ARCHIVES OF ACOUSTICS
19, 2, 139–146(1994)

SOUND LEVELS PRODUCED AT AND IN THE OCCLUDED EAR OF THE TALKER

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Sound pressure levels (SPL) generated in the ear of the talker depend on both air and bone conduction feedback paths. In the present study six talkers (three females and three males) produced six phonemes: /u/, /a/, /i/, /m/ and /v/ and three shouts "help", "fire", and "no". The SPLs generated in the occluded and at the unoccluded ear of the talker were measured. Results indicated that occluding the ear canal enhanced auditory feedback for /u/, /i/, /m/, and /v/ sounds and reduced it for /a/ and loud shouts. These findings may have implications for speech rehabilitation programs and hearing aid fitting.

1. Introduction

Talkers monitor their speech by auditory feedback received via air and bone conduction pathways. Auditory feedback is important for the quality of speech production but at the same time masks external sounds arriving at the talker's ear. The opposite effect is also possible when a strong external sound, such as high level background noise, may mask acoustic feedback and consequently affect speech production.

An important property of auditory feedback is the air-to-bone feedback ratio (ABFR), that is, the ratio of speech energy arriving to the ear of the talker via air-conduction and bone-conduction pathways. The ABFR depends on several factors but is most considerably affected when the talker's ears are occluded by hearing aids or hearing protectors. Occlusion of the ear canals of the talker results in two phenomena altering ABFR: (a) a decrease in sound pressure level (SPL) arriving to the ear of the talker via air conduction and (b) an increase in SPL generated in the ear canal via bone conduction (occlusion effect). Both these effects are frequency dependent.

Dunn and Farnsworth [1] and Bekesy [2] were the first to measure SPLs at the ear of the talker. Bekesy [2] observed that the intensity of a speech signal rapidly decreases outside of the talker's mouth and is attenuated by as much as 15 dB three centimeters away from the lips. Speech levels at the talker's ear were attenuated by 12 dB for the lower to 30 dB for the higher frequencies compared with the levels at the talker's lips. PLOMP and FESTEN [3] reported that SPLs measured at the ear of the talker exceeded by 5 dB the levels measured at the listener's ear 60 cm away from the talker. CORNELISSE, GAGNE and SEEWALD [4] observed similar 5 dB level differences (with a standard deviation of 3.0 – 3.5 dB) at a shorter distance 30 cm in front of the talker's lips. They also reported that the relative speech levels at the ear of the talker were similar for male, female and child voices.

PLOMP and FESTEN [3] observed also that masking of an incoming speech signal by the talker's speech does not affect conversation between normal hearing persons but a hearing impaired person is forced to choose between talking and listening. They estimated that when two talkers speak equally loud, the critical distance at which the talker's own voice makes it impossible to understand another talker at a distance is about 1.7 meter (2.6 m with speech-reading). For a person with hearing loss characterized by a 10 dB increase of speech recognition threshold (SRT), the above distance is reduced to about 50 cm (75 cm with speech-reading).

ZWISLOCKI [5], and later KHANNA, TONNDORF, and QUELLER [6], BERGER and KERIVAN [7], and KILLION, WILBER, and GUDMUNDSEN [8] demonstrated that occluding the ear with the earplug increases low frequency SPLs in the ear canal of the talker in comparison to those measured in the unoccluded ear. This effect can be greatly reduced or even eliminated by a deep insertion of the earplug into the bony (osseous) part of the ear canal.

The intensity of bone- relative to air-conducted sounds can be measured by occluding the ear canal which excludes air-conducted sounds from entering the ear. BEKESY [2] observed that attenuation of auditory feedback due to the elimination of air conduction was about 6 dB and varied from 0 to 12 dB depending on the talker and the speech sound. KILLION, WILBER and GUDMUNDSEN [8] investigated one male and one female talker vocalizing vowels /a/, /i/, and /u/ and reported that the most dramatic occlusion effects were observed at 250 Hz and practically nonexisting at 1000 Hz. The 250 Hz octave band sound pressure levels (SPLs) measured in the occluded ear of the talker differed from SPLs measured at the ear (80 dB SPL) by 20 to 30 dB for vowels /u/ and /i/ and – 5 to + 24 dB for vowel /a/ depending on the type of occlusion (type of earplug and depth of insertion). In another experiment involving only the male talker and a single earmold the authors reported very little difference in SPL between deep and shallow earmold fitting for the vowel /a/ and about 15 dB difference for vowels /i/ and /u/.

SIEGEL and PICK [9] reported that amplification of the talker's own voice by hearing aid(s) tends to reduce the overall level of speech produced by the talker. KUK [10] suggested that due to the differences in ABFR hearing impaired individuals might prefer different amounts of insertion gain and different frequency responses from their hearing aids for listening and speaking. He reported that the preferred insertion gain differed as much as 3 dB at 1000 Hz and 7 dB at 2000 and 4000 Hz for vented and unvented earmolds. Multi-memory programmable hearing aids make satisfying such requirements feasible. The question, however, remains what should be the difference between the two frequency responses in question to maximize hearing aid performance under both cicrumstances.

KRYTER [11] studied the effects of hearing protectors on speech communication and reported that wearing earplugs in noise causes the talker to lower his/her voice level by 1 to 2 dB. Similarly, HOWELL and MARTIN [12] and MARTIN, HOWELL and LOWER [13] found that voice levels decreased by 3 to 4 dB when the talkers wore earplugs in noise. Talkers using earmuffs demonstrated similar [13] or slightly lower [12] decrease of their voice levels. The lowering of speech production level may lead to the overall degradation of communication in noise, especially when both the talker and the listener wear hearing protectors [14]. According to HOWELL and MARTIN [12] the adjustment in speech by the talker results in a reduction in intelligibility score for the listener by more than 25% in "noise" (93 dB SPL) and about 4% in "quiet" (54 dB SPL) when the listener also wears hearing protectors. This reduction in speech communication effectiveness has to be mainly credited to changes in speech production pattern since several authors have demonstrated that wearing hearing protectors not by itself reduce speech recognition at noise levels exceeding 85 dB (A) [15, 16, 17, 18]. On the other hand, KRYTER [11] reported that when the talker wears the earplugs in quiet "he raises his voice level by three to four decibels since his own voice now sounds weaker to him because of attenuation of the air-borne components of the speech wave."

Unfortunately, it is still unclear as to what extent hearing aids and hearing protectors influence speech production and the amount and the spectral composition of the overall auditory feedback available to the talker. Thus, the purpose of the present study was to determine sound pressure level and spectral differences for various speech sounds measured at the ear and in the occluded ear of the talker. The second objective of the study was to determine the effects of gender and type of speech on ABFR.

2. Method

The talkers were three males and three females, between 20–25 years of age. Each talker produced three prolonged vowels /a/, /i/ and /u/; two consonants /m/ and /v/; and three shouted warning phrases "fire", "help", and "no". All speech recordings were obtained in a hearing test booth (IAC 400). A reference microphone (B&K 4144) was located 15 cm in front of the talker's lips. Another microphone (custom-built probe microphone based on Knowles S&P transducers) was either inserted through an EAR foam earplug into the occluded ear canal or located at the tragus of the talker's ear. In order to secure good repeatability of microphone insertion, the earplug holding the microphone was always inserted by an experimenter and the earplug's end was flush with the concha (intermediate insertion). The attenuation provided by the EAR plug with the probe tube attached varied from 26 to 41 dB depending on frequency as shown in Table 1. The frequency response of the probe microphone was ±2 dB from 100 to 4000 Hz.

Table 1. Mean attenuations and standard deviations (SD) provided by the E.A.R. earplug (with probe microphone attached) as measured (ANSI S12.6–1984) for six of the talkers. The values in the table are differences in sound pressure level measured at the ear and in the ear of the subject.

	FREQUENCY (Hz)							
	125	250	500	1000	2000	3150	4000	6000	8000
MEAN	28.5	26.8	29.0	28.3	30.5	38.7	39.3	41.3	40.7
SD	3.4	2.1	1.8	2.6	2.4	2.0	2.1	2.1	3.1

Each speed sounch was produced four times with the probe microphone located either in the occluded ear of the talker [productions 1 and 3] or at the tragus [productions 2 and 4]. The talkers were asked to produced their speech samples at a comfortable speech effort. All voice samples were recorded on an Ampex AG 440 tape recorder and subsequently analyzed using an octave band B&K 2113 audio frequency spectrometer. The recording equipment was calibrated in dB SPL and all controls were fixed for the length of the experiment. Calibration was verified following data collection.

3. Results and data analysis

The mean SPL and standard deviations of speech sounds are shown in Table 2.

Table 2. Mean level (dB) and standard deviation (in parentheses) of the sound pressure level measured at 15 cm distance in front of the talker's lips, at the tragus, and in the occluded ear of the talker.

SPEECH SOUND	SOUND PRESSURE LEVEL (dB)					
	AT LIPS		AT TRAGUS		IN THE EAR	
/ u /	85.0	(6.6)	86.0	(6.2)	96.6	(6.5)
/ a /	90.3	(9.4)	93.0	(9.3)	86.3	(8.8)
/ i /	83.0	(5.2)	83.8	(4.7)	95.3	(6.2)
/ m /	85.3	(3.9)	85.8	(3.8)	95.7	(4.6)
/ v /	81.3	(3.8)	82.8	(3.2)	97.3	(5.0)
help!	97.8	(7.8)	101.3	(7.1)	94.3	(6.7)
fire!	100.8	(3.8)	102.3	(2.9)	96.0	(3.5)
no!	102.3	(6.4)	103.5	(5.7)	96.2	(4.7)

The speech levels measured at the lips of the talker have been averaged across all four recordings. A single factor analysis of variance (unoccluded – occluded) indicated that there were no significant differences in speech levels produced at 15 cm from the lips of the talker speaking with both ears open and with one ear occluded by the microphone assembly. An additional two factor analysis of variance (male – female, test – retest) showed that there were no significant differences in respective SPL differences between male and female talkers and between test and retest data.

Inspection of Table 2 reveals that average attenuation of the vowel /a/ and shouted words due to the occlusion effect and obstruction of air conduction pathway was about 6 – 7 dB which agrees well with BEKESY (1949) [2]. Other investigated sounds, however, generated higher SPL by 10 – 15 dB in the closed ear than at the tragus due to the occlusion effect. In general, the SPLs recorded in front of the lips at 15 cm varied overall from 73 to 106 dB depending on the talker and the type of speech sound. The SPLs recorded at the tragus and in the occluded ear varied from 75 to 107 dB and from 68 to 104 dB SPL, respectively.

The mean differences and standard deviations between SPL recorded either at the tragus or in the occluded ear and the SPL recorded 15 cm from the talker's lips are shown in Table 3. The mean SPLs recorded at the tragus exceeded the levels in front of the talker's lips by 0.5 – 3.5 dB across all phonemes. These levels are lower than those reported by CORNELISSE *et al.* [4] but their reference microphone was located 30 cm away from the talker's lips. The differences between SPLs measured in the occluded ear and SPL measured in front of the talker's lips varied from −6.1 to +16.0 dB depending on the speech sound.

The differences between octave-band speech spectra measured at the tragus and in the occluded ear for speech sounds produced by the talkers are shown in Fig. 1. The

Table 3. Mean difference (dB) and standard deviation (in parentheses) between the sound pressure level of speech measured at the tragus or in the occluded ear of the talker and the sound pressure level measured at 15 cm distance in front of the talker's lips

SPEECH SOUND	RELATIVE SOUND PRESSURE LEVEL (dB)			
	AT THE TRAGUS		IN THE OCCLUDED EAR	
/u/	1.0	(2.3)	11.6	(2.6)
/a/	2.7	(1.5)	−4.0	(2.0)
/i/	0.8	(1.6)	12.3	(2.5)
/m/	0.5	(1.8)	10.4	(2.9)
/v/	1.5	(1.5)	16.0	(3.1)
help!	3.5	(1.9)	−3.5	(4.7)
fire!	1.5	(2.6)	−4.8	(3.0)
no!	1.2	(1.4)	−6.1	(3.6)

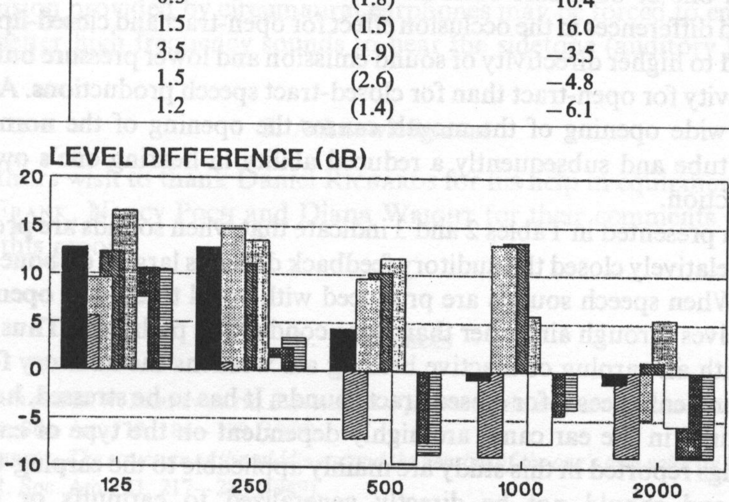

Fig. 1. Octave band speech levels in the occluded ear of the talker measured in reference to respective levels at the tragus of the talker. The level differences have been averaged across all sounds and talkers.

absolute speech levels measured in the individual bands varied from 72 to 100 dB SPL and depended on talker, speech sound, and the center frequency of the octave band. For the phonemes /u/, /i/, /m/ and /v/ the highest SPLs were measured in the 250 Hz octave band and varied from 72 to 84 dB across all six talkers. The SPLs of the phoneme /a/ consistently peaked at 1000 Hz and varied from 79 to 94 dB SPL. All three shouted sounds had spectral maxima of 80 – 100 dB SPL in 500 – 1000 Hz range with two female voices being the most intense and the third one being the weakest.

4. Discussion and conclusions

The high variability of the difference between SPL in the occluded ear canal and SPL measured in front of the talker's lips shown in Table 3 indicates a strong dependence of the bone conduction feedback on the type of speech production. An inspection of the differences presented in the table leads to the conclusion that speech sounds produced with wide open vocal tract (/a/, shouts) resulted in SPLs that were 6 to 7 dB SPL lower in the ear than at the tragus of the talker. Conversely, speech sounds produced with greater degree of vocal tract closure (/u/, /i/, /m/, /v/) resulted in SPLs in the occluded ear which exceeded the level measured at the tragus by 10 to 13.5 dB. These latter levels are about 10 to 15 dB lower than those reported by KILLION *et al.* [8]. One possible explanation of these differences can be the difference in the ear occlusion investigated in both studies. It is also unclear whether KILLION *et al.*'s subjects had one or both ears occluded.

Observed differences in the occlusion effect for open-tract and closed-lip sounds can be attributed to higher directivity of sound emission and lower pressure build-up in the laryngeal cavity for open-tract than for closed-tract speech productions. According to BEKESY [2], wide opening of the mouth causes the opening of the normally closed Eustachian tube and subsequently a reduced ability in hearing one's own voice via bone-conduction.

The data presented in Tables 2 and 3 indicate that when sounds are produced with vocal tract relatively closed the auditory feedback depends largely on bone conduction pathways. When speech sounds are produced with vocal tract wide open the talkers hear themselves through air rather than bone conduction pathways. Thus, closing the ear canal with an earplug or inactive hearing aid weakens the auditory feedback for open-tract and enhances it for closed-tract sounds. It has to be stressed, however, that SPLs measured in the ear canal are highly dependent on the type of ear occlusion. Thus, findings reported in this study are mainly applicable to the earplug-type hearing protectors and should not be directly generalized to earmuffs or circumaural earphones. Since in both latter cases the occlusion effect will be less pronounced than in the case of the E.A.R earplugs, reported differences can serve as an upper limit estimate of the investigated effect.

The octave-band data (Fig. 1) indicate that the SPLs measured in the occluded ear canal were primarily controlled by bone conduction at low frequencies with increased importance of air conduction at medium frequencies (1 – 2 kHz). The actual ratio of energies transmitted to the ear canal by bone and air conduction at a particular frequency dependent on the type of speech sound. Inspection of Figure 1 leads, however, to a rough estimate that the doubling of frequency in the 125 Hz to 2000 Hz range results in a 5 dB decrease in the actual ratio of bone- to air-conduction feedback. This relationship is additionally modified by resonant properties of the open ear canal.

Hearing aid users are frequently dissatisfied with the quality and intelligibility of their own voices received by hearing-aid feedback. A low frequency emphasis of the auditory feedback may explain why ear-level hearing-aid users prefer less low frequency gain when listening to their own voices [19]. Thus, it seems desirable to equip hearing aids with a setting deemphasizing low frequency speech sounds for those cases when a hearing aid user becomes a talker (loud reading, public presentation, etc.). Such a setting could be quite easily implemented in a programmable hearing aid.

In the case of hearing protectors, reported data emphasize the importance of reducing bone-conduction feedback for speech communication in noise. Such reduction can be achieved by deep insertion of earplugs into the bony part of the ear canal and elimination of contact with the fleshy (cartilaginous) part of the canal. Moreover, it might be beneficial to add a narrow opening (tubing) tuned to approximately 3000–5000 Hz to the hearing protector in order to provide some "hiss" sound that may simulate the presence of high frequency sounds and facilitate better speech communication in industrial settings.

The fact that the occlusion effect greatly emphasizes low frequency energy of speech sounds may also have implications for speech rehabilitation. A client with some degree of ear occlusion provided by circumaural earphones may be forced to emphasize and articulate better high frequency sounds to hear the sidetone (auditory feedback).

5. Acknowledgment

The authors wish to thank Daniel Richards for his help in equipment calibration and Tom Frank, Nancy Poch and Diana Wright for their comments on the initial version of this report.

6. References

[1] H.K. Dunn and D.W. Farnsworth, *Exploration of pressure field around the human head during speech*, J. Acoust. Soc. Am., **10**, 184–199 (1939).

[2] G. von Bekesy, *The structure of the middle ear and the hearing of the one's own voice by bone conduction*, J. Acoust. Soc. Am., **21**, 217–232 (1949).

[3] R. Plomp and J.M. Festen, *Factors determinig speech-hearing handicap in noise*, Paper presented at the 121 Acoustical Society of America Meeting, Baltimore, MA, May 1991.

[4] L.E. Cornelisse, J.-P. Gagne and R.C. Seewald, *Ear level recordings of the long-term average spectrum of speech*, Ear and Hearing, **12**, 47–54 (1991).

[5] J. Zwislocki, *Acoustic attenuation between the ears*, J. Acoust. Soc. Am., **25**, 752–759 (1953).

[6] S.M. Khanna, J. Tonndorf and J. Quellar, *Mechanical parameters of hearing bone conduction*, J. Acoust. Soc. Am., **60**, 139–154 (1976).

[7] E.H. Berger and J.E. Kerivan, *Influence of physiological noise and the occlusion effect on the measurement of real ear attenuation at threshold*, J. Acoust. Soc. Am., **74**, 81–94 (1983).

[8] M.C. Killion, L.A. Wilber and G.I. Gudmundsen, *Zwislocki was right...*, Hearing Instruments, **39** (1), 14–18 (1988).

[9] G.M. Siegel and H.L. Pick, *Auditory feedback in the regulation of voice*, J. Acoust. Soc. Am., **56**, 1618–1624 (1974).

[10] F.K. Kuk, *Preferred insertion gain of hearing aids in listening and reading-aloud situations*, J. Speech Hear. Res., 33, 520–529 (1990).

[11] K.D. Kryter, *Effects of ear protective devices on the intelligibility of speech in noise*, J. Acoust. Soc. Am., **18**, 413–417 (1946).

[12] K. Howell and A.M. Martin, *An investigation of the effects of hearing protectors on vocal communication in noise*, J. Sound Vib., **41**, 181–196 (1975).

[13] A.M. Martin, K. Howell and M.C. Lowry, *Hearing protection and communication in noise*, In: Disorders of Auditory Function — II, S.D.G. Stephens (ed.), London, GB: Academic Press, 1976.

[14] W.I. Acton, *Problems associated with the use of hearing protectors*, Ann. Occup. Hyg., **20**, 387–395 (1977).

[15] W.I. Acton, *Effects of ear protection on communication*, Ann. Occup. Hyg., **10**, 423–429 (1967).

[16] P.E. Michael, *Ear protectors: Their usefulness and limitations*, Arch. Environ. Health, **10**, 612–618 (1965).

[17] P.A. Wilkins and A.M. Martin, *The effect of hearing protectors on the masked threshold of acoustic warning signals*, Proc. 9th ICA Congress, Paper H77 (p. 401), Madrit, 1977.

[18] P.A. Wilkins and A.M. Martin, *Hearing protection and warning signals in industry — A review*, Applied Acoustics, **21**, 267–293 (1987).

[19] F.K. Kuk, P. Stubbing and R.S. Tyler, *Hearing aid characteristics for speaking and listening*, Asha, **31** (10), 65 (1988).

Received January 28, 1993