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Research paper

Spectral and binaural loudness summation for hearing-impaired listeners☆

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ABSTRACT

Sensorineural hearing loss typically results in a steepened loudness function and a reduced dynamic range from elevated thresholds to uncomfortably loud levels for narrowband and broadband signals. Restoring narrowband loudness perception for hearing-impaired (HI) listeners can lead to overly loud perception of broadband signals and it is unclear how binaural presentation affects loudness perception in this case. Here, loudness perception quantified by categorical loudness scaling for nine normal-hearing (NH) and ten HI listeners was compared for signals with different bandwidth and different spectral shape in monaural and in binaural conditions. For the HI listeners, frequency- and level-dependent amplification was used to match the narrowband monaural loudness functions of the NH listeners. The average loudness functions for NH and HI listeners showed good agreement for monaural broadband signals. However, HI listeners showed substantially greater loudness for binaural broadband signals than NH listeners: on average a 14.1 dB lower level was required to reach "very loud" (range 30.8 to −3.7 dB). Overall, with narrowband loudness compensation, a given binaural loudness for broadband signals above "medium loud" was reached at systematically lower levels for HI than for NH listeners. Such increased binaural loudness summation was not found for loudness categories below "medium loud" or for narrowband signals. Large individual variations in the increased loudness summation were observed and could not be explained by the audiogram or the narrowband loudness functions.

1. Introduction

Loudness is an important factor in human auditory perception: it can be assigned to any stimulus and ranges from very soft near threshold to too loud at high sound pressure levels. For communication devices, particularly those involving speech processing and presentation, for example hearing aids, loudness affects preference ratings (Mueller et al., 2008; Smeds, 2004) and has an impact on spontaneous acceptance (Kreikemeier, 2011). Moreover, loudness complaints are one of the most frequent reasons for revisiting the hearing aid dispenser (Jenstad et al., 2003). Loudness depends on sound pressure level but also on other factors e.g., duration and bandwidth. Many studies have shown that increasing the bandwidth of a signal of constant overall level increases the loudness (e.g., Fletcher and Munson, 1933; Zwicker et al., 1957; Appell, 2002; Verhey and Kollmeier, 2002). This effect is referred to as spectral loudness summation or loudness summation across frequency.

Individual loudness perception can be measured quickly and intuitively using categorical loudness scaling. Test signals with randomized levels are presented to a subject. The subject indicates the perceived loudness on a scale from "not heard" to "too loud" (ISO 16832, 2006). The responses are used to estimate a loudness function relating the loudness categories to the sound level in dB SPL or dB HL. Hearing-impaired (HI) listeners typically show loudness functions starting at higher levels (increased thresholds) and rising more steeply (recruitment) than for normal-hearing (NH) listeners (Brand and Hohmann, 2001). To compensate for the changed loudness perception in HI listeners, a level-dependent amplification strategy with high gain for weak signals and reduced gain for high signal levels is required. In many cases, the hearing

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loss is frequency dependent, e.g., for typical age-related hearing loss hearing threshold increases at higher frequencies (Morrell et al., 1996). Therefore, a combination of frequency- and level-dependent amplification is required to compensate for hearing impairment.

Current hearing aids usually include multiband dynamic compression capable of applying frequency- and level-dependent gains. Fitting rationales for adjusting the gain parameters for an individual patient typically aim to optimize speech intelligibility and/or to restore normal loudness perception. Current prescriptive fitting methods are typically based on audiometric hearing thresholds, while loudness scaling is not widely used in clinical practice to fit hearing aids. The widely used fitting formula NAL-NL1 (Byrne et al., 2001) aims to optimize speech intelligibility. Gains are calculated based on a modified speech intelligibility index (ANSI S3.5, 1997) combined with a loudness model (Moore and Glasberg, 1997). In a retrospective study of patients fitted using NAL-NL1, 33% rated the applied gains as “too loud” immediately after fitting (Keidser et al., 2012). Therefore, gain reductions to avoid “too loud” ratings were included in the successor fitting rule NAL-NL2, emphasizing that loudness plays a considerable role in hearing-aid fitting. The gain reductions were empirically determined, but the underlying perceptual mechanisms are not entirely understood.

Many studies have used amplification intended to restore normal loudness perception for HI listeners (e.g., Barfod, 1978; Allen et al., 1990; Killion and Fikret-Pasa, 1993; Cox, 1995; Herzke and Hohmann, 2005; Kreikemeier, 2011; Rasetshwane et al., 2014). Typically, monaural loudness perception of narrowband sounds is measured and gains of a multiband compressor are adjusted to match loudness functions for narrowband sounds to those observed for NH listeners. Hearing aids using such a fitting rationale produce on average gains that are too high for broadband signals when loudness perception is judged on a categorical scale and compared with that for NH listeners: Latzel et al. (2004) measured loudness functions using categorical loudness scaling after narrowband loudness compensation. The loudness function for broadband sounds matched quite well the NH reference function for levels up to “medium” loud. However, loudness ratings for levels above “medium loud” were obtained at considerably lower levels than for NH listeners. As a possible solution, Latzel et al. (2004) suggested considering loudness summation effects in the gain calculation. Several studies have shown that HI listeners have lower-than-normal spectral loudness summation (Bonding and Elberling, 1980; Brand and Hohmann, 2001; Florentine and Zwicker, 1979; Garnier et al., 2000; Verhey et al., 2006) but the implications for broadband loudness compensation are not straightforward. The required correction values for compression algorithms to restore normal loudness perception for broadband sounds might depend on the hearing loss but also depend on details of the compression algorithm, including the number of compression channels and the bandwidth of the level estimators. Both factors influence the estimated channel levels for broadband signals and change the gain, while the level estimation stays unchanged for narrowband signals.

Another factor influencing loudness perception is binaural loudness summation. To evoke equal loudness perception, a higher signal level is required if a sound is presented to one ear than if it is presented to both ears (Marks, 1980). The effect for HI listeners is assumed to be similar to or slightly less than for NH listeners (Dermody and Byrne, 1975; Hall and Harvey, 1985; Hawkins et al., 1987; Moore et al., 2014), but only limited data are available in the literature. Moore et al. (2014) assessed binaural loudness summation of narrow- and broadband signals for HI listeners. No significant effect of bandwidth was observed, but the HI listeners were only tested without amplification. Binaural loudness perception is also slightly affected by interaural correlation. Culling and Edmonds (2007) showed that uncorrelated narrowband signals are perceived as louder than correlated signals by NH listeners. This effect was not observed for broadband signals.

Taken together, it is not well understood how bandwidth and binaural presentation affect loudness perception by HI listeners aided with a narrowband loudness compensation strategy. Particularly, loudness perception as a function of bandwidth for monaural and for binaural presentation have never been assessed systematically for such a compensation strategy. Moreover, when using loudness models, it has been shown that the required gain for narrowband loudness compensation of a certain hearing loss differed by more than 10 dB depending on the model (Oetting et al., 2013). Therefore, the present study systematically investigated loudness perception of stationary signals by older HI listeners when their individual narrowband loudness perception was matched to the average for younger NH listeners. Loudness functions for NH and HI listeners were measured for narrowband signals and for signals with greater bandwidths using the ACALOS procedure (adaptive categorical loudness scaling; Brand and Hohmann, 2002). HI listeners were aided with static gains in six bands to restore narrowband loudness perception. Monaural and binaural measurements were conducted to disentangle effects of spectral and binaural loudness summation for NH and HI listeners. It was assessed whether (i) spectral loudness summation is altered for HI listeners when aided with a narrowband loudness compensating strategy, (ii) aided binaural loudness summation is different for HI and NH listeners for narrowband and broadband signals, (iii) individual differences in loudness perception of broadband sounds can be predicted by the audiogram. Additionally, (iv) the effect of diotic and interaurally uncorrelated presentations on the average NH loudness function was assessed.

2. Methods

2.1. Listeners

Nine NH listeners and ten HI listeners participated in this study. The NH group was aged between 21 and 33 years (mean: 26 years, standard deviation: 3 years) and had pure-tone thresholds not exceeding 15 dB HL at the standard audiometric frequencies between 125 and 8000 Hz except for one listener with a threshold of 25 dB HL for the left ear at 1 kHz. The HI group was aged between 69 and 76 years (mean: 74 years, standard deviation: 3 years) with slight-to-moderate sensorineural hearing losses and no self-reported tinnitus. The pure-tone average over 0.5, 1, 2, and 4 kHz was between 20 and 44 dB HL (mean: 34 dB HL). Eight of the HI listeners had symmetric hearing thresholds with differences between left and right ear not exceeding 15 dB. Listener HI05 had a better left ear with a threshold difference of more than 15 dB at four frequencies. Listener HI09 had a 20-dB difference at 125 Hz but otherwise differences not exceeding 15 dB. The pure-tone thresholds of the HI group are shown in the results section in Fig. 8. All listeners had a high-frequency hearing loss. In the last experiment (Section 3.5) only a subset of the listeners (4 NH) participated. All listeners were paid for their participation in the study.

2.2. Apparatus and procedure

Listeners participated in three (NH) or four (HI) sessions, each lasting about 1 h. Measurements were conducted in a sound-insulated booth. Pure-tone hearing thresholds were determined using manual pure-tone audiometry in the first session. The procedure described by the American Speech-Language-Hearing