 2.46 years). Fourteen of these children (eight males, six females) were clustered in the experimental group (EG), with a hearing impairment that required the use of at least one CI. The other six participants (two males, and four females) were clustered in the control group (CG), with typical hearing. The participants' recruitment process was entrusted to the hospital staff of the Martini Hospital in Turin and the first steps of the recruitment process were not affected by the distinction of gender or age. In particular, participants in the EG were patients at the Ear Nose and Throat (ENT) Department of the hospital, while the six CG participants were siblings of the EG patients with typical hearing, involved voluntarily. The parents of the EG and CG children gave written consent for the execution of the tests. The criteria for the selection of the EG participants are briefly listed in Table 1.

Table 1. Inclusion and exclusion criteria for the involvement of young listeners in the study.

Inclusion Criteria	Exclusion Criteria
1. Ability to speak and understand the Italian language. 2. Binaural stimulation (either bilateral cochlear implants or bimodal stimulation with cochlear implant and contralateral hearing aid). 3. Early diagnosis and treatment of the pathway. 4. Fully developed language at phonetic and phonological levels. 5. Auditory intelligibility test in binaural mode with words, sentences, and phonemic confusions (to verify optimal perceptual competence). 6. Speech audiometric test with recognition threshold at 50 dB HL.	1. Attention and executive function impairment. 2. Speech disorders. 3. Cognitive impairment.

As far as the EG is concerned, children received a hearing loss diagnosis between 1 month and 12 months of age and were then prothesized with at least one CI between 2 months and 36 months of age. The CIs with which they were equipped, as well as the transmission device to which they were coupled, were overall of three different models. All the CI and transmission device models considered within this study can be considered equivalent, as underlined by the ENT specialists who selected the EG sample.

2.2. Face Masks

To investigate the effect of face masks on speech intelligibility for children with CI, three surgical face masks were selected according to different criteria of market availability and acoustic properties. As they have all undergone commercial distribution, they were all correctly certified as far as their breathability and filtration efficiency characteristics are concerned. In the design of the experiment, it was planned to test each mask and acoustic scenario combination in terms of signal-to-noise ratio exposure, also considering a reference no-mask base condition.

Masks 1 and 2 were selected due to their large availability on the market, as surgical masks that are commonly used for everyday activities. Mask 3 was supplied by the non-profit organization "C.I.A.O. Ci Sentiamo" which (i) participated in the study, (ii) allowed for the establishment of first contact with the patients, and (iii) distributed these masks among its members, who include teachers and families who deal with HoH children.

Table 2 reports the supply and acoustic characteristics of the selected face masks, and Figure 1 shows them while mounted on the head and torso simulator in the anechoic room of the Politecnico di Torino for acoustic measurements. These measurements were conceived to obtain outcomes on absorption and transmission loss for all face masks; therefore, the following parameters were measured: sound absorption (α_0) in the third-octave band range of (1–5) kHz, sound transmission loss (STL), and sound attenuation ΔSPL in the third-octave band ranges of (0.4–5) kHz and (1.6–5) kHz. As far as α_0 is concerned, measurements were carried in agreement with ISO 10534-2 [25] and ASTM E1050-19 [26], using the impedance tube two-microphone technique that allows for accurate measurements, especially in the frequency range between 1000 Hz and 4000 Hz, which are the main ones of interest for the assessment of speech intelligibility [20] and therefore for the aims of the present study. STL was measured in agreement with ASTM 2611-09 (four-microphone technique) [27]. To extend the face-mask characterization to the analysis of their properties of frequency, ΔSPL was calculated as the difference between the sound pressure levels, measured at a distance of 1 m in the anechoic chamber, in the reference condition without a face mask, and in the test conditions with the considered face masks. Figure 2 represents such sound attenuation ΔSPL in third-octave bands, for each face mask, in the range from 0.4 kHz to 10 kHz.

Table 2. Face-mask characteristics.

	Mask 1	**Mask 2**	**Mask 3**
Supplier	Available on the market	Available on the market	"C.I.A.O Ci Sentiamo"
Sound absorption 1–5 kHz ($\alpha_{0,}$ −)	0.13	0.11	0.12
Sound Transmission Loss 1–5 kHz ($STL_{1\text{–}5\ kHz}$, dB)	1.95	1.58	1.50
Sound attenuation 0.4–5 kHz ($\Delta SPL_{0\cdot4\text{–}5\ kHz}$, dB)	3.33	1.02	1.15
Sound attenuation 1.6–5 kHz ($\Delta SPL_{1\cdot6\text{–}5\ kHz}$, dB)	6.73	1.83	2.08

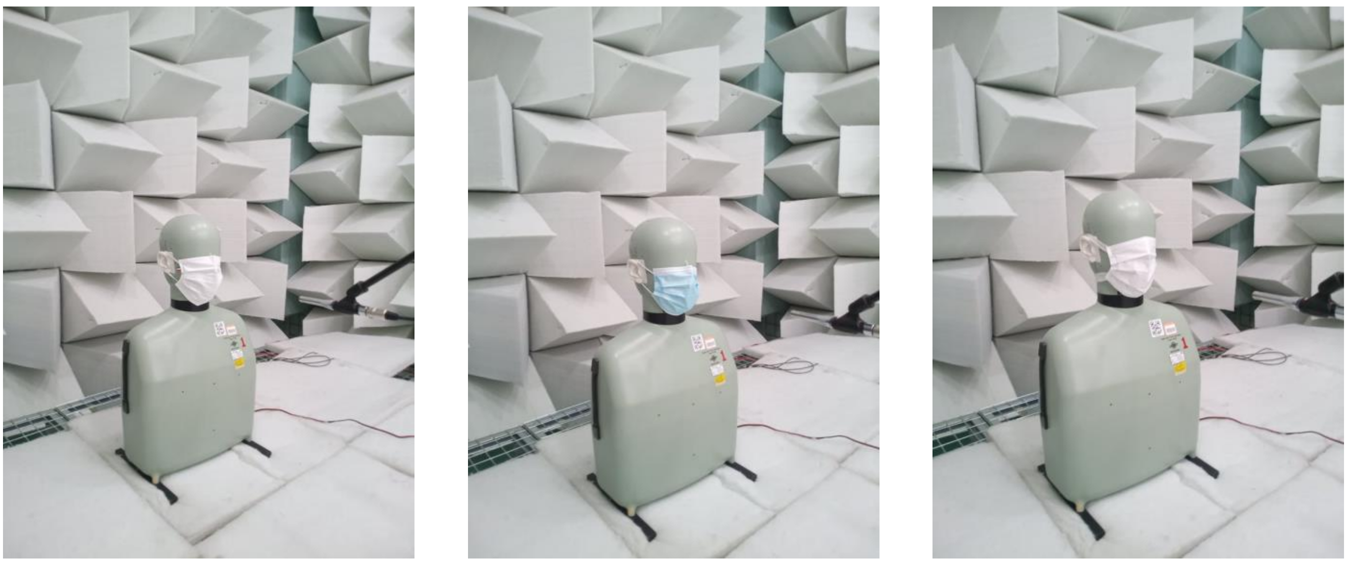

Figure 1. Face masks mounted on the head and torso simulator in the anechoic room of the Politecnico di Torino. From left to right: Mask 1, Mask 2, Mask 3.

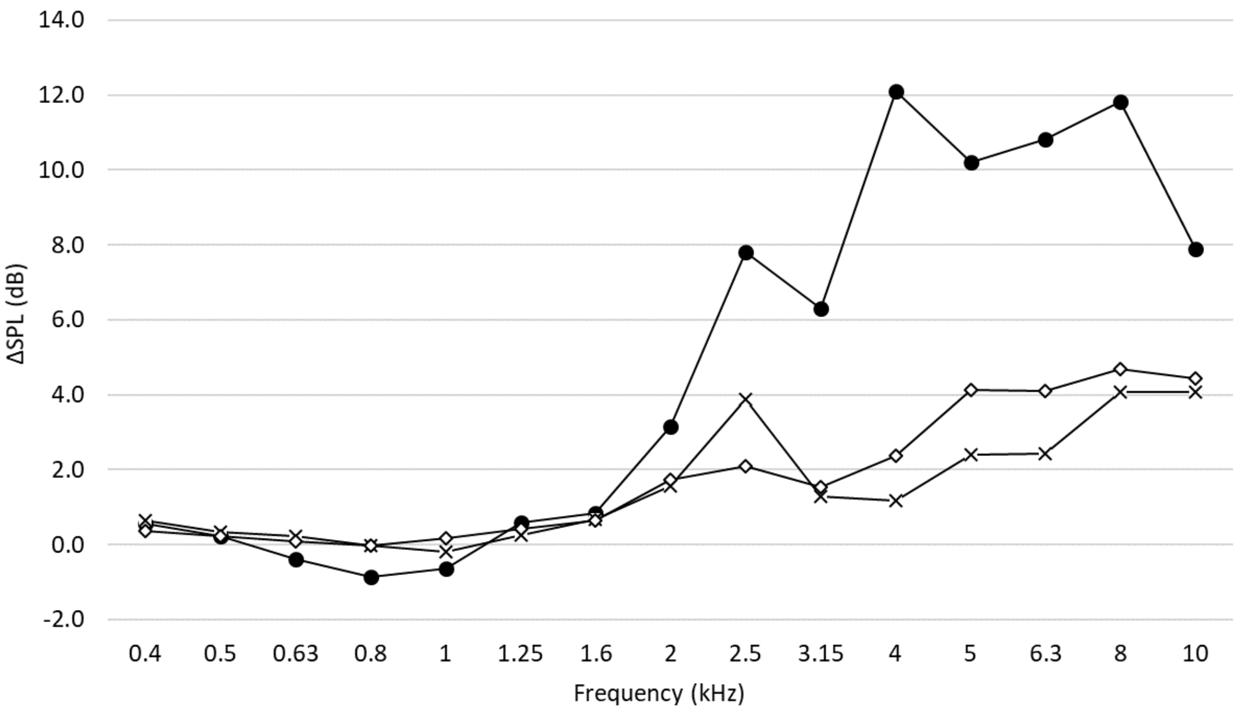

Figure 2. Measured sound attenuation ΔSPL in third-octave bands for Mask 1 (•), Mask 2 (×), and Mask 3 (◊).

2.3. Listening Test Preparation

2.3.1. Speech Material and Speech Intelligibility Assessment

Listening tests were aimed at assessing speech intelligibility under realistic acoustic conditions using speech material described by Puglisi et al. [28], particularly the open-set format. This material, already used in research studies as it is based on the extended version of the test that has been optimized for the Italian language [29] and for other languages of the world [30] to provide accurate results, allows for the reduction of the duration period of the tests and the decrease of deconcentration bias. In summary, the test consists of the administration of syntactically correct but semantically unpredictable words and sentences randomly built from a 7 × 3 matrix of words ("number, object, adjective"). Such sentences, which were uttered in anechoic conditions, were then presented under realistic and significant signal-to-noise ratios (SNRs) to evaluate speech intelligibility in terms of the percentage of correctly understood words overall. The words of the sentences were simple, of common use, and easy to understand even by young children, who may not have a huge vocabulary yet. An example of a sentence is "*Sette sedie utili*" meaning "Seven useful chairs".

2.3.2. Acoustic Conditions and Stimuli Preparation

As HoH listeners wearing a cochlear implant are subject to a modification of the acoustic field in which speech communication takes place, e.g., the minimization of reverberation and background noise reduction, the objective of this study was to understand the extent to which SNRs could influence speech intelligibility while a talker is wearing face masks with different properties in terms of breathability, filtration efficiency, and acoustic attenuation. To reflect realistic and ecological situations, three SNRs were defined that represent acoustic conditions from the less challenging to the most challenging, which are, +10 dB SNR, +5 dB SNR, and 0 dB SNR. A baseline to which the results could be compared was also added; therefore, a no-noise configuration corresponding to a quiet condition was tested. As far as the selection of the noise type to be added to the listening tests, typical classroom noise was used. The noise included children talking and moving in the classroom. It was measured in a typical Italian primary school classroom, where reverberation time was very low, and represented an ecological noisy situation that included not only energetic but also informational content, which is indeed one of the most challenging sources of masking to be faced in everyday acoustic scenarios [31,32].

The sentences described in Section 2.3.1 were mixed, with noise at different levels to obtain each SNR condition (i.e., 0 dB, +5 dB, and +10 dB). To account for the effect of the face mask provided on the speech produced, the sentences were recorded in the anechoic room of the Applied Acoustics Laboratory of the Politecnico di Torino using a head and torso simulator (HaTS, model 4128-C by Brüel & Kjær), which was used as an artificial mouth that was cover by the masks themselves. A calibrated class-1 sound level meter was then placed 1 m from the mouth to acquire the speech signal filtered using the masks. According to the test length given by Puglisi et al. [28], which corresponded to 14 sentences produced under the same acoustic condition to obtain reliable results, a first set of 14 sentences $\times$ 4 noise conditions (i.e., no noise, +10 dB SNR, +5 dB SNR, 0 dB SNR) $\times$ 4 mask conditions (i.e., no mask, Mask 1, Mask 2, Mask 3) was prepared.

As the length of the tests was challenging for the participants involved, a subset of 10 sentences was extracted from the original dataset to shorten the trial and allow a higher concentration rate to be maintained for the children. A statistical analysis was conducted to compare the results, which matched between the ones obtained with the long (14 sentences $\times$ 4 noise conditions $\times$ 4 mask conditions = 224 sentences overall) and with the short (10 sentences $\times$ 4 noise conditions $\times$ 4 mask conditions = 160 sentences overall) versions of the test. For this reason, all the results were considered together. Overall, the number of sentences administrated per listener typology can be summarized as follows:

- 5 listeners from the EG were administered with the long version test (i.e., 14 sentences) under the no noise, +10 dB SNR, +5 dB SNR, 0 dB SNR, and No Mask, Mask 1 and Mask 2 conditions;
- 9 listeners from the EG were administered with the short version test (i.e., 10 sentences) under the no noise, +10 dB SNR, +5 dB SNR, 0 dB SNR, and No Mask, Mask 1 and Mask 2 conditions;
- 6 listeners from the CG were administered with the short version test (i.e., 10 sentences) under the no noise, +10 dB SNR, +5 dB SNR, 0 dB SNR, and No Mask, Mask 1 and Mask 2 conditions.

2.4. Listening Test Administration

The data for this paper was collected online using the Qualtrics XM platform (Qualtrics, Provo, UT, USA; https://www.qualtrics.com, accessed on 29 January 2023). Participants were tested remotely due to COVID-19 and accessibility reasons. They accessed a Zoom call together with their parents who handled the first steps of the test. Parents were asked to ensure a LAN or stable Wi-Fi internet connection for the entire duration of the listening test and to close all the applications installed on the laptop/tablet that could receive real-time notifications (e.g., social network apps, emails, pop-ups) so that they could not interfere.

Then, the children involved were instructed by the experimenter on the test procedure. Lists were presented in a randomized order to all the participants to avoid biases in the results. Table 3 summarizes the steps that were followed for each listening test.

2.5. Statistical Analysis of Data

A statistical analysis of the acquired data was carried out. Both speech intelligibility values and subjective listening difficulty scores were investigated, considering their dependency on different noise conditions, type of mask, and individual factors such as gender and age. Generalized linear mixed models (GLMM), performed using the software R3.6.0 and the lme4 package, were applied to analyze the database.

Table 3. Procedure of administration of the listening tests.

Phase	Description
1—instruction	The experimenter instructs the participant in the presence of her/his parents on the test procedure and makes sure that the environment in which the test takes place is as quiet as possible and free from sources of noise (e.g., television, radio, chatting, household appliances).
2—cochlear implant setting	This phase was valid for the experimental group (EG) only. Here, the experimenter instructs the participant to set the cochlear implant in "Roger mode", i.e., with the MicroLink FM device set to the mode defined and suggested by the Martini Hospital Audiology Centre to perform the test comfortably. Such a condition is essential to isolate acoustically the listener from the external environment.
3—training	This is supposed as a preliminary phase to make the participants familiar with the speech material and with the test procedure. It consisted of a trial with a similar structure to the rest of the test, made of an 8-sentence list presented in the no-mask condition. Such sentences were further divided into subgroups of two sentences each, corresponding to the no noise, 0 dB SNR, + 5 dB SNR and +10 dB SNR conditions.
4—experiment (part 1)	The participant listens to the sentence and repeats it aloud, exactly as s/he understands it. The experimenter then takes note of the correctly understood words and assigns a 0 or 1 value whether it was wrong or correct, respectively. Please note that reporting a word in singular when it was plural, feminine when it was masculine, was considered to be an error.
5—experiment (part 2)	In this final experimental part, after repeating the sentence aloud, the participant must assess the degree of difficulty that s/he experienced right before. It is considered to be the self-evaluation of the difficulty in listening and understanding the sentence, and it is evaluated on a 5-point colored scale (green > no difficulty at all; red > very high difficulty).

3. Results

3.1. The Role of Face Masks and Different Noise Conditions on Speech Intelligibility

This analysis aimed at assessing the extent to which the presence of different types of face masks affects speech intelligibility under increasingly complex noise conditions, i.e., from a no-noise condition to several competitive conditions of SNRs. The analysis was performed separately for the participants in the EG and for those in the CG. As far as the two less-competitive acoustic scenarios are concerned, i.e., the no-noise and the +10 dB SNR conditions, the EG performed similarly to the CG and overall very well, as they always exhibited an average speech intelligibility value above 0.82 (i.e., 82%). In the cases of the two most competitive acoustic scenarios, i.e., at SNRs decreasing to +5 dB and 0 dB, speech intelligibility values lowered and became different for the two groups, especially in the latter condition. Figure 3 and Table 4 show the outcomes of the listening tests in terms of speech intelligibility mean scores and standard errors across participants.

Based on GLMM analysis, outcomes show that HoH listeners experience a higher complexity in facing speech intelligibility challenges under realistic acoustic scenarios. The probability of correctly recognizing a word (PCR) among the participants of EG was 86% less than the one in CG (OR = 0.14, $p < 0.001$).

As far as the noise condition is concerned, the no-noise setting allowed for higher (better) speech intelligibility values, as expected. PCRs for SNR of +10 dB, +5 dB, and 0 dB, were 70% (OR = 0.30, $p < 0.001$), 85% (OR = 0.15, $p < 0.001$), and 96% (OR = 0.04, $p < 0.001$) lower than in the quiet condition, respectively.

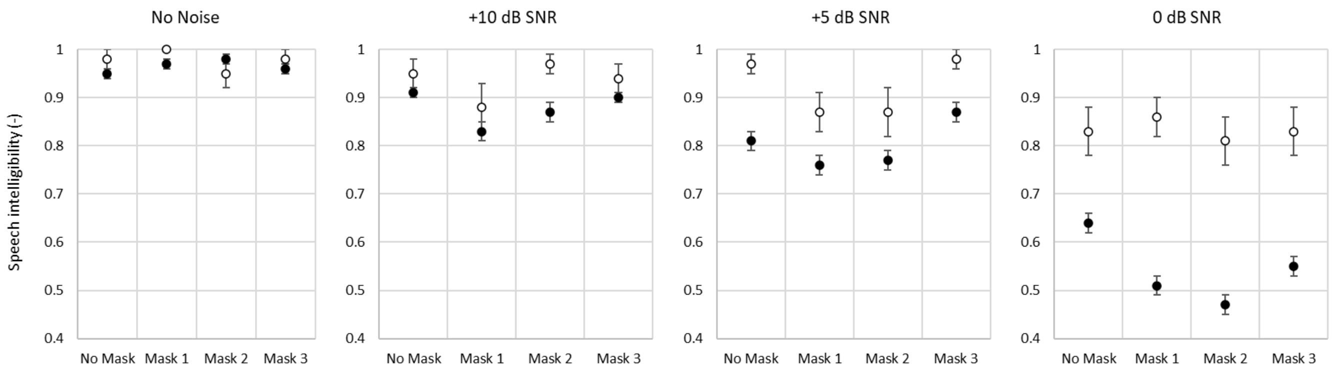

Figure 3. Mean speech intelligibility scores and related standard errors (error bars). Black circles (●) show the Experimental Group (EG) results; empty circles (○) show the Control Group (CG) results.

Table 4. Mean values of speech intelligibility scores and related standard errors in brackets.

	No Mask	Mask 1	Mask 2	Mask 3
		Experimental group (EG)		
No noise	0.95 (0.01)	0.97 (0.01)	0.98 (0.01)	0.96 (0.01)
+10 dB SNR	0.91 (0.01)	0.83 (0.02)	0.87 (0.02)	0.90 (0.01)
+5 dB SNR	0.81 (0.02)	0.76 (0.02)	0.77 (0.02)	0.87 (0.02)
0 dB SNR	0.64 (0.02)	0.51 (0.02)	0.47 (0.02)	0.55 (0.02)
		Control group (CG)		
No noise	0.98 (0.02)	1.00 (0.00)	0.95 (0.03)	0.98 (0.02)
+10 dB SNR	0.95 (0.03)	0.88 (0.05)	0.97 (0.02)	0.94 (0.03)
+5 dB SNR	0.97 (0.02)	0.87 (0.04)	0.87 (0.05)	0.98 (0.02)
0 dB SNR	0.83 (0.05)	0.86 (0.04)	0.81 (0.05)	0.83 (0.05)

As far as the effect of the mask type is concerned, SI was lower under Masks 1 and 2 with respect to the no-mask condition. In particular, PCRs were 40% (OR = 0.60, $p < 0.001$) and 37% (OR = 0.63, $p < 0.001$) lower than in the no-mask condition for Masks 1 and 2, respectively. The use of Mask 3, despite degrading the quality of speech and therefore speech intelligibility, had a negligible impact that brought to exhibit no statistically significant differences from the no-mask condition.

3.2. The Role of Face Masks and Different Noise Conditions on Listening Difficulty

With this analysis, the researchers aimed to assess the extent to which the presence of different types of face masks affects listening difficulty for children under several competitive conditions of SNRs. As with the analysis presented in Section 3.1, Figure 4 and Table 5 report the outcomes of the listening tests in terms of listening difficulty mean values, which may vary between the less difficult (score 1) and the most difficult (score 5), and standard errors across participants. They are shown separately for each experimental condition related to the type of mask and noise.

HoH listeners experienced a higher listening difficulty compared to the CG participants ($p < 0.001$). Furthermore, in relation to the type of masks, Masks 1 and 2 were the most competitive with respect to the no-mask condition, as they lead to higher listening difficulty values ($p < 0.001$), whereas Mask 3 did not differ significantly with respect to the no-mask condition ($p > 0.05$).

Considering the effect of noise, the no-noise condition was less challenging compared to SNR of +10 dB ($p < 0.001$), SNR of +5 dB ($p < 0.001$), and SNR of 0 dB ($p < 0.001$). Furthermore, listening difficulty values in the no-noise condition were not statistically different between EG and CG participants.

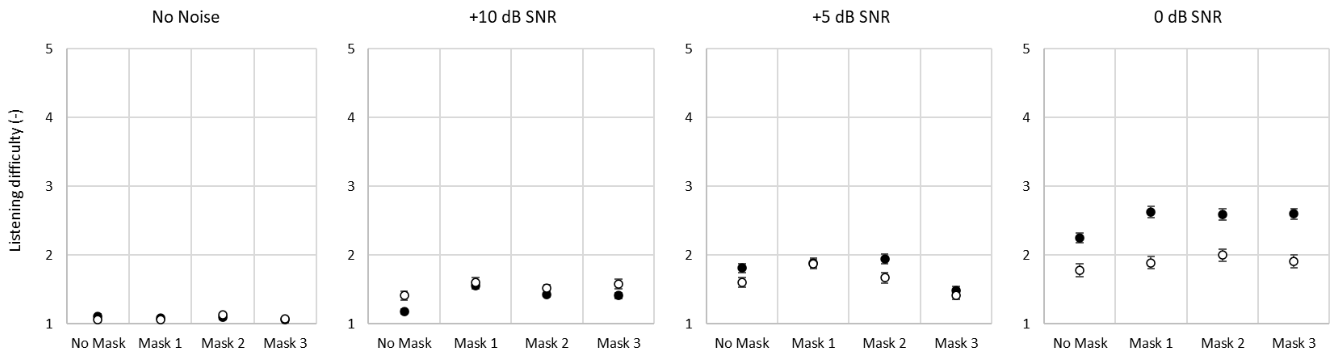

Figure 4. Mean listening difficulty scores and related standard errors reported as error bars. Black circles (●) show the Experimental Group (EG) results; empty circles (○) show the Control Group (CG) results. Values on the y-axis correspond to the degrees of perceived difficulty, i.e., 1—no difficulty at all, 2—very low difficulty, 3—slight difficulty, 4—high difficulty, 5—very high difficulty.

Table 5. Mean values of listening difficulty scores and related standard errors in brackets.

	No Mask	Mask 1	Mask 2	Mask 3
		Experimental group (EG)		
No noise	1.11 (0.03)	1.09 (0.02)	1.10 (0.02)	1.06 (0.02)
+10 dB SNR	1.18 (0.03)	1.56 (0.05)	1.43 (0.04)	1.41 (0.04)
+5 dB SNR	1.81 (0.06)	1.89 (0.06)	1.95 (0.07)	1.49 (0.05)
0 dB SNR	2.25 (0.07)	2.63 (0.08)	2.59 (0.08)	2.60 (0.08)
		Control group (CG)		
No noise	1.06 (0.04)	1.06 (0.02)	1.13 (0.04)	1.08 (0.04)
+10 dB SNR	1.41 (0.06)	1.60 (0.08)	1.52 (0.05)	1.58 (0.07)
+5 dB SNR	1.60 (0.07)	1.88 (0.08)	1.67 (0.08)	1.42 (0.06)
0 dB SNR	1.78 (0.09)	1.89 (0.09)	2.00 (0.09)	1.91 (0.09)

4. Discussion

Challenges for children with CIs are increasing in everyday listening scenarios. Indeed, these determine a risk source for HoH children due to their role in the degradation of speech understanding related to the presence of reverberation and noise, as highlighted also by McCreery et al. [33]. The main outcomes of this work corroborate the few available similar studies. The presented outcomes, however, only consider the effects of noise and the presence of different face masks as competitive factors for speech understanding.

As far as the exclusive effect of noise is concerned (i.e., no mask effect is considered), this work highlighted that speech intelligibility for children with CIs degrades when SNR decreases. In particular, it shifts from about 90% to about 80% to about 62% under the +10 dB SNR, +5 dB SNR, and 0 dB SNR conditions, respectively. McCreery et al. [33] found that children with CIs need an average SNR of about 10 dB to reach 50% speech intelligibility. This result slightly differs from that of the present study; however, it is possible to compare them, as they are dependent on the type of noise considered in the experiments, and that differed between the two. Indeed, McCreery et al. [33] considered a speech-shaped artificial noise, whereas in this work it has been considered a real classroom noise with a degree of informative content. Furthermore, the compared study of McCreery et al. [33] presents a high variability in the results.

Concerning the effect of face masks on speech intelligibility, Kataoka et al. [34] found that both HoH and TH listeners experienced difficulties in the speech communication process, which is referred to speaking as well as to listening, due to wearing a mask or communicating under noisy conditions. This finding is corroborated by the presented experiments, as HoH listeners in the EG experienced a higher listening difficulty compared to the participants with TH in the CG. Indeed, this difference was statistically significant and, overall, with an increasingly competitive acoustic scenario (i.e., with lower SNRs) even listeners with TH revealed a tendency of increased difficulty in the listening task to which they were subjected. A recently published paper by Kumar et al. [35] underlined that the combined effect of face masks and competitive noise scenarios further hampers speech intelligibility for HoH listeners. In their study, they showed that at decreasing SNRs, i.e., from +15 dB SNR to +10 dB SNR to 0 dB SNR, speech intelligibility drops from averages of 95%, 90%, and 50%, respectively. In particular, it lowers per noise condition when a more acoustically absorbent face mask is considered. However, they did not perform any acoustic measurements of the masks used in the study, so specific conclusions regarding the acoustic effects of these masks could not be determined and a perfect comparison with this study is not possible. This study shows that, on average, speech intelligibility decreases for HoH and TH listeners in the presence of Masks 1 2. Mask 1 was characterized by a higher sound absorption and attenuation. Masks 2 and 3 were similar in terms of sound absorption and attenuation; however, the latter was significantly higher for Mask 2, at 2.5 kHz. In a very recent study, Flaherty et al. [36] showed that an increased sound attenuation at around 2 kHz may decrease the second formant of speech, with the main negative consequence being the reduction of vowel discrimination. Therefore, such an effect could explain the difference in intelligibility scores between Masks 2 and 3. Overall, the result was also corroborated due to statistical analyses, which were based on the search for the probability of correctly recognizing a word (PCR). Similarly, listening difficulty was higher for the higher competitive acoustic characteristics of face masks.

As a general consideration, possible solutions to account for all the premises at the same time, i.e., the need to improve speech intelligibility towards HoH children under realistic acoustic scenarios and the need to reduce the spread of COVID-19 infection, are needed. So far, studies have proposed the use of face shields and see-through prototype masks, as they are effective in allowing for lip-reading [22,34]. However, they are not easy to find and are not commonly used in everyday practice. This study is thus a step forward to acknowledging the importance of accounting for the combined effect of personal behavior (e.g., wearing face masks to protect society) together with environmental modifications to support the speech communication process. Indeed, increasing SNR in the environment is an effective strategy to increase speech intelligibility. Although this objective can be reached because of the setting of the cochlear implant, it is also a design challenge for researchers and professionals in acoustics, who should guarantee an adequate acoustic environment where everyday activities take place. Therefore, the control of reverberation and noise is essential.

The presented study fills in gaps in the available literature [35] (i) it is based on speech and noise stimuli that were recorded under controlled acoustic conditions and therefore are highly repeatable; (ii) the laboratory characterization of the face masks was based on well-defined standards and procedures; (iii) the presentation of the listening tests was performed to two ears at the same time, so binaural hearing cues were accounted for as in ecological listening situations; (iv) a comparison between the EG of HoH listeners and the CG with TH ones could be performed to obtain results that have larger applicability in everyday life situations.

However, some limitations are still present, and the main ones can be summarized as follows. First, a small number of participants was achieved. The main obstacle to involving a wider group of HoH listeners was related to the restrictions due to the COVID-19 pandemic, which also included the fact that the experimenters only met the listeners and their families remotely, so little mutual knowledge was possible. Second, the great variability in HoH treatment did not allow for the inclusion of a greater number of participants with similar characteristics. Third, it would be useful to investigate the learning effect on speech perception, thus on speech intelligibility, for HoH and TH listeners. Indeed, recent studies [37,38] have introduced the need to control quantities such as the response time in complex listening tasks, which may vary significantly under different noise types (e.g., stationary, interrupted, or single-talker noises), but that may inform aspects that can help the acoustic design of everyday environments or the teaching techniques for inclusive learning.

5. Conclusions

This study aimed to assess the effect of noise and face masks on speech intelligibility in bilateral hard-of-hearing young listeners, equipped either with bilateral cochlear implants or with a monolateral cochlear implant and contralateral hearing aid. Twenty participants were recruited voluntarily, who were clustered into an experimental group of 14 hard-of-hearing children and a control group of six children with typical hearing. A specific listening test was built according to the requirements of this project, i.e., to assess speech intelligibility and listening difficulty under different noise conditions, accounting for the presence of different types of face masks. The participants were able to carry out the test remotely using a computer and an internet network. Since the involved participants were all in the age range between 7 and 15 years of age, their parents' consent and presence during the execution of the listening tests was required. This strategy allowed researchers to overcome the limitations imposed by the pandemic rules and therefore to collect data without the possibility of performing the test in the presence of the researchers.

Two main outcomes were found within this study. First, concerning the effect of different SNRs on speech intelligibility, the presence of noise at all levels significantly degraded speech intelligibility and also prompted higher (worse) listening difficulty. Considering SNRs of +10 dB, +5 dB, and 0 dB, a drop in speech intelligibility from an average of 90% to 85% to 60%, respectively, was found for hard-of-hearing listeners. Listeners with typical hearing, instead, exhibited a reduced drop in speech intelligibility at the three SNRs that consisted of 95% to 90% to 85%. From a practical point of view, until an SNR as low as +5 dB, it was found that speech intelligibility was higher than 75% for hard-of-hearing listeners. This is a satisfactory value that can still be acceptable within a classroom. Therefore, a possible strategy to support the design of classrooms to make them adequate for several listeners, e.g., young children with cochlear implants or hearing impairment in general, can be to emphasize this aspect at an early stage. Second, concerning the effect of different types of face masks on speech intelligibility, data confirmed that they play a crucial role in the speech communication process. The no-mask condition proved to be the one with higher speech intelligibility values, as expected. For children with hard-of-hearing listeners, using Masks 1 and 2, lower speech intelligibility values were obtained and a corresponding higher listening difficulty was shown. Conversely, Mask 3 provided speech intelligibility and listening difficulty values that were comparable to the no-mask condition. It had the least impact on speech comprehension and, therefore, this could be considered to be the most suitable for the teacher to wear. In summary, due to the main difference in the intrinsic characteristics of face masks with respect to their acoustic properties, the use of masks with lower sound absorption and transmission loss is worthwhile in those contexts where the speech communication process is of primary importance, and where vulnerable subjects, such as hard-of-hearing children, are present.

Author Contributions: G.E.P. and P.B. conceptualized the research; P.C., M.S.B. and G.P. selected, invited, and involved the participants; L.S. conducted acoustic characterization measurements of the face masks; M.D.I. and G.E.P. performed the listening tests; M.D.I., P.B., S.M. and G.E.P. organized the database and performed the statistical data analysis; G.E.P. wrote the first draft of the manuscript; all the authors reviewed the article drafts; A.A. supervised the research activity. All authors have read and agreed to the published version of the manuscript.

Funding: This research was sponsored by the C.I.A.O Ci Sentiamo ONLUS.

Institutional Review Board Statement: The Inter-Company Ethical Committee (Comitato Etico Interaziendale) and the Bio-Ethic Committee (Comitato di Bioetica) of the University of Torino (Italy) stated that this project presented by Patrizia Consolino (number 00330/2022 with the original Italian title "Studio osservazionale senza farmaco") is exempted from ethical approval. The proposed protocol does not involve medical treatments on the subjects and can be considered as an observational research study conducted remotely without further authorizations.

Informed Consent Statement: Informed consent was obtained from the parents/caregivers of all participants involved in the study, and assent was obtained from all the participants.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors thank the Administration of Politecnico di Torino for the funding received during the pandemic period in 2020 to start this research and other related ones, and the families of the children involved in their availability and enthusiastic participation in the project.

Conflicts of Interest: The authors declare no conflict of interest.

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