Lost in Transmission?

Understanding and minimizing undesired side effects of hearing devices

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Introduction

Headphones, hearing aids and similar devices are becoming increasingly smart while the boundaries between consumer electronics, medical hearing aids and hearing protectors are blurring [1, 2]. Despite different applications, they all have in common that the user hears the world through them electro-acoustically. One potentially limiting factor for the performance of these devices is how acoustically transparent they are, meaning that apart from a desired modification, listening through these devices should be no different from hearing through one's own, open ears. However, acoustic transparency is principally and practically limited by imperfections in sound capturing, processing and reproduction of the hearing device. This circumstance often leads to undesired side effects regarding sound perception as illustrated in Figure 1. These may including impairments of spatial hearing, lower performance and higher experienced effort in speech perception tasks, on top of poor sound quality of the surroundings and the wearer's own voice [3, 4, 5, 6, 7, 8, 9].

Side-effects of hearing devices and their origins

The underlying reason for such perceptual side-effects are imperfections in the transmission chain of the hearing device that lead to an undesired, and often subtle change in the sound pressure reaching the eardrums (see Figure 2). First, due to design constraints the microphone locations are usually located where especially directional cues normally created by the direction-dependent acoustic transmission around the head, through the pinna and ear canal are distorted [10, 11, 12, 13]. These distortions mainly affect spatial hearing abilities [3, 14, 15], up to the point that with signals obtained with microphones behind the ear approaches chance rate in median plan localization [3]. However, altered HRTF cues may also cause a disadvantage regarding speech intelligibility when the target signal and the interference are spatially separated, due missing pinna directionality [14, 16].

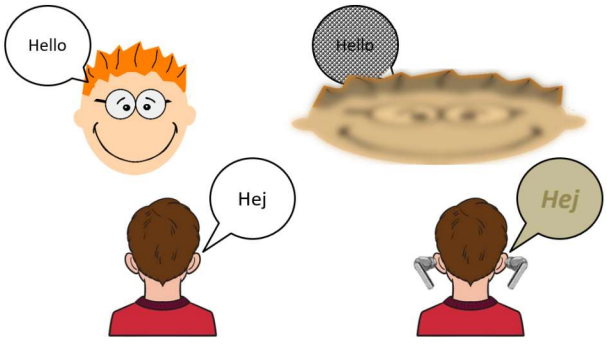

Figure 1: Visualization of possible perceived side-effects when listening through hearing devices: External sound sources may have an unnatural timbre, may be perceived spatially biased and might be harder to understand. Sounds generated by the user, such as the own voice, might sound unnatural.

Second, sound processing may introduce rather subtle artefacts, including processing delays, imperfect time-frequency analysis and reconstruction, and sensor noise may be added [8]. As an example, it as found that speech perception is impaired by wearing transparent hearing devices, even if speech and interferer are collocated and the hearing devices are individually fitted to not change the level or signal to noise ratio at ear [8, 14, 16]. Besides a significant effect regarding speech intelligibility, large effects on neural markers of listening effort have been demonstrated in this condition [17]. While speech intelligibility models were unable to predict these outcomes, a significant correlation between sound quality models and the disadvantage of transparent hearing devices regarding speech intelligibility was found [8]. This interesting observation illustrates that subtle artefacts of hearing devices are not a luxory issue, but may cause audiologically serious side-effects like a lowered ability to process speech.

Third, the reproduction of processed sound at the eardrum is often limited by the capabilities of miniature drivers, which results in the restriction the frequency range both towards low (below 1 kHz) and high (above 6 kHz) frequencies, in addition to nonlinear distortions [18]. Especially in the low frequency end, the reproduction capabilities of miniature loudspeakers heavily depends on the coupling, i.e. how acoustically sealed the ear canal is [19, 20]. The limited low-frequency response affects mainly affects the sound quality for sound playback and is a main limiting factor for the effectivity of noise reduction algorithms with fittings that do not fully

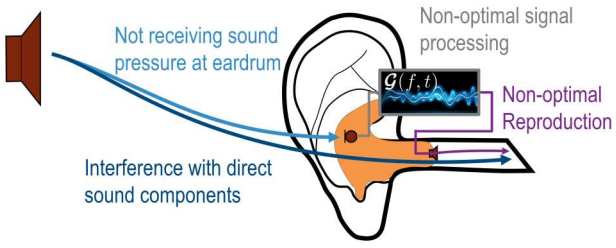

Figure 2: Potential origins of perceptual side-effects along the sound transmission chain in a hearing device.

occlude the ear [21]. The limited high-frequency response also affects sound quality, and hinders the effective transmission of high-frequency cues that are crucial for full spatial hearing fidelity [3, 10].

Fourth, also depending on the coupling, interference with direct sound components can lead to disturbing interference effects if there is a non-negligible processing delay, so-called comb-filtering artefacts [22, 23, 24, 25, 26]. The term comb-filter originates from the fact that the superposition of a sound with a delayed version of itself leads to alternating constructive and destructive interferences across the frequency axis, leading to a rippled, comb-like spectrum. These artifacts can be detected magnitudes below the echo threshold, showing that spectral distortions drive their perception. Besides an unnatural or "hollow" sound for both external and the own voice, comb filtering artifacts have also been shown to contribute to spatial hearing deficits [3].

These deviations do not only hold for sounds from our acoustic environment or conversational partners, but also sounds generated by the wearer of the hearing device, like the own-voice, and sounds generated by walking, chewing or swallowing. For these kind of sounds, besides the processing of airborne sound components that are equally affected by hearing device processing as external sounds, the influence of hearing devices on body-conducted sound components are highly important. In particular, vibration in bone or tissue constitute another sound source inside the ear canal of the user, which is amplified if a device is worn in the ear, in a strength depending on the insertion depth and grade of sealing of the ear canal [27, 9, 28, 29, 30]. This amplification occurs mainly in the frequency regime below 1 kHz and leads to an unnatural perception of body sounds that is often described as "boomy". This so-called occlusion effect is a major concern and among the most frequent complaints from users of hearing aids or hearing protectors [31, 32].

Towards achieving acoustic transparency

The reduction of perceptual side-effects can only be achieved if the physical origins can be identified, and possibly reduced - which may not be possible for every application. While it is clear that the hearing device microphone location is critical for spatial hearing, the device size, cosmetics, or the need to place multiple microphones prevent placement in the ear canal for many applications. Also, disturbing effects of a processing delay cannot be solved ultimately by reducing delays, since to some extent they are a direct consequence of time-frequency analysis that is usually performed for noise reduction or frequency-dependent compression as applied in hearing aids. For the occlusion effect, both active suppression [33] and optimized earmold designs have been demonstrated to provide suitable tools to reduce perceptual effects of ear canal occlusion, without sacrificing device performance that is connected to the traditional venting approach [27]. The origins of other, more subtle side-effects that have been traditionally been summarized as "sound quality" are yet to be identified.

Alltogether, there is some growing evidence that achieving acoustic transparency is a worthwhile goal in hearing instruments across many application scenarios, in order to improve their functionality and aid their acceptance. Only if the negative side effects of a hearing device does not outweigh its benefits, a person is likely to use it. Arguably, acceptance of hearing devices is most critical in hearing aids and hearing protectors- either to start early treatment of a hearing loss and minimize the risk of cognitive decline and other health factors [34], or to prevent it in the first place.

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