Effects of Sound Wave Transmission Pathways on Acceptable Noise Level (ANL)

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Abstract

The act of hearing is known as audition. Audition is the primary means by which language is learned and all activities around the listeners are perceived. There are two transmission pathways by which physical sound waves from surroundings can be transformed into mechanical vibrations that stimulate the inner ear: air conduction (AC) and bone conduction (BC). This study investigates the differences between the levels of noise listeners will be willing to accept when listening to signals through AC and through BC hearing systems. Twelve students currently enrolled at North Carolina A & T State University (NCA&T) volunteered to participate in the study. Their ages ranged from 20 to 37 years old with an average age of 28.8 years and a standard deviation of 4.93. Results of the pairwise t-test comparison showed statistically significant differences ($\alpha = 0.05$, $t(22) = 9.11$, $p < 0.0001$) between AC and BC transducers. This indicated that participants accepted more background noise when the signal was delivered through the bone conduction transducer than when it was delivered through the earphone (air conduction hearing process). The findings of this study are applicable in the areas of law enforcement agents most especially, with the police officers who use radio communication systems and the military in the battlefield. Studies on bone conduction have become critically important in an extremely loud environment such as in the military battlefield and a flight deck of an aircraft carrier, where the noise levels can reach as high as 140–150 dB SPL (sound pressure level).

Introduction

Research has shown that earphones offer numerous desirable benefits ranging from convenient portability to greater external noise isolation. Many users of earphone are subjected to listening to loud level of signals. Research has shown that one of the most common reasons why people suffer from noise induced hearing loss is listening to loud music through earbuds for extended periods of time [1]. A 2009 study by Hodgetts et al. [2] investigated the influence of background noise and exercise on users' listening levels of portable listening devices. They found that participants selected significantly higher listening levels in both noise conditions than in a quiet condition. Another means of hearing through a device is through bone conduction transducer. Bone-conduction and air-conduction hearing share the same end organ: the cochlea [3].

According to Stenfelt [4], BC sound transmission involves multiple pathways, and there is no obvious way to distinguish between them. Bone headphones translate sound waves and change them into vibrations that can be received directly by the cochlea. By doing so, the eardrum does not get involved in the hearing process. According to Lundgren [5], when the bone vibrates, the cochlea can be directly stimulated, which produces the same sensation of hearing that is achieved through air conduction.

Effects of noise on both sound transmission pathways are crucial; much research has been conducted on the AC pathway. Some of the metrics used by researchers to quantify the level of noise accepted by human are signal-to-noise ratio (SNR), acceptable noise level (ANL), etc. The processes of ANL metrics are a result of the brain interpretation of both the signal and the noise. Listening by means of air conduction is bilateral, but bone conduction is unilateral. Conversely, from the reception of a sound signal (mechanical energy) in the cochlea to the auditory cortex for interpretation, the hearing processes follow the same path. Therefore, a hearing process under any conditions is the same when it goes through the central auditory processing. Recent research has confirmed that hearing protection worn by workers exposed to high noise levels effectively reduces air-conducted sound, but that bone-conducted noise may still be harmful in the presence of high background noise [6].

Factors affecting bone conduction testing are (a) interaural attenuation for bone conduction signal, which is normally between 0- to 10 dB; (b) effects of environmental noise; (c) tactile response from bone conduction simulation at 250 Hz and 500 Hz for intensity 35 dB and 55 dB; and (d) the variation in the sizes of the skull and the skull skin thicknesses. Because of bone conduction hearing, humans are able to hear their own voices even when ear canals are completely occluded. This is because the action of speaking sets up vibrations in the bones of the body, especially the skull. These vibrations are so strong that if a contact microphone is placed on the head, the sound can be easily picked up and used as a source of a speech signal. Thus, bone-conducted signals carry information that is more than adequate to reproduce spoken information. As a result, McBride, Letowski, and Tran [7] report that BC signals transmitted to and from the head can be used as effective signals in radio communication [8]. The Fasanya et al. [9] study expanded the research on air conduction and determined the new intensity level for just noticeable differences in auditory signal detection task.

McBride, Letowski, and Tran [7, 10], reported that out of 12 locations tested across the head, locations closest to the ear and across the frontal region of the head resulted in the lowest pure tone hearing thresholds. In 2008 McBride, Hodges, and French [10] observed that when listeners are seated in a high noise environment, the intelligibility of bone conducted vocal signals is affected by the location of the BC vibrators as well as the fundamental frequency of the voice being transmitted. Stanley and Walker [11] bone-conduction transducers offer a unique advantage for radio communication systems, allowing sound transmission while the ear canals remain open for access to environmental sounds or plugged for blocking environmental sounds.

Another advantage of bone conduction for communication interfaces is that the transducers are lightweight, inconspicuous, and can easily be integrated into military headgear [7]. These devices can provide radio communication in quiet and noisy environments, especially when combined with an appropriate hearing protection system [12, 13]. Studies have shown better signal delivery both through the earphone and through the bone conduction transducer. The effects of background noise on air conduction sound transmission pathway have been extensively studied, while bone conduction sound transmission pathway potentials have not been fully researched. Although some work has been done on BCT speech intelligibility, more studies are needed to provide full insight into using bone conduction for radio communication systems. Therefore, this study explored the acceptable noise level metric developed by Nabelek, Tucker, and Letowski [14] and compared the acceptable SNR of BCT and air conduction sound transmission pathways. Acceptable SNR is a viable factor that can help determine the liability is BCT to radio communications. Based on the current research findings on the subject matter, it is hypothesized that when BCT is used as a means of signal delivery, the average ANL recorded during the process will not be statistically significantly different from that recorded when earphones is used to deliver the same type of speech signal under the same background noise type. Thus, the objective of this study was to investigate the effect of sound waves transmission pathways on ANL.

Methodology

Participants were current students enrolled at North Carolina A & T State University. Twelve students participated in this experiment. Their ages ranged from 20 to 37 years, with an average age of 28.8 years and standard deviation of 4.93. The experiment was designed to have 80% power of test. A two tailed t-test formula shown in equation 1 from *Engineering Statistic Handbook* by the US Commence Department [15] was used to determine the population with $\alpha = 0.05$, $\beta = 0.2$, $s = 8$, $d = 7.5$; thus, n was calculated to be 12.

$$n = \left(t_{\alpha/2} + t_{\beta} \right)^2 \left(\frac{s}{d} \right)^2 \quad (1)$$

Apparatus and Test Materials

The study was conducted in a large industrial acoustics chamber audiometric booth of the Department of Industrial & Systems Engineering at North Carolina Agricultural and Technical State University. The audiometric booth meets noise criteria for uncovered ears [16] and is equipped with only one Studiophile BX5A loudspeaker placed at 0^{o} azimuth to the seated position of the listener. Multi-talker babble was used as the background noise. The noise was delivered via the loudspeaker placed three feet away in front of the listener (0^{o} azimuth reference to the listener's seated position). Each participant chooses one comedian's speech among the four available speeches as the signal type. The ANLs were measured in two ways: (1) signal delivered through earphone (air conduction) and (2) signal delivered through bone headset (bone conduction). Figures 1 and 2 show the experimental set up for the study.

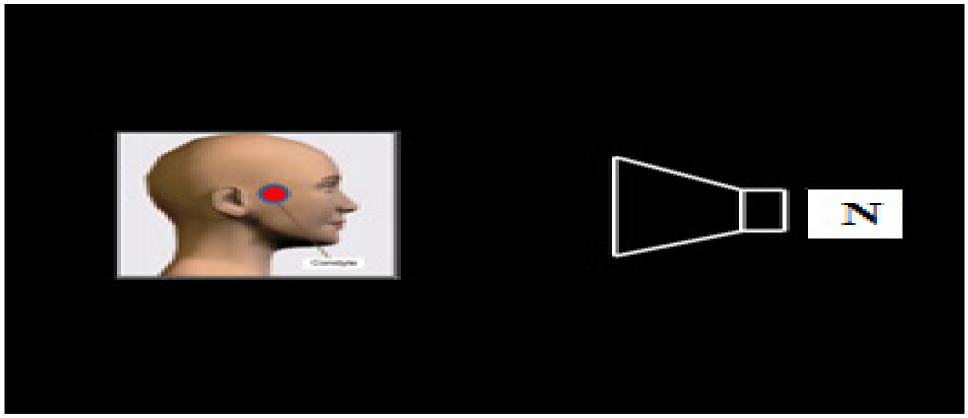

Figure 1. Experimental set-up (bone conduction)

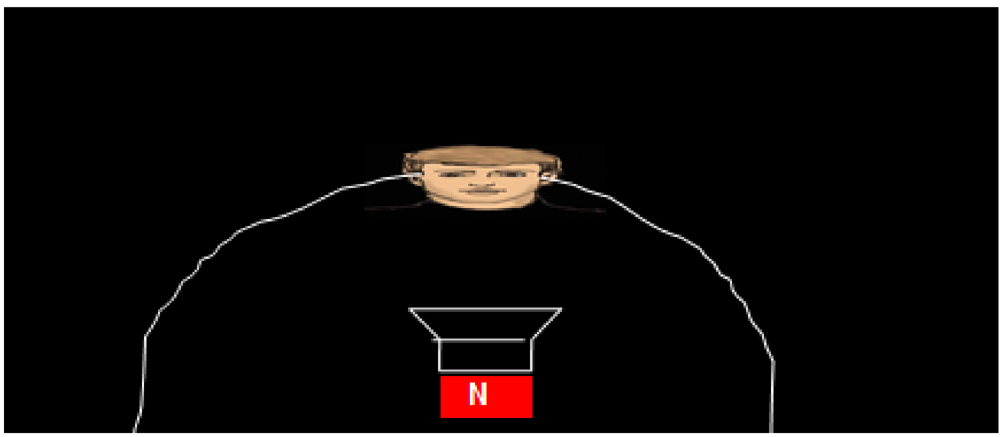

Figure 2. Experimental set-up (air conduction)

The signals (four comedians' speeches) and noises (1 background noise) were stored on two PC computers with M-Audio sound cards and Sony Sound Forge 7.0 software. The four comedian speeches used in the study were "Bar Jokes," "Complimentary Peanuts," "Mad Cows and Udders," and "Are There Golf Courses in Heaven?" All signals are excerpted from the "Delight Yourself and Be the Enemy of Others" CD by Garrison Keillor, *Prairie Home Companion* (2004). Each listener used the preferred speech signal. The background noise was multi-talker noise of 12 voices (Frank and Craig, 1984). All the signals were stored in Gateway PC computer and normalized to have the same relative average RMS level of -25.0 dB measured at the output of the M-audio sound card. Both the speech and the noise were played from Gateway PC computers using Sony Sound Forge 7.0 software and WINAMP software for looping. Positions of all volume controls, except for M-audio volume control, were fixed.

Procedure

Preliminary procedures included obtaining informed consent through the university's Institutional Review Board. Participants were recruited through posted flyers and personal

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acquaintance. Prior to the start of the experiment, the audiometer, the bone conduction transducer, and the loudspeaker in the acoustic chamber were set to pre-determined readings. Pre-run tests of the signal and the noise on the loudspeakers were conducted to ensure that all equipment worked perfectly before the experiment began.

As the participants arrived, they were welcomed and briefed about the purpose of the experiment, and any questions that arose from the briefing were answered. Participants who agreed to proceed with the experiment were given an informed consent form to sign and a pre-test hearing screening form to complete the demographic portion. Next, the hearing screening task was explained to all the participants. They were asked to push a button in response to every tone they heard, and to do nothing if they heard no tone. At the beginning of the hearing screening test, each participant was asked to sit at the center of the acoustic booth with a headphone and a push button provided. Participant responses were recorded on their hearing screening form. The hearing screening was conducted on the participant's ears at 25 dB for octave band at frequencies between 250 and 4000 Hz. With the use of pure tone, the hearing screening was conducted to ensure that all participating subjects had normal hearing.

The audiometric testing was performed using a Fonix Hearing Evaluator (FA-10 Digital Audiometer) and TDH-39P, C13357 Telephonics headphones calibrated according to 1996 ANSI specifications for audiometers. Participants who passed the hearing screening continued with the experiment, and those who failed were released from the experiment. Prior to starting the experiment, each participant was instructed to imagine him/herself working in a factory performing a mundane task and listening to a recording of a comedian's performance for on-the-job relaxation. At a certain point, a coworker started a noisy operation that made listening to the recording more difficult. The noise from the operation was represented by the background noise from the speaker. The listener's task was to first adjust the signal level (i.e., the volume of the recording) to a most comfortable listening level (MCLL) and then to adjust the noise level to the maximum tolerable level above which s/he would simply stop listening to or turn off the source of the signal.

Participants were told to use hand gestures to request changes in the signal levels. Hand up, hand down, and hand flat indicated volume up, volume down, and volume okay, respectively. There were two signal sources (BCTs and earphones) and one noise type (multitalker-babble noise) used in the experiment. Condyle bone location was used for the bone conduction transducer, since [16] found no statistically significant difference between speech delivered through headphones and BCTs placed on the condyle.

Results

The average and standard deviation of the ANLs recorded when earphone was used as signal source are -1.83 dB and 1.78 and when bone conduction transducer was used as the signal source are -8.70 dB and 1.91. These values are shown in Table 1; the average ANL value is approximately 83% lower during BCT signal listening condition. This indicates that participants accepted more background noise when the signal was delivered through BCT than when it was delivered through earphone.

Table 1. Average, standard deviation and range of ANLs for both AC and BCT

Average	Earphone (AC)	Bone Conduction Transducer (BC)
	-1.83 (dB)	-8.70 (dB)
SD	1.78	1.91
Range	[(-4.32) - (1.28)] dB	[(-11.26) - (-5.45)] dB

Figure 3 shows the relationship between participants' ANL during the two listening conditions. To better understand the differences pictorially, Figure 4 shows a graphical comparison between the average ANLs for the two sound waves transmission pathways. The bone conduction transducer in the average has a higher negative ANL value than the earphone by the values of approximately 65%.

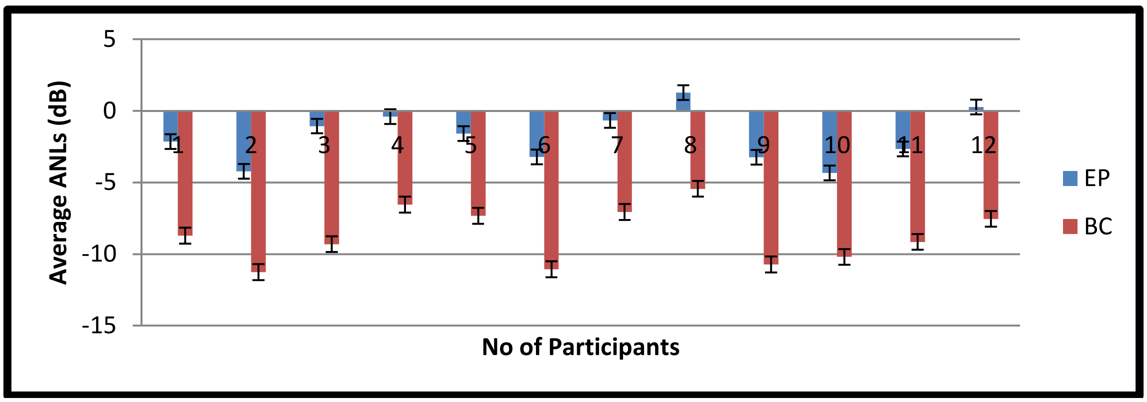

Figure 3. Average ANL and standard error across trials for each participant during earphone (EP-earphone & BC-bone conduction transducer)

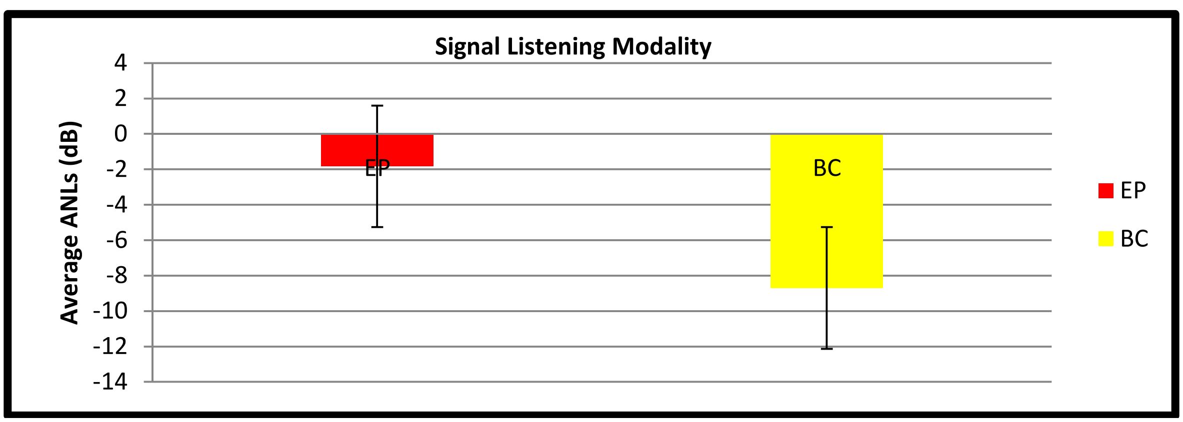

Figure 4. Average ANLs (dB) and standard error for both earphone and bone conduction transducer sound waves transmission pathways

Figure 5 shows the differences in graphical representation for BNL. No much difference was noticed between the maximum background noise participants accepted when the signal was delivered through an earphone and when it was delivered through the bone conduction transducer.

Figure 6 is the graphical representation for the differences in the MCLLs recorded during listening to signal through EP and through BCT. This graph indicates that participants have accepted higher signal level in decibel (dB) when the signal was delivered through an earphone compare with when it was delivered through the bone conduction transducer.

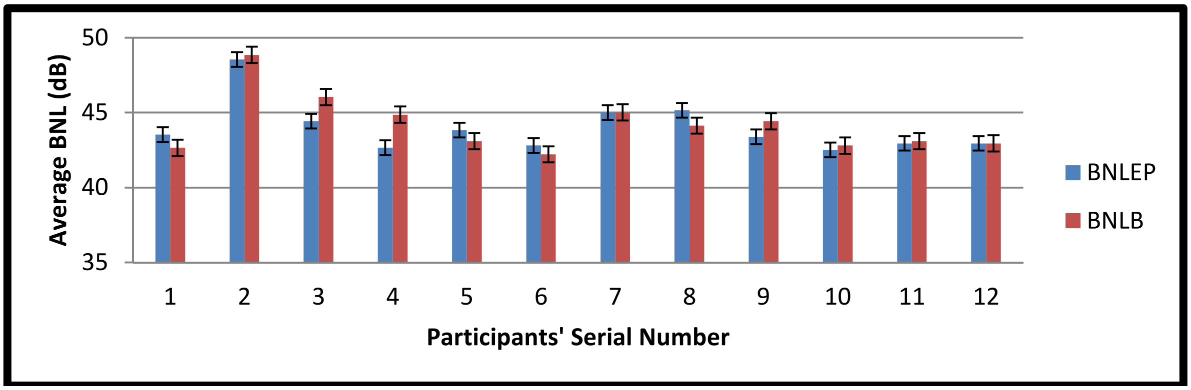

Figure 5. Average BNL and standard error across trials for participants during earphone and bone conduction signal listening conditions (BNLEP = BNL for earphone, BNLB = BNL for BCT)

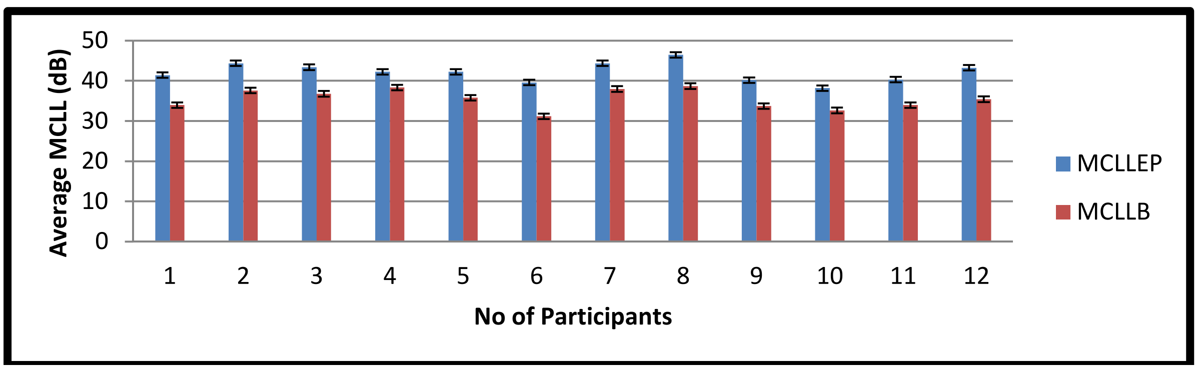

Figure 6. Average MCLL and standard error in dB across trials for participants during earphone and bone conduction signal listening conditions (MCLLEP = MCLL for earphone, MCLLB = MCLL for BCT)

To further understand the differences, a paired t-test analysis was conducted using SAS version 9.2 on the ANLs, to identify significant differences between listening through the earphone and listening through the bone conduction transducer. Prior to analysis, the dataset was checked for normality. Dataset for earphone were showed to be normally distributed with Shapiro-Wilk test W = 0.953, P= 0.678 and Anderson-Darling test A2 = 0.232 p =

0.734. The dataset for bone conduction was also normally distributed with Shapiro-Wilks W = 0.931, p = 0.422 and Anderson-Darling test $A^2 = 0.331$, p =0.449. Results show a significant difference between the two sound waves transmission pathways in ANL values. Pairwise comparisons showed significant results ($\alpha = 0.05$, $t(22) = 9.11$, $p < 0.0001$) for earphone vs. bone conduction transducer. This indicated that participants accepted more background noise when the signal was delivered through the bone conduction transducer than when it was delivered through the earphone.

To ascertain the source of the significant differences found in ANL values, further analysis was conducted with t-tests on the maximum BNL and the MCLL during both transmission pathways. Findings reveal no significant difference between the BNL during the two listening conditions ($\alpha = 0.05$, $t(22) = 0.29$, $p = 0.7717$). In agreement with Hodgetts et al.'s [1] study on normal-hearing listeners, while a significant difference between the MCLL for earphone and for BCT was revealed ($\alpha = 0.05$, $t(22) = -7.40$, $p < 0.0001$). As shown in Figure 6, there was a significant difference in MCLL. This shows that the significant differences found in the ANL were a result of differences in signal level accepted by participants during the two listening conditions. The higher levels of signal noticed during the AC could be traced to the fact that participants tried to compensate for the level of the noise chosen as their BNL.

Table 2. Output of MCLL participant t-test for earphone and bone conduction transducer

Method	Variances	DF	t-value	Pr > \t\
Pooled	Equal	22.000	9.110	< 0.0001
Satterthwaite	Unequal	21.886	9.110	< 0.0001

Conclusions and Discussion

Based on the results of the analyses, ANLs obtained using the two sound waves transmission pathways with multitalker (babble) noise are reliable over the short period of three minutes used in the experiment for listeners with normal hearing. Findings of this study show that, on the average, participants listened to speech signal at higher level from earphone than the level they would accept when listening to a similar speech signal through the BCT. However, no statistically significant difference was found in the maximum background noise level that participants accepted during the two listening conditions. Further analysis on the average ANL between the two sound waves transmission pathways revealed that participants have higher ANL with the earphone than with the BCT. Findings of this study support the previous studies that BCT is a viable means of listening in a noisy environment [12, 13]. This finding also supports one of the "Genuine Motorola Accessories" reports online, which stated, "the advantage of sound and voice being transmitted by vibration is that communication remains viable in environments where it is not feasible or is too noisy for air transmission of sound or voice."

The finding of this study showed a better speech understanding in BCT than air conduction hearing process under the same range of background noise level. Hence, the findings on BCT contradicted [17]'s findings, whose study showed that the sound quality of BCT is impaired because of the sound energy that is lost in the soft tissue over the skull bone. This is especially true for the higher sound frequencies so important for speech understanding in noise. Since researchers have considered the use of bone-conduction microphones for speech communication in a military context [18, 19], the findings of this study will be very important not only for the military but also for communication companies, security, and the law enforcement officers. Moreover, researchers are recognizing that the comparison of air-conducted hearing thresholds with bone-conduction thresholds will allow audiologists to localize where in the auditory system a problem exists in a hearing-impaired person. Therefore, the expansion of ANL to explore the effectiveness of a BCT is a novel idea. It is recommended that more research should be conducted in this area of research so that the BCT can realize its full potential.

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Biography

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