

Age-Dependent Changes of Gap Detection in the Mongolian Gerbil (*Meriones unguiculatus*)

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ABSTRACT

Gap detection using broadband noise was characterized in a group of young gerbils from the breeding colony of the University of Regensburg (RB gerbils), old RB gerbils, and old gerbils from the breeding colony of the University of South Carolina (SC gerbils). Data from old RB and old SC gerbils were not significantly different and were subsequently combined for a comparison with data from the group of young RB gerbils. Level dependence of gap-detection thresholds in young and old domesticated gerbils resembled the typical mammalian pattern of level dependence. Gap-detection thresholds of old gerbils were significantly elevated at 30 dB SL and 50 dB SPL as compared with young gerbils. Compared with young gerbils tested at 30 dB SL and 50 dB SPL, the distribution of gap-detection thresholds in old gerbils was broader with a spread to higher gap-detection thresholds. Some old animals retained excellent temporal resolution, while some showed impaired gap detection. The gap-detection data collected in young and old gerbils resemble previously published data from humans of different age and confirm that gerbils are a useful model to study age-dependent changes in temporal processing.

Keywords: central presbycusis, auditory temporal processing, temporal resolution, aging, hearing loss, psychoacoustic data

INTRODUCTION

It is well documented that aging affects hearing, one of our most important senses for communication (review, Davis 1997). For example, the understanding of speech is more often impaired in elderly people compared with young people (e.g., Working Group on Speech Understanding and Aging 1988). A large part of the elderly population is hearing-impaired showing moderate to high losses of absolute auditory sensitivity predominantly at high frequencies (Moscicki et al. 1985; Cruickshanks et al. 1998; Kim et al. 2000). However, elevated absolute threshold is not the only factor that influences speech understanding. The temporal resolution of the auditory system also plays an important role in processing complex signals (Frisina and Frisina 1997). In elderly listeners, the temporal resolution capacity may be reduced independent of and in addition to a sensorineural hearing loss (Snell 1997; Snell and Frisina 2000). Thus, important auditory cues are not available to these listeners which might affect speech understanding.

Because of its importance for auditory processing, the temporal resolution of the auditory system is well studied in human subjects with respect to age (e.g., McCroskey and Kasten 1982; Schneider et al. 1994; Strouse et al. 1998; Phillips et al. 2000; Snell and Frisina 2000). A common method of assessing the temporal acuity of the auditory system in humans is the gap-detection paradigm (e.g., Moore et al. 1992; Schneider et al. 1994; Snell 1997; Strouse et al. 1998; He et al. 1999; Snell and Frisina 2000). It has been shown that sensorineural hearing loss leads to impaired gap detection (Fitzgibbons and Wightman 1982; Florentine and Buus 1983; Buus and Floren-

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tines 1985; Fitzgibbons and Gordon–Salant 1987; Glasberg et al. 1987). However, even in the absence of a hearing loss, older humans show impaired performance in a gap-detection task and gap-detection threshold is not always correlated with audiometric threshold in normal-hearing subjects (Schneider et al. 1994; Snell 1997; Snell and Frisina 2000).

A number of psychoacoustic studies have provided data on gap detection in animals (e.g., chinchilla: Giraudi–Perry et al. 1982; Salvi and Arehole 1985; starling: Klump and Maier 1989; budgerigar: Okanoya and Dooling 1990), but only the studies by Ison et al. (1998) and Barsz et al. (2002) in the mouse addressed the effect of age on gap detection. An animal model that more closely resembles the auditory capabilities of humans, especially at low frequencies, is the gerbil (Ryan 1976). In contrast to chinchilla and guinea pig, gerbils have a shorter life span of 3–4 years (Cheal 1986), which makes them more practical for studying the effects of aging. Another advantage is that many studies have already investigated various aspects of age-dependent changes in the auditory system of the gerbil (e.g., Henry et al. 1980; Czibulka and Schwartz 1991; Tarnowski et al. 1991; Schulte and Schmiedt 1992; Boettcher et al. 1993, 1996; Gratton et al. 1995, 1996; Hellstrom and Schmiedt 1996; Schmiedt et al. 1996; Sinnott et al. 1997; Gleich and Strutz 2002; Hamann et al. 2002). Among these, the study by Boettcher et al. (1996) using auditory brainstem recordings already provides physiological data on the effect of age on temporal resolution in the gerbil. They suggested that age may affect the processing of gap stimuli at the brainstem level. In our study we provide behavioral data from young and old gerbils for comparison with the physiological data. Our study also indicates whether gerbils are a useful animal model of age-dependent changes of temporal auditory processing in humans.

METHODS

The setup and methods for psychoacoustic measurements in gerbils have been described in detail before (Hamann et al. 2002) and are summarized only briefly. Testing was performed in sound-shielded setups (IAC Mini 250) presenting acoustic stimuli via a stereo amplifier (Kenwood KA 1030 or KA 3300) and a calibrated free-field speaker (Canton Plus XS). Presentation of stimuli, delivery of food reward for correct responses, and recording of the test results were under computer control using custom software and Tucker Davis components (Windows PC with AP2 signal processor, System II interface with DA3, PA4,

PI2, and SM3). The animal's behavior could be monitored using a closed-circuit video system.

Stimuli

Pulses of broad-band noise (no ramps and rise/fall time limited in bandwidth by the frequency response of the speaker from 65 to 30,000 Hz; for details see Hamann et al. 2002) were generated by randomly selecting 800-ms samples from a sound file of 10 of white noise generated by Cool Edit (Syntrillium [Software Corporation, Phoenix, AZ, USA]; 50-kHz sampling rate). Silent gaps of the desired duration (determined between zero amplitude points) were introduced in the center of the 800-ms noise pulse, keeping the total duration of the stimulus constant. Noise bursts without a gap served as a background stimulus that was repeated every 1.6 s as a reference. Acoustic calibration was performed using a Brüel & Kjaer 0.5-in. 4134 microphone connected to a 2804 microphone power supply and a Hewlett Packard 35665A Dynamic Signal Analyzer (for details see Hamann et al. 2002). Noise pulses containing gaps of variable duration were used to construct psychometric functions using the method of constant stimuli. Most animals were tested at presentation levels of 50 dB SPL (overall level) and 30 dB sensation level (SL). Fewer data could be collected at 10 dB SL. In some animals data were obtained at additional levels. For presentation levels of 50 dB SPL and 30 dB SL, gap durations of 1, 2, 3, 4, 6, 8, and 10 ms were used to construct psychometric functions and determine gap-detection thresholds. Three gerbils (1 young and 2 old) did not respond to the longest gap durations of 8 and 10 ms. In this case the gap duration ranged from 1 to 7 ms. At 10 dB SL, gaps of 3, 6, 9, 12, 15, 18, and 21 ms were used. In one old animal with an exceptionally high gap-detection threshold at 10 dB SL, gaps ranging from 9 to 27 ms had to be used to obtain a valid threshold.

In an additional series of experiments, we examined the contribution of frequencies above 10 kHz on gap-detection thresholds. The broadband noise of the 10-s sound file was low-pass and high-pass filtered (slope >200 dB/octave) at 10 kHz using Cool Edit and both filtered versions were stored, separately. Eight hundred-ms samples from both sound files were selected and played through the two channels of a Tucker Davis DA3/2 digital-to-analog converter. The outputs of both channels were separately attenuated by two Tucker Davis PA4 devices, then combined in a Tucker Davis SM3 mixer and connected via an amplifier to the speaker. The spectra of the original noise and the combined high-pass- and low-pass-filtered noise (using the same attenuator settings for both channels) were identical. Gaps were introduced

only in the middle of the low-pass-filtered noise serving as signal carrier. For testing, the high-pass-filtered noise was attenuated by 20 dB relative to the low-pass noise. This level was sufficient to provide masking above 10 kHz without exiting the auditory system too much at frequencies below 10 kHz. Gap-detection thresholds were determined at a presentation level of 30 dB above the threshold determined for broadband noise pulses. The combined low- and high-pass-filtered noise without a gap served as background. In this type of stimulus, frequencies above 10 kHz did not provide any cues about the gaps.

Procedures

Each session consisted of 110 trials divided into blocks of 10 trials. Each block contained 3 sham trials, during which no gap was present, and 7 trials presenting test stimuli with different gap durations. Within each block the trials were presented in random order. The first 10 trials of a session were considered as a warming-up phase and only the last 100 trials were used to construct a psychometric function. Threshold was statistically determined using signal detection theory (Green and Swets 1966). The d' used as a threshold criterion was 1.8. Sessions were included in the analysis only if the false-alarm rate was not higher than 20%, at least 80% of the two longest gaps were detected, and the shortest gap tested was below the calculated gap-detection threshold. The trials from two consecutive valid sessions were combined to calculate a final threshold. The statistical analysis of the data was performed using SigmaStat 2.03.

Subjects

Data in this study using broadband noise pulses were collected from animals of two different breeding colonies of domesticated gerbils and from two age groups. The young animals were below 16 months and the old animals were over 30 months, with most data collected between 30 and 36 months of age. Data were obtained from 13 young and 19 old gerbils originating from the breeding colony at the University of Regensburg (RB gerbils). In addition, we were able to test 8 old gerbils from the breeding colony at the University of South Carolina that were kindly provided by R.A. Schmiedt and F.A. Boettcher (SC gerbils). For the experiments investigating the contribution of frequencies above 10 kHz on gap detection threshold, we used 3 RB gerbils below 6 months of age.

The use of animals in this study was approved by the "Regierung der Oberpfalz" (621-2531.1-19/98) and compiled with the "Guide for the Care and Use

of Laboratory Animals" [NIH publication No. 86-23 (revised 1985)] and the current "German Law on the Protection of Animals."

RESULTS

Training and performance of the gerbils

In a first step, all gerbils were trained to respond to a pulse of broadband noise in quiet and the threshold for the detection of the noise pulse was determined (Hamann et al. 2002). After threshold measurements in quiet, the animals had to learn to discriminate a stimulus with a gap from a background stimulus without a gap. This training began with a stimulus level of 50 dB SPL, which is also the highest level used in this study. The time it took the animals to learn the new task was highly variable between individuals, lasting from a few days to several weeks. The time necessary to learn the new task was not related to the age of the animals nor to their noise threshold or the gap-detection threshold. Overall gap-detection thresholds from 40 gerbils were collected at 50 dB SPL. After reducing the stimulus level from 50 dB SPL to 30 dB SL (corresponding on average to 40.7 ± 4.5 dB SPL, range=32–50 dB SPL), valid gap-detection thresholds from 36 gerbils were generally obtained within 1–3 weeks. Reducing the level from 30 dB SL to 10 dB SL made the task quite difficult for the animals and testing was attempted in 17 gerbils. They produced 81% of invalid sessions during testing at 10 dB SL. Most of these sessions were invalid because they did not respond to the longest gap duration (38%) or they missed this criterion and showed a false-alarm rate of more than 20% (37%). In 6% of the sessions at 10 dB SL, the gerbils exhibited a false-alarm rate of more than 20%. In some animals it was necessary to lower the presentation level to 10 dB SL using intermediate levels to get them to work at 10 dB SL. The average time needed to obtain a valid threshold at 10 dB SL was 4 months. Four old and 2 young gerbils died before producing a valid threshold. Because of the problems associated with threshold measurements at 10 dB SL, testing was not attempted in 23 gerbils that had been tested at higher presentation levels.

Gap-detection thresholds

Figure 1 shows the minimum detectable gap (gap-detection threshold) as a function of the presentation level in dB SL for young (Fig. 1A) and old (Fig. 1B) gerbils. Included are all valid gap-detection thresholds obtained during this study in the groups of young and old gerbils, including repeated measurements from most individuals, to show a qualitative

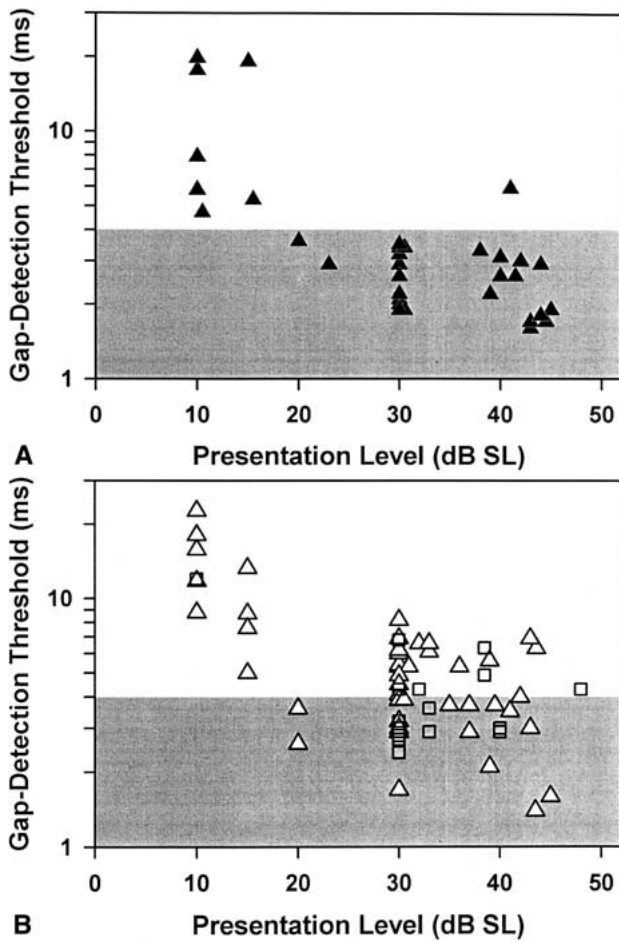


FIG. 1. Comparison of behaviorally determined gap-detection thresholds as a function of presentation level for two gerbil age groups. Shown are all valid gap-detection thresholds collected during the course of this study. This includes repeated measurements from most gerbils (young $N = 34$; old $N = 62$ thresholds). **A.** Data of young gerbils (<16 months) from the colony of the University of Regensburg (RB, filled triangles). **B.** Gap-detection thresholds for old gerbils (>30 months) from two different genetic origins (RB gerbils, open triangles; SC gerbils, open squares). The gray-shaded area includes thresholds up to 4 ms.

comparison between groups (data used for a statistical comparison of age groups that contain one data point per animal at each of the test levels are shown in Fig. 2). The minimum detectable gap shows a prominent increase with decreasing presentation level below 20–30 dB SL. At 10 dB SL, interindividual variability is high in young and old gerbils. At 30 dB SL and above, the minimum detectable gap shows little variation with level. Gap-detection thresholds in the two different groups of old gerbils (open triangles and open squares in Fig. 1B) are similar for sensation levels of 30 dB SL and higher, for which sufficient data are available. A statistical comparison of gap-detection threshold from old gerbils of the two breeding colonies (Mann–Whitney U -test) at 30 dB

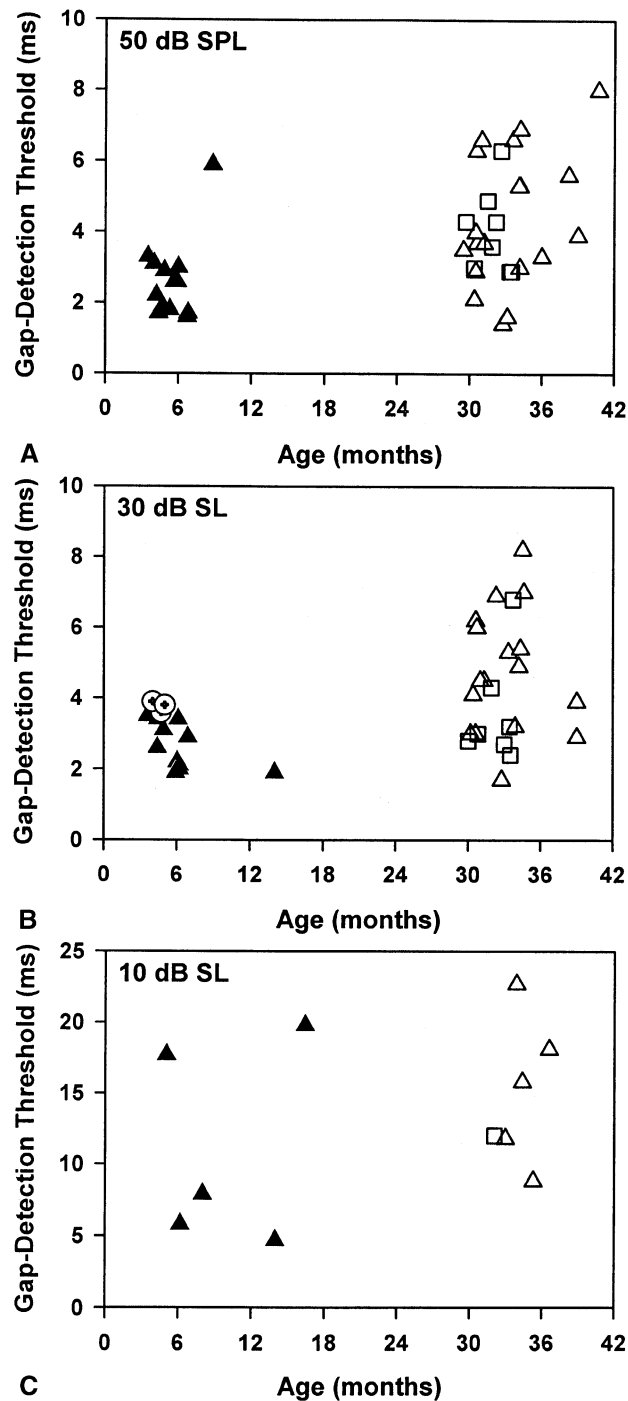


FIG. 2. Gap-detection thresholds as a function of age. Filled triangles represent data from young RB gerbils, open triangles show data from old RB gerbils, and open squares show data from old SC gerbils. Open circles with a crosshair in **B** show data from young RB gerbils tested with stimuli that contained information about the gap only for frequencies below 10 kHz. **A.** Signal level 50 dB SPL ($N = 13$ young RB, 19 old RB, and 8 old SC gerbils). **B.** Signal level 30 dB SL ($N = 12$ young RB, 17 old RB, and 7 old SC gerbils) for broadband noise stimuli. Open circles with a crosshair show gap-detection thresholds at 30 dB SL from 3 young RB gerbils tested using stimuli with gap cues only for frequencies below 10 kHz. **C.** Signal level 10 dB SL ($N = 5$ young RB, 5 old RB, and 1 old SC gerbils).

SL (RB, $N = 17$, mean = 4.75 ± 1.69 ms; SC, $N = 7$, mean = 3.60 ± 1.42 ms; $p = 0.08$) as well as at 50 dB SPL (RB, $N = 19$, mean = 4.42 ± 1.85 ms; SC, $N = 8$, mean 4.03 ± 1.11 ms; $p = 0.61$) revealed no significant difference between the two groups. Consequently, data from both groups of old gerbils were pooled for the following comparison with data from young RB gerbils.

Although the graphs in Figure 1 from young and old gerbils appear quite similar at first glance, closer inspection reveals that gap-detection thresholds from old gerbils at higher presentation levels show an increased spread compared with those from young gerbils. Considering the data at 30 dB SL and above, only 1 out of 25 gap-detection thresholds (4%) was above 4 ms in young RB gerbils. In contrast, 24 out of 50 gap-detection thresholds (48%) were higher than 4 ms in old gerbils (Fig. 1B). The comparison of young and old gerbils in Figure 1 suggests that gap-detection thresholds are elevated in some but not all old gerbils.

Gap-detection thresholds as a function of age are illustrated in Figure 2 for 50 dB SPL (A), 30 dB SL (B), and 10 dB SL (C). Mean gap-detection thresholds of old gerbils are 33–63% higher than those of young gerbils. For 50 dB SPL [13 young gerbils (mean \pm SD), 2.64 ± 1.10 ms; 27 old gerbils, 4.29 ± 1.68 ms], the analysis showed significantly elevated gap-detection thresholds in old gerbils ($p = 0.002$, two-tailed Mann–Whitney U -test). At 30 dB SL [12 young gerbils (mean \pm SD), 2.71 ± 0.64 ms; 24 old gerbils, 4.41 ± 1.70 ms], the difference between both groups was also significant ($p = 0.005$, Mann–Whitney U -test). The 3 young gerbils tested with the gap stimuli containing no high-frequency information in the gap are shown as open circles with a crosshair in Figure 2B. Although the gap-detection thresholds of these 3 young gerbils (that had gap information only for frequencies below 10 kHz) were at the upper end of the distribution of gap-detection thresholds in young gerbils, they were all below 4 ms. At 10 dB SL [5 young gerbils (mean \pm SD), 11.28 ± 7.04 ms; 6 old gerbils, 14.87 ± 5.04 ms], data from the groups of young and old animals were not significantly different (Mann–Whitney U -test, $p = 0.33$).

Correlation of gap-detection thresholds and thresholds for broadband noise

Previous studies in humans have shown that peripheral hearing loss, especially at high frequencies, can affect performance in gap-detection tasks (e.g., Fitzgibbons and Wightman 1982; Buus and Florentines 1985; Glasberg et al. 1987). In the present sample of gerbils, thresholds for broadband noise varied

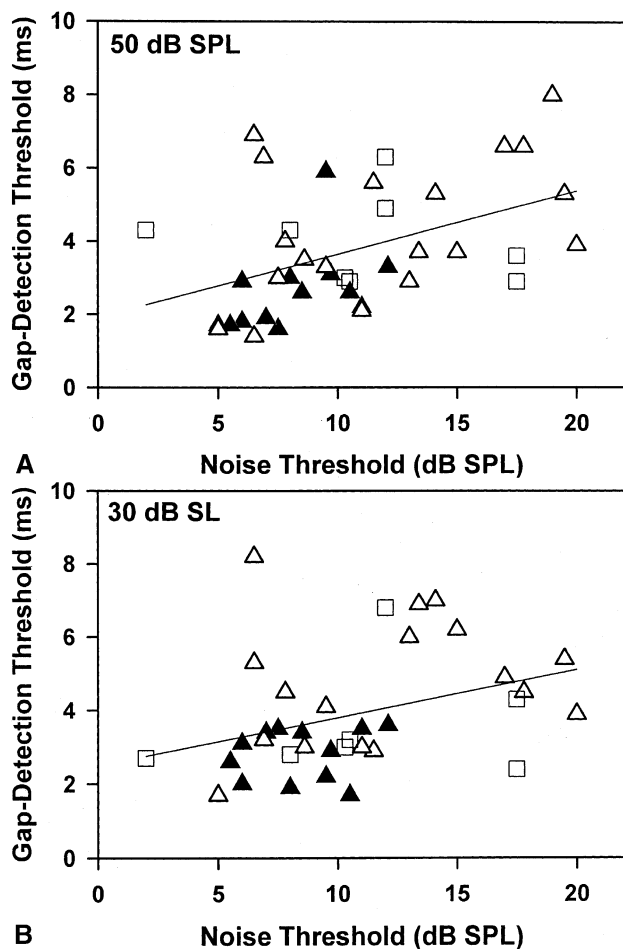


FIG. 3. Gap-detection thresholds determined at a presentation level of 50 dB SPL (A) and 30 dB SL (B) in relation to the absolute thresholds for broadband noise pulses. Filled triangles represent data from young RB gerbils, open triangles show data from old RB gerbils, and open squares show data from old SC gerbils. A linear-regression analysis revealed significant correlations at a test level of 50 dB SPL and at 30 dB SL (regression lines shown in A and B).

between 2 and 20 dB SPL, indicating that these animals were not affected by severe sensorineural hearing loss. Median, mean, and standard deviation for the detection thresholds for broadband noise were 8.00, 8.17, and 2.18 dB in 13 young and 11.50, 11.83, and 4.78 dB in 27 old gerbils, respectively. Although the difference in mean threshold between the two groups is less than 4.0 dB, it was statistically significant (Mann–Whitney U -test, $p = 0.018$). The variance in noise thresholds was significantly higher in old compared with young gerbils (Levene median test, $p = 0.021$). Gap-detection thresholds determined at 50 dB SPL (Fig. 3A) and 30 dB SL (Fig. 3B) are shown as a function of the detection threshold of a pulse of broadband noise for young RB (filled triangles), old RB (open triangles), and old SC (open squares) gerbils. Only 7 of the 27 old gerbils had thresholds for broadband noise above 15 dB SPL. A linear

regression through the combined data of young and old gerbils revealed a significant relationship at 50 dB SPL ($N = 40$, $r = 0.453$, $p = 0.003$, Fig. 3A) and at 30 dB SL ($N = 36$, $r = 0.371$, $p = 0.026$, Fig. 3B). If the two data sets for gap-detection thresholds determined at 50 dB SPL were analyzed separately, the correlation coefficients of $r = 0.323$ ($N = 27$) and $r = 0.466$ ($N = 13$) were not statistically different for old and young gerbils, respectively, and therefore the results of the analysis could be combined using Fisher's r to z transform. The weighted joint correlation coefficient r was 0.385, which is also significant ($p < 0.02$). If the two data sets determined at 30 dB SL were analyzed using this method, the weighted joint correlation coefficient r was 0.217, which is not significant ($p > 0.05$). The lower degree of correlation at 30 dB SL is not unexpected since Glasberg et al. (1987) reported that the difference in gap-detection thresholds comparing normal and hearing-impaired ears is reduced when comparisons are made at equal SLs. An analysis using the Spearman rank correlation coefficient yielded similar results. In any case, the variation of the noise threshold accounted for only 20% of the variation in gap-detection threshold or less.

DISCUSSION

General aspects

In the present study, gap-detection data were determined in gerbils from two different genetic backgrounds (RB and SC) and two age groups (<16 and >30 months of age). Initially, the data from RB and SC gerbils were analyzed separately because differences with respect to the morphology of the cochlear nucleus (CN) and in psychophysical, performance had been reported when comparing laboratory gerbils bred in captivity for many generations with gerbils originating from animals recently collected in the wild (Sinnott et al. 1997; McGinn and Faddis 1998; Gleich et al. 2000). Thus, it is possible that gerbils from colonies being bred separately for decades differ from one another. However, we found no significant difference between old RB and SC gerbils with respect to temporal resolution. This is consistent with our earlier observation that RB and SC gerbils were not different with respect to their pure-tone thresholds (Hamann et al. 2002). Despite the reported difference between laboratory and wild-stem gerbils in CN morphology (McGinn and Faddis 1998; Gleich et al. 2000) and the degree of age-dependent threshold elevation for the detection of vowels (Sinnott et al. 1997), gap-detection thresholds from our young RB gerbils closely resembled those of young wild-stem gerbils (Wagner et al. 2003). All 14 gap-detection thresholds determined at levels

greater than 30 dB SL by Wagner et al. (2003) in 6 young gerbils were below 4 ms. The similarity of the two independently collected data sets from two groups of young gerbils illustrates that gap detection is a very robust measure of temporal resolution and emphasizes the changes that we observed in the group of old gerbils.

Correlation of gap-detection thresholds and audiometric thresholds

Sensorineural hearing loss reduces performance in gap-detection tasks (Fitzgibbons and Wightman 1982; Florentine and Buus 1983; Buus and Florentine 1985; Fitzgibbons and Gordon-Salant 1987; Glasberg et al. 1987) in humans as well as in animals (chinchilla: Salvi and Arehole 1985; mouse: Ison et al. 1998), but the spread of gap-detection threshold for a given degree of hearing loss can be considerable (Glasberg et al. 1987). It was also shown that the minimum-detectable gap increases if the energy of the signal containing the gap is restricted to lower frequencies (human: Fitzgibbons 1984; Buus and Florentine 1985; Moore et al. 1993; Snell 1997; Snell and Frisina 2000; zebra finch and budgerigar: Okanoya and Dooling 1990). We did not determine pure-tone thresholds for the old gerbils during the collection of gap-detection thresholds. However, in a previous study we observed the age-dependent changes of absolute thresholds for broadband noise, 2-kHz, and 10-kHz pure-tone stimuli (Hamann et al. 2002). Comparing 30–36-month-old gerbils with a group of young animals we found no significant threshold shift for the noise and the 10-kHz stimuli. However, old animals had a small threshold elevation (mean 7 dB) at 2 kHz. In some gerbils above 3 years of age, more pronounced threshold loss was observed. In 5 animals we had data on threshold loss for noise and 10-kHz stimuli (see Table 2 in Hamann et al. 2002) that showed a significant correlation ($N = 5$, $r^2 = 0.826$, $p = 0.032$). In addition, a reanalysis of threshold pairs determined for noise and 10-kHz stimuli revealed a highly significant correlation ($N = 35$, $r^2 = 0.618$, $p < 0.001$), suggesting that the noise thresholds are an adequate indicator also for high-frequency hearing loss in gerbils. Here we report data on gap-detection thresholds from old gerbils most of which were determined before they reached 3 years of age (Fig. 2), and noise thresholds were close to normal even in the oldest animals tested (Fig. 3). Thus, it is unlikely that high-frequency hearing loss is responsible for the impaired temporal resolution observed in some of the old gerbils. This notion is supported by the data from 3 young gerbils that were tested with gap stimuli that contained information about the gap only in the frequency range below 10 kHz (Fig. 2B). Although

data from these 3 gerbils were at the upper end of the distribution of gap-detection thresholds from young gerbils, they were all below 4 ms. Consequently, it is unlikely that increased thresholds for frequencies above 10 kHz in old gerbils could explain gap-detection thresholds above 4 ms. This is an important point because epidemiologic studies have shown that increasing age in humans leads to a progressive high-frequency hearing loss (Davis 1997), and one has to discriminate between the contribution of peripheral hearing loss and central auditory processing deficits resulting from aging. Studying young and old humans with comparable hearing (as defined by pure-tone audiometry), it was concluded that there was a decreased temporal resolution independent of peripheral hearing loss in older subjects (Moore et al. 1992; Schneider et al. 1994; Snell 1997; Snell and Frisina 2000; Poth et al. 2001). In some of these studies with normal-hearing subjects, gap detection was not correlated with audiometric thresholds (Schneider et al. 1994; Snell and Frisina 2000). In our study we found in 40 gerbils with thresholds for noise pulses that varied between 2 and 20 dB SPL that the variation of audiometric threshold explained only 14%–20% in the variation of gap-detection thresholds (Fig. 3). Although the mean noise threshold in the group of old gerbils was almost 4.0 dB higher than in the group of young gerbils, this indicates no substantial decrease in sensitivity and shows that the old gerbils were not affected by severe sensorineural hearing loss. This is consistent with our previous observation that behavioral thresholds remain stable for up to 3 years of age in gerbils (Hamann et al. 2002). Consequently, the elevated gap-detection thresholds above 4 ms that were found in some of the old gerbils (Figs. 1 and 2) at high presentation levels (30 dB SL, 50 dB SPL) are unlikely to result from peripheral hearing loss. Rather, deficits in central auditory processing seem to contribute to impaired temporal resolution in these animals. This view is also supported by the ABR data from Boettcher et al. (1996). Presenting two short noise pulses that were separated by a variable gap, they showed that the CAP latencies were very similar in young and old gerbils, but latencies to the second noise pulse were slightly higher for wave II and clearly longer for wave IV at shorter gap duration, suggesting a deficit at the level of the brainstem. Additional support for the hypothesis that central auditory processing deficits rather than peripheral hearing loss contribute to impaired gap detection comes from a study that demonstrated that the drug Sabril (gamma-vinyl-GABA) can reversibly improve impaired gap detection in gerbils (Gleich et al., in press). This drug leads to increased levels of GABA in the brain by blocking a GABA-degrading enzyme. Such increased levels possibly affect central

temporal processing but not the peripheral sensitivity of the auditory system. These results suggest that a deficit of the GABAergic system in the ascending auditory pathway may contribute to impaired gap detection.

Level dependence of gap detection

The presentation level clearly influences the gap-detection ability (e.g., Plomp 1964; Fitzgibbons 1983; Shailer and Moore 1983; Klump and Maier 1989; Wagner et al. 2003; Fig. 1, this study). Thus, if gap-detection thresholds of hearing-impaired and normal-hearing subjects are compared using a fixed sound-pressure level, the individual presentation level (SL) is lower in hearing-impaired subjects and may contribute to higher gap-detection thresholds compared with normal-hearing subjects. Indeed there is evidence that a comparison of gap-detection thresholds on the basis of equal SL reduces the difference between normal and hearing-impaired subjects (Glasberg et al. 1987). This view is also supported by observations in the chinchilla with experimentally induced hearing loss (Giraudi-Perry et al. 1982). However, for SLs above 20–30 dB, gap-detection thresholds reach asymptotic values and are virtually independent of the presentation level (Fig. 1, this study; Irwin et al. 1981; Buus and Florentine 1985; Moore et al. 1993). Our data in the gerbil (Figs. 1 and 2) suggest that a further increase in the presentation level would not improve performance of gap detection, neither in animals with elevated gap thresholds nor in gerbils with low gap thresholds. Assuming similar effects occur in humans, amplifying the sound input in hearing-impaired patients may not always be sufficient to restore impaired temporal resolution. The benefit of amplification in patients with impaired temporal resolution would be limited, especially under difficult conditions (e.g., speech in background noise).

Gap detection and aging

Several studies have shown that age can affect the minimum-detectable gap in humans (Moore et al. 1992; Schneider et al. 1994; Snell 1997; Strouse et al. 1998; Schneider and Hamstra 1999; Snell and Frisina 2000). In addition, several studies also demonstrated in animal models that gap-detection ability is influenced by age. Ison et al. (1998) provided behavioral evidence for a reduced ability to detect short gaps by old mice. Response patterns of single neurons in the inferior colliculus to gap stimuli differed between young and old mice, and the proportion of cells responding to the shortest gaps was reduced in old animals (Walton et al. 1998). Barsz et al. (2002) used

behavioral measures to show that the distribution of gap-detection thresholds becomes wider with a spread toward longer values in old humans and old mice. At advanced age, some old humans and some old mice retain excellent temporal resolution while some individuals show impaired performance. In a recent ABR study in gerbils using gap stimuli, Boettcher et al. (1996) demonstrated age-specific latency shifts of wave IV in response to the stimulus following the gap and concluded that temporal processing at the level of the brain stem is affected in old animals. Using the same methods, Poth et al. (2001) showed that a subpopulation of older human subjects with normal pure-tone thresholds showed similar deficits in the response to gap stimuli at the level of the brain stem.

Here we characterized age-dependent changes in the ability to detect gaps in gerbils using behavioral methods. At 30 dB SL and 50 dB SPL, gap-detection thresholds in the group of old gerbils were significantly elevated compared with those of young gerbils (Fig. 2). Data from young wild-stem gerbils collected at 50 dB SPL (Wagner et al. 2003) resembled gap-detection thresholds from young RB gerbils and thus support the view that gap-detection thresholds in old gerbils are, on average, elevated. In addition, the distribution of gap-detection thresholds in old gerbils at 30 dB SL and 50 dB SPL exhibits a greater variance with a higher proportion of increased thresholds than in young animals (Fig. 2). The lack of significant differences between the old and young gerbils' performance at 10 dB SL may be due to the small sample size and the fact that small errors in determining the noise threshold result in a large variation of the gap-detection threshold.

The present psychoacoustic observations in old gerbils with at most minimal sensorineural hearing loss are in good agreement with results from several studies investigating age-dependent changes of gap detection in normal-hearing humans, despite the fact that experimental conditions and stimuli varied between different studies. The mean increase in the gap-detection threshold in old compared with young subjects has a similar magnitude in aged gerbils and humans (Moore et al. 1992; Schneider et al. 1994; Snell 1997; Strouse et al. 1998; Snell and Frisina 2000). In addition, the increased variability and the spread of gap-detection thresholds that we observed in the gerbil with a large overlap of the data from young and old animals (Fig. 2) has also been found in elderly humans and mice (Barsz et al. 2002). Thus, aging differentially affects gap detection in individual subjects (gerbils, mice, and humans) leaving some quite sensitive while affecting temporal processing to a more severe degree in others. In summary, these similarities of age-dependent temporal processing

deficits in humans and gerbils, both in the degree and in the pattern of variation between different subjects, indicate that the gerbil is a valid model for studying age-dependent changes of temporal processing in the human auditory system.

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