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Effect of age on envelope regularity discrimination

Brian C. J. Moore[a)]
Department of Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, United Kingdom

Vinay
Audiology Group, Department of Neuromedicine and Movement Science, Faculty of Medicine and Health Sciences, Norwegian University of Science and Technology (NTNU), Tungasletta 2, Trondheim 7491, Norway

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The ability to discriminate irregular from regular amplitude modulation was compared for young and older adults with audiometric thresholds within the normal range for frequencies from 250 to 8000 Hz, using the "envelope regularity discrimination" (ERD) test. The amount of irregularity was parametrically varied and quantified by an "irregularity index." The carrier frequency was 2000 Hz, the modulation rate was 8 Hz, and the baseline modulation index was 0.3. Stimuli were presented both at 80 dB sound pressure level (SPL) and at 20 dB sensation level (SL) in the presence of a threshold-equalizing noise. There was a significant effect of level, performance being better at 80 dB SPL than at 20 dB SL. There was also a significant effect of age, performance being worse for the older subjects. There was no significant interaction of level and age. The thresholds for the ERD test were not significantly correlated with absolute thresholds at the test carrier frequency of 2000 Hz, for either group, or for the two groups combined. The worse envelope regularity discrimination for the older group may be related to the age-related synaptopathy that has been established from recent studies of human temporal bones. © *2019 Acoustical Society of America*. https://doi.org/10.1121/1.5122794

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I. INTRODUCTION

Recent studies of human temporal bones have shown that increasing age is associated with loss of synapses between the inner hair cells in the cochlea and the nerve fibers that contact them (Viana *et al*., 2015; Wu *et al*., 2019). This synaptopathy, which effectively reduces the number of neurons conveying information from the cochlea to the brain, is likely to reduce the fidelity of the neural coding of the properties of sounds, including their temporal envelopes. These temporal envelopes are thought to carry important information for speech perception (Plomp, 1983; Shannon *et al*., 1995). A test of the fidelity of envelope coding is the "envelope regularity discrimination" (ERD) test, which assesses the ability to discriminate regular amplitude modulation (AM) from irregular AM (Moore *et al*., 2019b). This paper assesses the hypothesis that performance of the ERD test will be worse for older than for young subjects, even when the audiograms of the older subjects are within the normal range.

Following the suggestion of Moore *et al*. (2019b), hearing difficulty associated with synaptopathy is called "hidden hearing disorder" (HHD). It has sometimes been assumed that higher (poorer) AM detection thresholds are associated with increasing HHD (Stone and Moore, 2014; Bharadwaj *et al*., 2015). However, thresholds for the detection of AM worsen only slightly, if at all, with increasing age (Schoof and Rosen, 2014; Füllgrabe *et al*., 2015; Wallaert *et al*., 2016). The lack of effect may have occurred because AM detection thresholds are not very sensitive to "noise" in the auditory coding of AM caused by synaptopathy (Oxenham, 2016). For example, HHD may cause the internal representation of the envelope of stimuli with sinusoidal AM to be somewhat corrupted (as if the envelope were irregular in depth and shape), but unless the HHD is extreme the overall periodicity of the envelope will be preserved, and that would allow detection of the AM via a template-matching mechanism (Dau *et al*., 1997). In addition, in some studies the older subjects had slightly higher audiometric thresholds than the young subjects, perhaps indicating a small degree of outer hair cell (OHC) dysfunction, and a loss of cochlear compression, which is associated with loudness recruitment. Loudness recruitment is often associated with an improved ability to detect AM (Jerger, 1962; Füllgrabe *et al*., 2003; Ernst and Moore, 2012; Schlittenlacher and Moore, 2016), and this may offset deleterious effects of synaptopathy on AM detection.

The ERD test described by Moore *et al*. (2019b) was intended to overcome these problems. A two-alternative forced-choice (2AFC) task is used. In the non-signal interval the stimulus is a sinusoidal carrier that is sinusoidally amplitude modulated at a low rate with a clearly audible modulation index, *m*. The spectrum of this stimulus has a component at the carrier frequency, f_c, and two sidebands at $f_c - f_m$ and $f_c + f_m$, where f_m is the modulation frequency. All components in the non-signal stimulus have a starting phase of 0°. The amplitudes of the sidebands relative to the amplitude of the carrier are determined by the modulation index, *m*. The amplitude of each sideband relative to the amplitude of the carrier is denoted A_{ns}. The stimulus in the signal interval has the same mean AM rate, but the AM is irregular in rate and amount. The spectrum of the stimulus in the signal interval contains the same frequency components as for the non-signal interval, but the relative amplitude of the two sidebands

[a)]Electronic mail: bcjm@cam.ac.uk

(A_s) is lower; $A_s < A_{ns}$. In addition the spectrum contains components with frequencies spaced at 1-Hz intervals from ($f_c - f_m + 1$) to ($f_c + f_m - 1$) Hz. The phases of these additional components are chosen randomly for each trial. These components all have the same amplitude relative to that of the carrier component. This relative amplitude is denoted B. The ratio B/A_s is called the irregularity index, II [usually expressed in dB, i.e., as $20\log_{10}(B/A_s)$]. When the II is large, there is more irregularity. The alternating current (AC)-component of the envelope for the signal interval is scaled by adjusting B and A_s by the same factor so as to equate its root-mean-square (RMS) value to that for the AC-component of the envelope in the non-signal interval. In addition, the RMS value of the waveform for the signal interval is scaled so that it matches the RMS value for the non-signal interval. Hence, the II expresses the amount of irregularity relative to the baseline modulation index m. For examples of the envelopes of the stimuli, the reader is referred to Fig. 1 of Moore *et al.* (2019b).

In the ERD test, the value of the II is adaptively varied to determine the threshold at which the signal stimulus can just be discriminated from the non-signal stimulus. If the representation of envelopes in the auditory system is "noisy" as a result of synaptopathy, then regular AM may sound somewhat irregular in rate and/or amount. This should lead to worse performance on the ERD test. Note that f_m is chosen to be much less than f_c, so the frequency range of the stimuli is much less than the bandwidth of the auditory filter centered at f_c. This means that the task cannot be performed using spectral cues.

Performance of the ERD test probably depends mainly on the fact that the peak-to-valley ratio (PVR, expressed in dB) of the envelope varies from one modulation cycle to the next for the signal stimulus but not for the non-signal stimulus. The variability in PVR can be quantified by its standard deviation, PVR_{SD}. Moore *et al.* (2019b) showed that the threshold value of the II corresponds approximately to a fixed ratio of PVR_{SD} to the mean PVR, PVR_{mean} (which is approximately the same for the signal and non-signal intervals), for m in the range 0.2–0.5. In the case of slight age-related hearing loss, the effect of the loss of compression is similar to that of magnification of the PVR by a certain factor, when the modulation depth is expressed in dB (Moore *et al.*, 1996). Such magnification would not affect the ratio PVR_{SD}/PVR_{mean}. Hence, since performance of the ERD test appears to depend on this ratio, loss of cochlear compression should not affect the outcome of the ERD test.

Evidence from studies of animals suggests that synaptopathy induced by noise exposure selectively affects auditory neurons with low spontaneous rates and high thresholds (Furman *et al.*, 2013). However, for humans there is evidence that noise exposure can also affect the perception of low-level sounds (Stone *et al.*, 2008; Stone and Moore, 2014). It is unclear whether age-related synaptopathy in humans has different effects for low-threshold and high-threshold neurons. In the present study, to assess effects of level, the ERD test was conducted both at a relatively high signal level of 80 dB sound pressure level (SPL) and at a relatively low level of 20 dB sensation level (SL). In both cases, the stimuli were presented in the presence of a broadband threshold-equalizing noise (TEN) (Moore *et al.*, 2000), to limit the range of characteristic frequencies of the neurons that responded to the signal. The TEN level is specified as the level in a 1-ERB_N-wide band centered at 1000 Hz, where ERB_N stands for the mean value of the equivalent rectangular bandwidth of the auditory filter for people with normal hearing (Glasberg and Moore, 1990). The TEN level was set 25 dB below the level of the signal. The output of an auditory filter centered at the carrier frequency in response to the TEN would have an envelope with a relatively broad spectrum, with only a small amount of modulation energy in the frequency region of the 8-Hz modulator (Dau *et al.*, 1997). Given this, and given the relatively low level of the TEN, we expected any modulation masking produced by the TEN to be very small (Dau *et al.*, 1997).

It should be noted that age might have a deleterious effect on performance of the ERD test for reasons other than synaptopathy. Possible other reasons are addressed in Sec. IV.

II. METHOD

A. Subjects

There were ten young subjects (five female) whose ages ranged from 20 to 27 years (mean = 23.5 years, standard deviation, SD = 2.1 years). There were ten older subjects (five female) whose ages ranged from 64 to 80 years (mean = 69.4 years, SD = 5.4 years). Audiometric thresholds were assessed using an Otometrics (Taastrup Denmark) Aurical Otosuite or Primus and Telephonics (Huntington, NY) TDH-39P headphones, with the method recommended by the British Society of Audiology (2011). Middle-ear function was checked using a GSI (Eden Prairie, MN) Tympstar Pro tympanometer; all subjects had normal middle-ear function.

Each subject was tested using one ear only. The test ear for the young subjects was selected randomly; five were tested using the left ear and five using the right ear. The test ear for the older subjects was selected as the ear with the lowest (best) audiometric threshold at the test carrier frequency of 2000 Hz; six subjects were tested using the left ear and four using the right ear. For the test ear, all subjects had audiometric thresholds better than or equal to 20 dB hearing level (HL) for frequencies from 250 to 8000 Hz.

B. The ERD test

A 2AFC task was used, with the two observation intervals separated by 200 ms. Each interval contained an amplitude-modulated 2000-Hz sinusoidal carrier lasting 1000 ms, including 20-ms raised-cosine rise/fall ramps. In the randomly chosen non-signal interval, the AM was regular 8-Hz sinusoidal AM with $m = 0.3$. In the signal interval, the AM was irregular in rate and amount, i.e., the modulator was noise-like. The starting phase of the modulator was randomly chosen for each interval. The subject was asked to pick the interval in which the AM sounded irregular. Trial-by-trial feedback was provided on a screen in front of the subject, to help them to "learn what to listen for." The amount of irregularity was specified by the II, expressed in dB.

The starting value of the II was usually 9.5 dB, a large value, so as to make it easier to "know what to listen for." The value of the II was varied from trial to trial using an adaptive 2-down 1-up procedure, to estimate the value of the II leading to 70.7% correct. The II was changed by a factor of 2.5 dB until two reversals had occurred and by a factor of 0.8 dB until six more reversals occurred. To avoid "overmodulation" the maximum value of the II was set to 9.5 dB. Whenever the adaptive procedure called for an II greater than 9.5 dB, the II was set to 9.5 dB. This happened only very rarely after the initial practice (see below for details). The threshold was estimated as the mean of the values of the II at the last six reversal points. Thresholds that are close to 9 dB might result from random guessing, reflecting either a complete inability to perform the task or a failure to understand "what to listen for."

All testing was conducted in sound-attenuating rooms. Stimuli were generated using a PC with a sample rate of 48 000 Hz and 24-bit precision. Stimuli were converted to analog form using a Realtek (Hsinchu, Taiwan) High Definition Audio sound card with 24-bit precision and presented to one ear via Sennheiser HDA200 headphones (Wedemark, Germany).

C. Stimuli, conditions, and procedure

Each subject was tested using two levels of the 2000-Hz sinusoidal carrier, 80 dB SPL and 20 dB SL. To set the SL, absolute thresholds for a 2000-Hz 1000-ms sinusoid were determined using a 2AFC task and a 2-down, 1-up procedure tracking the 70.7% correct point on the psychometric function. The absolute threshold was estimated twice and the mean of the two estimates was used.

For the ERD test, initially each subject was given two practice runs at 20 dB SL. Two runs are usually sufficient to give stable performance (Moore *et al.*, 2019b). If the threshold for the second run was 8 dB or more, indicating a poor or no ability to perform the task, at least two more practice runs were given, until a threshold below 8 dB was obtained. Then the experiment proper began. In the main experiment, the order of testing the two levels (20 versus 80 dB SPL) was counterbalanced across subjects for each group: half were tested first at 20 dB SL and half were tested first at 80 dB SPL. Four runs were obtained at the first level used and then four runs at the next level used. Results were averaged across the four runs for each subject and each level.

III. RESULTS

The mean absolute threshold at the test carrier frequency of 2000 Hz, measured using the 2AFC task, was 8.1 dB SPL (SD = 6.9 dB) for the young group and 22.9 dB SPL (SD = 9.9 dB) for the older group. The difference between the groups was significant: $t(9) = 3.9$, $p = 0.001$. The implications of this are discussed below.

Thresholds for the ERD test did not vary systematically across the four successive runs for a given level for either age group, confirming that the initial practice was sufficient to lead to stable performance. All subjects achieved thresholds well below 9 dB, indicating that the task could be performed reliably. Figure 1 shows box plots of the II values at threshold for each group and each level. A mixed analysis of variance was conducted with within-subjects factor of level and between-subjects factor of group. The condition of sphericity was met. There was a significant effect of level [$F(1, 18) = 26.2$, $p < 0.001$]. The mean thresholds across groups were –3.8 dB at 20 dB SL and –6.6 dB at 80 dB SPL. Moore *et al.* (2019b) found a small trend in the same direction, but the effect of level was not significant in their data for a carrier frequency of 4000 Hz. There was a significant effect of group [$F(1, 18) = 57.4$, $p < 0.001$]. The mean thresholds across levels were –7.0 dB for the young group and –3.4 dB for the older group. There was no significant interaction of level and group [$F(1, 18) = 0.001$, $p = 0.96$]. In summary, the older group performed more poorly than the young group for both levels tested, consistent with the hypothesis that age-related synaptopathy would adversely affect performance of the ERD test.

For both groups, II thresholds for the two levels were significantly correlated: for the young group, $r = 0.60$, $p = 0.032$, one-tailed (a one-tailed test was used since it was hypothesized that there would be a positive correlation); for the older group, $r = 0.84$, $p = 0.0011$, one tailed. This shows that performance differences between subjects within each group were reasonably consistent across levels. For the two groups combined, the ERD thresholds averaged across the two levels were significantly correlated with age ($r = 0.44$, $p = 0.026$, one-tailed; a one-tailed test was used since we hypothesized that performance on the ERD test would worsen with increasing age).

The ERD thresholds averaged across the two levels were not significantly correlated with the absolute thresholds at 2000 Hz: for the young group, $r = -0.11$, $p > 0.05$; for the older group, $r = -0.13$, $p > 0.05$; for the two groups

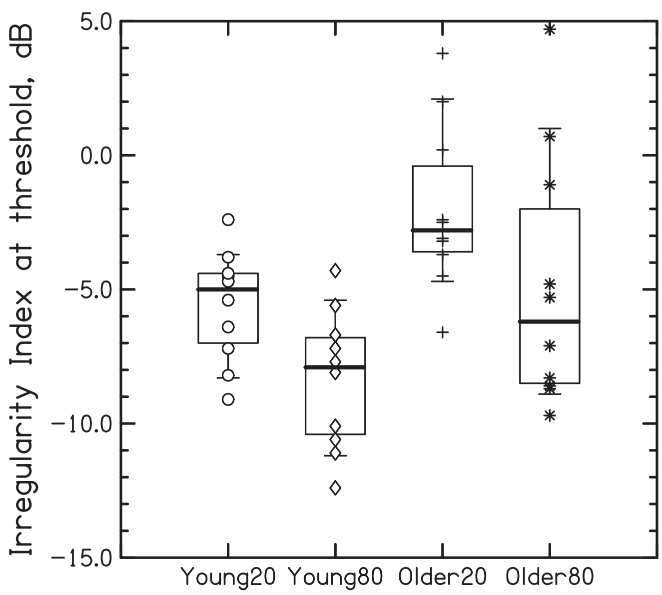

FIG. 1. Box plots showing the values of the II at threshold for the young and older groups at each level (20 dB SL, denoted "20" and 80 dB SPL, denoted "80"). The thick horizontal lines show medians, the lower and upper edges of the boxes show the first and third quartiles, and the whiskers indicate the 10th and 90th percentiles. Individual thresholds are shown by symbols.

combined, $r = 0.27$, $p > 0.05$. Moore *et al.* (2019b) also found that ERD test thresholds were not correlated with absolute thresholds for young subjects. Variations in absolute threshold probably partly reflect variations in the functioning of the active mechanism mediated by the OHCs, so the lack of correlation is consistent with the idea that performance of the ERD test is not affected by small variations in the functioning of the OHCs. Overall, it seems likely that the effects of age found here are a consequence of age per se, rather than being a consequence of slightly higher absolute thresholds for the older than for the young group.

IV. DISCUSSION

The results are consistent with the hypothesis that age-related synaptopathy would lead to worse performance on the ERD test for older than for young listeners. The grand mean thresholds across levels were –7.0 dB for the young group and –3.4 dB for the older group. The results of studies of animals (mainly rodents) suggest that age-related synaptopathy selectively affects neurons with low spontaneous rates and high thresholds (Furman *et al.*, 2013). It is not to our knowledge known whether distinct classes of neurons with different spontaneous rates and thresholds exist in humans. If they do, and if synaptopathy selectively affects neurons with low spontaneous rates and high thresholds, then one might expect the effect of age to be greater at 80 than at 20 dB SL. In fact, our results showed similar effects of age for the two levels tested. However, the situation is not clear cut. First, when the thresholds of primary auditory neurons are defined as the level leading to a statistically significant increase in discharge rate, the thresholds of the high-threshold neurons are only about 5 dB higher than the thresholds of the low-threshold neurons (Geisler *et al.*, 1985). Furthermore, although most low-threshold neurons show saturation of their discharge rates in response to steady tones with a level of 80 dB SPL (Winter *et al.*, 1990; Yates, 1990), they can still signal the envelope fluctuations of high-level stimuli by fluctuations in their discharge rate (Carney, 2018). Hence, some information about the 20-dB SL stimuli might have been conveyed by the high-threshold neurons and some information about the 80-dB SPL stimuli may have been conveyed by the low-threshold neurons. Hence, our results do not rule out the possibility that synaptopathy in humans selectively affects high-threshold neurons.

It is possible that the age-related worsening in performance of the ERD test reflects a general decline in "processing efficiency," which refers to the ability to make use of a given amount of sensory information. Processing efficiency may reflect a general auditory ability that affects performance on many tasks. There is evidence for age-related declines in performance on a range of auditory tasks (Moore, 2014; Füllgrabe *et al.*, 2015; Whiteford *et al.*, 2017; Füllgrabe *et al.*, 2018). It remains unclear whether this reflects the effects of synaptopathy on those tasks or whether it reflects more central processes, perhaps related to reduced cognitive abilities (Wingfield, 1996; Füllgrabe *et al.*, 2015). However, effects of age have been found even in studies that have controlled for the effects of processing efficiency by using a measure based on the difference between two conditions (Pichora-Fuller and Schneider, 1991; Moore *et al.*, 2018; Moore *et al.*, 2019a). Hence, it seems likely that at least some age-related effects on performance cannot be explained in terms of processing efficiency.

It might be argued that the effect of age on performance of the ERD test is simply a reflection of a general decline in auditory temporal processing with increasing age (Wingfield *et al.*, 1985; Gordon-Salant and Fitzgibbons, 2001), which may partly depend on central processes (Caspary *et al.*, 1990; Gleich *et al.*, 2003; Frisina and Walton, 2006). However, the 8-Hz modulation rate used here was chosen to be well within the range where the modulation can be easily "followed." Furthermore, age appears to have little or no effect on the shapes of temporal modulation transfer functions, which implies no effect of age on the central temporal processing of AM per se, although age may have a small effect on detection efficiency (Schoof and Rosen, 2014; Füllgrabe *et al.*, 2015; Wallaert *et al.*, 2016). Hence, it seems more plausible that the effect of age on performance of the ERD test reflects an age-related change in the fidelity of the coding of the envelopes of the stimuli.

As was found in our earlier work on normal-hearing young subjects (Moore *et al.*, 2019b), there was considerable individual variability in performance of the ERD test. For the ERD thresholds averaged across the two levels, only four of the older group had thresholds above the range for the young group, indicating that factors other than age influence the ERD thresholds. For the young group, thresholds ranged from –9.1 to –2.4 dB (SD = 2.1 dB) at 20 dB SL and from –12.4 to –4.3 dB (SD = 2.6 dB) at 80 dB SPL. For the older group, thresholds ranged from –6.6 to 3.8 dB (SD = 3.1 dB) at 20 dB SL and from –9.7 to 4.7 dB (SD = 4.8 dB) at 80 dB SPL. Based on two-tailed variance-ratio tests, the difference in variability across groups was not significant either at 20 dB SL ($F(9, 9) = 2.2$, $p = 0.26$) or at 80 dB SPL ($F(9,9) = 3.4$, $p = 0.082$). The individual variability may reflect a combination of the effects of variations in processing efficiency and variations in the degree of synaptopathy. For the young subjects, the former may dominate, while for the older subjects the latter may play a greater role. Since there is quite substantial individual variability in synaptopathy among older people (Wu *et al.*, 2019), this could account for the trend for greater individual variability among the older subjects tested here.

V. CONCLUSIONS

Performance of the ERD test varied markedly across subjects within each group, but for each group there were significant correlations between thresholds obtained at 80 dB SPL and at 20 dB SL. This indicates that the individual differences were reasonably consistent. ERD thresholds were significantly better at 80 dB SPL than at 20 dB SL, on average by 2.8 dB. ERD thresholds were significantly higher for the older than for the younger group, on average by 3.6 dB. This is consistent with the hypothesis that age-related synaptopathy leads to poorer envelope regularity discrimination. However, part of the effect of age might be a consequence of generally poorer processing efficiency for the older subjects.

The thresholds for the ERD test were not significantly correlated with absolute thresholds at the test carrier frequency of 2000 Hz, for either group, or for the two groups combined. This suggests that performance of the ERD test is not affected by minor variations in the functioning of the OHCs. Software for running the ERD test can be obtained by request from author B.C.J.M.

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