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The Effect of Stimulation Position and Ear Canal Occlusion on Perception of Bone Conducted Sound

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Abstract

The position of a bone conduction (BC) transducer influences the perception of BC sound, but the relation between the stimulation position and BC sound perception is not entirely clear. In the current study, eleven participants with normal hearing were evaluated for their hearing thresholds and speech intelligibility for three stimulation positions (temple, mastoid, and condyle) and four types of ear canal occlusion produced by headphones. In addition, the sound quality for three types of music was rated with stimulation at the three positions. Stimulation at the condyle gave the best performance while the temple showed the worst performance for hearing thresholds, speech intelligibility, and sound quality. The in-ear headphones gave the highest occlusion effect while fully open headphones gave the least occlusion effect. BC stimulated speech intelligibility improved with greater occlusion, especially for the temple stimulation position. The results suggest that BC stimulation at the condyle is generally superior to the other positions tested in terms of sensitivity, clarity, and intelligibility, and that occlusion with ordinary headphones improves the BC signal.

Keywords

bone conduction, hearing threshold, speech intelligibility, subjective sound quality evaluation

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Introduction

Sound can be perceived by air conduction (AC) and bone conduction (BC). In AC, the sound passes through the outer ear and middle ear to the cochlea where the sound stimulates the basilar membrane and the auditory neurons (Stenfelt et al., 2003). With BC, skull vibrations transmit the sound signals to the cochlea. BC has been suggested to have the following five main transmission pathways (Stenfelt & Goode, 2005a): a) sound radiation in the ear canal that is subsequently transmitted to the cochlea via the middle ear (Stenfelt et al., 2003; Surendran & Stenfelt, 2021); b) inertial motion of the ossicular chain (Stenfelt, 2006; Stenfelt et al., 2002); c) inertial motion of the cochlear fluids (Stenfelt, 2015, 2020); d) vibration of the bone around the inner ear leading to compression and expansion of the inner ear space (Stenfelt, 2015); e) sound pressure transmission from the cerebrospinal fluid (Roosli et al., 2016; Sohmer et al., 2000). Moreover, the human head is a complex mechanical system with multiple vibration modes during BC stimulation (Dobrev et al., 2017; Stenfelt & Goode, 2005b).

The core component of a BC device is the BC vibrator, which is a transducer that converts an electrical signal into vibration. The use of BC allows an open ear canal, so sound can be heard through AC and BC simultaneously. Moreover, sound leakage to the surrounding air is low (Chang et al., 2018), which means that BC has advantages in complex and dangerous environments, such as military and emergency rescue. The transmission characteristics of BC sound depend on the stimulation position, the site where the transducer is located at the head (Dobrev et al., 2016; Eeg-Olofsson et al., 2008; Stenfelt, 2012). Consequently, different positions of BC headphones affect

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BC-evoked sound sensitivity and quality, influencing the ability of a listener to detect and identify a sound correctly.

BC headphones are receiving more attention and are used in several applications (Barde et al., 2019). This evolution is partly driven by the feature of receiving sound signals while maintaining sensitivity to environmental sounds information, since the BC headphones leave the ear canal open. Therefore, BC headphones have become popular for sports, driving, in public places, and for military communication. An optimal position of the BC vibrator improves the user experience and can reduce the power consumption of the device, thereby increasing the usage time.

Studies have been conducted on BC hearing thresholds and intelligibility in non-clinical settings. Studebaker (1962) measured pure tone hearing thresholds for BC stimulation at three positions: the mastoid, forehead and vertex, and the lowest thresholds were obtained at the mastoid position. The vertex position gave significantly lower thresholds than the forehead position for frequencies below 1 kHz, whereas at other frequencies the thresholds were similar for the two positions. McBride et al. (2008) reported hearing thresholds for BC headphones at 11 positions based on military application requirements. The lowest thresholds were found with stimulation at the condyle. Dobrev et al. (2016) found that hearing thresholds and cochlear promontory velocity were better with stimulation on the condyle than on the mastoid.

The above studies investigated BC sound sensitivity, but the stimulation position may also have an impact on speech intelligibility and subjective sound quality. Gripper et al. (2007) used the Callsign Acquisition Test (CAT) to investigate BC speech intelligibility with stimulation at the condyle, and reported that participants' intelligibility performance under three different SNRs (−6 dB,-9 dB,-12 dB) were significantly different. Osafo-Yeboah et al. (2009) also used the CAT and found no statistically significant differences in intelligibility between stimulation at the condyle and the mastoid. Stanley and Walker (2009) used the diagnostic rhyme test and showed that AC stimulation gave the best speech intelligibility scores, followed by BC stimulation at the condyle, at the mastoid, and finally at the vertex. The test material of the CAT is composed of numbers and military terms, while the material of the diagnostic rhyme test is English dialogues. These three studies all tested with English language and there are no reports with Mandarin Chinese that have investigated the effect of BC stimulation position. Mandarin Chinese and English vary greatly in phonology and results such as speech intelligibility in English may not translate directly to results using Mandarin Chinese. For example, Mandarin Chinese use four tones to express words while English use raising and falling tones to express emotions. Consequently, there is a need to investigates speech intelligibility with Mandarin Chinese using BCDs at different stimulation positions and also to explore sound quality with Chinese Mandarin speech and music at these stimulation positions.

When the opening of the ear canal is occluded, for example with earplugs or headphones, the BC hearing improves at low frequencies, which is called the occlusion effect (Stenfelt & Reinfeldt, 2007). There are numerous studies investigating its origin. Stenfelt et al. (2002) found a decrease, but not a complete reduction, of BC-generated ear canal sound pressure after removal of soft tissue and cartilage from the external auditory canal in cadavers, suggesting that the ear canal sound pressure is caused by soft tissue and bony vibrations in the external canal. Aazh et al. (2005) found that changes in the static pressure of the external canal influence the occlusion effect, a pressure difference between the outer and middle ear decreasing the occlusion effect. Geal-Dor et al. (2020) found that there was an occlusion effect irrespective of whether the BC vibrator was placed on the bony part of the head or on the skin and soft tissues. The occlusion depth and the type of occluding device, for example different types of earmuffs, influence the occlusion effect (Stenfelt & Reinfeldt, 2007). When the occlusion is deep enough, the occlusion effect is minimal or even not perceived (Békésy, 1939).

One example where BC communication can be used is in environment with excessive noise requiring protections of the ears, usually by earplugs or earmuffs. Consequently, the use of occlusion devices together with BC stimulation can influence the intelligibility and sound quality of the BC sound and interact with the stimulation position. To explore the influence of different occlusion effects and also investigate occlusion effects of different types of headphones, four types of headphones were used in the current study as occlusion devices. The four types of headphones that represent four different occlusion conditions were: (1) in-ear headphones, (2) semi-open headphones, (3) fully open headphones, and (4) closed headphones. The in-ear headphones cause similar occlusion effect as earplugs while the closed earphones have occlusion characteristics similar to ear-muffs.

The aim of this study was to investigate the influence of BC stimulation position on the occlusion effect, speech-in-noise intelligibility, and subjective sound quality of Mandarin Chinese. This aim was accomplished by (1) measurement of the occlusion effect as a function of the position of the BC transducer and type of occlusion device, (2) intelligibility measurement of Mandarin Chinese words through BC stimulation as a function of SNR and type of background noise, and (3) subjective evaluation of the perceived sound quality of BC stimulation at the different stimulation positions.

Material and Methods

Measurement Setup and Participants

The experiments were conducted in a sound insulated room (6.78 m × 3.51 m × 2.26 m). The reverberation time (T_{60}) was about 250 ms and the background noise level was 21 dB SPL. The stimuli were generated using a computer equipped with a sound card (RME Fireface UFX II) and

Figure 1. The four types of headphones used. (a) fully open headphones, Koss Porta Pro; (b) semi-open headphones, Sennheiser HD650: (c) in-ear headphones, Sennheiser IE800; (d) closed headphones, Sennheiser HD280.

the outputs were routed to a Sennheiser IE800 headphone for AC stimulation and a Radioear B81 vibrator for BC stimulation. For occlusion, four types of headphones were used: (1) fully open headphones, Koss Porta Pro (Fig. 1a), (2) semi-open headphones, Sennheiser HD650 (Fig. 1b), (3) in-ear headphones, Sennheiser IE800 (Fig. 1c), and (4) closed headphones, Sennheiser HD280 (Fig. 1d). The positions for the BC transducer were on the mastoid, on the condyle, and on the temple.

Eleven participants with normal hearing (six male and five female) with a median age of 24 years (23−25 years) volunteered to participate in the study. All participants were native Chinese speakers and were able to read and write Chinese proficiently. They all had otologically normal ears (ISO, 2003) with hearing thresholds equal or better than 20 dB HL over the frequency range 0.125−8.0 kHz. The hearing thresholds for AC and BC were tested according to ISO 8253-1:2010 (ISO, 2010). All experiments were approved by the Ethics Committee of the University of Guangzhou.

Calibration

The probe tube microphone (ER-7C) was calibrated using a Brüel & Kjær type 4134 1/2-inch microphone which had a level deviation of less than 2 dB in the frequency range 0.1 −10 kHz. First, the sensitivity of microphone was determined with a Brüel & Kjær type 4230 sound level calibrator. Then the probe tube opening was placed 1 mm from the 1/2-inch microphone, a swept sine was presented, and the calibration curve of ER-7C was obtained for the frequency range 0.1 −10 kHz.

The stimulation level of the BC sound for the experiments was set according to a loudness balance procedure for AC and BC. The stimulus for the loudness balance procedure was a 1-kHz pulse-train of three sinusoidal 200-ms bursts with a 500-ms silence between bursts. The AC stimulus was presented by the Koss Porta Pro headphones that were calibrated on a dummy head (KU100, Neumann, Berlin, Germany) to equal 65 dB SPL. The BC stimulus was presented by the BC transducer at the mastoid. The stimulation was alternated between AC by the Koss Porta Pro headphone and BC by the Radioear B81 at the ipsilateral side. The participants adjusted the BC stimulus to match the perceived loudness of the AC stimulus at 65 dB SPL (Qin & Usagawa, 2017). The level of the BC stimuli was recorded for each individual and used in the following experiments.

Statistics

Statistical analyses were performed using SPSS (version 21). To assess the effect of different test conditions on the occlusion effect, BC speech intelligibility, and BC sound quality, a repeated-measures analysis of variance (ANOVA) was performed. When Mauchly's Test of Sphericity was violated, corrections were applied according to Greenhaus-Geisser. Pair-wise post hoc comparison using LSD correction were performed to gain more insight into the nature of effects. The level of statistical significance was set as $p < 0.05$.

Experimental Procedures

Measurement of Occlusion Effect. The occlusion effect was estimated based on BC hearing thresholds. The occlusion effect was defined as the difference between the hearing threshold with occlusion and the hearing thresholds with an open ear. The occlusion effect was estimated for the four different headphones in Fig. 1, in an order that was randomized across participants. The stimulation was provided by the Radioear B81 at the three stimulation positions (mastoid, condyle, and temple). According to a power analysis with 80% power and $p = 0.05$, 11 participants enable detection of differences of 1.0 dB.

The up-down method was used to estimate the hearing thresholds (ISO, 2014). The participant was requested to press a button when a tone was heard. The stimulation level at the subsequent trial was reduced if the button was pressed and increased otherwise. The thresholds were obtained at 6 frequencies: 250, 500, 1000, 2000, 4000 and 8000 Hz. The initial step size was 32 dB and the step-size was halved after the 2nd, 4th, 6th, 8th and 9th turning points (Tang, Xiaodong, & Sang, 2019). The hearing threshold was computed as the average level at the last four points in the threshold estimation, which were from the 9th point to the 12th points.

Measurement of Bone Conduction Speech Intelligibility. This experiment investigated the effects of noise type, SNR, and the occlusion effect on the intelligibility of BC sound. The main motivation for this testing is the difference between Western non-tonal languages and Mandarin Chinese where in English, the intonation indicates emotion while the intonation indicates meaning in Mandarin Chinese. Compared to English, Mandarin Chinese phonemes and tones have different time-frequency characteristics and carry different information. Therefore, in a noisy environment, different types of noises can mask the speech different from English leading to different intelligibility functions for Mandarin Chinese (Kang, 1998).

The experiment comprised two parts. The first part explored the effects of background noise type, SNR, and stimulation position on BC speech intelligibility. Two background noises (white noise and babble noise from the NOISEX-92 noise library) and three SNRs (−5 dB, 0 dB, and 5 dB) were used. The BC transducer (B81) was applied at the temple, mastoid, and condyle, and AC stimulation was included as a reference (Sennheiser IE800). All stimuli were presented unilaterally at a level corresponding to 65 dB SPL described above. A power analysis with 80% power and $p = 0.05$ showed that 11 participants enabled detection of within-subject difference of 1%.

The second part investigated the effect of different amount of occlusion on BC speech intelligibility where the four headphones were used as occlusion devices. After the speech intelligibility testing with different SNRs and background noises, the intelligibility tests with occlusion were conducted with white noise as masker at an SNR of −5 dB. The choice of −5 dB SNR was due to ceiling effects at the other SNRs. The stimulation positions were the mastoid, temple and condyle.

The national standard GB15508-1995 Chinese intelligibility test syllable table—KXY table for speech intelligibility test (GB, 1995) was used. There are 10 standard KXY tables, each with 75 syllables (each syllable corresponds to a Chinese character). Table 1 shows a fragment from one of the tables. To prevent memory effects and familiarity affecting the results, the syllable table was shuffled and combined randomly to generate the test signals. A group contained three syllables and a leading sentence such as "The first group is: x, y, z", where x, y and z represented three different syllables. The Neospeech TTS speech library was used to generate the syllables of the speech test with a sampling rate of 16 kHz. The syllable list was presented in random order and the participants noted the perceived syllables by writing. Speech intelligibility was scored as the percentage correct syllables.

Table 1. Fragment of the Syllable Table of the Speech Intelligibility Test.

Serial No.	Three syllables
1	ā、àn、áng
2	áo、bǐ、biàn
…	…
24	chǐ、chōng、dé
25	zì、zǔ、zuò

Subjective Evaluation of Bone Conduction Sound Quality. The sound quality was assessed by the paired comparison method (Thurstone L,1927; Meng 2008). In the Thurstone paired comparison method, a psychological scale is created based on the outcome from paired comparisons where each psychological quantity is considered a random variable with a normal distribution. According to the method, all stimuli are compared by all participants where the participant judges the best sound quality in the pair. Based on the outcomes, z-scores for each comparison are computed and finally the mean z-scores for each condition are obtained.

Here, the comparison was the sound quality as a function of stimulation position. This was evaluated for three types of sound material: (1) male pop music, (2) female pop music, and (3) string music. The male pop music was 20 s of pop music with a male singer, the female pop music was 20 s of pop music with a female singer, and the string music was 20 s of piano music. For each type of music, the perceived sound quality was compared between two BC stimulation positions at a time by changing place of the BC transducer and recording the preference. Each pair of stimulation positions was assessed one time (3 pairs of positions times 3 types of music per participant, 3×3), meaning that

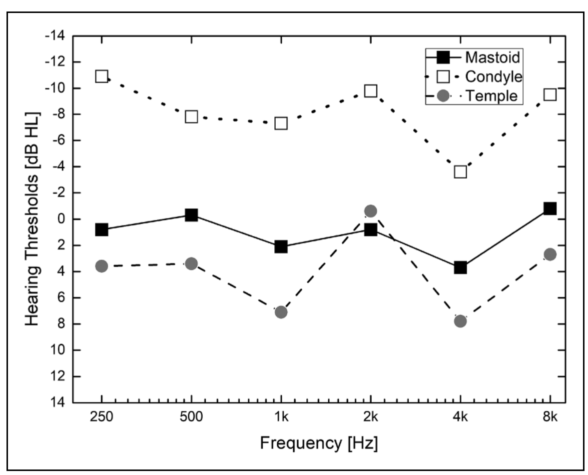

Figure 2. Hearing thresholds with stimulation at the temple, mastoid and condyle when the ear canal was open.

the subjective evaluation was conducted nine times for each participant.

Results

Occlusion Effect

The mean open ear hearing thresholds with BC stimulation at the temple, mastoid, and condyle are shown in Fig. 2. The occlusion effects based on hearing thresholds are shown in Figures. 3 and 4. Each panel in Fig. 3 shows results for one of the four headphones. All headphones produced occlusion effects for frequencies below 2.0 kHz, although Koss and HD650 had weaker occlusion effect than IE800 and HD280. Among the headphones the IE800 gave the highest occlusion effect while the Koss headphone's occlusion effect was less than 5 dB for all frequencies tested. The occlusion effect for all four headphones was less than or equal to 5 dB for frequencies above 2 kHz.

The occlusion effects for the four headphones are shown in Fig. 4 for each stimulation position. IE800 had the highest occlusion effect, followed by HD280, then HD650, and finally Koss when frequencies were below 2 kHz. All occlusion effects were weak when frequencies were higher than 2 kHz. A repeated-measures ANOVA was conducted on the occlusion effect with occlusion device, stimulation position, and frequency as within-subject factors. A Shapiro-Wilk test of normality supported the use of ANOVA. All within-subject factors except occlusion device satisfied Mauchly's Test of Sphericity. Therefore, the degrees of freedom for occlusion device were adjusted according to Greenhouse-Geisser. There were significant main effects of stimulation position ($F(2,20) = 3.987$, $p < 0.05$, $\eta^2 = 0.285$), frequency ($F(5,50) = 15.366$, $p < 0.05$, $\eta^2 = 0.606$) and occlusion device ($F(1.997,19.974) = 24.575$, $p < 0.05$, $\eta^2 = 0.711$). There were significant interactions between occlusion device and position ($F(6, 60) = 2.629$, $p < 0.05$, $\eta^2 = 0.208$), and between frequency and occlusion device ($F(11.718, 117.176) = 11.917$, $p < 0.05$, $\eta^2 = 0.544$). An analysis of simple effects of occlusion device and position indicated that these two factors influence the occlusion effect significantly for frequencies below 2 kHz and there was a significant influence of frequency for the IE800 and HD280. Post hoc test (LSD) of stimulation position showed that the occlusion effect with stimulation at the mastoid was significantly ($p < 0.01$) higher than with stimulation at the temple. The difference between stimulation at the mastoid and condyle was not significant. Post hoc tests showed that the differences between headphones were all significant ($p < 0.01$) except between HD650 and HD280. Detailed results of the statistical analysis are shown in Tables 2 and 3.

Speech Intelligibility Results

Effect of Noise Type and SNRs. The speech intelligibility scores with open ear and white noise as masker are shown in Fig. 5. The scores with BC stimulation were worse than with AC stimulation for all three SNRs. When the SNR was 5 dB, the AC score was 80%, while scores with BC stimulation at the mastoid, condyle, and temple were 74%, 77% and 66%, respectively. The speech intelligibility scores worsened with decreasing SNR and were 70%, 71% and 58% at the SNR of 0 dB and 53%, 55% and 43% at the SNR of −5 dB with stimulation at the mastoid, condyle, and temple, respectively. Figure 6 shows the results with babble noise as the masker and the pattern of the results was similar to the results in Fig. 5 while the overall speech intelligibility was higher with babble noise than with white noise.

When the SNR increased from −5 dB to 0 dB with white noise as the masker (Fig. 5), the average intelligibility score across the three positions improved by 15.8 percentage points while it improved by 5.7 percentage points when the SNR increased from 0 dB to 5 dB. When the masker was babble noise, intelligibility improved by 10.6 percentage points when the SNR increased from −5 dB to 0 dB, and by 5.9 percentage points when it increased from 0 dB to 5 dB (Fig. 6).

With stimulation at the mastoid, the highest score was 74% with white noise (at 5 dB SNR) and 76% with babble noise. With stimulation at the condyle, the highest score was 77% with white noise and 79% with babble noise. With stimulation at the temple, the highest score was 66% with white noise and 69% with babble noise. Stimulation at the temple gave worse speech intelligibility than for the other positions, but there was no clear difference between stimulation at the mastoid and condyle.

A repeated-measures ANOVA on the intelligibility scores was conducted with noise type, SNR, and stimulation position as within-subject factors. There were significant main effects of noise type ($F(1,10) = 18.096$, $p < 0.01$, $\eta^2 = 0.644$), SNR ($F(2,20) = 16.721$, $p < 0.01$, $\eta^2 = 0.626$), and position ($F(3,30) = 55.748$, $p < 0.01$, $\eta^2 = 0.848$). The only significant interaction was between SNR and noise type ($F(2,20) = 270.958$, $p < 0.05$, $\eta^2 = 0.964$). As expected, intelligibility at an SNR of 5 dB with babble noise was significantly higher than for other SNRs and noise types. The results of the post-hoc analysis (LSD) for stimulation position are presented in Table 4 showing that AC stimulation gave the best intelligibility, followed by BC stimulation at the condyle, at the mastoid, and finally at the temple.

Occlusion Effect. Figure 7 shows the BC intelligibility scores for the three stimulation positions when different headphones were occluding the ear. Occlusion with the IE800 gave the highest intelligibility (also the highest occlusion effect, see Fig. 3) while the open condition gave the lowest intelligibility. Compared with the open condition, occluding with the IE800 increased intelligibility by 8.5 percentage points averaged across the three stimulation positions, and the HD280 increased the intelligibility by 7.2 percentage points. The occlusion effect varied across BC position and so did the

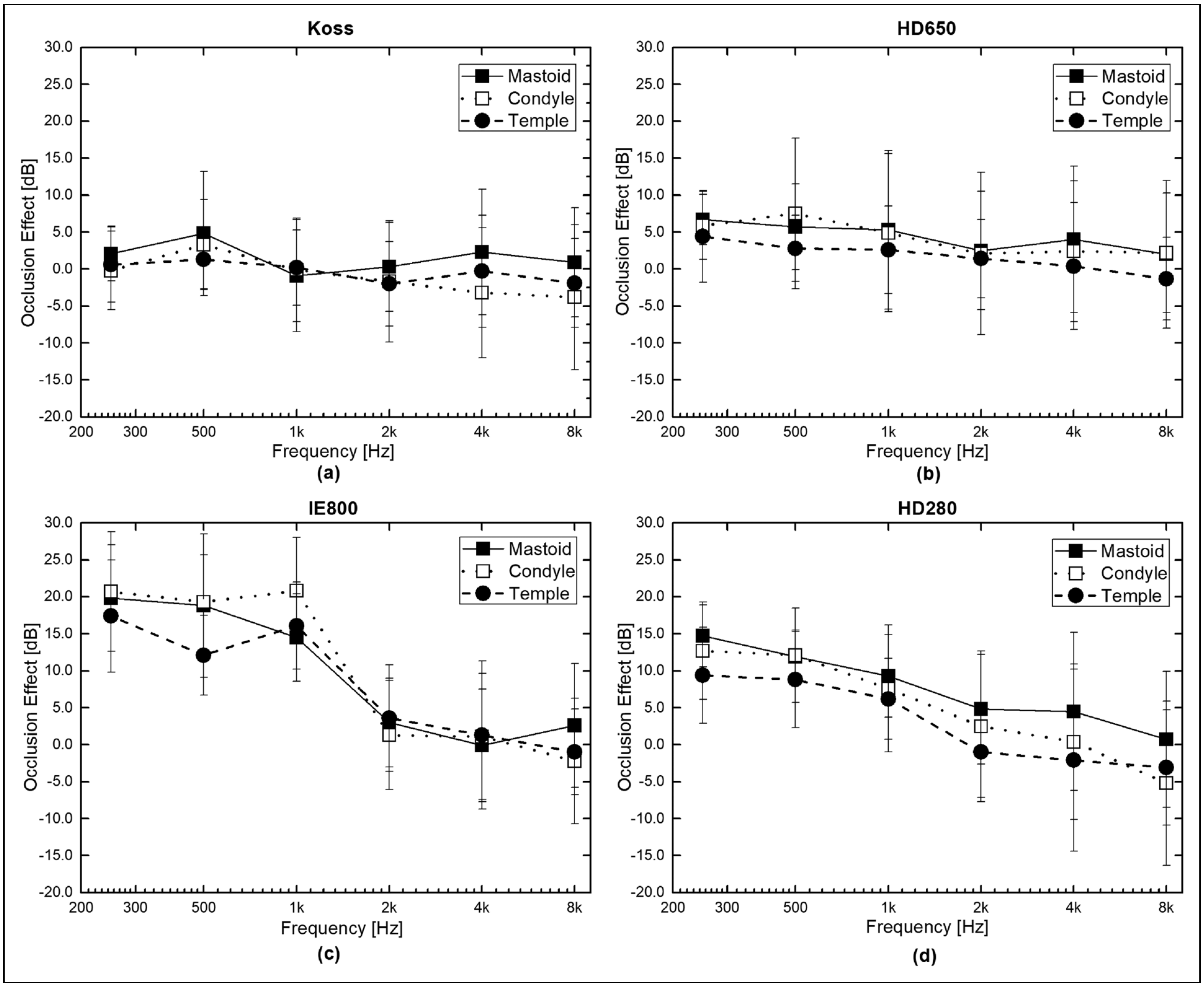

Figure 3. Occlusion effect for the four headphones with stimulation at the three positions. (a) Koss headphone; (b) HD650 headphone; (c) IE800 headphone; (d) HD280 headphone.

speech intelligibility. For stimulation at the temple, occluding with the IE800 gave 13.6 percentage points higher score than for the open situation, while the HD280 gave an increase of 10.3 percentage points, the HD650 gave an increase of 5.1 percentage points, and the Koss gave an increase of 3.5 percentage points. The improvements were between 2.6 and 7.3 percentage points for BC at the mastoid and between 0.9 and 5.7 percentage points for BC at the condyle.

A repeated-measures ANOVA on the intelligibility scores was conducted with occlusion device and stimulation position as within-subject factors. There was a main effect of occlusion device (F (2.021,20.206) = 5.593, $p < 0.05$, $\eta^2 = 0.359$) (adjusted according to Greenhouse-Geisser) and of stimulation position (F (2,20) = 15.004, $p < 0.05$, $\eta^2 = 0.600$). There was no significant interaction. Table 5 gives results of post hoc tests of occlusion condition (including open ear). The open condition was significantly worse than the IE800 ($p < 0.01$), HD650 ($p < 0.05$) and HD280 ($p < 0.05$), while it was not significantly different from the Koss headphones. Table 6 shows the result of post hoc tests for the three stimulation positions. The results differed significantly for all positions.

The relationship between the mean of the six hearing thresholds and speech intelligibility scores for the different occlusion conditions (including open ear) and stimulation positions was assessed with Pearson correlation. The correlation was strong, significant, and negative ($r = -0.861$, $p < 0.001$). Better hearing (lower thresholds) was associated with higher intelligibility. This analysis indicated that 74% of the variance in speech perception was explained by the variance in hearing thresholds.

Sound Quality Estimations

During the test of paired comparison, the participants gave one preference from each comparison. The preference

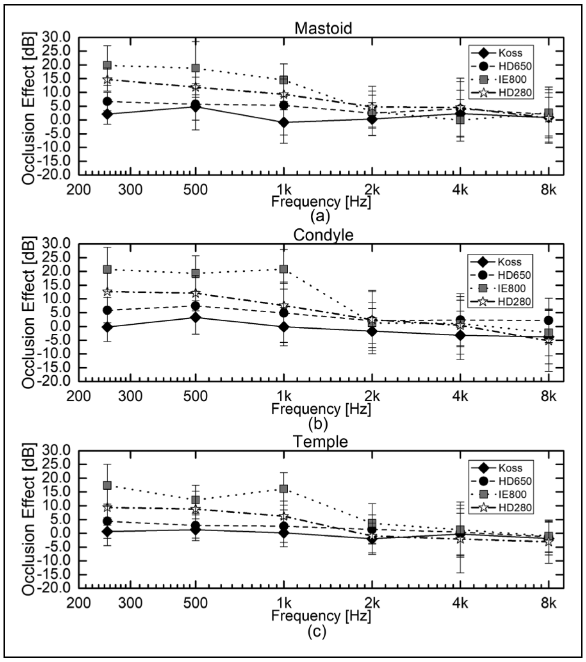

Figure 4. Occlusion effect for each headphone at the three stimulation positions. (a) mastoid; (b) condyle; (c) temple.

Table 2. Results of LSD Post hoc Tests for the Effects of Stimulation Position on the Occlusion Effect. the Occlusion Effect was Computed Averaged Over all Frequencies and Headphones Tested. the Roman Number Indicates for Stimulation Position.

Position	Mean ± SD Occlusion Effect / dB	*p* value I	II	III
Mastoid (I)	5.9 ± 1.1			
Condyle (II)	4.6 ± 1.1	0.273		
Temple (III)	3.2 ± 1.1	**0.007**	0.170	

results were recalculated to relative occurrences, i.e., the number a specific condition was chosen in relation to the number of comparison for that condition, shown in Table 7. Based on these relative occurrences, the z-scores are computed and presented in Table 8. To limit the z-scores, the max and min z-scores were set to 2.33 and −2.33 which equals the z-score for a relative occurrence of 0.01 and 0.99. This means that the relative occurrence of 0 gave a preference probability of 0.01 and the relative occurrence of 1 gave a preference probability of 0.99.

From the results in the Table 8 the mean z-scores for each stimulation position and type of music are computed and given in Table 9. For easier interpretation, the highest value in each music type is given the preference score 100 and the lowest value is given the preference score 0. Values between the highest and lowest values are given preference scores based on a linear transformation. For example, in Table 9, the temple showed the lowest mean

Table 3. Results of LSD Test for the Effects of Headphone on the Occlusion Effect. the Occlusion Effect was Averaged Over all Frequencies and Stimulation Positions Tested. the Roman Number Indicates for Occlusion Device.

Occlusion device	Mean ± SD Occlusion Effect / dB	*p* value I	II	III	IV
Koss (I)	0.1 ± 1.1				
HD650 (II)	3.4 ± 1.1	**<0.001**			
IE800 (III)	9.4 ± 1.1	**<0.001**	**<0.001**		
HD280 (IV)	5.2 ± 1.1	**0.002**	0.134	**0.017**	

z-score of −2.33 with female pop music and the temple was set a preference score of 0. The condyle showed the highest mean z-score of 1.33 with female pop music and was set a preference score of 100. Finally, a linear transformation converted the mean z-score for the mastoid of 0.985 to a preference score of 91 [100 × (0.985-(−2.330))/(1.330- (−2.330)) = 91].

Figure 8 shows the preference scores for stimulation at the three positions for male pop music, female pop music, and string music. For all three music types, stimulation at the condyle gave the highest score (100), followed by stimulation at the mastoid, and finally at the temple (0).

Discussion

Occlusion Effect

Occlusion Effect for Different Stimulation Positions. Reinfeldt et al. (2013) used hearing thresholds and ear-canal sound pressure (ECSP) measured by a probe tube microphone to estimate the occlusion effect for stimulation at three positions on the skull (ipsilateral mastoid, contralateral mastoid, and forehead). The occlusion effect was significantly lower for ipsilateral stimulation than for the other stimulation positions, especially below 500 Hz when the occlusion effect was estimated via thresholds. Here, hearing thresholds were used to estimate the occlusion effect for BC stimulation at the mastoid, temple, and condyle. The in-ear headphones (Fig. 3c) gave the highest occlusion effect of the four headphones, where the occlusion effect was higher at the condyle position than at the temple, but similar to the mastoid, for frequencies below 2 kHz. It is likely that stimulation at the mastoid and condyle positions, due to their proximity to the ear canal, produces higher ear canal sound pressure than with stimulation at the temple. So even if the ear canal sound pressure does not dominate BC perception when stimulation is at the condyle (like stimulation at the mastoid), it influences the ear canal pathway more than when the stimulation is at the temple. Consequently, a BC stimulation position closer to the ear canal increases the ear canal sound pressure more than other pathways for BC

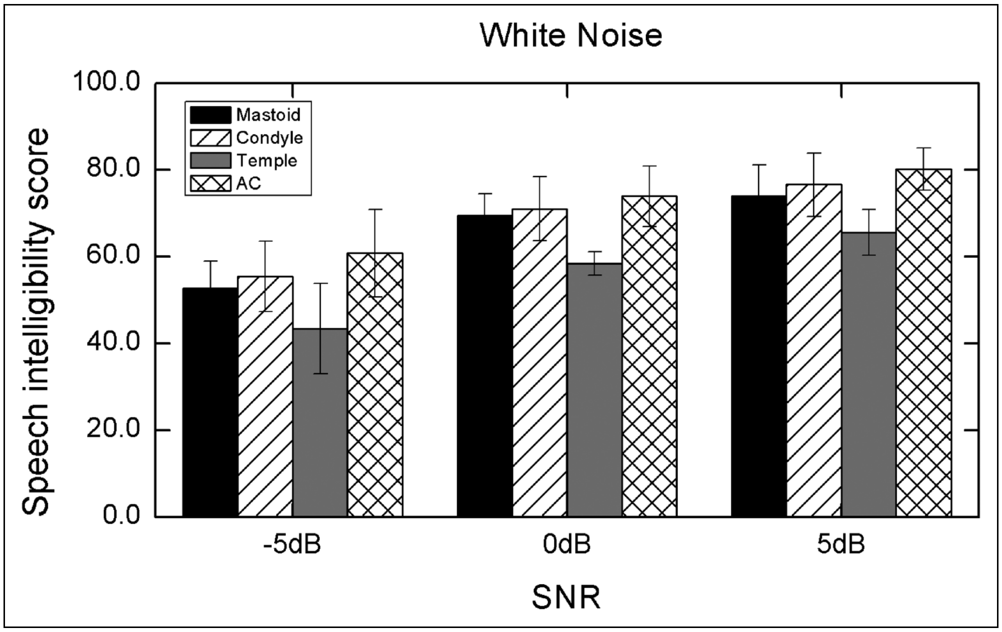

Figure 5. Speech intelligibility scores with white noise.

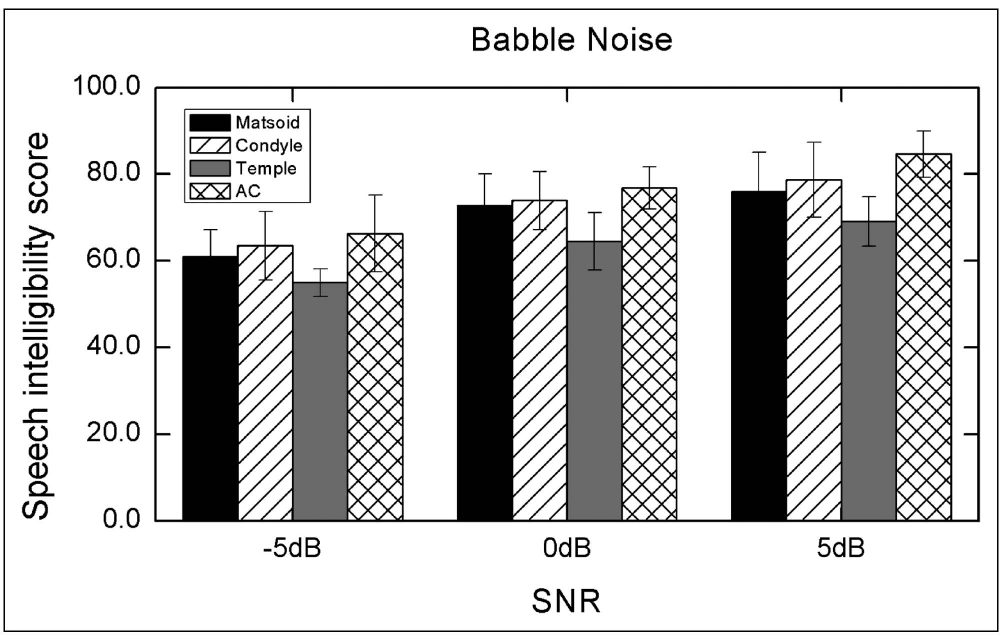

Figure 6. Speech intelligibility scores with babble noise.

hearing, resulting in an increase of the occlusion effect as obtained by hearing thresholds (Nishimura et al., 2015; Surendran & Stenfelt, 2021).

The higher occlusion effect at the condyle compared to at the temple indicate that sound radiation from the BC transducer did not affect the measurements. If air-borne sound radiation from the BC transducer affected the ear canal sound pressure, it would do so most with stimulation at the condyle since the BC transducer is closest to the ear canal opening at that place. The air-borne sound radiation only affects the open ear since the occlusion device attenuates sound outside the ear canal. Consequently, if air borne radiation affects the measurements, it results in better hearing thresholds in the open ear condition and thereby lower occlusion effect. Here, the result indicates the opposite, and the measurements seem not to be affected by sound radiated from the BC transducer.

Table 4. the Results of LSD Post hoc Tests for the Effects of the BC Position and AC on Intelligibility. the Intelligibility Scores Were Averaged Across the Three SNRs and two Types of Background Noise. Significant Effects are Given in Boldface.

Position and AC	Mean ± SD Score / %	*p* value I	II	III	IV
Mastoid (I)	67.7 ± 1.3				
Condyle (II)	69.9 ± 1.8	**0.010**			
Temple (III)	59.3 ± 1.1	**<0.001**	**<0.001**		
AC (IV)	73.8 ± 1.8	**<0.001**	**0.015**	**<0.001**	

Table 5. Results of Post hoc Tests of the Effects of Occlusion Condition on Intelligibility at an SNR of −5 dB with White Noise, Averaged Over Three Stimulation Positions.

Occlusion Level	Mean ± SD Score/ %	*p* value I	II	III	IV	V
Open (I)	52.1 ± 2.3					
Koss (II)	54.5 ± 2.9	0.265				
HD650 (III)	56.0 ± 3.2	**0.035**	0.339			
IE800 (IV)	60.6 ± 2.2	**<0.001**	**0.001**	**0.033**		
HD280 (V)	59.4 ± 1.6	**0.006**	0.129	0.306	0.562	

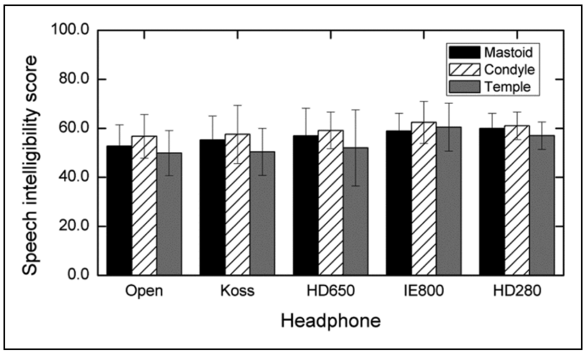

Figure 7. Intelligibility scores for five different occlusion conditions.

Table 6. Results of Post hoc Tests of the Effects of Stimulation Positions on Intelligibility at an SNR of −5 dB with White Noise, Averaged Over Five Occlusion Conditions.

Position	Mean ± SD Score / %	*p* value I	II	III
Mastoid (I)	56.8 ± 2.0			
Condyle (II)	59.4 ± 2.1	**0.021**		
Temple (III)	53.4 ± 2.4	**0.004**	**0.001**	

Occlusion Effect with Different Headphones. The results in Figs. 3 and 4 show that the occlusion effect primarily occurs for frequencies below 1 kHz and only frequencies of 1 kHz and below led to occlusion effects that were significantly greater than zero. Stenfelt and Reinfeldt (2007) reported threshold-based occlusion effects with supra-aural and circum-aural headphones of up to 15 dB while insert headphones gave approximately an occlusion effect of 25 dB at low frequencies. Those results correspond well to the occlusion effects shown in Fig. 3, where the insert headphone (IE800) gave a 20-dB occlusion effect and the circum-aural headphone (HD280) gave a 15-dB occlusion effect for mastoid stimulation at the lowest frequencies. Aazh et al. (2005) occluded the ear canal with an impedance audiometer probe and reported an occlusion effect that decreased from 27.1 dB at 0.25 kHz to 4.7 dB at 2.0 kHz. Their results are similar to those for the insert headphone (IE800) used here (Fig. 3). Consequently, the occlusion effects produced by the headphones in the current study are similar in level and frequency range to those for other studies reported in the literature.

Stenfelt and Reinfeldt (2007) reported a model of the occlusion effect based on the sound pressure in the ear canal with BC stimulation. They showed that a deeper position of the occlusion device in the ear canal gave less occlusion than a shallower position and that a larger air volume in a closed headphone gave less occlusion than a small enclosed air volume. If the enclosed air volume is large enough so the acoustic impedance of the volume (compliance) is similar to the radiation impedance of the open ear, the occlusion effect vanishes (Khanna et al., 1976; Reinfeldt et al., 2010). Stenfelt and Reinfeldt (2007) ascribed the different occlusion effects between the ear and headphones to differences in the radiation impedance at the ear canal opening. Another possible contributor to the difference in occlusion effects are inertial effects from the headphones inducing low-frequency sound pressure (Schroeter & Poesselt, 1986). This theory explains the higher occlusion effect using in-ear headphones (IE800) than using semi-open headphones (HD650) and closed headphones (HD280). Also, a semi-open headphone (HD650) lead to a lower radiation impedance than a closed headphone (HD280), and thereby a lower occlusion effect. Moreover, the Koss headphone is predicted to give the least occlusion effect, which was confirmed in our measurements (Fig 4 and Table 3).

The differences between the four types of headphones indicate that the largest occlusion effects are obtained by in-ear and closed headphones. These two types of headphones simulate hearing protection devices (ear-plugs and ear-muffs) and, consequently, the occlusion effect with hearing protection devices are expected to significantly influence the perception of BC sound. This finding is important since BC headsets are commonly used in combination with hearing protection devices. Moreover, the occlusion effects with open and semi-open headphones are small and although statistically significantly different

Table 7. Preference Probabilities $P_{(Column>Row)}$ in the Three Positions for String Music, Male pop Music and Female pop Music.

	String			Male			Female		
$P_{(Column>Row)}$	Mastoid	Condyle	Temple	Mastoid	Condyle	Temple	Mastoid	Condyle	Temple
Mastoid		8/11	2/11		8/11	1/11		7/11	0
Condyle	3/11		0/11	3/11		1/11	4/11		0
Temple	9/11	11/11		10/11	10/11		11/11	11/11	

Table 8. Normal Distribution Variables $Z_{(Column,\ Row)}$ in the Three Positions for String Music, Male pop Music and Female pop Music.

	String			Male			Female		
$Z_{(Column,\ Row)}$	Mastoid	Condyle	Temple	Mastoid	Condyle	Temple	Mastoid	Condyle	Temple
Mastoid		0.58	−0.92		0.58	−1.34		0.33	−2.33
Condyle	−0.61		−2.33	−0.61		−1.34	−0.36		−2.33
Temple	0.88	2.33		1.28	1.28		2.33	2.33	

from zero, they are small enough to be perceptually insignificant.

Speech Intelligibility

Speech Intelligibility for Different Stimulation Positions. Others who studied English speech intelligibility with BC stimulation at different stimulation positions reported similar results to those in Figs. 5 and 6; AC stimulation gave the best speech intelligibility, followed by BC stimulation from a B81 transducer at the condyle, at the mastoid, and finally at the temple. Osafo-Yeboah et al. (2009) used the CAT speech material with a −9 dB SNR to study BC speech intelligibility and found no significant difference between stimulation at the condyle and mastoid. Although the speech intelligibility scores were around 2 percentage points higher when the stimulation was applied at the condyle than at the mastoid in the current study, the difference was not significant, consistent with the findings of Osafo-Yeboah et al. (2009). Stanley and Walker (2009) reported a significant effect of stimulation position; AC stimulation gave the highest intelligibility followed by BC stimulation at the condyle, then at the mastoid, and finally at the vertex. They reported that the significance was driven by the higher score with stimulation at the condyle than at the vertex. In the current study, stimulation at the condyle always gave better speech intelligibility than for the other positions. Consequently, speech intelligibility with BC stimulation using Mandarin Chinese resembles the results with English as speech material.

Since the SNR of the signal delivered to the BC transducer was the same for all stimulation positions, the intelligibility score depended primarily on the audibility and bandwidth of the signal. To explore this, the long-term spectrum of the stimulation was investigated for the three stimulation positions, by measuring the speech spectrum of the ECSP using a probe tube microphone (Etymotic Research ER-7C) (Reinfeldt et al., 2013) with BC stimulation at the three positions for the eleven participants. The limitation of this analysis is that the ECSP is only one of the pathways that ultimately stimulates the cochlea with BC sound (Stenfelt & Goode, 2005a; Stenfelt, 2011). However, Surendran and Stenfelt (2021) showed that the ECSP is close to other contributors for BC hearing at frequencies up to 4 kHz. Also, Rigato et al. (2019) showed that the ECSP and cochlear promontory vibrations obtained with a LDV (laser Doppler vibrometer) gave similar results of transcranial attenuation of BC sounds, in line with the results of Reinfeldt et al. (2013). Since BC transmission is linear for the levels used in the current study (Håkansson, Carlsson, Brandt, & Stenfelt, 1996), relative changes of the BC sound at the cochlear level would be reflected in the ECSP.

The results in Figure 9 show that stimulation at the condyle resulted in 10 to 20 dB higher levels than for the other two positions, but there was no clear difference between stimulation at the mastoid and the temple. This great difference between the condyle and the mastoid is not reflected in the speech intelligibility results in Fig. 7. This indicates that the ECSP is enhanced when the stimulation is at the condyle compared to the other positions. The results are in-line with the threshold data in Dobrev et al. (2016) where the stimulation at the condyle position gave lower thresholds compared to stimulation at the mastoid or the temple. However, the data in Fig. 9 illustrates that the ECSP is enhanced for stimulation positions close to the ear canal compared when further away from the ear canal. This closeness to the ear canal seems also to facilitate transmission of BC sound at higher frequencies improving speech perception.

According to Table 4, the speech intelligibility with stimulation at the mastoid was 8 percentage points better than

Table 9. Mean Normal Distribution Variables and Preference Scores in the Three Positions for String Music, Male pop Music and Female pop Music.

	String		Male		Female	
	Mean Value	Preference Score	Mean Value	Preference Score	Mean Value	Preference Score
Mastoid	0.135	57	0.335	74	0.985	91
Condyle	1.455	100	0.930	100	1.330	100
Temple	−1.625	0	−1.340	0	−2.330	0

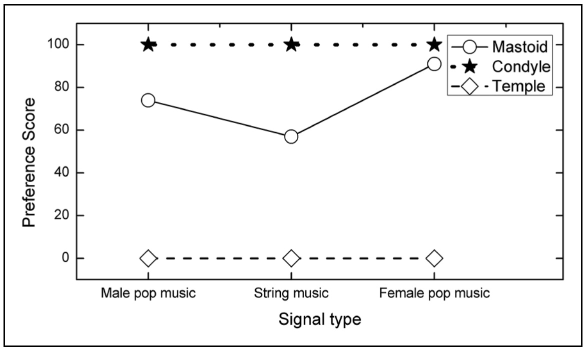

Figure 8. Sound quality scores for the three types of music for each stimulation position.

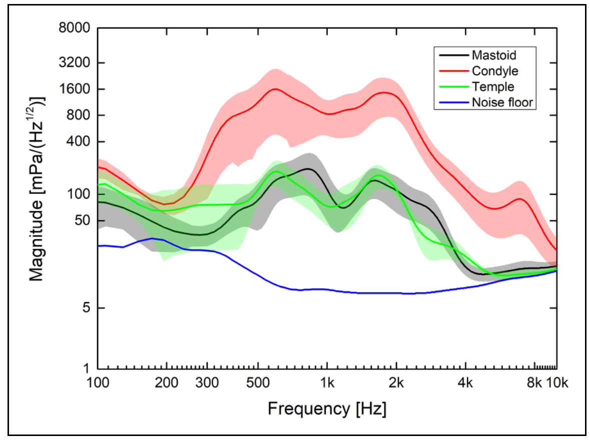

Figure 9. Long-term spectrum of speech material for stimulation at the three bc positions. The shaded areas indicate the standard deviation of the measurement data. The blue line indicates the noise floor.

with stimulation at the temple, but the difference between mastoid and condyle applied stimulation was only 2 percentage points. One explanation for this seemingly large difference between mastoid and temple applied speech in noise can be found at around 3 kHz in Fig. 9. At around 3 kHz, the BC sound from the temple is around 10 dB below the mastoid applied sound. This low level for temple applied BC sound could have limit the upper frequency range compared with the other two positions, and be the origin of the worse speech-in-noise results for the temple applied BC sound. Since the output levels for stimulation at 2 and 4 kHz is nearly identical for stimulation at the mastoid and the temple in Fig. 9, the threshold differences at these frequencies are expected small. This is confirmed by the threshold measurements in Fig. 2. Consequently, similar hearing thresholds measured at octave frequencies does not guarantee similar stimulation levels at all frequencies.

Speech Intelligibility with Occluded Ears. The speech intelligibility results in Fig. 7 and Table 5 indicate that occluding the ear can improve speech intelligibility when stimulation is by BC. Fujimoto and Mori (2016) conducted a speech intelligibility study with BC stimulation using Japanese syllabic word lists. They found that speech intelligibility with occlusion was better than when the ear canal was open. Wang and Wang (2011) showed that the energy of Chinese consonants and vowels was concentrated at frequencies below 5 kHz, and that energy below 1.2 kHz dominated. Stenfelt, Hato, et al. (2002) showed that the external ear canal sound pressure increased by 15−20 dB for frequencies below 1 kHz when the external ear canal was occluded, similar to the results shown in Fig. 4. This indicates that the Chinese speech spectrum has most of its energy in the same frequency range as where the occlusion effect increases the level of the BC sound and may be the reason why the occlusion effect can improve the speech intelligibility of BC sound in Mandarin Chinese.

To investigate this further, the speech spectrum in the ear canal was measured similar to that in Fig. 9 but with the ear canals occluded with foam earplugs (3M^{TM} EAR Classic). Figure 10 shows the long-term speech spectrum with BC stimulation at the mastoid, the condyle and at the temple with and without occlusion. As expected, the occlusion increased the ECSP, especially for stimulation at the condyle. The lower sound pressures with occlusion at the mastoid and temple between 5 kHz and 10 kHz were expected based on the data of Stenfelt and Reinfeldt (2007), but this reduction in ear canal sound pressure does not result in a reduction of the perceived sound, since other pathways dominate BC sound transmission at these high frequencies (Stenfelt, 2016, 2020). These results show that occlusion increases the ECSP primarily in the 0.5 to 2 kHz range, and this increase improves speech intelligibility in

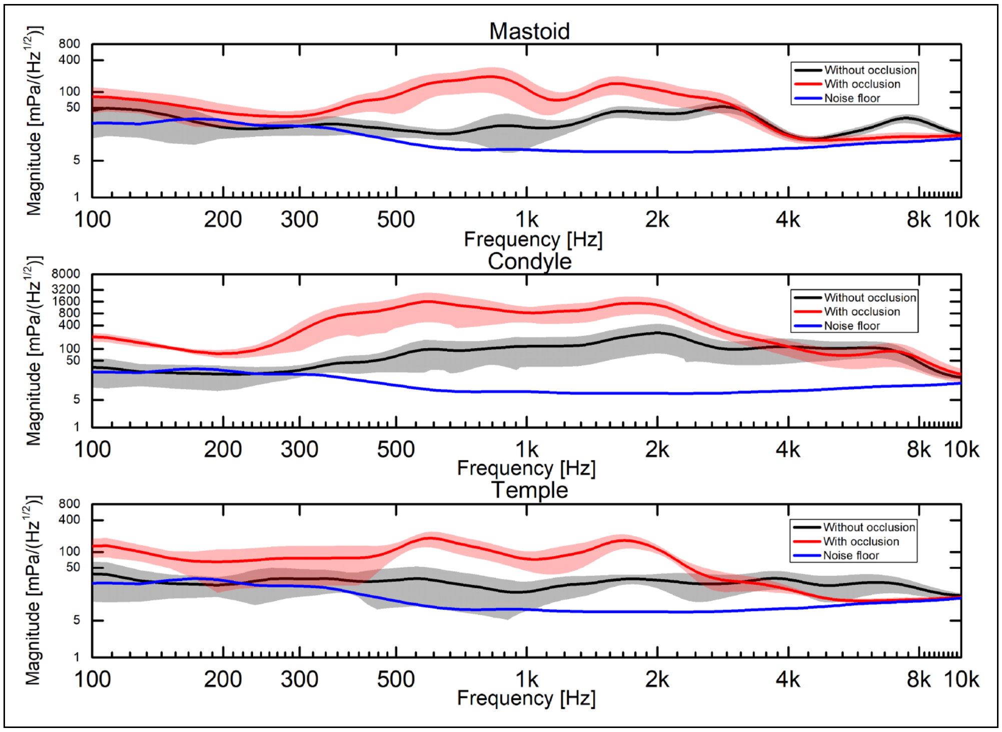

Figure 10. Long-term spectrum of the speech material for bc stimulation positions at (a) the mastoid; (b) the condyle; (c) the temple. The shaded areas indicate the standard deviations of the measurement data. The blue line indicates the noise floor.

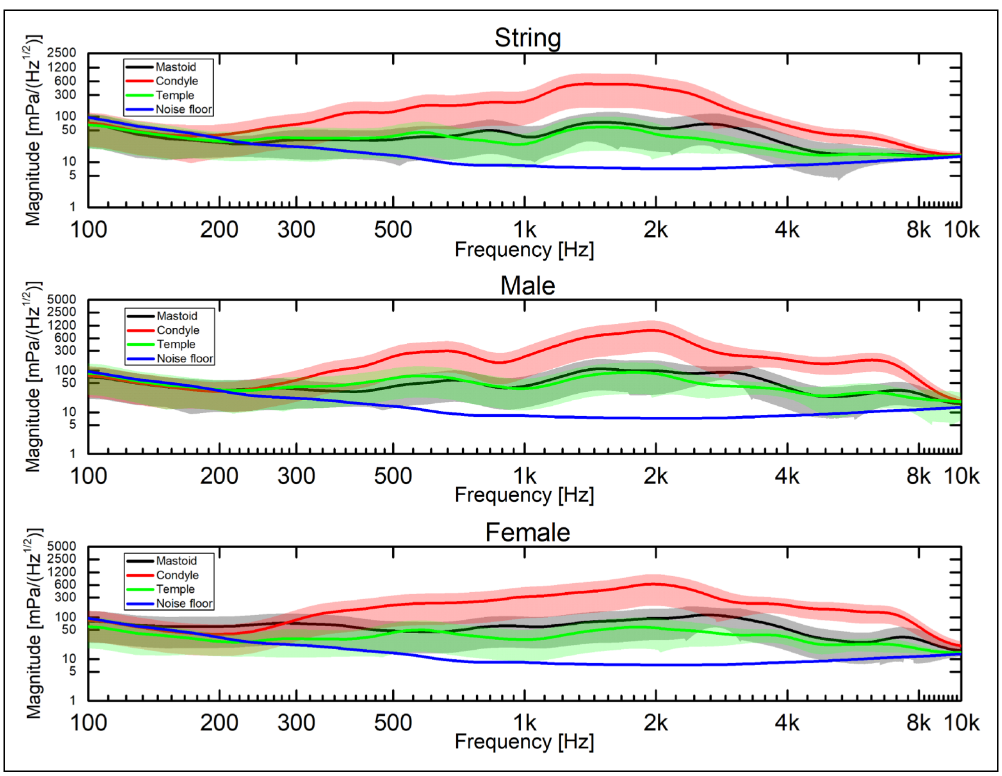

Figure 11. Long-term spectra in the ear canal for the three test materials for bc stimulation at the three positions. The shaded areas indicate the standard deviations of the measurement data. The blue line indicates the noise floor.

Mandarin Chinese. Consequently, it is not the increased bandwidth but overall higher sound levels at mid-frequencies that is the reason for the improvement of speech intelligibility in Mandarin Chinese with occlusion.

Sound Quality

BC sound is transmitted through vibrations of the skull and the soft tissues to the inner ear. This transmission differs between the three stimulation positions, resulting in coloring of the sound signal due to filtering effects. This was investigated similar to Figs. 9 and 10 with the ECSP during BC stimulation with the three music types at the three stimulation positions, shown in Fig. 11. Stimulation at the condyle gave an overall higher level than for the other two positions, and the level was higher for male pop music than for the female pop music and string music. However, the levels with stimulation at the mastoid and temple are nearly indistinguishable, and that is not surprising since the hearing thresholds only differed a few dBs between these two positions (Fig. 2). Even so, the stimulation at the temple was always rated inferior to stimulation at the other two positions, independent of music material. The spectral information given in Fig. 11 did not reveal the reason for this rating.

Conclusions

Hearing thresholds and speech intelligibility testing were conducted for BC stimulation at the temple, mastoid and condyle under different conditions of occlusion produced by headphones. The different headphones produced significantly different occlusion effects at low frequencies. The in-ear headphones gave the highest occlusion effect and the fully open headphones gave the least. Stimulation at the condyle gave the best performance while stimulation at the temple gave the worst performance in terms of hearing thresholds and speech intelligibility. The occlusion effect improved BC speech intelligibility and a higher occlusion effect improved speech intelligibility more than a lower occlusion effect. BC speech intelligibility at a given SNR was better for babble than for white noise. Stimulation at the condyle was judged as having the highest sound quality while stimulation at the temple gave lowest sound quality. An analysis of the sounds' spectral content in the ear canal indicated that making high-frequency information audible improved the sound quality. The results suggest that BC headphones or hearing aids should be positioned at the condyle to obtain the best performance.

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