Age-related changes in detecting a mistuned harmonic

Claude Alain[a)]
Rotman Research Institute, Baycrest Centre for Geriatric Care, 3560 Bathurst Street, Toronto, Ontario M6A 2E1, Canada and Department of Psychology, University of Toronto, Mississauga, Ontario L5L 1C6, Canada

Kelly L. McDonald and Jodi M. Ostroff
Rotman Research Institute, Baycrest Centre for Geriatric Care, 3560 Bathurst Street, Toronto, Ontario M6A 2E1, Canada

Bruce Schneider
Department of Psychology, University of Toronto, Mississauga, Ontario L5L 1C6, Canada

(Received 20 September 2000; revised 16 January 2001; accepted 26 February 2001)

The effects of age on discriminating simultaneous sounds were investigated by comparing the hearing threshold in detecting a mistuned harmonic in young, middle-aged, and older adults. The stimuli were complex sounds containing multiple harmonics, one of which could be "mistuned" so that it was no longer an integer multiple of the fundamental. Older adults had higher thresholds than middle-aged or young adults. The effect of age was greater for short than for long duration sounds and remained even after controlling for hearing sensitivity. The results are consistent with an age-related decline in parsing simultaneous auditory events, which may contribute to the speech perception difficulties in the elderly.
[DOI: 10.1121/1.1367243]

PACS numbers: 43.71.Lz, 43.71.Pc, 43.66.Fe, 43.66.Lj [MRL]

I. INTRODUCTION

A common complaint of older adults is that they have difficulties understanding speech, especially when the competing signals are voices rather than homogeneous background noise (e.g., Duquesnoy, 1983; Prosser *et al.*, 1991) or in the presence of reverberation (Gordon-Salant and Fitzgibbons, 1993). Although sensory neural hearing loss is highly correlated with the speech reception threshold (Humes and Lisa, 1990; van Rooij and Plomp, 1990; van Rooij *et al.*, 1989), it is unlikely that peripheral factors alone can account for all of the observed changes in auditory perception that accompany aging. Speech perception problems experienced by older adults are somewhat greater than would be expected based solely upon reduction in auditory sensitivity (Marshall, 1981) and they remain significant even after controlling for age-related differences in hearing sensitivity (Divenyi and Haupt, 1997a). In addition, some individuals with near-normal sensitivity exhibit speech discrimination problems, while others with hearing loss receive little benefit from hearing aids despite restoration of near-normal sensitivity levels. It is also unclear how age-related changes in hearing sensitivity would account for difficulties in understanding speech, which primarily occur in the presence of noise or competing speech signals.

Difficulties in understanding speech in the presence of noise or speech signals may result from age-related changes in central auditory functions that are crucial for the perceptual segregation of co-occurring sounds (e.g., Divenyi and Haupt, 1997a). To follow a conversation during a cocktail party, a listener must be able to separate the acoustic elements that correspond to the conversation of interest from those that correspond to other "competing" conversations. This requires parsing the acoustic wave into two or more sound sources (i.e., auditory objects) and integrating the ongoing acoustic information from a particular source ("auditory scene analysis"). The perceptual segregation of sounds occurring simultaneously is enhanced by differences in frequency regions and spatial origin while fusion is favored by synchronous changes in amplitude or frequency that occur in different spectral regions [for reviews see Bregman (1990) and Hartmann (1988)]. For example, sounds that have similar stimulus onset, intensity, amplitude modulation, and/or frequency periodicity are more likely to be perceived as originating from the same source than sounds that differ in onset, intensity, and/or frequency periodicity. Thus deficits in processing either one or more of these acoustic cues could have dramatic consequences on the perception of complex auditory signals by hindering the perceiver's ability to adequately separate the spectral components of the speech event from the background noise (figure-ground segregation), thereby making the speech more difficult to understand.

The present study focused on age-related changes in one of the cues that lead to segregation of sounds. Frequencies that are harmonically related to one another are usually perceived as originating from a single source. However, if one of these frequencies departs from a harmonic relationship with the others, it is likely to be perceived as emanating from a second source. Thus age-related deficits in the ability to detect mistuned harmonics may deleteriously affect an older adult's ability to segregate concurrent auditory events. In the present study, we used a paradigm similar to that of Moore *et al.* (1985) who used loudness-matched complex sounds that either had all tuned harmonics or one mistuned harmonic. Participants were presented with signals; one that had

[a)]Electronic mail: calain@rotman-baycrest.on.ca

tuned harmonics (or "partials") and one with a mistuned harmonic (i.e., the harmonic was no longer an integer multiple of the fundamental). They indicated by pressing a button which signal contained the mistuned harmonic. Participants were better at detecting inharmonicity for higher than for lower harmonics and for long than for short duration signals (see also Hartmann *et al.*, 1990; Moore *et al.*, 1985).

In the present study, participants were presented with short and long duration signals to explore whether age effects on detecting a mistuned harmonic would interact with sound duration. Given that older adults have deficits in temporal processing (e.g., Schneider and Hamstra, 1999), one might expect to see greater age differences in thresholds for short than for long duration signals. We also included a group of middle-aged adults to characterize in more detail age-related changes in concurrent sound segregation. Lastly, we examined the relationship between the ability to distinguish a mistuned harmonic and the ability to recognize speech in a multi-talker noise background. Because the voiced components of speech emanating from a single talker will be harmonically related, age-related declines in the ability to detect mistuned harmonics may lead to difficulties in segregating voices when two or more people are speaking simultaneously. In particular, it may lead to difficulties in attending to a single voice against a multi-talker background. Previous results have shown that older adults have higher thresholds than younger adults for correctly reporting the last word of a sentence in the Speech Perception in Noise (SPIN) test, a test in which the noise background is a multi-talker babble (e.g., Gordon-Salant and Fitzgibbons, 1993; Hutchinson, 1989; Pichora-Fuller *et al.*, 1995). In the present study, we compared the ability to detect inharmonicity with performance on the SPIN test in a subset of participants.

II. METHOD

A. Participants

Ten young (mean age=22 years, s.d.=2; range=19–25; 4 men), 10 middle-aged (mean age=43 years, s.d.=6; range =35–49; 5 men), and 10 older (mean age=72 years, s.d.=6; range=65–82; 4 men) adults participated in the study. All participants had pure-tone thresholds less than or equal to 30 dB HL in the range 250 to 3000 Hz in the tested ear. Each participant signed a consent form according to University of Toronto guidelines. The young adults were recruited from local colleges whereas middle-aged and older adults were recruited from the community and local volunteer groups.

B. Stimuli and task

The complex sounds had a fundamental frequency of 200 Hz and were composed of the first ten harmonics at equal levels. Stimulus duration was either 100 or 400 ms including 10-ms rise/fall time. Stimuli were generated digitally with 16-bit resolution and a sampling rate of 20 kHz, passed through a digital-to-analogue converter, and then low passed filtered at 10 kHz using an anti-aliasing filter (Tucker Davis Technology, Gainesville, FL). Stimuli were presented at 80 dB SPL to the left ear through TDH-49 headphones.

Thresholds were defined as the percentage of mistuning required to detect the signal. They were determined using a two-interval, two alternative forced-choice procedure with a three-down and one-up rule that estimates the 79% correct point on the psychometric function (Levitt, 1971). Each trial consisted of two stimuli separated by an inter-stimulus interval of 500 ms. The interval containing the mistuned harmonic was either the first or the second at random (probability=0.5 for each interval) and the mistuning from trial to trial was either upward or downward at random. The listener's task was to select which of the two stimuli contained the mistuned harmonic. After each response, visual feedback was provided on the performance. Inter-trial interval was controlled by the participant whose response initiated the presentation of the next trial. After three consecutive correct responses, the mistuning of the partial was decreased by a factor of 1.4. After each incorrect response, the mistuning was increased by the same factor. Threshold was determined as the mean level for the final 8 of 12 reversals.

Three different harmonics, the second, fifth, and eighth, were mistuned in separate blocks. Findings from a pilot study showed that the mistuning of the second harmonic was particularly difficult to detect: To ensure that all participants could detect the second mistuned harmonic, the initial value of mistuning was set at 12%. For the fifth and eighth harmonics, the initial mistuning was set at 10%. For all participants, thresholds were first estimated for the long duration signal in separate blocks of trials, but the order of presentation of the second, fifth, or eighth harmonic was counterbalanced between participants. The thresholds reported are based on three estimates per condition. Participants were tested individually in a single-walled sound-attenuating chamber. They participated in three testing sessions, each lasting approximately 60 min.

C. Speech in noise SPIN test

In a second experiment, a subset of participants performed the SPIN test. They were presented with sentences embedded in babble and asked to identify the last word of the sentence. Participants were also required to indicate whether the last word was a high or low context word (e.g., for the sentence "I ate dinner at the RESTAURANT" participants would have to repeat the word "restaurant" and indicate that it is a high context word). The SPIN threshold was estimated by calculating the signal/noise ratio at which participants correctly identified 50% of the low context words embedded in babble. The SPIN test always followed the experiment on perception of the mistuned harmonic. Seven young (mean age=22 years, s.d.=2; range=19–24; 2 men), four middle-aged (mean age=42 years, s.d.=6; range =37–48; 2 men), and six older adults (mean age=72 years, s.d.=6; range=66–82; 3 men) participated in the second experiment. All participants were native English speakers.

III. RESULTS

Table I summarizes the audiometric thresholds for young, middle-aged, and older participants. ANOVA with age group as a between subjects factor and frequency (i.e.,

TABLE I. Group mean audiometric (HL) threshold (and standard deviation) in young, middle-aged, and older participants.

	Frequency				
Groups	250	500	1000	2000	3000
Young	2.0(5.9)	1.5(3.4)	1.0(4.6)	−0.5(5.5)	−0.5(6.4)
Middle-Aged	7.0(5.9)	5.5(4.4)	9.0(7.0)	10.0(9.4)	7.0(8.2)
Older	9.5(7.3)	7.5(4.9)	9.0(7.8)	14.0(9.1)	14.5(7.6)

threshold at 250, 500, 1000, 2000, and 3000 Hz) as a within subjects factor yielded a main effect of group, $F(2,27) = 12.91$, $p<0.001$. Young adults had lower thresholds than middle-aged or older adults, $p<0.01$ in both cases. There was no significant difference in audiometric threshold between middle-aged and older adults.

Figures 1(A) and (B) show the group mean threshold for the short and long duration stimuli, respectively. The threshold for detecting the mistuned harmonic is expressed as a percent of mistuning relative to the "tuned" harmonic. Overall, the threshold estimates were lower for long than for short duration stimuli, $F(1,27)=113.68$, $p<0.001$. Participants were also better at detecting inharmonicity when the fifth or eighth harmonic was mistuned than when the second harmonic was mistuned, $F(2,54)=12.08$, $p<0.001$. The interaction between stimulus duration and harmonic number tended toward significance, $F(2,54)=2.88$, $p=0.07$. The thresholds for the second harmonic were less affected by signal duration than the thresholds for the fifth or eighth harmonics.

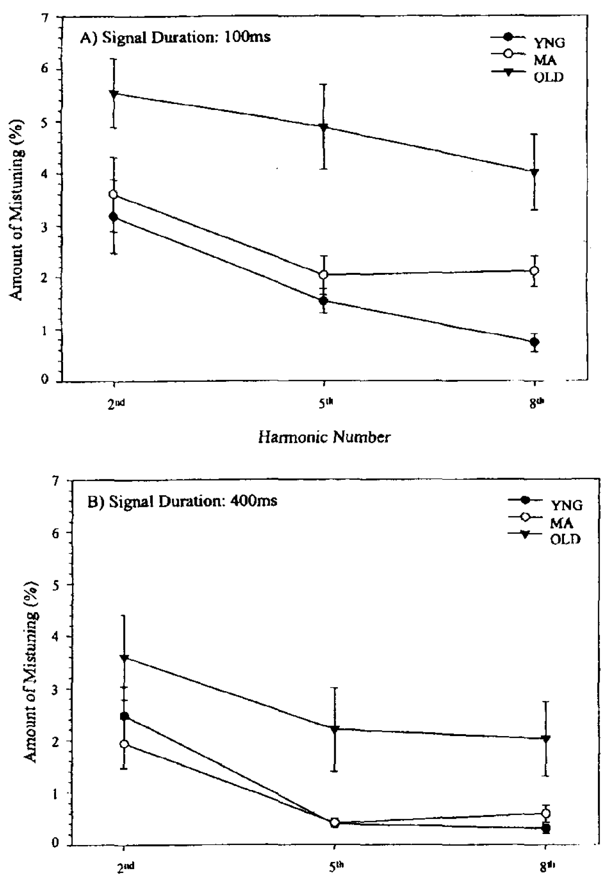

FIG. 1. (A) Thresholds for detecting inharmonicity for the 100-ms duration sounds in young, middle-aged, and older adults. (B) Thresholds for detecting inharmonicity for the 400-ms duration sounds in young, middle-aged, and older adults. The threshold for inharmonicity is expressed as percent mistuning of the harmonic concerned.

A mixed design ANOVA with group as a between-subject factor and stimulus duration and harmonic number as within-subject factors yielded a main effect of group, $F(2,27)=7.16$, $p<0.01$. Pairwise comparisons revealed that older adults had elevated thresholds compared with middle-aged and young adults, $p<0.01$ in both cases. The group ×harmonic number interaction was not significant nor was the interaction between group, stimulus duration, and harmonic number. However, the group×stimulus duration interaction was significant, $F(2,27)=6.95$, $p<0.01$, reflecting greater age effects for short than for long duration stimuli.

These observed age effects on detecting a mistuned harmonic could be partly attributed to the elevated audiometric thresholds in older adults. However, this cannot account for the performance differences between older and middle-aged listeners since there were no significant differences in audiometric thresholds (Table I) between these two groups. To show that there is an age effect after controlling for audiometric differences, we used the average audiometric threshold for 250, 500, 1000, 2000, and 3000 Hz, and the slopes of the audiogram for these five frequencies as covariates in an analysis of covariance. (To obtain the slope we fit straight lines to individual plots of dB HL versus log frequency.) The analysis of covariance yielded a main group effect, $F(2,26) =4.31$ and 6.82, for pure-tone threshold average and slope, respectively, $p<0.05$ in both cases. These analyses indicate that the age effects on detecting a mistuned harmonic remained even after controlling for age differences in hearing sensitivity.

Group differences in detecting a mistuned harmonic may be partly due to differences in learning the task. In order to examine the role of learning in detecting the mistuned harmonic, the thresholds measured at the first, second, and third sessions were compared between the three groups. The ANOVA yielded a main effect of session, $F(2,54)=12.39$, $p<0.001$, indicating that thresholds decreased significantly from the first to the third session. All pairwise comparisons were significant, $p<0.05$. Although the group×session interaction was not significant, the group×session×harmonic number interaction tended toward significance, $F(8,108) =2.17$, $p=0.056$. For the second harmonic, young and middle-aged adults improved their performance as a function of session whereas older adults did not. For the fifth and eighth harmonic, the effect of practice was similar in young, middle-aged, and older adults.

In each group a subset of participants also completed the SPIN test. The signal-to-noise ratios in dB to detect 50% of the low context words were −0.29, 1.77, and 1.97 in young, middle-aged, and older adults, respectively. Older adults had a higher SPIN threshold than younger adults, $t(11)=2.57$, $p<0.05$. There was no group difference between young and middle-aged or between middle-aged and older adults. In this subgroup of participants, there was a main effect of age on audiometric thresholds, $F(2,14) = 16.17$, $p < 0.001$. Pairwise comparisons revealed that young adults had lower audiometric thresholds than middle-aged or older adults, $p < 0.01$ in both cases. There was no significant difference in audiometric threshold between middle-aged and older adults. We also compared the threshold for detecting a mistuned harmonic for this sub-group of participants. As in the whole-group analysis, we found a main effect of signal duration, $F(1,14) = 49.42$, $p < 0.001$, with lower thresholds for long than for short stimuli. The main group effect was significant, $F(2,14) = 8.49$, $p < 0.01$, revealing higher thresholds in older adults compared to young and middle-aged adults. There were no differences between young and middle-aged adults. The interaction between group and signal duration was also significant, $F(2,14) = 6.62$, $p < 0.01$, reflecting greater age differences for short than for long signals. In this small sample of participants, the correlation between the threshold for detecting a mistuned harmonic and SPIN threshold was not significant.

IV. DISCUSSION

One of the most common complaints of older adults is that they have difficulty following a conversation, especially in complex listening situations where more than one sound source is present at a time. This speech perception problem in older adults has been attributed to several factors including changes in hearing sensitivity, in central auditory processing, and in higher cognitive functions such as memory and attention. Here, we show that older adults have difficulties in detecting a mistuned harmonic. Such difficulties may contribute to the speech perception problems experienced by older adults because perception of a mistuned harmonic, like speech signals embedded in babble or noise, depends on the ability to parse auditory events based on their spectral pattern. Deficits in processing spectral patterns may have dramatic consequences on the perception of concurrent auditory signals by making the perceiver unable to adequately separate the spectral components of the speech event from the background noise (figure-ground segregation), thereby making the perception of speech more difficult.

Previous research showed that the speech perception problems in older adults are prevalent in the presence of multiple sound sources (e.g., Divenyi and Haupt, 1997a). In the present study, older adults showed higher SPIN thresholds than young adults, consistent with numerous studies showing age-related declines in speech reception threshold (e.g., Bergman, 1980; Frisina and Frisina, 1997; Gelfand *et al.*, 1988). The increased threshold for detecting a mistuned harmonic in individuals who also showed deficits in speech reception threshold is consistent with the hypothesis that age-related changes in processes critical for sound segregation may contribute to the observed speech perception problems in older adults. Yet, the threshold in detecting a mistuned harmonic did not significantly correlate with the SPIN threshold. Although this may seem counterintuitive, the small sample size did not allow sufficient power to draw any conclusions or rule out a potential relationship between age-related decline in concurrent sound segregation and the SPIN threshold.

The age difference in detecting a mistuned harmonic was present even after controlling for audiometric threshold. This indicates that age-related increases in detecting inharmonicity do not depend solely on peripheral factors but must also involve an age-related decline in central auditory functions. The fact that middle-aged adults did not show elevated thresholds in detecting mistuning despite higher audiometric thresholds relative to young adults provides further evidence for an age-related decline in central auditory functions. If the threshold for detecting a mistuned harmonic was solely related to hearing sensitivity then performance should have been similar in middle-aged and older adults. The fact that middle-aged adults performed as well as the young adults suggests that in middle-aged adults top-down controlled processes may compensate for impoverished sensory input. Although our results point toward age-related changes in central auditory functions, one cannot exclude the possibility that age-related changes in detecting inharmonicity could also be mediated by peripheral factors that are distinct from those mediating absolute sensitivity.

Several factors could contribute to age-related changes in detecting a mistuned harmonic. One possibility is that older adults have broader auditory filters than young and middle-aged adults. Previous studies have shown that sensorineural hearing loss is often associated with broader auditory filters than normal (e.g., Glasberg and Moore, 1986; Lutman *et al.*, 1991). One consequence of having broader auditory filters would be a reduction in the ability to resolve the individual harmonics of the complex sound thereby resulting in higher thresholds for detecting a mistuned harmonic. However, it remains equivocal whether mild hearing impairment and/or age per se affect frequency selectivity. For example, the decrease in frequency resolution is usually minimal for pure-tone thresholds ranging from 0 to 30 dB (Glasberg and Moore, 1986; Lutman *et al.*, 1991). There is also evidence suggesting that age, independent of hearing loss, does not impair frequency resolution (Peters and Moore, 1992; Sommers and Gehr, 1998; Sommers and Humes, 1993), and audiometric thresholds in young and older listeners do not always correlate with performance on tasks assessing frequency selectivity (Divenyi and Haupf, 1997b). The relation between frequency selectivity and auditory discrimination is also ambiguous. Performance on discriminating complex sounds is only weakly correlated with frequency selectivity (Moore and Peters, 1992). Furthermore, young and old listeners may differ on frequency discrimination tasks and yet have similar auditory filter widths (Moore and Peters, 1992).

Given that the perception of complex sounds requires the analyses of rapid ongoing fluctuations in sound frequency and intensity, an age-related decline in temporal resolution could contribute to the elevated thresholds in detecting mistuned harmonics in older adults. For example, older adults typically showed elevated thresholds in detecting a silent gap within a signal (e.g., Moore *et al.*, 1992; Schneider and Hamstra, 1999; Snell, 1997). This age-related effect is greater when short rather than long duration markers are used (Schneider and Hamstra, 1999). Similarly, greater age effects in frequency difference limens have been reported for short than for long duration signals (Cranford and Stream, 1991). In the present study, the age difference in detecting a mistuned harmonic was greater for short than for long duration signals, which is consistent with the proposal that older adults have impaired temporal processing. The age-related decline in temporal resolution may be related to inaccurate phase-locking of auditory neurons. There is evidence from the animal literature showing that older mice have a reduced number of neurons in the inferior colliculi that respond to brief gaps compared to younger mice (Walton *et al.*, 1998). The recovery of the phase-locking response was also of a lower magnitude in the older mice (Walton *et al.*, 1998). Inaccuracy in the phase-locking of auditory neurons with aging would impair the ability to accurately extract the frequency of each harmonic thereby making the detection of inharmonicity more difficult.

The age difference in detecting a mistuned harmonic could also be caused by age-related slowing in perceptual and cognitive processing (Salthouse, 1996). According to the processing-speed theory, age-related decline in perceptual and cognitive tasks can be accounted for by the reduced speed with which various perceptual and cognitive operations can be performed in the available time. In the present context, this suggests that the speed with which the harmonic template could be processed by the auditory system would be reduced for older adults. With short duration signals, older individuals had little time to extract frequency periodicity, leaving the perceptual analysis partly incomplete. When long duration signals were used, these individuals had time to complete the perceptual analysis, thereby improving their performance in detecting the mistuned harmonic.

In all participants, the threshold for detecting inharmonicity decreased when both signal duration and harmonic number increased. This is consistent with other studies involving well-trained listeners (e.g., Moore *et al.*, 1985). Differences in threshold between low and high harmonic number are thought to reflect differences in sensitivity for detecting roughness or beating. Previous work has shown that as the frequency of a mistuned harmonic increased, the rate of fluctuation increased, making the beats and roughness effective cues, especially at long signal durations.

As previously observed in the literature, the threshold for the lowest harmonic was less affected by signal duration than the middle or highest harmonic. This is consistent with the proposal that different processes may mediate processing of low and high harmonics (e.g., Moore *et al.*, 1985; Moore and Glasberg, 1986). In the present study, the effect of age did not interact with both duration and harmonic number, suggesting that these different processes were similarly affected by aging.

All participants improved their performance over the course of the experiment. Although the older adults seemed to benefit most from repeated sessions, the effect of learning/practice on detecting inharmonicity was similar in all three age groups. It remains possible that with additional training older adults may asymptote at a similar threshold value as middle-aged or younger adults. However, it is unclear what amount of training would be required to reach such asymptote values. In the present study, the short duration signals were always presented after the long duration signals. Therefore, the lower threshold for short duration signals cannot be accounted for by a practice effect. Further research is needed to evaluate the effects of training on detecting a mistuned harmonic and to assess whether training modulates the age-related difference in detecting inharmonicity observed in the present study.

ACKNOWLEDGMENTS

We gratefully thank Jane Carey and Melinda Ciffolillo for technical assistance, and Patricia van Roon and David Shore for helpful comments on earlier versions of the manuscript. This research was funded by a grant from the Canadian Institute for Health Research to C.A.

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