EVALUATION OF HYPERACUSIS AND LOUDNESS ESTIMATES AS PART OF AN EXTENDED AUDIOLOGICAL TEST BATTERY

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ABSTRACT

Hyperacusis describes the condition in which individuals perceive mid-level sounds as uncomfortably loud, despite exhibiting normal hearing thresholds. Audiological assessments of hyperacusis commonly include the typical audiometric test battery, including uncomfortable loudness levels (ULLs), and a hyperacusis questionnaire (HQ). An estimate of the loudness growth function is often not included. This study investigated the correspondence between HQ scores, loudness functions, and key audiological measures. All twenty-two listeners had normal hearing (< 20 dB HL within the range 0.25-8 kHz) and no tinnitus. Extended high-frequency thresholds (10–16 kHz) were also measured. Listeners completed a HQ and Categorical Loudness Scaling (CLS) test. ULLs were also measured using pure-tone stimuli and the audiometric standard procedure (ULL-SP) and an adaptive procedure using speech-shaped noise stimuli adapted from the CLS task (ULL-CLS). The results indicated that elevated thresholds in the 12–16 kHz range were associated with a straightening of the entire loudness function. Additionally, significant correlations were observed between HQ scores and ULL-SP at 0.5, 2, and 4 kHz. Listeners with higher HQ scores exhibited steeper lower segment of the loudness function, indicating a more rapid growth in perceived loudness for low- to mid-level stimuli.

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1. INTRODUCTION

A three-round Delphi survey involving hearing healthcare professionals has proposed a consensus-based (90% agreement level) definition of hyperacusis as: "A reduced tolerance to sound(s) that are perceived as normal to the majority of the population or were perceived as normal to the person before their onset of hyperacusis, where "normal" refers to sounds that are generally well tolerated." [1]. The reported prevalence of hyperacusis can vary depending on the definitions and assessments used [2] but is typically cited as ranging between 8-15% [3, 4]; with a higher prevalence associated with certain syndromes and autism spectrum disorders [5]. Hyperacusis can be associated with fear of certain acoustic and social environments, avoidance behaviours, and reduced quality of life [6]. Hyperacusis is known to often share some comorbidity with tinnitus [7], and both conditions are considered to emerge as a consequence of the brain's attempt to compensate for cochlear trauma resulting from acoustic over-exposure. Hyperacusis may arise as a result of damage to synapses between inner hair cells and auditory nerve fibres, known as cochlear synaptopathy [8], which may manifest as a degradation in the neural coding of speech [9].

Clinical assessments of hearing are based on an assessment of hearing thresholds for sounds presented at the standard audiometric frequencies (SAF) of 0.25-8 kHz. Hyperacusis and early stages of cochlear synaptopathy may not be evident as elevated SAF thresholds [10]. Low uncomfortable loudness levels (ULLs) measured using pure-tone signals, as part of a standard audiological hearing test battery, may also be associated with hyperacusis. However, pure-tone ULLs may be variable amongst a population that reports hyperacusis [11], so ULLs on their own may be insufficient as a psychophysical indicator of hyperacusis. For that reason, combined assessment criteria may provide an improved indicator of hyperacusis [5], for instance, combining ULLs with scores from the Hyperacusis Questionnaire (HQ) [12]. Aazh and Moore suggested a minimum average ULL of 77 dB HL (averaged across test pure-tones of 0.25, 0.5, 1, 2, 4, and 8 kHz) and a score of at least 22 at the HQ as best indicators of hyperacusis [13]. Audiological assessments commonly include measures of ULLs and/or measures of the stapedius reflex as well as the HQ, but an estimate of the loudness growth function is often not conducted. Individual loudness perception can be assessed using the Categorical Loudness Scaling (CLS) test, in which the loudness perception for stimuli of different levels is assessed [14].

There is growing evidence supporting the assessment of hearing thresholds at an extended range of audiometric frequencies (EAF), such as 9 to 20 kHz, for providing an early indication of vulnerability to risk factors such as ageing, disease, ototoxic drugs, and noise exposure [15]. Although cochlear synaptopathy may contribute to difficulties in perceiving and understanding speech in adverse listening conditions, it may not necessarily manifest as elevated hearing thresholds in a SAF audiogram [16, 17]. It has been suggested that EAF audiometry might be useful as a biomarker of cochlear synaptopathy [10, 17], but it is still unclear how, and by which mechanisms, cochlear synaptopathy and EHF hearing loss are associated with hyperacusis, despite normal thresholds in the SAF range [18].

The current study investigated the correspondence between HQ scores, loudness growth functions, ULLs, and SAF and EAF audiograms.

2. METHOD AND PROCEDURE

2.1 Participants

Twenty-two listeners participated in the measurements (14 women, 8 men; mean age 26.9 years). All provided signed consent for the study, which had been approved by the UCL Ethics Board. The test session took 1.5 hours.

2.2 Facilities and Apparatus

The measurements took place in a double-walled sound-attenuated room. Audiometric thresholds, standard audiometric ULLs, and the CLS test were measured using a calibrated clinical audiometer, Auritec Audiometer with Ear3.0 software, Earbox3.0 soundcard and Sennheiser HDA300 headphones.

2.3 Audiometry

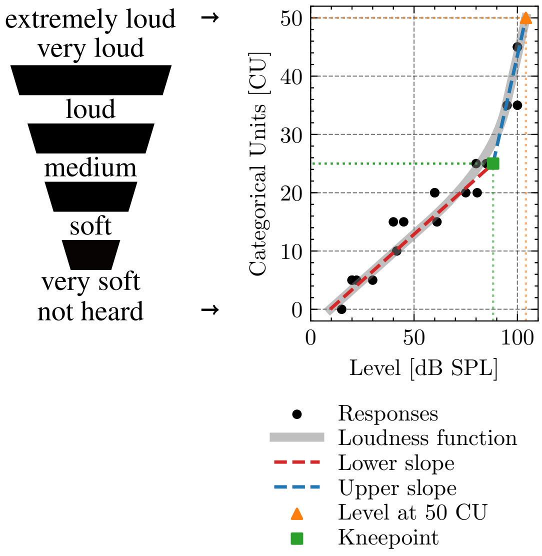
Audiometry was performed separately for listeners' right and left ears using pure-tone sound signals of 0.25, 0.5, 1, 2, 4, 6 and 8 kHz, following the British Society of Audiology (BSA) recommended procedure to obtain a SAF audiogram. All listeners had normal hearing as assessed by a SAF audiogram (i.e., hearing thresholds $<$20 dB HL) and no reported tinnitus. Listeners were also assessed with an EAF audiogram using pure-tone sound signals of 10, 12, 14 and 16 kHz.

ULLs were measured using pure-tone stimuli and following the audiometric standard procedure (ULL-SP). Aazh and Moore suggested a slight amendment to the BSA protocol when measuring ULLs using pure-tone signals for individuals with hyperacusis [19]. We followed such a protocol, which only slightly extended the overall audiological testing time. This approach allows for a more gradual exploration of the loudness space when measuring ULL-SP values in a population with hyperacusis.

The ULL-SP values were obtained separately for the right and left ears for 0.5, 2, and 4 kHz pure-tone signals, and then averaged across both ears. For comparison, ULLs were also measured using speech-shaped noise and an adaptive procedure based on the one used in the CLS test (ULL-CLS). A MatLab script was specifically created to run this adaptive CLS procedure to obtain the ULL-CLS thresholds. The ULL-CLS measurements were conducted for the right and left ears individually (monaural) and then averaged across both ears. Additionally, measurements were taken with both ears simultaneously (binaural diotic).

2.4 Categorical Loudness Scaling Test

The CLS test provides measures of loudness categorisation across an individual's dynamic range of hearing. In the CLS procedure, listeners categorised the subjectively-perceived loudness of a test signal using a pre-defined 11-point categorical scale (see Fig. 1a). Each of the categories is assigned a numerical value, referred to as a Cat-



(a) (b)

Figure 1: a) Representation of the 11-level categorical scale presented to listeners during the CLS test. Categories are mapped to categorical units (CUs) from 0 to 50. b) Example of loudness functions fitted to a participant's CLS test responses. The levels corresponding to the kneepoint at 25 CU and inferred at 50 CU, derived from the fitted functions, are indicated by the green and orange dotted lines, respectively.

egorical Unit (CU), from 0 to 50 CU. The stimuli consisted of speech-shaped noise of 1-s duration, including on- and off-ramps of 50 ms. The CLS adaptive procedure described in [14] was used to automatically adjust the stimuli presentation levels based on listeners' responses. Each listener first undertook a practice run with the CLS test followed by three recorded runs of the test.

Loudness functions were obtained by minimizing the least-square error between two linear segments intersecting at a fixed loudness level of 25 CU and the participants' responses to the CLS test. The upper and lower linear segments were smoothed between 15 and 35 CU using a quadratic Bezier curve. The fitting procedure 'BTUX' used in this study is described in [14]. Four parameters could then be derived from the loudness functions: slope values of the lower and upper linear regression segments, sound level at the point of intersection (kneepoint), and inferred level at 50 CU. The kneepoint describes the point at which the growth rate changes between the lower and upper portions of the function. For each listener, the four parameters were averaged over 3 repeated runs. Figure 1b depicts the process of defining the lower and upper function slopes, the kneepoint, and the level at 50 CU from the fitted CLS data of a single run.

2.5 Hyperacusis Questionnaire

Each listener completed the Hyperacusis Questionnaire (HQ) to quantify and evaluate potential hyperacusis symptoms. The HQ is a standardized questionnaire designed based on the literature on this pathology and consists of 14 items [12]. It was shown to be sensitive enough to discriminate between individuals based on their hyperacusis symptoms. The overall score ranges from 0 to 42, and a score greater than 28 could indicate strong auditory hypersensitivity according to [12]. Studies [13] and [20] suggested cut-off scores of 26 and 22 respectively.

3. RESULTS AND DISCUSSION

The current study investigated the correspondence between HQ scores, CLS results, and audiogram (SAF and EAF).

Figure 2 illustrates the relationship between upper and lower slopes of the loudness function and averaged audiometric thresholds, averaged across listeners' right and left ears, within each of three frequency ranges: 0.25–4 kHz, which is the main speech frequency range of the SAF; 6–10 kHz, where early indications of noise damage may be evident at the higher-frequency end of the SAF; and 12–16 kHz, an extended audiometric frequency range (EAF). This resulted in three mean thresholds per listener.

The lower slope of the loudness function shows minimal correlation with the averaged audiometric thresholds of 0.25-4 kHz and 6-10 kHz. In contrast, the lower slope of the loudness function is positively correlated (although not significantly) with the averaged audiometric thresholds at 12-16 kHz.

As listeners' thresholds increased in the 12-16 kHz EAF range, the lower slope of the loudness function became steeper. For all these listeners, thresholds were within normal limits for the SAF, indicating that for these listeners loudness perception at medium sound levels is increased compared to listeners that do not show elevated thresholds in the EAF range. The upper slope is negatively correlated (although not significantly) with the averaged audiometry thresholds at 12-16 kHz. Thus, as listen-

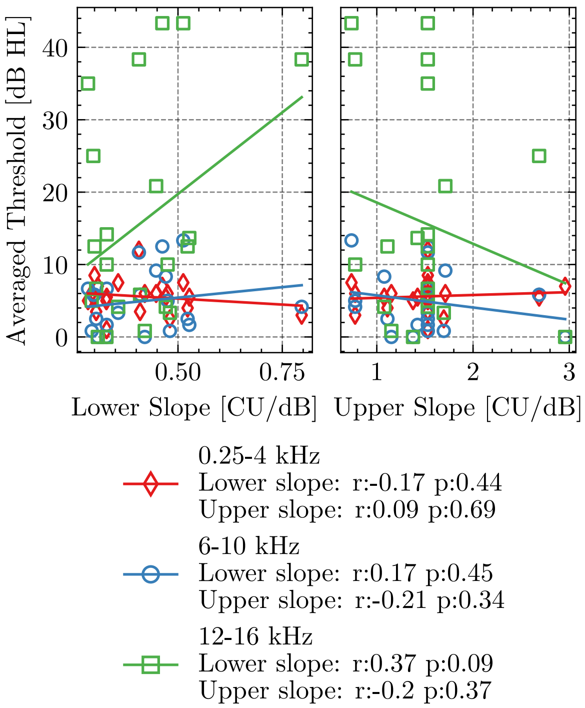


Figure 2: Data from all listeners. Averaged audiometric thresholds (across ears and within frequency ranges) as a function of CLS loudness function fit parameters, lower slope (left) and upper slope (right); and linear regressions for each frequency range.

ers' thresholds increase in the 12-16 kHz range, the upper slope of the loudness function becomes shallower. Note that a similar trend, although smaller in size, is found for the averaged thresholds in the 6-10 kHz range but is not found for the averaged thresholds of 0.25-4 kHz. This indicates the importance of the EAF audiogram in characterising early indication of a change in loudness perception. These trends suggest that for individuals with elevated audiometric thresholds in the 12-16 kHz range, the slopes of the lower and upper segments of the loudness function become more aligned.

For those individuals with audiometric thresholds within normal limits (<20 dB HL) as measured for sound frequencies of the SAF but elevated thresholds as measured for sound frequencies of the EAF, loudness perception grows more quickly with physical sound level for low- to mid-level sounds (a linearisation across both parts of the loudness function).

Some previous studies have indicated minimal or no relationship between audiometric thresholds and hyperacusis scores [7]. This may be the case for thresholds measured between 0.5 and 8 kHz, frequencies that are often tested within clinics (SAF). However, evaluation at higher signal test frequencies may be useful in monitoring and understanding the progression of altered loudness coding and its association with hyperacusis [13].

There is physiological and psychophysical evidence that assessment of hearing integrity at signal test frequencies above 8 kHz may provide a useful indicator of hearing health and an early indicator of hearing dysfunction [21]. The cochlear regions associated with the response to higher-frequency sounds are known to be especially sensitive to the effects of ageing [22], and to the use of ototoxic drugs [23]. Studies report mixed findings with respect to the relationship between high-frequency threshold elevation and noise exposure [24, 25]. Overall, elevated high-frequency thresholds may be indicative of early hearing damage prior to a noticeable perceptual change in hearing, and may be useful for early diagnosis and monitoring of hearing health [15].

Figure 3 shows the hyperacusis score per listener plotted against their ULL-SP scores (ULLs obtained using the standard audiometric procedure with pure-tone stimuli) and ULL-CLS scores (ULLs obtained using the adaptive procedure as in the CLS test with the speech-shaped noise of the CLS test). The dB HL values for ULL-SP were converted to dB SPL for comparison with the ULL-CLS values.

ULL-SP at 0.5, 2, and 4 kHz present a strong significant correlation with the HQ score (all $p<0.05$); a higher HQ score is associated with a lower ULL-SP value. One of the definitions of hyperacusis that reaching a 78.8% agreement in a three-round Delphi survey of hearing healthcare professionals suggested that hyperacusis may also be characterised by the following statement: "Hyperacusis can *sometimes* be described as a reduction in the uncomfortable loudness levels (ULL) in pure tone audiometry (PTA)" [1].

Whilst both monaural and binaural ULL-CLS are also correlated with the HQ score in the same direction, and with a correlation strength approaching that seen between the HQ score and ULL-SP, the results for ULL-CLS are not significant. The ULL-CLS binaural thresholds are observed to be lower than monaural ULL-CLS thresholds as expected due to binaural summation [26]. Overall, the binaural and monaural ULL-CLS thresholds are lower than all the ULL-SP thresholds. This is also expected for

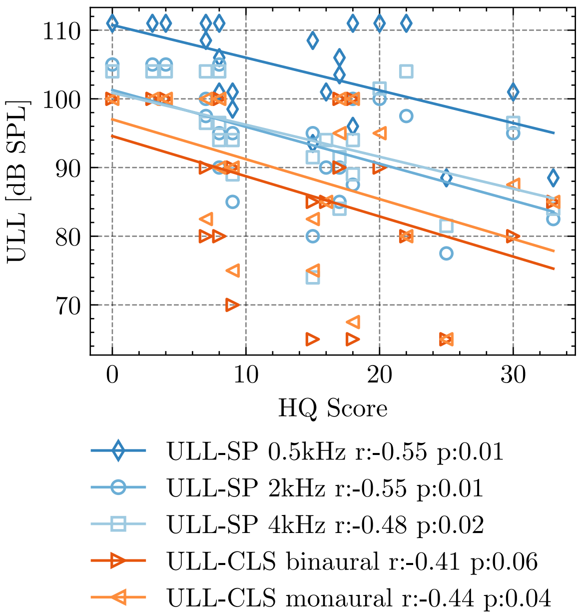


Figure 3: Data from all listeners. i) ULL-SP estimates obtained using pure tones and the BSA procedure and ii) ULL-CLS estimates obtained using the method based on the CLS adaptive procedure and CLS speech-shaped noise stimuli, with monaural (averaged across both ears) and binaural presentations. The ULLs are plotted as a function of the Hyperacusis Questionnaire (HQ) scores.

complex sound stimuli, such as the speech-shaped noise used in this case, which inherently include modulations, compared to pure tone signals [27, 28].

Figure 4 illustrates the relationship between the CLS loudness function parameters and the HQ score. As HQ scores increase, the value of the lower slope remains essentially the same, while the upper slope tends to decrease. The values for the kneepoints and the sound levels inferred at 50 CU tend to decrease with increasing HQ scores. Note that these trends are similar to those observed for the comparison between CLS and audiometric thresholds (EAF). Individuals who scored higher on the HQ tended to demonstrate a categorical loudness function that had a steeper lower portion of the function, representing a more rapid increase in loudness with increasing sound level, and a shallower upper portion of the function. Individuals that scored higher on the HQ also displayed a

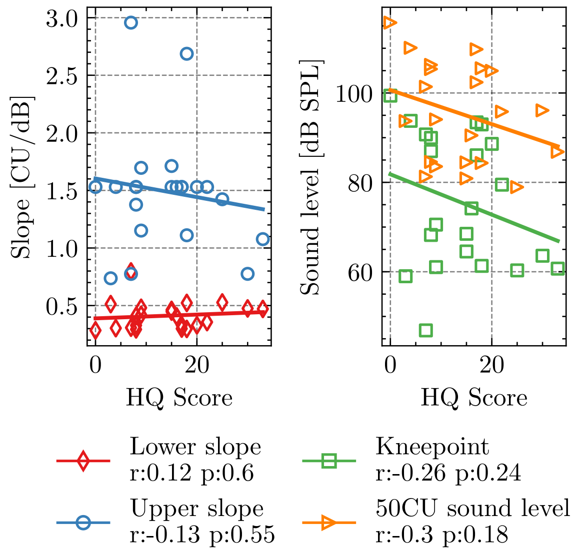


Figure 4: Data from all listeners. Loudness function parameters: lower and upper slopes (left) and kneepoint and level estimates at 50 CU (right) as a function of the Hyperacusis Questionnaire (HQ) scores.

lowered kneepoint of the function fit to the CLS data.

4. CONCLUSION

There is a straightening of the entire loudness function for low- to mid-level sounds for individuals with elevated thresholds for sound frequencies of 12-16 kHz. These individuals had audiometric thresholds within normal limits (<20 dB HL) for sound frequencies of 0.5-8 kHz, and no tinnitus. High frequency thresholds (>12 kHz) are informative regarding the perceptual effects of increased loudness growth which may be associated with hyperacusis. There was a strong significant correlation between the HQ score and ULL-SPs obtained at 0.5, 2, and 4 kHz (all $p<0.05$). Individuals who scored higher on the HQ tended to exhibit a categorical loudness function with a steeper lower portion, indicating a more rapid increase in perceived loudness, and a shallower upper portion of the function. Individuals who scored higher on the HQ also displayed a lower kneepoint in the function fitted to the CLS data, defined as the intersection between the lower and upper portions of the fitted curve.

5. ACKNOWLEDGMENTS

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