Intelligibility of cartilage conduction speech in environmental noises

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ABSTRACT

The cartilage conduction is sound transmission route involved by the vibration at the aural cartilage, that was found by Hosoi (Nara Medical University) in 2004. When a transducer is gently put on the outer ear, clear sound can be heard due to the cartilage conduction. The cartilage conduction has two acoustical advantages. First one is to amplify the low-frequency sound in the ear canal without occluding the canal. Another one is that the sound in the canal can be increased for higher contact pressure of the transducer. The first advantage can be applied to a open-typed hearing aid, which can much reduce the stress of feeling fullness when worn an earplug. While the second advantage can be applied to a smartphone, which can control the speech volume with one hand operation by adjusting the contact pressure of the mounted transducer. Actually we have developed the test models of cartilage conduction hearing aid and smartphone, and now the practical performances are verified by the psycho-acoustical experiments. In this study, assuming the use in outdoor, speech intelligibility obtained passing through the cartilage conduction was examined in some noisy conditions. In the experiment I, the speech intelligibility of Japanese monosyllable was measured changing the kind and noise levels of the environmental noises. In the experiment, the ring-shaped transducer was used for the sake of remaining the ear canal opened. In the experiment II, the suitable application force of the transducer to listen to the Japanese continuous speech was measured in the same noise environments. As results, the monosyllable recognition from the cartilage presentation was inferior to that from the another open-fitting presentation, and the cartilage conduction hearing aid remains an issue to improve the output power in the middle frequency (> 1kHz). However, pressing the transducer on the tragus much improved the speech intelligibility, and the cartilage conduction speech was audible even in the highly noisy environment (80 dB). The cartilage conduction smartphone can realize the conversation even in the running train car.

INTRODUCTION

Hosoi (2004) found that clear sound can be heard through the aural cartilage vibration (Hosoi 2004a and 2004b), and we have developed a cartilage conduction transducer which is fitted on the entrance of external auditory canal as shown in Figure 1a (Hosoi et al. 2010). The cartilage conduction can generate sound in the canal especially for the lower frequency range than 3 kHz (Shimokura et al. 2014). An advantage of the cartilage conduction is to be able to amplify the sound remaining the canal opened unlike the other speaker device when the ring-shaped transducer is used (Shimokura et al. 2013). Therefore, in the case of the cartilage conduction hearing aid, the people with hearing loss, who has to wear a hearing aid during all the daytime, can be much less stressed by the feeling of ear fullness (Nishimura et al. 2013; Morimoto et al. 2014). When the concept is applied for a smartphone, the robust signal toward to the environmental noise can be realized (Tanaka 2013),

because the cartilage conduction sound in the canal is hard to leak from the canal, and is amplified by strengthening the contact pressure of the transducer at the cartilage.

Although the advantage of the cartilage conduction is to remove the annoyance by the ear occlusion, it may work against the hearing in the environmental noise because the opening of the transducer allow the noise to flow into the canal through it. So the aim of this study is to evaluate the speech intelligibility of the cartilage conduction sound changing the kind and noise levels of the environmental noises. This study was conducted with two experiments. First one is assuming the cartilage conduction hearing aid, and 50 Japanese monosyllables presented by the ring-shaped transducer were written down in the environmental noise. Another one is assuming the cartilage conduction smartphone, and an adequate sound volume to listening to Japanese speech was determined by adjusting the application force of the cartilage conduction transducer to the participant's ear tragus.

Cartilage conduction

The aural cartilage comprises the outer ear and is distributed around the exterior half of the external auditory canal. When the transducer is put on the entrance of the ear canal, the aural cartilage vibrates well (Shimokura et al, 2013). Figure 2 shows the distribution of the transmitted vibration at and around the outer ear. The aural cartilage vibrates effectively in the lower frequency range than 3 kHz, and the ear tragus, scaphoid fossa, and concha, which each of which contains cartilage, vibrated more strongly than did any other tissues at the other measurement points. This is why the device is called a ‘‘cartilage conduction transducer’’.

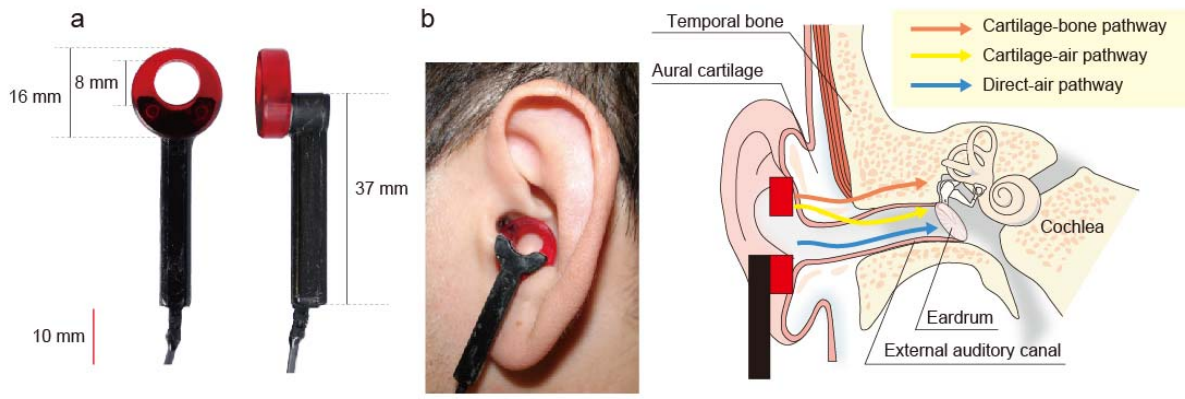

Figure 1: (a) Ring-shaped transducer, and (b) possible sound transmission routes when wearing it

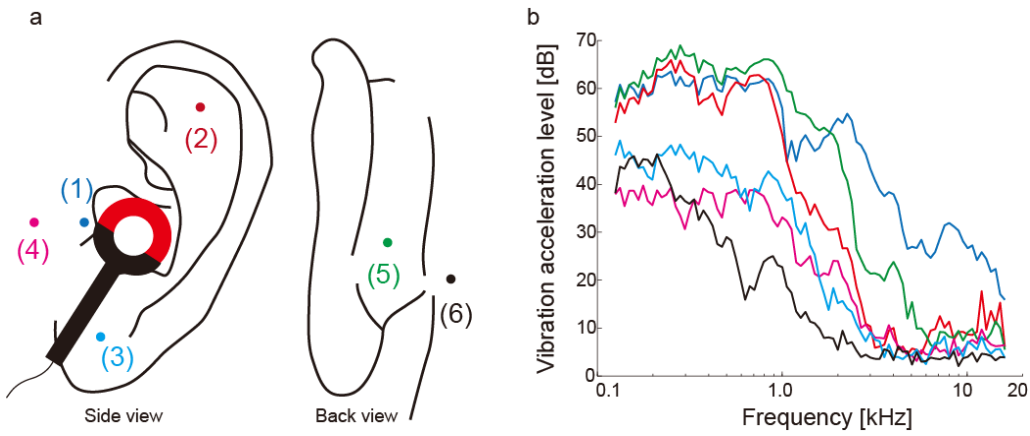

Figure 2: (a) Positions of vibration measurement, and (b) vibration acceleration level of each position

The vibrated aural cartilage generates sound directly in the external auditory canal. Figure 3 compared sound pressure level (SPL) in the canal in the touching and non-touching conditions (Shimokura et al, 2014). The touching condition means that the transducer touches at the entrance of canal, while the non-touching condition means that the transducer placed in essentially the same position but not touching the aural cartilage. When the aural cartilage was stimulated, the increase in SPL for frequencies lower than 1 kHz reached 35 dB. Although the cartilage conduction has often been assumed to be a type of bone conduction because both devices use vibrational transducers, the cartilage conduction transducer does not vibrate the skull bone, but the generated sound in the canal contributes dominantly to the hearing (Shimokura et al. 2014; Nishimura et al. 2014).

The cartilage conduction is distinguished from the bone conduction, so that it has some special acoustical characteristics seen only in the cartilage conduction. For example, the sound volume by the bone conduction does not change according to the application force of the transducer located on the mastoid, while the SPL in the canal is increased with the strengthen application force of the transducer at the ear tragus, and the SPL reaches maximum due to the occlusion of the external auditory canal by folding of the ear tragus (Figure 4) (Shimokura et al, 2014). Since the folding ear tragus can work as an insulation wall against environmental noise, the cartilage conduction enables to take a conversation even in highly noisy condition.

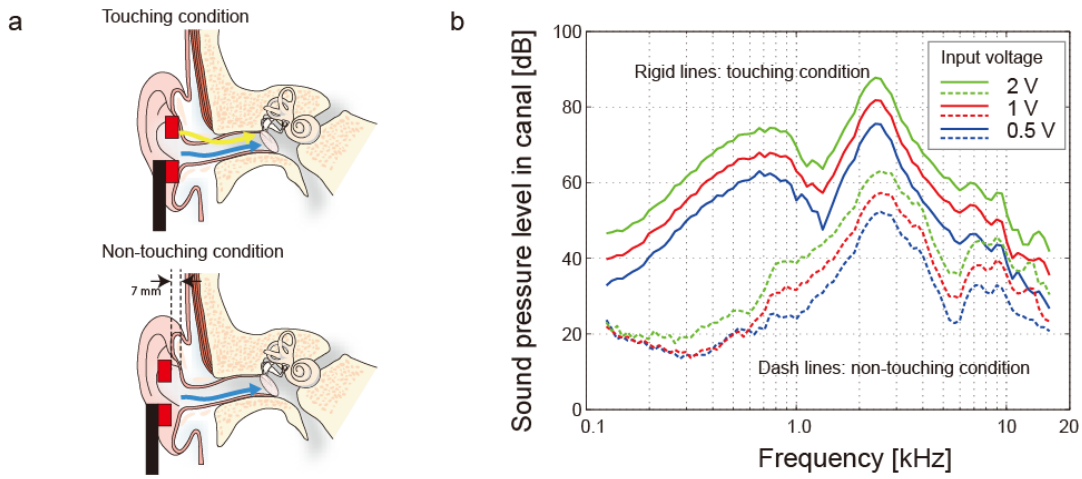

Figure 3: (a) Touching and non-touching condition, and (b) comparison of SPL in the canal under the two conditions

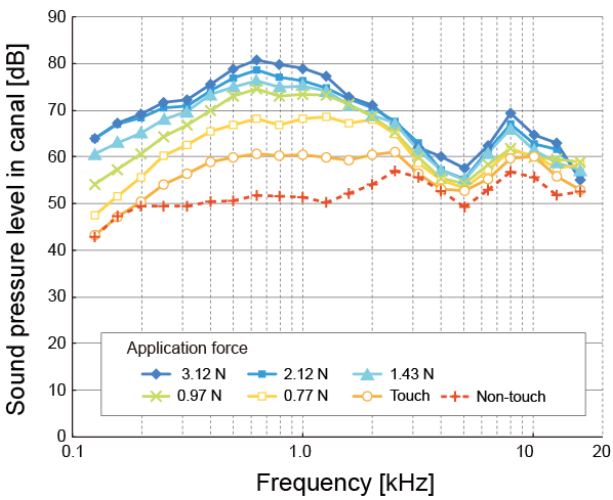

Figure 4: SPL in canal according to the different application forces of the transducer

METHODS

Experiment I (Speech intelligibility test in environmental noise condition)

Participants: Three native Japanese speakers with normal hearing (24 to 37 years) participated this experiment. They did not report having any hearing disorders, and in an audiometry test, the averaged detection threshold for 500, 1000 and 2000 Hz tones did not fall below 20 dB.

Signals: We used 50 Japanese monosyllables (e.g., /a/, /shi/, /ji/) pronounced by a professional female speaker, and the signals are generally used in Japanese medical institute for a speech audiogram (57-S monosyllable table). The monosyllables were presented binaurally to the participants using the cartilage conduction transducer (ring-shaped type) and open-fitting earplug for comparison. The open-fitting earplug also has some openings on the earplug for the purpose of reducing the feeling of fullness (Figure 5a), and the open-fitting hearing aid becomes widely used now. The output powers of the cartilage conduction and open-fitting presentations were identified by an 1-kHz calibration tone including in the CD of the 57-S monosyllable table (60 dB in the external auditory canal). Figure 5b compares the spectral powers of /a/ in the ear canal for the cartilage and open-fitting presentations. The open-fitting presentation is superior to output in the middle frequency range (1-2 kHz) because low-frequency sound is leaked from the openings, while the cartilage conduction is superior to output in the low frequency range (< 1 kHz) because the aural cartilage is vibrated well in the frequency range.

Environmental noises: We used four kinds of environmental noises (speech noise, street noise, train station noise, and cleaner noise) in four steps of noise level (50, 55, 60, and 65 dB) (Kawai et al. 2004). The noise level was calculated using a Head and Torso Simulator (type 4128, Brüel & Kjaer, Naerum, Denmark) sitting at the same position as the participant. Since the amplitudes of the street noise and train station noise were fluctuated dynamically, the amplitudes were smoothed for the sake of removing the unneeded silence. Figure 6a shows the spectral shapes of the four environmental noises.

Procedures: The environmental noises were presented two loudspeakers which were located oblique with respect to the participants (Figure 6b). The stereo outputs are uncorrelated. In the noisy environment, the participants wrote down the 50 Japanese monosyllable in a PC just as he heard.

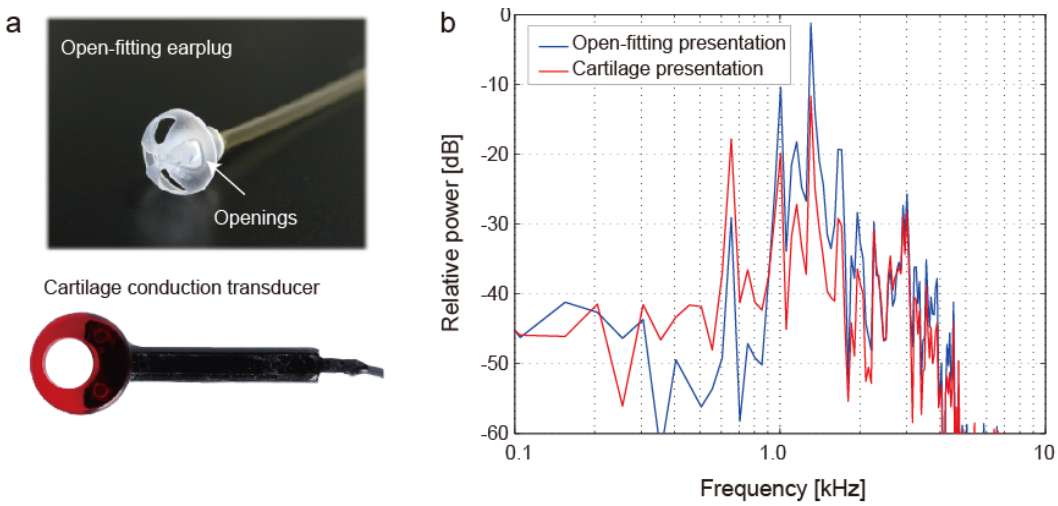

Figure 5: (a) Presentation methods, and (b) relative power for each presentation method in the canal

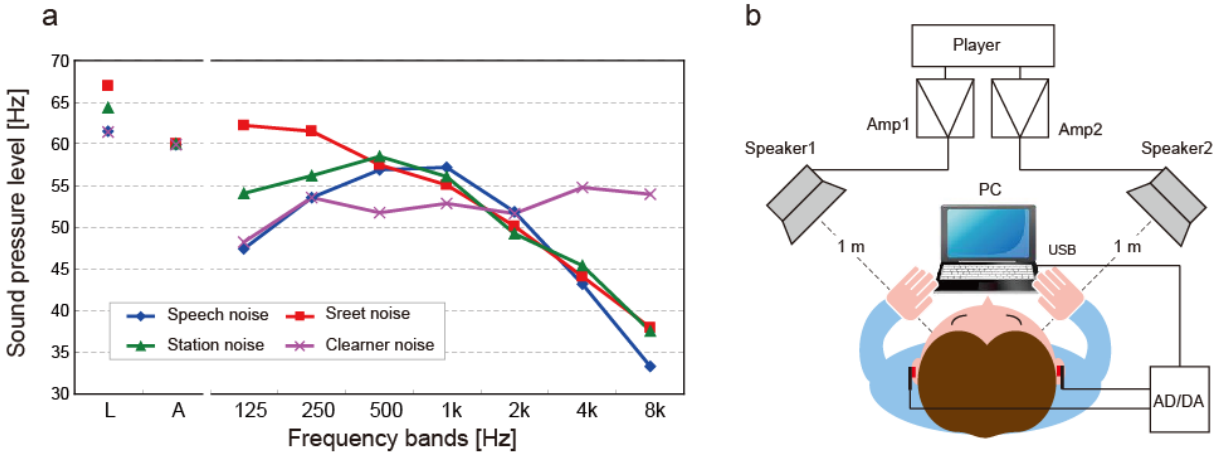

Figure 6: (a) SPL of each environmental noise in each bands and (b) block diagram for Experiment I

Experiment II (Application force in environmental noise condition)

Participants: Four native Japanese speakers with normal hearing (22 to 37 years) participated this experiment.

Signal: We used recorded Japanese radio news spoken by a professional male announcer. The contents of the news was wide-ranging (e.g., politics, diplomacy, economy, sports, etc.).

Environmental noises: The environmental noise was same as that used in the experiment I, but the noise levels were varied in 50, 60, 70 and 80 dB.

Procedures: The Japanese radio news was presented monaurally to the participants using the closed-typed transducer (Figure 7a and 7c). The participants heard the radio news putting the transducer on their ear tragus. The input voltage for the signal was fixed on 1 V, at which all of them could hear the radio news well in the silent condition. Between the transducer and their tragus, a mechanical pressure sensor (FSR400, Interlink Electronics Inc., Camarillo, CA) was sandwiched, and the force applied on the tragus was measured through a 2/1-ch. Input/Output module (Type 3110, Brüel & Kjaer).

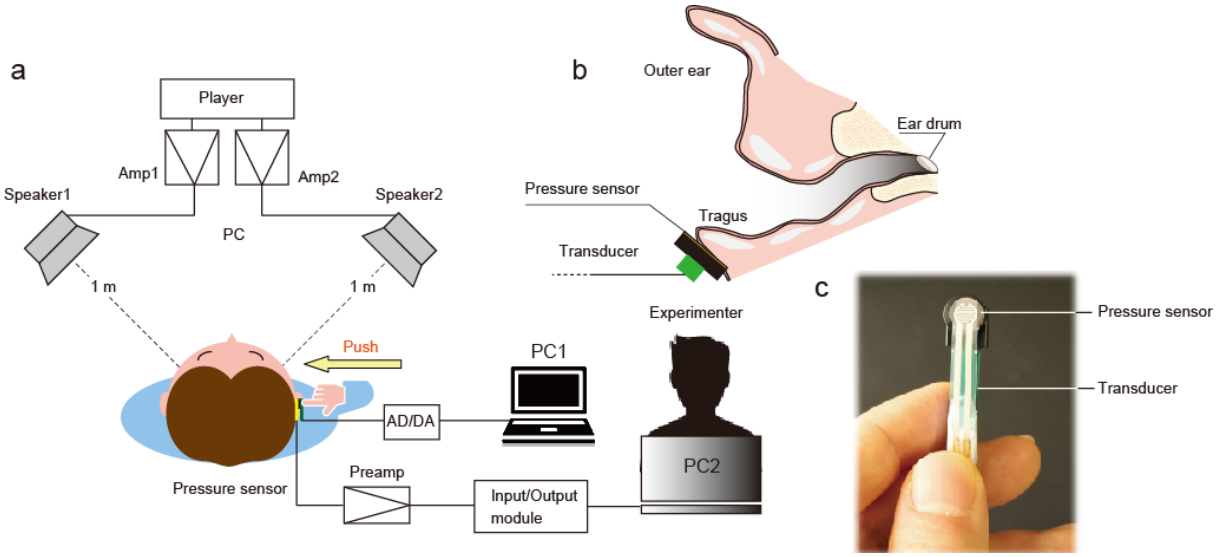

Figure7: (a) Block diagram for Experiment II, (b) transaxial plane of the external auditory canal, and (c) pressure sensor placed on the transducer

During the experiment, the environmental noises were presented two loudspeakers like the Experiment I. Since the cartilage conduction sound increases in the canal for the strengthening the application force of the transducer (Shimokura et al. 2014), the participants were instructed to adjust the application force in order to pick up the words enough in the noisy environment. After the adjustment, the participants gave the fact verbally (e.g., "Yes"), and then the experimenter recorded the application force at the moment.

RESULTS AND REMARKS

Figure 8 shows the averaged speech recognition score in each environmental noise with the different noise levels. Although the difference of noise kind was not significantly, the scores obtained from the open-fitting presentation was always superior to that from the cartilage conduction transducer. The open-fitting can emphasize the second and third formants of the monosyllables due to the spectral characteristics in the canal (Figure 5b), so that the open-fitting presentation could enable the participants to discriminate more consonants than the cartilage presentation. In the further development of the hearing aid, we have to improve the transducer in order to output higher power in the frequency range above 1 kHz.

Figure 9 shows the application force of the transducer adjusted in order to hear the radio news enough in the different environmental noises. For more noisy environment, the participants pushed the transducer on their tragus more strongly. A interior train noise generally reaches to 80 dB (Shimokura et al. 2012). So the cartilage conduction smartphone can realize the communication even in the running train car by pushing the embedded transducer on user's tragus. Above the 1 N, the ear tragus is folded and occludes the ear canal (Shimokura et al. 2014). So for the environmental noise with above 70 dB, the sound insulation effect by the tragus might help the speech recognition. In the further study, we will add the number of participant and consider the difference of the noise kind accurately.

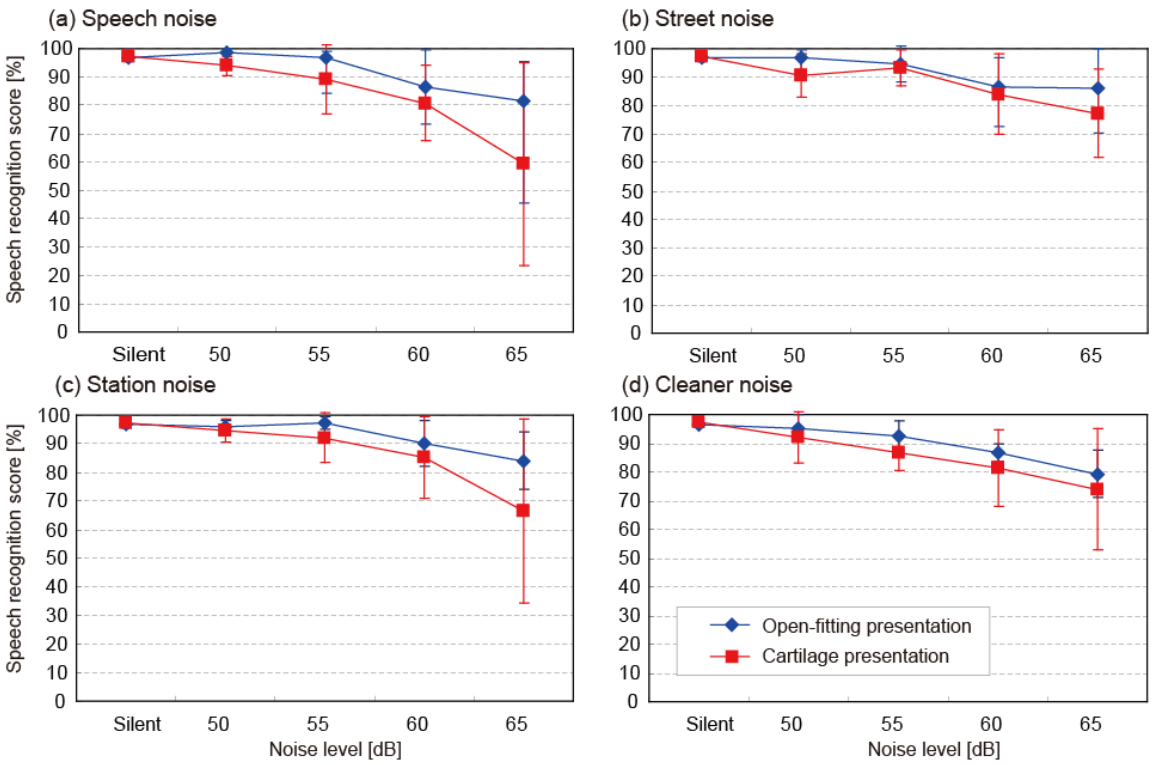

Figure 8: Speech recognition score in each environmental noise

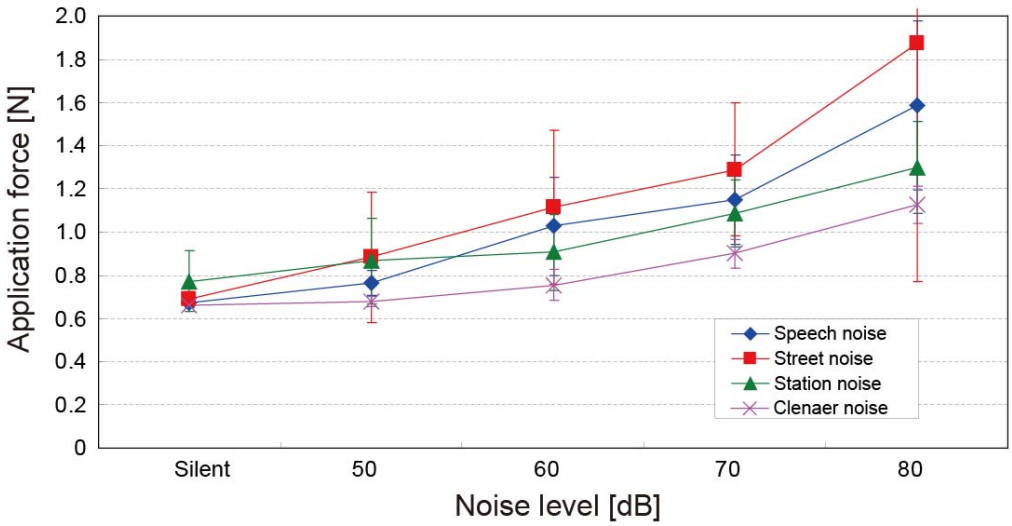

Figure 9: Application force of the transducer in each environmental noise

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