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RESEARCH ARTICLE

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Inharmonicity detection

Effects of age and contralateral distractor sounds

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Abstract Detection of mistuned partials in otherwise harmonic complex tones was investigated in naïve subjects of three different age groups. Signals were presented at constant sensation level to compensate for differences in hearing sensitivity and to specifically examine age-related changes in inharmonicity perception. Performance was measured under two conditions, monaural signal presentation and dichotic signal-noise presentation, with the latter aiming at the influence of contralateral distractor sounds. Stimuli were complex tones with ten harmonics and 125-Hz fundamental frequency. Mistuning detection was measured for the first, second, fourth, and eighth harmonic. In a three-interval, three-alternative forced-choice procedure, subjects were required to distinguish a complex tone containing one mistuned partial from two reference tones, with all partials at their harmonic frequencies. Thresholds were measured as the amount of frequency shift necessary for the mistuning to be detected. Performance deteriorated moderately with age for the two higher partials tested, but not for the lower ones. Thresholds for dichotic signal/noise presentation did not differ significantly from monaural ones in any of the age groups. Results are discussed in relation to hypotheses of harmonicity perception in auditory scene analysis and with respect to the investigation of patients suffering form respective deficits due to acquired brain lesions.

Keywords Inharmonicity · Age · Distractor sounds

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Introduction

Harmonicity represents a salient cue in segregating sounds to form distinguishable auditory objects. Representations of a harmonic complex‘s partials—integer multiples of the fundamental—are preconsciously fused into a unitary percept, while unrelated components are not integrated. Harmonicity processing thus facilitates auditory streaming and thereby enhances speech perception in noisy, multi-talker backgrounds (Duifhuis et al. 1982; Bregman 1990). Little is known about the neural basis of the perceptual fusion of harmonic tones. A central pitch processor is suggested to form harmonic templates and fuse matching components (Goldstein 1973; Terhardt 1979). The perceptual fusion and mistuning detection for different partials simultaneously presented to the two ears and similar effects which are not explainable by local peripheral interaction provide further evidence for the central location of harmonicity processing (Beerends and Houtsma 1986; Lee and Green 1994; Lin and Hartmann 1998). Perceptual suppression of the components of a periodic complex tone support the hypothesis of harmonic templates (Brunstrom and Roberts 1998). Apparently, slots of the templates are set to harmonic frequencies and yet have a certain tolerance range, with shifts of 2–3% reported as the acceptable amount of mistuning (Moore et al. 1984, 1985, 1986; Hartmann et al. 1990). Lowest mistuning thresholds are found between the third and the fifth harmonic (Moore et al. 1984, 1985). Inharmonicity detection is more difficult for the harmonics above and below this range, in particular for the fundamental. For higher-order harmonics, performance improves again, most likely due to roughness cues (Lee and Green 1994). Two perceptual notions of a mistuned partial have been reported: For lower frequencies or larger shifts, it is heard as a separate tone; whereas, for higher frequencies and longer durations, beats or roughness are perceived. It is not clear yet whether the two kinds of percepts are mediated by different mechanisms or merely representing the ends of a continuum.

Difficulties in auditory streaming are a common complaint among the elderly (Duquesnoy 1983), in spite of normal pure-tone audiograms (Middelweerd et al. 1990), and similar symptoms have been observed in patients with acquired brain lesions independent of aphasic deficits (Olsen et al. 1975; authors' experience). Those difficulties may be caused by deterioration of harmonicity-based sound segregation making auditory object formation more difficult. Alain et al. (2001) have investigated age-related changes in mistuning detection and found a decrease in performance, weakly correlating with their speech-in-noise test. Subjects were stimulated at a given sound pressure level, and the proportion of age-related deterioration that had to be accounted for by hearing loss was estimated in a post-hoc analysis. The present study aimed more specifically at age-related changes in inharmonicity detection by studying the respective performance at a constant sensation level.

The influence of distractor sounds on harmonicity perception has barely been investigated. In the tests designed for the present study, signals were presented monaurally and in combination with distractors at the contralateral ear. The latter aimed at central masking in a hemisphere-specific manner. The idea of the dichotic signal/distractor presentation is based on dichotic speech experiments (Kimura 1967). In these, different stimuli were simultaneously presented to the two ears, which yielded higher identification scores for the ear contralateral to the speech-dominant hemisphere. This can be explained by the anatomic specificities of the auditory pathway (Pickles 1988; Nieuwenhuys et al. 1988). Both auditory cortices receive input from both ears, with contralateral projections markedly stronger than ipsilateral ones. Apparently, dominant representations of contralateral stimuli are established, suppressing ipsilateral information in competitive situations. Based on these findings, the dichotic signal/distractor presentation was developed to test auditory discrimination in a hemisphere-specific manner by presenting signals to one ear to be processed in the respective contralateral auditory cortex while keeping the other one busy with the distractors. The Gaussian noise as distractor sound has proven versatile and effective in other discrimination tasks, e.g. duration, frequency or intensity, revealing specific deficits in patients with unilateral cortical lesions (Bungert et al. 2003; F. Biedermann, unpublished work).

The study‘s objective was to investigate inharmonicity perception in naïve, normal-hearing subjects, with special interest in age-related changes and effects of contralateral distractors. The test tools were designed with specific respect to the examination of patients with acquired brain lesions on the basis of the results obtained in this study.

Methods

Subjects

Psychoacoustically inexperienced adults of three age groups (each 16 subjects, 8 men, 8 women) participated in the study: young (20–29 years), middle-aged (40–49 years), and elderly (50–59 years). All subjects had normal hearing according to age-matched normative data (Bungert et al. 2003). The study was approved by the ethics committee of the University of Leipzig.

Stimuli and procedure

Stimuli were digitally generated using a 32-bit digital-analog converter (DAC) and a sampling rate of 50 kHz, the output low-pass filtered at 20 kHz (System II; Tucker Davis Technologies, Fla.) and presented via Beyerdynamic DT770pro headphones, with sound pressure level calibrated by a Bruel & Kjaer 2610 measuring amplifier. Subjects were seated in a sound-attenuated room.

Each trial was comprised of three intervals: two reference signals with ten harmonic partials, and one test signal, with one of the partials mistuned upwards from its harmonic value. The test signal interval was chosen at random. Subjects were required to indicate which of the three intervals contained the mistuning by pressing the appropriate button on the response box. Performance was tested under monaural signal presentation and under dichotic signal/noise presentation. Signals were complex tones with 125-Hz fundamental frequency and the first ten partials present (125–1250 Hz). The partials started in sine phase and their relative intensities were counterbalanced with the frequency specificity of audiometric thresholds (Bungert et al. 2003). The frequency-specific difference relative to 1000-Hz thresholds, averaged across the different age groups, was added to the lower components' intensities (125 Hz, 25 dB; 250 Hz, 15 dB; 375 Hz, 10 dB; 500 Hz, 5 dB). The mistuned partial, and its counterpart in the reference signals, was additionally incremented in level by 3 dB in order to avoid effects of individual frequency-specific hearing sensitivities and to enhance recognition of the feature to be discriminated, specifically for patients' investigations. Mistuning thresholds were measured for the fundamental (125 Hz), the second (250 Hz), fourth (500 Hz), and eighth harmonic (1000 Hz). Stimuli were presented at 35 dB sensation level. The overall signal level underwent an intertrial roving of 6 dB in 1-dB steps. Three Gaussian noise bursts (0.02–20 kHz) were simultaneously presented to the other ear at 65 dB SPL, equaling an average sensation level of approx. 35 dB. Signal duration was 250 ms, with 10 ms on- and offsets shaped according to a $\cos^2$ function. Intersignal and intertrial intervals were 500 ms, response time unlimited. A three-interval, three-alternative forced-choice procedure following a one-down, one-up tracking strategy was used to estimate the 50% point on the psychometric function (Levitt 1970), chosen specifically with respect to the work with neurological patients. For each run, the initial value of mistuning was set to approx. 66% of the harmonic frequency, so that the mistuned partials fell between two higher harmonics in the beginning of a run and were adaptively shifted back toward their original frequency without falling onto an in-between harmonic. After each correct or false response, the mistuning was decreased or increased by the factor of 2 without feedback. Thresholds were determined as the arithmetic mean amount of mistuning in the final four of eight reversals measured per run. These parameters yielded stable threshold estimates and low measurement times as necessary with neurological patients. test sessions lasted 2 h. Order of conditions, mistuned partials within conditions and the two ears, alternately tested, was systematically varied between subjects. Statistical analysis of the data acquired in this study was carried out with the Friedman repeated-measure ANOVA and Page test for ordered alternatives for frequency effects, the Kruskal-Wallis ANOVA and Jonckheere test[1] for ordered alternatives for age-related changes, and the Wilcoxon signed-rank test for effects of signal presentation. Results were Bonferroni-corrected.

Results

The ability to detect a mistuned partial in an otherwise harmonic complex tone was measured in naïve subjects of three different age groups (20–29, 40–49, and 50–59 years) for the first, second, fourth, and eighth components of a tone with 125-Hz fundamental frequency. The acquired inharmonicity detection thresholds were screened for ear and gender effects, and no significant or systematic differences between left and right ear or male and female subjects were found. For further analysis, data were pooled over both ears and sexes within the three age groups. The inharmonicity detection thresholds were measured as absolute values in hertz; relative values were calculated as percentage of the mistuned partial‘s frequency and octave parts.

Effects of partials’ order

The absolute values of mistuning thresholds generally increased with higher mistuned partials’ frequencies, both under monaural signal and dichotic signal/noise presentation (Fig. 1). The overall effect of the partials’ order on the absolute threshold values was significant for the two conditions in all three age groups ($P<0.001$, Friedman repeated-measures ANOVA on ranks). More specifically, the frequency-related elevation of thresholds was validated by the Page test for ordered alternatives for both signal-presentation conditions in all three age groups ($P<<0.001$). Relative mistuning thresholds were also investigated for effects of the partials’ order (Figs. 2, 3).

In the young group, relative values slightly depended on the partial‘s frequency; the effect was significant only for the monaural condition ($P<0.001$, Friedman repeated-measures ANOVA on ranks). The Page test for ordered alternatives validated the alternative hypothesis, confirming that the monaural threshold medians monotonically decreased for higher frequency partials ($P=0.013$). In the two older age groups, relative thresholds did not significantly vary over the range of components tested, except from a tendency in the elderly subjects’ thresholds to be smallest for 250- and 500-Hz components.

Age-related changes

The amount of mistuning necessary for detection was examined with respect to its age dependency. Greater mistuning thresholds with increasing age were found for the two higher frequency components, 500 Hz and 1000 Hz (Figs. 2, 3). The analysis of the absolute threshold values (in hertz), with the Kruskal-Wallis one-way ANOVA on ranks, yielded P-values of 0.014 and 0.005 for monaural 500 and 1000 Hz, and $P=0.508$ and $P=0.032$ for dichotic 500 and 1000 Hz (not significant after Bonferroni correction). The rank-based Jonckheere test for ordered alternatives verified the significant monotonic increase in thresholds with advanced age for both higher-frequency components under monaural, and for 1000 Hz under dichotic presentation ($P<0.01$ for monaural 500 and 1000 Hz and dichotic 1000 Hz; $P=0.233$ for dichotic 500 Hz). No systematic age-related differences in inharmonicity detection thresholds were found for the two lower harmonics, 125 and 250 Hz.

Effects of contralateral distractor sounds

Inharmonicity detection performance was evaluated with respect to interfering effects of the contralaterally presented noise bursts. Monaural and dichotic thresholds were compared within age groups in a component-specific manner by the Friedman repeated-measures ANOVA on ranks. None of the comparisons yielded a significant difference, confirming that neither in the young subjects nor in the two older groups did the contralaterally presented noise bursts influence inharmonicity detection.

Discussion

The main aspects of the study were to investigate inharmonicity perception in normal-hearing naïve subjects and to characterize age-related changes as well as the effects of contralateral distractor sounds. In order to separate changes in harmonicity processing from interfering effects of differences in hearing sensitivity, the latter were compensated for by signal presentation at constant sensation level. To provide good audibility for each of the partials, their relative intensities had been adjusted according to the human audiogram. The target component was additionally incremented in level, facilitating its detection (Moore et al. 1984, 1985). The mistuned harmonics’ frequencies at thresholds obtained in this study lay within 0.1-octave range of the partials’ harmonic frequencies. This indicates that, in spite of the fact that the mistuned components fell between two higher harmonics at the beginning of a trial, subjects did not accidentally match the mistuned components to an in-between harmonic during the course of the adaptive procedure.

Age-dependent increases in mistuning thresholds were found for the two higher components tested, i.e., the fourth and the eighth harmonic, while performance did not

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[1] The Jonckheere test for ordered alternatives tests the hypothesis that the groups are ordered in a specific a priori sequence, i.e., that medians monotonically change in magnitude with the preset order.

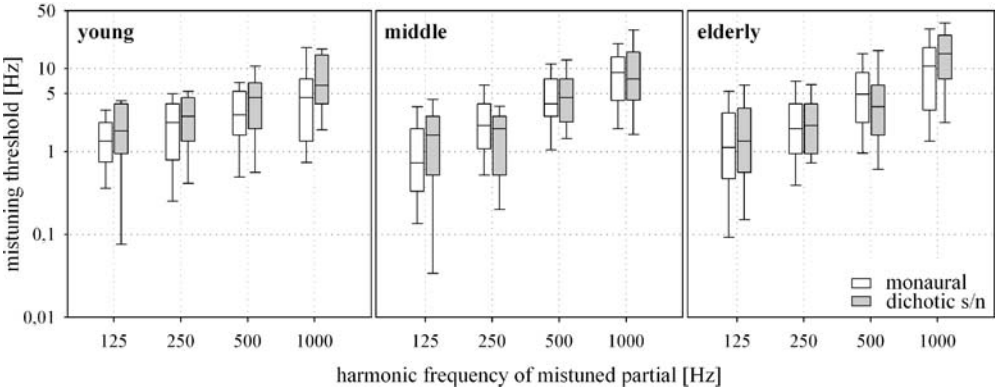

Fig. 1 Mistuning detection thresholds as absolute values in hertz for monaural and dichotic signal/noise conditions in young (*left*), middle-aged (*middle*) and elderly (*right*) subjects. Thresholds are plotted as a function of the harmonic frequency of the mistuned partial. (*Boxes* indicate 25–75% range, *whiskers* 10–90%, and the *horizontal line* the median)

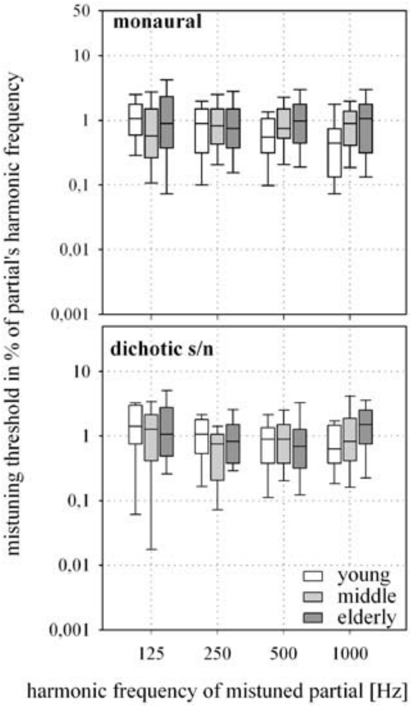

Fig. 2 Mistuning detection thresholds expressed in percentages of the partial‘s harmonic frequency for monaural (*top*) and dichotic signal/noise (*bottom*) conditions. Thresholds in young (white), middle-aged (*light gray*) and elderly (*dark gray*) subjects are plotted as a function of the harmonic frequency of the mistuned partial

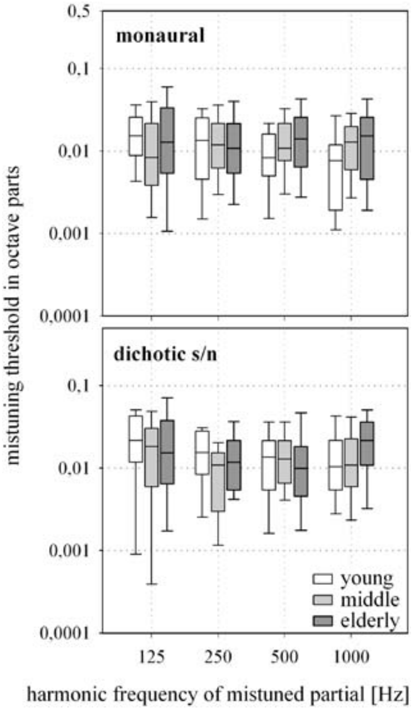

Fig. 3 Mistuning detection thresholds expressed in octave parts of the partial‘s harmonic frequency for monaural (*top*) and dichotic signal/noise (*bottom*) conditions. Thresholds in young (white), middle-aged (*light gray*) and elderly (*dark gray*) subjects are plotted as a function of the harmonic frequency of the mistuned partial

change significantly for the first and second. Alain and colleagues (2001) made a similar attempt, presenting stimuli at fixed intensities and with equal level harmonics. The authors report age-related differences, but had to take into account that those are at least partially due to increased audiometric thresholds. The authors still postulated a significant deterioration in inharmonicity detection, primarily for their oldest subjects (65–82 years). They also demonstrated the importance of signal duration, especially in aging subjects, as the observed deterioration is stronger for 100-ms than for 400-ms stimuli. Earlier, Moore et al. (1985) and Lee and Green (1994) had characterized the role of duration in mistuning detection in mostly young, trained subjects. Performance improved with longer durations, primarily in high-frequency components (Moore et al. 1985; Lee and Green 1994). To preclude effects of integration times and with respect to the tested partials’ frequencies, in the present study the signal duration was set to 250 ms. Thus, the age-related changes found in inharmonicity detection were to the greatest extent assessed without interfering differences in sensitivity or integration time. Taking into account that signal characteristics were chosen to facilitate detection and that subjects were naïve, our results fit well with the results of previous studies, in which mostly young and highly trained subjects were tested (Moore et al. 1984, 1985; Lee and Green 1994). In all these studies, harmonic order was found to effect mistuning detection. As to be expected, absolute threshold values in hertz increased with higher frequencies. Relative thresholds expressed in percentages or octaves of the partial‘s original frequency (the latter ones being the more sensible measure with respect to the basilar membrane‘s frequency representation) were reported to be smallest for the third to the fifth harmonic, matching the dominant region of harmonic complexes (Ritsma 1967; Plomp 1967). It has not yet been elucidated whether the partial‘s order or frequency is the critical factor. Attempts to differentiate between the two parameters by measuring mistuning detection for components of identical frequency in tones with different fundamentals yielded at the most slight trends toward larger thresholds with shorter periodicities (Hartmann et al. 1990; Moore et al. 1984; pilot experiments for this study). For higher-order harmonics, frequency is regarded as the critical parameter, as temporal precision is not sufficient to reliably code stimulus frequency anymore, making mistuning detection more difficult (Hartmann et al. 1990; Moore and Ohgushi 1993). With longer stimulus durations, roughness cues can in turn reduce mistuning thresholds in high-frequency auditory filters due to interactions between neighboring harmonics. In the present study, these effects may have occurred only for the 1000-Hz component. However, occurring beats did not appear salient, as the main proportion of thresholds fell below 10 Hz, not providing enough beat cycles for successful roughness perception (Lee and Green 1994). The age-dependency observed in the present study was most pronounced for mistuning of the 1000-Hz component, suggesting that this was caused by deteriorated temporal acuity (Strouse et al. 1998; Bungert et al 2003), and possibly partially by broadened auditory filters (Patterson et al. 1982). Different models for pitch perception have been postulated on the grounds of place-based excitation patterns (Terhardt 1979) or temporal processing (Hartmann and Doty 1996). However, the more subtle phenomena such as inharmonicity detection and pitch shifts of mistuned partials cannot be explained by those models and thus have become critical in attempts to understand the underlying processes (Lin and Hartmann 1998). Fused perceptions and inharmonicity detection for harmonics presented either separately to the two ears or successively monaurally, provide evidence for the central location of harmonicity processing (Beerends and Houtsma 1986; Lee and Green 1994). Further evidence for the harmonic template model comes from experiments with complex tones containing spectral gaps (Lin and Hartmann 1998). Complicating the matter, irregularity detection and pitch shifts of mistuned components also occur for regularly spaced inharmonic complexes (Roberts and Bailey 1996; Roberts and Brunstrom 1998). It still has to be explored whether this is due to the same mechanism as inharmonicity detection. Even for the two different notions of a mistuned partial‘s percept, seized either as an outstanding tone or as a “smeared” pitch of the whole tone, it is still unclear whether they are mediated by the same physiological mechanisms (Hartmann et al. 1990). Hearing out a separate tone requires frequency shifts of at least 1–3% (Moore et al. 1986), overlapping with the thresholds measured for plain inharmonicity detection (Moore et al. 1984, 1985), while components mistuned up to 8% can still influence the complex tone‘s residue pitch. In the inharmonicity detection tasks of the present study, both kinds of percept occurred as expected: For larger frequency deviations, subjects reported the mistuned partial heard as an “extra tone,” which slowly merged into a “vibrating pitch” of the whole tone for smaller mistunings. Thresholds obtained were about one order of magnitude smaller than monaural frequency difference limens and thereby about as low as interaural ones for identical frequencies in aged-matched, naïve subjects (Bungert et al. 2003), pointing to a detection mechanism almost as precise as the processing of binaural beats.

The effect of contralateral distractor sounds was investigated under dichotic signal/noise presentation, in which Gaussian noise bursts were presented contralaterally to the signals. In dichotic speech tests (Kimura 1967), on which the idea of the dichotic signal/noise tests is based, different stimuli were simultaneously presented to the two ears. In those studies, higher identification scores were reported for the right ear, i.e., the one opposite the speech-dominant hemisphere. In the present study, the tonal signals and noise bursts presented in the dichotic signal/noise tests thus ought to be predominantly represented in the respective contralateral auditory cortices. No systematic differences were found between left- and right-ear thresholds, suggesting that, in normal-hearing, healthy subjects, both hemispheres can independently analyze inharmonicity with comparable acuity. Furthermore, dichotic mistuning thresholds did not differ from monaural ones in any of the age groups, indicating that the contralateral distractor stimuli did not impair inharmonicity processing, as reported in more basic auditory discrimination tasks previously (Bungert et al. 2003). This leads to the conclusion that each hemisphere is capable of accurate inharmonicity detection by itself. In the examination of patients with acquired brain lesions, this dichotic signal/noise test targeting at hemisphere-specific processing may reveal deficits related to unilateral damage. It is to be expected that these remain undetected in monaural tests, as demonstrated by Thompson and Abel (1992) and Biedermann et al. (unpublished work) for basic auditory discrimination tasks.

In the present study, results were obtained from naïve subjects by means of test tools explicitly designed for this purpose. The straightforward up-down tracking method has proven a reliable technique both for naïve subjects and brain-damaged patients in prior experiments. Its advantages are the small amount of instruction necessary, its usability despite speech-related difficulties, its low time expenditure, and the fact that subjects need not have an explicit understanding of the target feature, but simply select the “different one.” Testing patients with acquired brain lesions based on the results of the present study may help identify the underlying processing strategies and neural correlates by revealing interrelations between circumscribed lesion sites and deficits in harmonicity perception.

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