The Effect of Age on Huggins' Pitch Processing and its Location in Auditory Cortex

André Rupp[1], Matthias Hauck[2], Hans Günter Dosch[3], Roy D. Patterson[4]

[1] Department of Neurology, Heidelberg University Hospital, Germany. andre.rupp@uni-heidelberg.de

[2] Physikalisches Institut, University of Heidelberg, Germany. matthias.hauck@uni-heidelberg.de

[3] Institut für Theoretische Physik, University of Heidelberg, Germany. h.g.dosch@thphys.uni-heidelberg.de

[4] Department of Physiology, Development and Neuroscience, University of Cambridge, UK. rdp1@cam.ac.uk

Summary

This paper begins with a description of a behavioural experiment with 72 listeners, 8–84 years of age, which shows that the upper frequency limit of Huggins' pitch (HP) decreases steadily with age. Subsequently, transient auditory-evoked-field (AEF) responses to the onset of HP and a change in HP were recorded from a subset of 21 of these listeners, 18–75 years of age. These neuromagnetic (MEG) responses were then compared to the onset and change responses produced by a monaural pitch-producing stimulus, namely, iterated rippled noise (IRN: Yost, 1996), and to a binaural control stimulus composed of broadband noise where a perceptual change was produced by inverting the interaural correlation from +1 to −1 or vice versa.

Source analyses revealed that the pitch onset responses (PORs) and the pitch change responses (PCRs) were located in the lateral portion of Heschl's gyrus (HG), whereas the correlation-change responses (CCRs) associated with the control noise were located in planum temporale (PT), along with the energy onset responses (EORs). Correlation analyses of these neuromagnetic responses with age revealed a somewhat complicated pattern of specific effects: The amplitudes of the PORs and PCRs evoked by HP were smaller for increasing age, and the CCRs were smaller in the older listeners. Moreover, the latencies of the POR and PCR to IRN stimuli were longer for the older listeners. However, the amplitude of the IRN responses did not correlate with age.

1. Introduction

When a diotic white noise is presented to both ears, we hear one source in the middle of the head. If a linear, 2π, phase shift is imposed across a narrow frequency band at one ear, listeners hear a Huggins' pitch (HP; [1]) in addition to the noise. If the waveform of the noise at one ear is inverted, this interaural correlation of −1 results in the perception of a spatially diffuse noise without a pitch. These interaural phase effects grow weaker with age, and there is some evidence to indicate binaural listening tasks are generally more difficult for older listeners [2]. It is assumed that this reflects an age related-reduction in the accuracy of phase locking or subsequent time-interval processing. In an MEG imaging study, Matilainen et al. [3] observed an increase in the delay of the N100m peak in older listeners, when presented either with tone pips or a speech sound. They did not, however, find corresponding differences in the amplitudes of these MEG transients. Together, these

studies prompted us to examine the effect of age on the upper and lower frequency limits of Huggins' pitch and the early components of the MEG responses they evoke. For comparison we recorded transient MEG responses to PORs and PCRs produced with diotic IRN, and the CCR produced by the inversion of the noise waveform at one ear.

2. Methods

2.1. Experiment 1

The first experiment was conducted to assess the upper and lower frequency limit of HP. Seventy-two subjects (32 female/40 male; 8–84 years) were included in the study. Listeners younger than 49 years of age had audiometric thresholds better than 25 dB HL between 125 and 8,000 Hz with between ear differences <15 dB. The older listeners (50–84 years) had audiometric thresholds less than 25 dB HL between 125 and 500 Hz and less than 40 dB between 1,000 and 4,000 Hz (between ear differences <15 dB). Both the upper and the lower frequency limits of HP were assessed using a 3-AFC, 2-up/1-down adaptive procedure

[4]. Listeners were presented with three 800-ms noise bursts and were asked to identify the one which contained the HP. The HP stimuli were broadband Gaussian noises with a 2π-phase transition in the right channel. The bandwidth of the phase transition was set to 10% of the HP frequency. The interaural phase difference was centered at f_0 of HP. The starting f_0 in the adaptive runs was 400 Hz and the change-factor for an increase or decrease in f_0 was 1.5. After two reversals the change-factor was set to 0.75. Fresh noise samples were used on every trial. The adaptive runs terminated after 15 reversals and threshold was taken to be the average value of the last six turnarounds. For each condition, we recorded one run. The stimuli were presented at 65 dB SPL using Etymotic Research (ER-3) earphones equipped with 90 cm plastic tubes.

2.2. Experiment 2

AEFs were recorded in a subset of 21 adult listeners (16 male/5 female; 18–76 years). The differences between their left and right audiometric thresholds were invariably less than 10 dB. Measurement of the upper frequency limit of HP always preceded recoding of their MEG responses. The IRN stimuli were created with 20 iterations of the delay-and-add manipulation; the delay was adjusted to produce the same set of pitches as for the HP sounds.

2.3. MEG recordings and analysis

The neuromagnetic response to the stimuli was measured with a Neuromag-122 (Electa Neuromag Oy) gradiometer system. Data were sampled at 1000 Hz and low-pass filtered at 330 Hz. During the passive measurements subjects watched a silent video of their own choice to maintain vigilance.

In order to separate energy onset responses (EORs) from pitch onset responses (PORs) and pitch change responses (PCRs) the stimulus on each trial was composed of three 750-ms segments. For the IRN- and Huggins' pitch conditions, we always applied a triple composed of a noise burst without pitch followed by a segment with a distinct f_0 and a third segment with a different f_0. The f_0 of the first sound after the initial noise burst was set to 220, 880, or 1760 Hz. The second sound was either a perfect 5th up or down from the first. Correlation change responses (CCRs) were measured using trials composed of two 750-ms Gaussian noise bursts between which correlation changed from $+1$ to -1 or vice versa. In order to avoid monaural energy cues at the transitions, crossfading was accomplished using square-rooted 10 ms Hanning ramps. Stimulus onset and offsets were shaped by a 50 ms Hanning ramp. Each condition was presented 200 times. The inter-sequence silent interval was randomly chosen from the range 800–900 ms.

Spatio-temporal source analysis [5] was performed offline using the BESA 5.2 software package (BESA GmbH). After the elimination of artefacts (amplitudes $> \pm 8000$ fT/cm and gradients $> \pm 800$ fT/cm/ms), separate source models, with one equivalent dipole in each hemisphere, were created to analyse the transient N100m
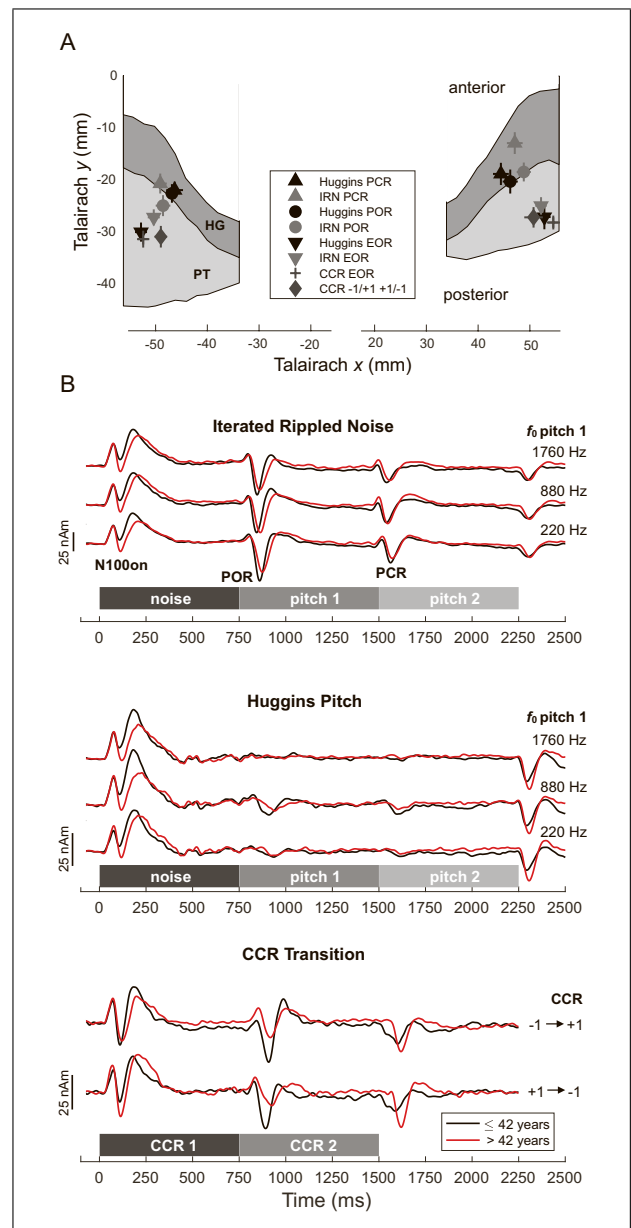

Figure 1. (Colour online) (A) Projection of the 2-dipole source locations onto a standard map of auditory cortex [6]. The error bars denote the standard error. The POR and PCR sources produced by IRN and HP stimuli are located on, or close to, HG; the energy onset sources (EOR) and the CCR sources are located behind HG in PT. (B) Grand-average source waves (pooled across hemispheres) in response to IRN (top panel), HP (middle panel) and correlation-inversion noise (bottom panel), with black waves for the younger listeners and red waves for the older listeners.

deflections of the EORs at the start of a trial and the PORs, PCRs, and CCRs at stimulus segment transitions. A 1–30 Hz bandpass filter was applied to restrict the fits to the appropriate frequencies in the data. Analysis of variance was employed to search for spatial separation of the transient EOR, POR, PCR and CCR generators along the anterior-posterior axis. In order to illustrate the effect of age, we plottet the data from participants below and above the median age ($<= 42$ (mean: 29.1 y) vs > 42 years
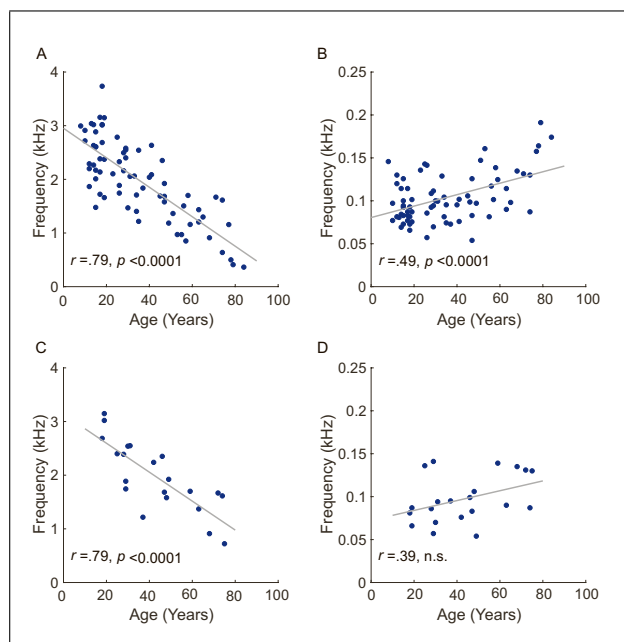
Figure 2. The perceptual upper (A) and lower (B) frequency limit of Huggins' pitch as a function of age, for the full set of 72 listeners. (C) and (D) depicts the upper and lower frequency limit for the subset of 21 listeners who participated in the MEG-experiment.
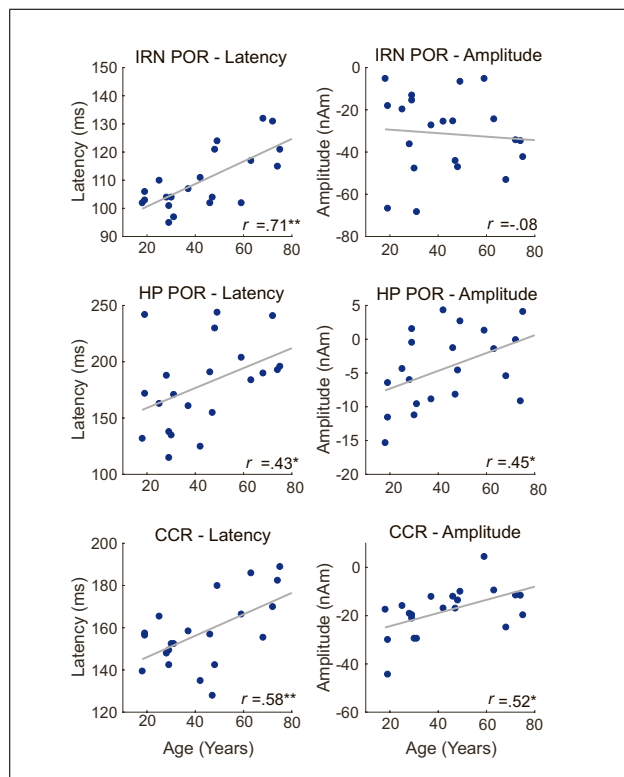

Figure 3. The correlation of age with the latency (left panels) and amplitude (right panels) for the IRN-POR (pooled across all f_0-conditions), the HG-POR (the middle f_0 conditions), and the CCR (pooled across the $+1/-1$ and $-1/+1$ transitions).

(mean: 60.1 y); see Figure 1B). Pearson correlation coefficients were used to assess the correspondence between age and the latencies and amplitudes of the transient MEG
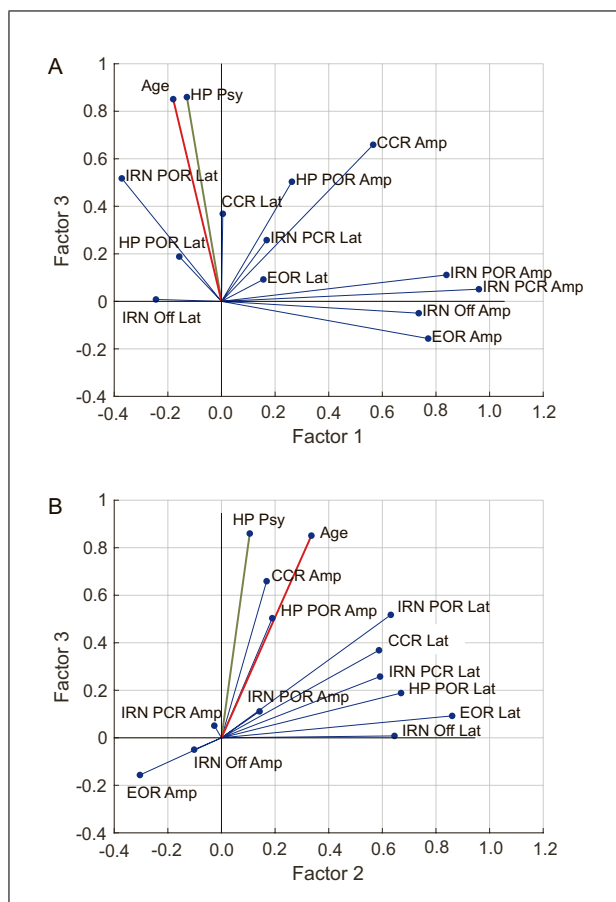

Figure 4. Scores of a factor analysis with three factors. Age is associated with the perceptual upper frequency limit of Huggins' pitch, the latency of the IRN-POR, HP-POR amplitude and CCR amplitude. In contrast, the amplitudes of the IRN-POR and IRN-PCR, as well as the amplitudes of the EOR-onsets and IRN-offsets, are more closely associated with orthogonal Factor 1.

responses. Finally, the structure of the correlation matrix was analysed with the aid of a factor analysis in which VARIMAX rotation was applied.

3. Results

Figure 2 shows that the upper frequency limit of Huggins' pitch decreases significantly with age, and the reduction begins at a relatively early age. The correlation coefficient $r = .79$ is the same for the large group in the behavioural experiment (upper left panel) and the subset who participated in the MEG experiment (lower left panel). In contrast, the lower frequency limit exhibited a small, but significant, increase with age.

The fitting of 2-dipole models was successful for all of the onsets and transitions. The PORs and PCRs are found to originate from Heschl's gyrus (HG), while the EORs and CCRs come from more posterior regions in planum temporale (see Figure 1A). An ANOVA revealed that the anterior-posterior differences were highly significant (POR-IRN vs EOR-IRN: $F(1, 20) = 20.83$, $p < 0.001$; POR-HP vs EOR-HP: $F(1, 20) = 20.51$, $p < 0.001$). The

locations of the HP and IRN PORs did not differ significantly ($F(1, 20) = 0.001$, $p = 0.99$).

The grand-average source waves are presented in Figure 1B. Since the grand-average waves for all conditions from the left and right hemispheres (not shown) were very similar, we averaged the data of both hemispheres. Peak-picking on the AEF waves was successful for all stimulus conditions of all subjects, except for the HP-POR and PCR response to high and low f_0-conditions. The waves in the upper panel of Figure 1B and the related correlation coefficients in Figure 3 show that the POR and PCR latencies of older listeners were greater than those of younger listeners, whereas the corresponding amplitudes did not covary with age. In contrast, HP-POR amplitudes in the medium f_0-range were lower for elderly listeners. Moreover, the CCRs showed both age effects, that is, a significant increase in latency and a significant decrease in amplitude with age (see also Figure 3).

Age was significantly correlated with IRN-POR latency, but not with IRN-POR amplitude. In contrast, the latencies and amplitudes of the HG-POR and the CCR were moderately, but significantly, correlated with age. This pattern of effects is reflected in the factor analysis which included latency and amplitude data for onsets, offsets, PORs, PCRs, CCRs, 'perceptual upper frequency limit of HG', and age (see Figure 4). The factor pattern shows that factor 3 is associated with age, the upper limit of HP and the amplitudes of binaural responses, whereas factor 1 is associated with monaural amplitude. In contrast, factor 2 is associated with latency. Interestingly, the CCR amplitudes exhibit medium loading on factors 1 and 3 which is in line with the scatter plots shown in Fig. 3. Similarly, IRN-POR latency presents a complex pattern with substantial loading on factors 2 and 3.

3.1. Conclusions

The data from the two experiments confirm that age has a strong impact on the upper frequency limit of HP and the reduction of this limit begins before there is pronounced hearing loss. The MEG data show that the latency of the N100m increases with age and the amplitude decreases with age for binaural stimuli. For monaural noise and pitch stimuli, the situation is more complicated; the latency of the POR increases but there is no evidence of a reduction in the amplitude. These findings are in line with the observations of [3] and show that the central effects of age are more readily observed with binaural phenomena, as might be expected. In order to dissociate central aging effects from peripheral deterioration, further experiments need to include listeners with and without hearing loss as carried out by Santurette et al. [7] who observed that perception of Huggins' pitch was not strongly associated with audiometric threshold but with deficits in temporal fine-structure processing. Nevertheless, the strong age-specific correlation between psychometric and neuromagnetic responses to HP stimuli, and the observation that AEF responses evoked by onsets and transitions to monaural and binaural stimuli exhibited a disjunct response pattern, together suggest that neuromagnetic responses to HP stimuli could be employed to separate age-related auditory deficiencies from other pathological processes objectively.

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