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Measures of the ecological loudness of speech

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Most laboratory studies of binaural loudness summation show ample amounts of summation (e.g., a tone presented binaurally is clearly louder than the same tone presented monaurally), but classroom demonstrations of this phenomenon in typical daily environments yield negligible loudness summation for most listeners. To gain insight into this difference, experiments were performed with different degrees of ecological validity. Statistical analysis indicates that the most ecologically valid condition results in less binaural loudness summation than traditional laboratory procedures. Implications for normal-hearing listeners and impaired listeners with hearing aids are discussed.

INTRODUCTION

Motivation for the present work came from the observation that classroom demonstrations of binaural loudness summation never yielded the magnitude of the effect that was reported in the literature. According to the literature, most earphone studies suggest binaural-to-monaural loudness ratios ranging from about 1.3 to 1.7, or almost 2 (Reynolds and Stevens 1960; Scharf and Fishken 1970; Marks 1978; Hellman 1991; Zwicker and Zwicker 1991; Schneider and Cohen 1997; Marozeau *et al.* 2006; Whilby *et al.* 2006; Epstein and Florentine 2009).

CLASSROOM DEMONSTRATIONS

In real-world classroom demonstrations of binaural loudness summation—first performed in 1975 at the Acoustics Laboratory of the Technical University of Denmark—a lecturer asked her students to estimate the loudness of sounds while they sat in their usual seats in a typical classroom. She recited memorized passages while attempting to keep her voice at a constant level that was typical for her lectures. The students’ task was to look at her and estimate the loudness of her voice while listening with both ears compared to the loudness of her voice while they were blocking one ear by pressing on a tragus with an index finger. They were encouraged to make several observations for each of the two conditions before making a judgment. The students’ subjective reports indicated that the loudness of speech changed a negligible amount, if at all. This phenomenon has been dubbed

binaural loudness constancy (BLC), which is an almost complete absence of binaural loudness summation (*i.e.*, a sound presented binaurally is about as loud as the same sound presented monaurally). Note that BLC is not the same as loudness constancy with distance in which loudness remains relatively constant while sound source distance is varied (Mohrmann, 1939; Zahorik and Wightmann, 2001; for review, see Sivonen and Ellermeier, 2011).

Since 1975, BLC demonstrations have been repeated more than 35 times to groups of students in many different classrooms in several countries. The results from these demonstrations are about the same if the students have not been told prior to the demonstration to expect a doubling or large increase in loudness. (This demonstration has been refined to check for asymmetries between the ears of the observers, which could negatively influence the outcome. It can be found at the end of this paper.)

REAL WORLD VS. TYPICAL LABORATORY EXPERIMENTS

The classroom demonstrations differed from the previous laboratory experiments in many ways: stimuli (tones, noises, recorded speech, live speech), mode of presentation (earphones, loudspeaker, without and with visual cues), test environment (sound-attenuating chamber, anechoic chamber, lecture room), and psychophysical procedure (magnitude estimation, equal-loudness matching, two-interval comparison, introspection). Could it be that the stimuli, mode of presentation, test environment, psychophysical procedure, and/or visual speech cues from the lecturer caused the difference in results from the classroom demonstrations and the laboratory experiments? There are reasonable hypotheses that can be made. For example, one could argue that tones and noises are processed differently than speech or other environmentally relevant sounds. One could also argue that in survival situations, loudness may be an important cue to distance. It might be advantageous if a listener was able to judge the distance of a sound source equally well whether listening with one or two ears because unilateral conductive hearing losses are quite common.

Bridging the gap between the real world and laboratory experiments

Epstein and Florentine (2009) made an initial attempt to study this complex issue of BLC. They examined the loudness of tones and speech presented binaurally and monaurally via earphones and via loudspeakers in a sound-attenuating audiometric test suite. Of course, it is impossible to achieve a clean monaural condition in bilaterally normal-hearing listeners due to attenuation limitations. Therefore, a properly inserted foam earplug was used to achieve an effective monaural condition. The earplug increased threshold by 20-24 dB at 1 kHz compared to unoccluded ears. This attenuation was deemed sufficient because it had been previously reported that BLS with a 20-dB difference between the ears indicate a 20% or smaller reduction in the ratio from the true monaural condition (Zwicker and Zwicker 1991). In any case, it is the relative difference in BLS across conditions that was of interest.

The results of Epstein and Florentine's experiment agree with both the classroom demonstrations and the previous laboratory experiments. The data also agree with the majority of the data in the literature and indicate that binaural loudness summation is far from complete (the ratio was clearly less than two) for all the test stimuli. Their data suggest that (1) the amount of BLS is significantly smaller for speech from a visually present talker than for recorded speech and tones, (2) the amount of BLS is significantly smaller for loudspeaker presentation than for earphone presentation, and (3) the amount of BLS is smallest for speech from a visually present talker presented via loudspeakers than any of their other test conditions. In fact, the data from a visually present talker heard via loudspeakers in a sound field were similar to the ecologically valid classroom demonstrations.

In a follow-up experiment (Florentine and Epstein, 2010) that only used speech stimuli, the following hypothesis was tested: A talker's speech presented under more ecologically valid conditions results in less binaural loudness summation than speech presented without visual cues and/or presented via earphones. The stimuli were recorded spondees with or without visually present male and female talkers. The stimuli were presented over a wide range of levels under four conditions: (1) video and audio via earphones, (2) audio only via earphones, (3) audio only via a loudspeaker, and (4) video and audio via loudspeaker. The stimuli were presented monaurally and binaurally via earphones or via a loudspeaker at a distance of 1 m in 3X3-m test booth. A flat-screen visual display was used to simulate a natural visual distance. Twelve young listeners with normal hearing made loudness judgments using magnitude estimation. Results indicate that the most ecologically valid condition (*i.e.*, video and audio presented via loudspeaker) resulted in significantly less binaural loudness summation than any of the other test conditions (*i.e.*, speech without visual cues presented via both earphones and loudspeaker, and speech presented with visual cues via earphones).

Is BLC surprising?

When viewed in the context of multidimensional interactions and perceptual constancy, BLC is not surprising. Vision can influence hearing. For example, if a subject observes a talker articulating /ga/ and simultaneously hears /ba/, the subject reports perceiving /da/ (McGurk and McDonald, 1976). Visual location can also take precedence over auditory spatial location in a phenomenon known as visual capture; an example of this is ventriloquism in which a talking dummy is perceived (Choe *et al.*, 1975). Research on multisensory interactions in ratings of loudness are common (see Fastl and Florentine, 2011). Sivonen and Ellermeier (2011) point out that BLC may be analogous to binocular brightness judgments; closing one eye does not make the world appear less bright.

What can we conclude about BLC?

In addition to the obvious conclusion of the existence of BLC, it is clear that conclusions drawn from controlled loudness experiments in laboratories may not be

directly applicable to the perception of loudness in rooms. In other words, BLC reinforces the importance of ecological validity in loudness research.

A prerequisite condition for BLC appears to be a visually present talker paired with the auditory stimulus presented in a room. Either condition alone—just the visually present talker heard via earphones or the visually absent talker heard via a loudspeaker—did not result in BLC. Reflections and reverberation are likely to be important cues, but not the only ones. The phenomenon of BLC is highly likely to reveal an effect of higher-level processing on the loudness of everyday sounds in daily environments and this provides a challenge for loudness models.

WHAT IS THE CLINICAL RELEVANCE OF BLC?

Binaural loudness summation is a common concern in hearing-aid fittings, because dissatisfaction with loudness is not uncommon among hearing-aid users. It is clinically important to adjust the loudness properly at the initial visit because loudness is correlated with annoyance [For a general discussion of loudness and annoyance, see Fastl and Florentine (2011)]. If sounds are annoying, the hearing-aid user will not want to use the hearing aids. The patient may think that the hearing aids are not good and/or lose trust in the hearing healthcare professional. Once a patient leaves an initial fitting unsatisfied, it may take a long time before returning to seek help.

Clinical data indicate that loudness functions of people with hearing losses can show considerable individual differences for speech and tones (Cox *et al.*, 1997; for review, see Marozeau and Florentine, 2007). Measures of binaural gain also show considerable differences as a function of level in the same listener and considerable differences among listeners with hearing losses (Whilby *et al.*, 2006). In fact, there are many factors that influence loudness in listeners with hearing losses [for review, see Smeds and Leijon (2011)]. Therefore, individual differences make it impossible to come up with one level of attenuation for binaural fittings that apply to all hearing-aid users.

Thus far, we have discussed what we believe we know about BLC and hearing losses. Based on what is known about BLC for listeners with normal hearing, there are some clinically relevant questions we need to ask. For example, are the binaural systems of people with hearing losses capable of maintaining BLC? If so, do the fitting algorithms for hearing aids allow the listener to maintain a stable perception? If the hearing-aid levels are changing to adapt to different situations, there may not be enough time for the hearing-aid user to adapt to the changing loudness. If the hearing-aid user cannot maintain perceptual constancy of loudness of the target signal (usually speech from a visually present talker), the loudness of the target—as well as the background noise—may be changing. Although speech may be intelligible to the hearing-aid user, processing speech could take more cognitive load and listening could be exhausting. Finally, it would be interesting to know if hearing aids work more like earphones or loudspeakers.

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Classroom Demo of BLC

Perhaps the best way to convince you of the existence of BLC is to encourage you to participate in a simple two-part introspection experiment. In the first part, it is important to verify that your ears are well matched. Listen to the loudness of a person talking directly in front of you with one ear then the other ear by alternately blocking the sound coming into each ear. Usually, this can be accomplished by simply pressing firmly on your tragus. This method will not block all the sound coming into your ear, but should provide enough attenuation for the present demonstration. If the loudness is the same when listening with each ear separately, your ears are matched in loudness enough to participate in the second part. If you perceive a different loudness in each ear, this demonstration may not work and you are encouraged to contact a hearing healthcare professional to determine the reason for the loudness asymmetry.

In the second part, stand about a meter from a person talking in a typical room. Look at the person and concentrate on what the person is saying while alternately blocking and unblocking the sound coming into one ear. While you are doing this, notice if the sound jumps up and down in loudness. Notice that the sound becomes clearer when listening with two ears, but not much louder. It is important that you focus on what the talker is saying as you would in a typical listening situation. If you focus only on loudness, you may revert to analytic listening and the demonstration will be less effective. Listening in psychoacoustic mode is an atypical mode of listening for most people listening in ecologically valid environments.

N.B.: It is likely that those of us who study hearing are a select group of trained auditory observers—we belong to the Tribe of the Ear—and are atypical listeners. It is common for us to quickly transition from synthetic to analytic listening when judging sounds. For example, we can enjoy listening to an entire symphony orchestra or switch our focus to hear out a single instrument or group of instruments. An untrained listener is not likely to spend much time listening in a psychoacoustic analytic mode. The fact that this demonstration works for many trained listeners is strong support for the existence of BLC. Please try this demonstration with untrained listeners, who are more typical of the average population. Please let us know the outcome!

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The role of working memory capacity and speed of lexical access in speech recognition in noise

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Cognitive skills are important for speech processing and comprehension. The objective of the present investigation was to address the role of working memory capacity and speed of lexical access in speech processing in noise. This was done by measuring speech recognition thresholds (SRTs) in background noise with the Hagerman test and the Swedish HINT. Cognitive capacities were measured by a lexical-decision making test and a reading-span test. Forty hearing impaired individuals, aged 44-86 years, participated in the study. The relations between SRTs and cognitive scores were studied using correlation analyses and analysis of variance for high and low cognitive performance groups. The individuals showed significant correlations between SRTs and cognitive scores which remained also after correcting for PTA4. A higher demand on cognitive processing was found for the criteria of 80% compared to 50 % speech recognition.

INTRODUCTION

Hearing speech yields not only the sensation of incoming auditory information, but also involves processing and interpretation of speech in the context of knowledge and previous experiences. Information regarding how speech is categorized and related, for example contextually, phonologically, lexically, syntactically, and semantically, is stored in a long-term memory. Speech processing includes elements of both top-down and bottom-up processing at all stages of information-processing (cf., Davis and Johnsruide, 2007).

The absolute hearing threshold is often a major factor in explaining the variation in speech recognition scores for hearing-impaired listeners in quiet as well as in noise (Plomp, 1986). Remaining variations may be caused by inter-subject variations in peripheral supra-threshold distortion (e.g. Plomp, 1986; Glasberg and Moore, 1989), and from variations in central auditory and cognitive processes (Humes, 2005; Pichora-Fuller, 2003).