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Auditory Perception with Ear and Cold Weather Face Protection Worn in Combination

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The effects on hearing thresholds, sound attenuation, and consonant discrimination of wearing a balaclava under hearing-protecting earmuffs were studied. This combination is commonly worn during cold weather military operations. One group of 20 normal-hearing adults (10 male and 10 female subjects) was tested. Within-subject measurements were made of diffuse-field hearing thresholds from 0.25 kHz to 8 kHz and consonant discrimination in quiet with the ears unoccluded and protected with the earmuffs alone and with the balaclava worn full face or rolled. Attenuation was derived from the protected and unoccluded thresholds at each frequency. When the balaclava was worn full face, attenuation decreased by 16 to 18 dB, relative to the muff alone, below 6.3 kHz. With the balaclava worn as a cap, there was an inverted U-shaped decrement in attenuation of 18 to 27 dB from 0.25 Hz to 4 kHz. Consonant discrimination decreased by 7% with the muffs alone. These findings underscore the importance of assessing protective equipment under the conditions in which it will be worn.

Introduction

Standards for personal protective equipment typically provide guidelines for the evaluation, classification, selection, and use of classes of devices, such as respirators, eyeglasses, or hearing protectors.[1-3] In practice, however, safety devices are generally worn in combination in both civilian and military operational environments. The Canadian standard on hearing protection, the subject of the present investigation, cautions that the performance of these devices may be compromised by other equipment worn around the head.[4] To date, however, only a few scientific studies have been conducted to determine the extent to which the combining of personal protectors may interfere with the components.[5-7] Chung et al.,[6] for example, investigated the effect on earmuff attenuation of long hair over the ears, either alone or with glasses or a thin or thick cap. The stimulus was 103-dBA pink noise (equal energy per octave). Decrements in insertion loss, the difference in the physical measurements of sound levels inside and outside the ear cup,[8] relative to short hair alone, were highly variable across subjects. They ranged, on average, from 2 dB for long hair to 13 dB for long hair with a thick cap. More recently, Abel et al.[7] measured the effects on earmuff attenuation of safety glasses and/or an air-purifying half-mask respirator worn in combination, using the real-ear attenuation at threshold procedure.[2] The sound attenuation observed for earmuffs worn alone decreased by 5 dB with either the glasses or respirator and by as much as 9 dB with both devices. Maximal decrements were observed below 1 kHz. The effect diminished with increases in the frequency of the test stimulus.

Decrements in attenuation observed in the studies cited above were attributed to leakage of sound under the ear cup of the hearing protector. Leakage results from any obstruction that precludes an airtight seal of the earmuff to the circumaural region surrounding the pinna of the ear.[9] Crabtree[10] modeled this scenario by using a passive earmuff and a flat plate coupler containing a measurement microphone. Measurements were confined to frequencies below 200 Hz. A 1.6-mm tube was inserted between the ear cushion and the coupler, to model the leakage that would be caused by the metal side frame of military-issue sunglasses worn under the muff. With an airtight seal, insertion loss increased from ~5 dB to ~30 dB with increases in frequency from 6 Hz to 137 Hz. With the tubing in place, there was virtually no attenuation below 100 Hz. In fact, negative insertion loss was observed in the region of 50 to 100 Hz, i.e., sound energy was amplified by 5 dB in the enclosed air space.

The decrement in sound attenuation attributable to sound leakage under the hearing protector may affect speech understanding. When hearing protectors are worn, subjects typically show a decrease in the percentage of words correctly recognized, which is proportional to their difficulty in hearing the speech stimulus. The attenuation provided by the protector adds to unoccluded hearing thresholds. Improvements in speech understanding in noise with protectors worn were reported for normal-hearing subjects. This effect may result from reductions in cochlear overload and concomitant signal distortion with the overall decrease in the level of signal plus noise.[9] In contrast, individuals with even mild hearing loss show decrements in speech understanding in noise.[11] Although one might predict that sound leakage would improve performance, at least one study showed the reverse. Wagstaff et al.[12] assessed the ability of normal-hearing male subjects to understand digits and words in 97-dBA helicopter noise while wearing a communication headset, with or without glasses. Performance was significantly poorer when the glasses were worn. The authors argued that breaking the seal of the earmuff resulted in greater low-frequency masking of the speech. In the study by Abel et al.,[7] no differences in consonant discrimination were observed across ear conditions, either in quiet or in noise. The difference in outcomes for the two studies may be attributable to differences in the type of background noise (low-frequency vs. speech spectrum) and/or differences in the noise level (97 dBA vs. 80 dB sound pressure level [SPL]).

The present study was conducted to extend the information available regarding the effects on auditory perception of wearing safety gear designed for the face and head. The specific goal was

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to assess hearing, sound attenuation, and speech understanding when conventional, passive, hearing-protective earmuffs were worn in combination with a balaclava. A balaclava is a close-fitting knitted covering designed to protect the head, face, and neck during cold weather operations. In military environments, it may also be worn under a helmet and with ballistic eyewear and/or a neck gaiter. Wearing the balaclava under an earmuff would be expected to result in sound leakage under the ear cup, decreasing the sound attenuation afforded by this device.

Methods

Experimental Design

One group of 20 subjects with normal hearing (18 to 55 years of age) participated. Equal numbers of male and female subjects were tested, to allow assessment of the effects of gender on the attenuation provided by the earmuffs. Head circumference is typically smaller for women, which might result in a poorer fit of the device and thus relatively less attenuation.[7] Because one of the tests involved speech understanding, all subjects were required to have English as their first language. Volunteers were screened for a medical history of ear problems or hearing loss, the use of medications that might affect concentration or the ability to complete the experimental protocol, and the need for glasses to view large print. The last of these constraints was designed to avoid possible leakage under the earmuff from uncontrolled sources.[7] Hearing was assessed only for volunteers who met the screening criteria. Individuals who had no more than slight hearing loss (i.e., whose pure-tone air-conduction thresholds were <25 dB hearing level at 0.25, 0.5, 1, 2, 4, and 8 kHz in each ear) were admitted to the study.[13]

Each subject participated in one 2.5-hour session. Tests were conducted with the ears (1) unoccluded, (2) fitted with E-A-R 3000 earmuffs, (3) fitted with the earmuffs in combination with a Canadian Forces standard-issue balaclava worn full face under the muffs, or (4) fitted with the earmuffs in combination with the balaclava rolled to cover the head and ears only (Fig. 1). Both the muffs and balaclava were fit by the experimenter to ensure optimal performance by the earmuffs.[14] The balaclava was always positioned over the ears, either covering the entire face or folded (rolled) to create three layers of material under the earmuffs. The order of the four ear conditions was counterbalanced across the ten subjects in each gender subgroup. For each ear condition, measurements were made of (1) diffuse-field hearing thresholds for eight third-octave noise bands with center frequencies ranging from 0.25 kHz to 8 kHz and (2) consonant discrimination at a comfortable listening level (70 dB SPL) in quiet. Sound attenuation was derived for each subject by subtracting the unoccluded value from the protected hearing threshold at each frequency for each of the three protected ear conditions.

Fig. 1. E-A-R 3000 earmuffs worn alone (left) or with a balaclava full face (center) or rolled (right).

Subjects

Subjects were recruited by means of an advertisement sent electronically to all civilian and military personnel based at Defence Research and Development Canada-Toronto. The study protocols were approved by the human research ethics committee, and each subject provided informed written consent before having his or her hearing screened. Compensation for participation conformed with institutional guidelines. Male and female subjects were 23 to 41 years of age (mean, 33 years) and 23 to 47 years of age (mean, 34 years), respectively. For all except two subjects, hearing thresholds at the six pure-tone frequencies tested were ≤15 dB hearing level. Hearing thresholds for the outliers were 20 dB at 4 kHz and 8 kHz, respectively, in the left ear.

Apparatus

The apparatus was described previously.[15] Subjects were tested individually while seated in a double-walled, semireverberant booth (IAC Series 1200; Industrial Acoustics Company, Bronx, New York) with inner dimensions of 3.5 m (length) × 2.7 m (width) × 2.3 m (height). Ambient noise levels in the booth met the requirements of American National Standards Institute Standard S12.6–1997.[2] Third-octave band noise stimuli for the hearing test were produced with a white-noise generator (B&K 1405; Brüel and Kjaer Instruments, Norcross, Georgia) and band-pass filter (B&K 1617; Brüel and Kjaer Instruments). Stimulus duration and envelope shape were controlled by means of a Coulbourn Instruments modular system (Coulbourn Instruments, Lehigh Valley, Pennsylvania). The speech test was available on audio cassette[16] and was played with a cassette deck (KX-393; Yamaha, Buena Park, California). Outputs were fed to a manual range attenuator (HP 350-D; Hewlett-Packard, Palo Alto, California) and receiver (RX-V620; Yamaha) and presented free-field over a set of three loudspeakers (DL10; Celestion, Maidstone, Kent, United Kingdom) positioned to create a uniform sound field. Devices were controlled from a personal computer via IEEE-488 (Institute of Electrical and Electronics Engineers, New York, New York) and LabLinc (Coulbourn Instruments, Lehigh Valley, Pennsylvania) interfaces and digital input/output lines. For the hearing threshold task, subjects used a handheld pushbutton switch to indicate that they had heard the stimulus. Paper and pencil were used for the consonant discrimination task.

Procedure

For each ear condition, hearing thresholds were measured once for each of eight third-octave noise bands (centered at 0.25, 0.5, 1, 2, 3.15, 4, 6.3, and 8 kHz) by using a variation of Békésy tracking.[17] The stimulus was a train of short pulses. The duration of each pulse was 250 milliseconds, including rise and fall times of 50 milliseconds. The time between pulses was 150 milliseconds. The subject was required to press a handheld pushbutton switch as soon as the sound was detected and to keep the button depressed until the sound was no longer audible. The sound level of consecutive pulses increased in steps of 1 dB until the button was depressed and then decreased at the same rate of change until the button was released. This procedure was continued until there were at least eight alternating-intensity excursions with a range of 2 to 20 dB. Hearing threshold was defined as the average sound level of the eight final peaks and valleys.

Consonant discrimination was assessed by using the Four Alternative Auditory Feature Test.[16] The subject was given a typewritten list of 80 sets of four monosyllabic consonant-vowel-consonant words. Randomly distributed throughout the list, the initial consonant (e.g., wet, bet, get, and yet) was contrasted in one-half of the sets and the final consonant (e.g., bad, bag, bat, and back) was contrasted in one-half. One word from each set was presented over the loudspeakers, and the subject circled the alternative heard on the typewritten form. There were five alternative lists available; these were counterbalanced across conditions and subjects in each gender subgroup.

Results

Mean hearing thresholds for the eight stimulus frequencies tested are presented in Table I for the four ear conditions, according to gender subgroup. The same data are shown in Figure 2, averaged across male and female subjects. An analysis of variance (ANOVA) applied to these data indicated that there were significant effects of gender ($p < 0.05$), ear condition ($p < 0.0001$), stimulus frequency ($p < 0.0001$), and ear condition by frequency ($p < 0.0001$). Averaged across ear condition and stimulus frequencies, hearing thresholds were 3 dB lower for female subjects than for male subjects. Averaged across gender subgroups and stimulus frequencies, hearing thresholds for the four ear conditions ranged from 7 dB SPL for the unoccluded condition to 41 dB SPL for the muff-alone condition, with the muff and balaclava conditions being midway between at 25 dB SPL (muff plus balaclava worn full face) and 22 dB SPL (muff plus balaclava rolled). Post hoc pairwise comparisons using Fisher's least significant difference test[18] indicated that there were significant differences among all four ear conditions ($p < 0.001$), whether averaged across or within each of the eight stimulus frequencies, except for muff plus balaclava rolled vs. muff plus balaclava worn full face at 4 kHz and 6.3 kHz and unoccluded vs. muff plus balaclava rolled at 0.25 Hz, which were not different.

Mean sound attenuation values derived for the muff and muff in combination with the balaclava, worn full face or rolled, are given in Table II for each stimulus frequency according to gender subgroup and in Figure 3 for each frequency averaged across gender. The manufacturer's specifications are shown for comparison with the observations in Figure 3. As can be seen, the results obtained with the muff worn alone were within 2 dB of the specification from 0.25 kHz to 6.3 kHz and 4 dB at 8 kHz. SDs for the two sets of data were within 2 dB. An ANOVA applied to the data for the protected conditions showed significant effects of ear condition, stimulus frequency, and ear condition by stimulus frequency ($p < 0.001$). Averaged across the eight frequencies, the muff and muff in combination with the balaclava worn full face or rolled provided 34 dB, 19 dB, and 15 dB of sound attenuation, respectively. Post hoc pairwise comparisons showed that, averaged across stimulus frequencies, there were significant differences among the three protected conditions ($p < 0.001$). Within frequency, there were again significant differences among all three protected conditions ($p < 0.001$) from 0.25 kHz to 3.15 kHz, with the greatest attenuation being observed for the muff and the lowest for the muff in combination with the balaclava rolled. Over this frequency range, the attenuation provided by the muff worn alone varied from 21 dB to 35 dB, by the muff and balaclava full face from 5 dB to 19 dB, and by the muff and balaclava rolled from 1 dB to 16 dB. From 4 kHz

TABLE I

HEARING THRESHOLDS WITH THE EARS UNOCCLUDED OR FITTED WITH E-A-R 3000 EARMUFFS WORN ALONE OR WITH A BALACLAVA

Gender	Frequency (kHz)	Hearing Threshold (dB SPL)			
		Unoccluded	Muff	MBF	MBR
Male	0.25	19.0 ± 5.0	39.4 ± 3.8	23.8 ± 2.4	18.7 ± 3.7
	0.5	9.5 ± 4.7	40.7 ± 4.6	22.8 ± 3.8	17.0 ± 5.4
	1.0	2.7 ± 3.3	45.0 ± 4.4	26.4 ± 4.4	20.1 ± 3.9
	2.0	5.1 ± 4.7	39.6 ± 6.6	23.5 ± 6.9	15.2 ± 4.5
	3.5	1.6 ± 6.2	36.3 ± 6.0	21.1 ± 6.6	18.7 ± 6.5
	4.0	2.9 ± 5.4	40.2 ± 6.4	23.4 ± 7.3	23.7 ± 5.2
	6.3	11.2 ± 7.0	46.8 ± 7.1	35.4 ± 7.5	37.0 ± 8.8
	8.0	12.3 ± 4.6	48.2 ± 7.2	36.3 ± 6.8	40.8 ± 5.7
Female	0.25	16.8 ± 2.9	38.7 ± 4.5	22.7 ± 5.2	18.5 ± 3.2
	0.5	8.4 ± 4.5	38.5 ± 4.1	19.8 ± 4.3	15.7 ± 4.3
	1.0	2.3 ± 3.9	44.8 ± 3.3	26.7 ± 3.7	16.5 ± 4.1
	2.0	3.4 ± 4.1	38.9 ± 3.8	23.1 ± 3.0	11.6 ± 4.5
	3.15	−1.7 ± 2.9	34.0 ± 2.4	17.2 ± 2.8	13.0 ± 2.4
	4.0	−2.1 ± 2.1	35.7 ± 3.3	18.0 ± 2.2	16.3 ± 2.2
	6.3	5.9 ± 3.6	41.2 ± 4.1	32.2 ± 3.3	31.5 ± 4.0
	8.0	10.5 ± 1.8	45.5 ± 3.9	35.2 ± 2.0	37.0 ± 1.8

Values are mean ± SD ($n = 10$). Muff, ears fitted with E-A-R 3000 earmuffs; MBF, ears fitted with the earmuffs in combination with a balaclava worn full face under the muffs; MBR, ears fitted with the earmuffs in combination with the balaclava rolled to cover the head and ears only.

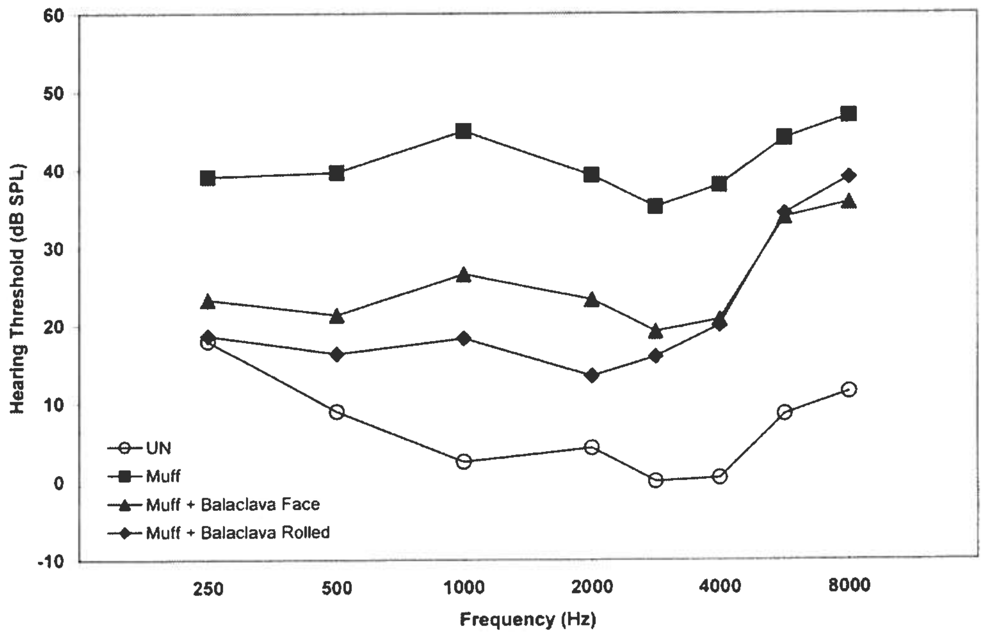

Fig. 2. Effects of the four ear conditions on hearing thresholds. UN, unoccluded.

TABLE II

SOUND ATTENUATION ACHIEVED WITH E-A-R 3000 EARMUFFS WORN ALONE OR WITH A BALACLAVA

Gender	Frequency (kHz)	Sound Attenuation (dB)		
		Muff	MBF	MBR
Male	0.25	20.4 ± 4.1	4.8 ± 4.6	−0.3 ± 3.4
	0.5	31.2 ± 2.9	13.4 ± 2.6	7.5 ± 2.6
	1.0	42.3 ± 4.0	23.7 ± 3.6	17.4 ± 4.9
	2.0	34.5 ± 3.7	18.4 ± 3.6	10.2 ± 3.1
	3.15	34.7 ± 2.6	19.5 ± 3.2	17.1 ± 3.4
	4.0	37.3 ± 2.6	20.6 ± 3.0	20.8 ± 1.9
	6.3	35.5 ± 2.6	24.2 ± 2.5	25.8 ± 2.9
	8.0	35.9 ± 2.8	24.0 ± 3.2	28.5 ± 3.4
Female	0.25	21.8 ± 4.1	5.8 ± 3.8	1.7 ± 2.9
	0.5	30.2 ± 2.4	11.4 ± 2.5	7.3 ± 1.7
	1.0	42.6 ± 4.4	24.4 ± 3.3	14.2 ± 3.4
	2.0	35.5 ± 3.9	19.7 ± 3.0	8.3 ± 2.1
	3.15	35.7 ± 2.3	18.9 ± 2.7	14.7 ± 1.9
	4.0	37.8 ± 2.0	20.1 ± 1.9	18.3 ± 2.1
	6.3	35.3 ± 2.1	26.3 ± 3.8	25.7 ± 2.2
	8.0	35.0 ± 3.4	24.6 ± 1.7	26.4 ± 2.6

Values are mean ± SD (n = 10). Ear conditions are as in Table I.

to 8 kHz, the muff alone again provided significantly more attenuation than did the other two conditions ($p < 0.001$). The muff plus balaclava conditions were no different at 4 kHz and 6.3 kHz, but the balaclava rolled provided significantly more attenuation than did the balaclava worn full face at 8 kHz. Above 3.15 kHz, the attenuation provided by the muff alone remained fairly stable at ~36 dB. In contrast, the attenuation provided by the muff plus balaclava worn full face ranged from 20 dB to 24 dB and by the muff plus balaclava rolled from 20 dB to 27 dB.

Table III shows the effect of ear conditions on consonant discrimination for each of the four ear conditions, according to gender. An ANOVA applied to these data showed significant effects of gender ($p < 0.05$), ear condition ($p < 0.001$), initial vs. final consonant position ($p < 0.0001$), ear by gender ($p < 0.01$), and ear condition by consonant position ($p < 0.05$). Mean scores for the four ear conditions ranged from 90% (muff alone) to 97% (unoccluded), with the muff plus balaclava conditions being midway between at 95% to 96%. Post hoc pairwise comparison indicated that the unoccluded and muff plus balaclava conditions were no different. All three conditions resulted in significantly higher scores than did the muff alone ($p < 0.001$). Averaged across consonant positions, the effect of gender was significant only in the muff-alone condition (93% for female subjects and 87% for male subjects; $p < 0.001$). Averaged across gender, accuracy scores were higher for discrimination of the initial consonant than the final consonant by 4% with the muff ($p < 0.001$) and by 3% with the muff plus balaclava worn full face ($p < 0.05$).

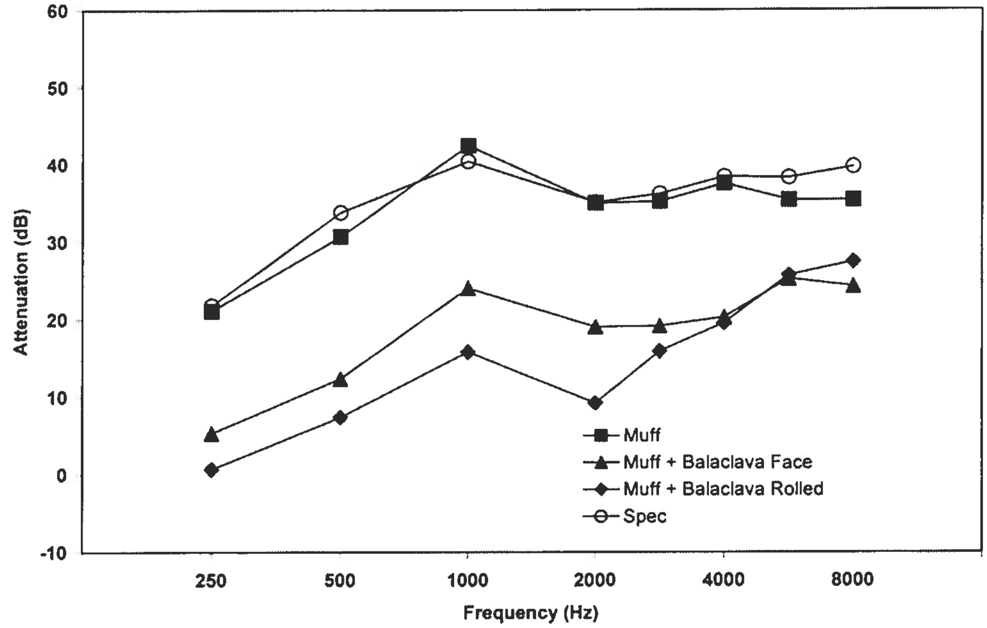

Fig. 3. Effects of the three protector conditions on sound attenuation. Spec, manufacturer's specifications.

TABLE III

CONSONANT DISCRIMINATION WITH E-A-R 3000 EARMUFFS WORN ALONE OR WITH A BALACLAVA

Gender	Consonant Position	Consonant Discrimination (%)			
		Unoccluded	Muff	MBF	MBR
Male	Initial	97.5 ± 0.9	90.3 ± 5.7	96.7 ± 2.2	97.2 ± 0.0
	Final	96.6 ± 2.2	84.8 ± 8.0	93.4 ± 2.3	94.6 ± 3.6
	Total	97.0 ± 1.1	87.3 ± 6.6	94.9 ± 2.0	95.8 ± 2.0
Female	Initial	98.0 ± 1.4	94.7 ± 3.0	96.9 ± 0.9	96.9 ± 1.6
	Final	97.3 ± 1.4	92.1 ± 6.4	94.6 ± 4.3	95.7 ± 2.2
	Total	97.6 ± 1.1	93.3 ± 4.1	95.6 ± 2.4	96.3 ± 1.3

Values are mean ± SD percentage correct (n = 10). Ear conditions are as in Table I.

Discussion

The aim of this research was to determine whether the performance of conventional sound-attenuating earmuffs would be compromised by a balaclava worn in combination. The results confirmed the findings of previous studies that the wearing of the earmuffs alone resulted in a significant increase in hearing thresholds.[11] Across the frequency range tested, the results showed that, for normal-hearing listeners, warning sounds would have to be 35 to 47 dB SPL to be detected with the muff worn alone, 19 to 36 dB SPL with the muff and balaclava worn full face, and 13 to 39 dB SPL with the muff and balaclava rolled. In all three conditions, protected thresholds were a U-shaped function of frequency, with the minimum occurring at either 2 kHz or 3.15 kHz. Thresholds levels at 8 kHz were relatively higher than those at 0.25 kHz, by 8 dB, 12 dB, and 20 dB for the three conditions, respectively.

The attenuation values of the earmuffs at the frequencies tested, derived by taking the difference between protected and unoccluded hearing thresholds, closely matched the manufacturer's specifications. Differences were within 2 dB below 8 kHz. The observed attenuation increased from 21 dB to 42 dB from 0.25 kHz to 1 kHz and then remained stable at 35 to 38 dB from 2 kHz to 8 kHz. Gender was not a significant factor in determining outcomes. This finding is in line with previous reports that suggested that male/female differences are more likely with earplugs than earmuffs, despite gender differences in both ear canal cross-sectional diameter and head circumference.[7,19] The wearing of the balaclava full face under the muffs resulted in fairly constant decreases in attenuation, relative to the muff alone, of 16 to 18 dB for frequencies below 6.3 kHz and 10 to 11 dB at 6.3 kHz and 8 kHz. This outcome is in contrast to previously reported, predominately low-frequency decrements of only 5 dB attributable to the wearing of either glasses or a respirator under earmuffs. When the balaclava was worn as a cap, decrements in attenuation, relative to the muff alone, increased from 20 dB to 27 dB from 0.25 kHz to 1 kHz and then deceased to 18 dB at 4 kHz. Decrements at 6.3 and 8 kHz were 8 to 10 dB, as in the case of the balaclava worn full face. The maximal effect was observed at 1 to 2 kHz. The difference in the decrement in attenuation attributable to wearing the balaclava as a cap rather than full face increased from 5 dB to 10 dB from 0.25 kHz to 2 kHz but was only ≤3 dB for higher frequencies.

Studies have suggested that, for individuals with hearing loss, the average hearing threshold for frequencies of ≤1 kHz is the best predictor of the speech reception threshold in quiet.[20] Despite the fact that the mean hearing threshold increased by 41 dB in this frequency region with the earmuffs, the percentage of consonants correctly perceived decreased by only 7% (5% for the initial consonant and 9% for the final consonant). This was likely attributable to the fact that the hearing loss induced by the device was not sufficient to interfere with the perception of the speech stimulus. When the balaclava was worn in either of the two modes, this effect disappeared. Accuracy was no different than that observed in the unoccluded condition. This outcome was expected because, below 2 kHz, there was a gain in level of 17 dB with the muff worn full face and 23 dB with the muff rolled. Differences attributable to consonant position (initial vs. final) were relatively small, albeit statistically significant. Female superiority in speech understanding when listening with the muff was not expected, because there was not a significant gender-ear condition interaction for the hearing thresholds. It was shown that, as individuals age, men but not women show declines in word recognition that are unrelated to differences in hearing.[21] Women also show an advantage over men in verbal memory.[22] It may be that the gender differences found in the present study and those cited may be related to the same underlying central processing mechanisms.

The findings support the following conclusions. (1) Wearing a balaclava full face under earmuffs resulted in a 16- to 18-dB decrement in sound attenuation for frequencies below 6.3 kHz. (2) Wearing the balaclava as a cap under the earmuffs resulted in an inverted U-shaped decrement in attenuation, ranging from 18 dB to 27 dB from 0.25 kHz to 4 kHz and peaking at 1 kHz. (3) Decrements in consonant discrimination of 7% were evident only when the muff was worn alone. These findings underscore the importance of assessing personal protective equipment under the conditions in which it will be worn. Although it would be important to study the additional effect of military operational noise on protected speech perception under controlled laboratory conditions, it is clear from the present study that the attenuation provided by the earmuffs in combination with the balaclava would be sufficient to protect against hearing loss only for a very limited exposure period.

Acknowledgments

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