

Processing Interaural Cues in Sound Segregation by Young and Middle-Aged Brains

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Abstract

Background: When listening to one speaker while another conversation is occurring simultaneously, we separate the competing sounds by processing physical cues such as common onset time, intensity, frequency harmonicity, and spatial location of the sound sources. Spatial location is determined in large part by differences in arrival of a sound at one ear versus the other ear, otherwise known as interaural time difference (ITD) or interaural phase difference (IPD). There is ample anecdotal evidence that middle-aged adults experience greater difficulty listening to speech in noise, even when their audiological evaluation does not reveal abnormal results. Furthermore, it has been shown that the frequency range for IPD processing is reduced in middle-aged adults compared to young adults, even though morphological changes in the auditory evoked potential (AEP) response were only observed in older adults.

Purpose: The purpose of the current study was to examine early aging effects (<60 years) on IPD processing in concurrent sound segregation.

Research Design: We examined the change AEP evoked by detection of a mistuned and/or phase-shifted second harmonic during the last 1500 msec of a 3000 msec amplitude-modulated harmonic complex. A passive listening paradigm was used.

Study Sample: Ten young (21–35 years) and 11 middle-aged (48–57 years) adults with normal hearing were included in the study.

Data Collection and Analysis: Scalp electroencephalographic activity was recorded from 63 electrodes. A temporospatial principal component analysis was conducted. Spatial factor scores of individual spatial factors were the dependent variable in separate mixed-design ANOVAs for each temporal factor of interest. Stimulus type was the within-subject independent variable, and age group was the between-subject independent variable.

Results: Results indicated a delay in the upward P2 slope and the P2 peak latency to a sudden phase shift in the second harmonic of a harmonic complex in middle-aged adults compared to young adults. This AEP difference increased as mistuning (as a second grouping cue) decreased and remained evident when the IPD was the only grouping cue.

Conclusions: We conclude that our findings reflect neurophysiologic differences between young and middle-aged adults for IPD processing in concurrent sound segregation.

Key Words: Auditory evoked potentials, concurrent sound segregation, dichotic grouping cues

Abbreviations: AEP = auditory evoked potential; IPD = interaural phase difference; ITD = interaural time difference; ORN = object-related negativity; PCA = principal component analysis

Successful extraction of speech from a noisy background requires the separation of simultaneous sounds, commonly referred to as concurrent sound segregation (Bregman, 1990; Carlyon, 2004). According to Bregman, two types of streaming mechanisms are used in concurrent sound segregation:

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“primitive grouping mechanisms,” a bottom-up process that relies on the use of acoustic stimulus properties; and “schema governed mechanisms,” a top-down process that relies on an individual’s past experiences and on cognitive factors. “Primitive grouping mechanisms” rely on the use of grouping cues, which are physical cues that inform us which sounds belong to the same source. For example, when listening to one speaker while another conversation is occurring simultaneously, we separate the competing sounds by processing physical cues such as common onset time, intensity, frequency harmonicity, and spatial location of the sound sources (e.g., Darwin and Hukin, 1998; Alain, 2007).

Spatial location is determined in large part by differences in arrival of a sound at one ear versus the other ear, otherwise known as interaural time difference (ITD) or interaural phase difference (IPD). It has been shown behaviorally that ITDs alone are not a strong cue for sound segregation (Buell and Hafter, 1991; Culling and Summerfield, 1995); however, when ITDs occur in conjunction with other grouping cues, they have been shown to augment concurrent sound segregation (Shackleton et al, 1994; Darwin, 1997). Furthermore, the importance of the ITD as a single grouping cue increases when referential sounds are present in the auditory environment, such as when the listener has independent evidence from other trials in the same experimental block about which harmonic of a complex sound may be from a separate sound source (Darwin and Hukin, 1998).

Neurophysiologic studies of simultaneous sound segregation derived from diotic grouping cues have focused on harmonic mistuning of one partial from an otherwise harmonic complex (for a review see Alain, 2007). For example, Alain and colleagues (2001) recorded cortical auditory evoked potentials (AEPs) to a harmonic complex with all harmonics in tune, and with one harmonic mistuned. The difference wave of the AEPs to these two stimuli generated a negativity around 180 msec, termed the “object-related negativity” (ORN), which overlaps in time with the N1 and P2 components of the AEP.

There is neurophysiologic evidence that the AEP can be used to study concurrent sound segregation based on dichotic grouping cues. Johnson et al (2003) documented changes in P2 morphology and confirmed that an ORN could be evoked by broadband noise with or without an embedded dichotic pitch (Hautus and Johnson, 2005). McDonald and Alain (2005) studied the relative contribution of harmonicity (frequency mistuning) and location cues (sounds presented from loudspeakers at $\pm 45^\circ$) in parsing concurrent sounds using AEPs. Their neurophysiologic and behavioral findings indicated that sounds can be segregated based on location or mistuning cues alone. It is of note, however, that the location cues were presented in free field, and therefore, in addition to dichotic cues, spectral and other monaural cues were available to the subjects.

Binaural hearing has been shown to decline with age (Koehnke and Besing, 2001). Middle-aged adults show early signs of neurophysiologic aging when processing pure tone IPDs (Ross et al, 2007). Ross and colleagues recorded cortical AEPs in response to changes in IPDs (occurring at 2000 msec of a 4000 msec stimulus) in young, middle-aged, and older subjects. AEPs were evoked by IPDs for frequencies up to 1225 Hz in young adults but only up to 940 Hz in middle-aged adults and 760 Hz in older adults. Changes in morphology of the cortical AEP became apparent later in life than the decline in the IPD threshold. The most pronounced effect was the P2 latency increase in the change response to a 500 Hz pure tone for the older adults relative to the young and middle-aged adults (Ross et al, 2007).

Aging in concurrent sound segregation has been shown using diotic grouping cues. Neurophysiologic and behavioral evidence demonstrates that older adults, but not middle-aged adults, are less able to detect a mistuned harmonic in an otherwise harmonic complex (Alain et al, 2001; Alain and McDonald, 2007).

To our knowledge, the effects of aging on IPD processing in concurrent sound segregation have not been investigated. In this study we used a 3000 msec amplitude-modulated harmonic complex. During the first 1500 msec all harmonics of a five tone complex were in tune and interaurally in phase. During the last 1500 msec the second harmonic was out of tune (diotic grouping cue) and/or out of phase between the ears (dichotic grouping cue); the rest of the harmonic complex remained unchanged. Our goal was to determine whether the change AEP evoked by the detection of a mistuned and/or phase-shifted second harmonic differed for young and middle-aged adults. Based on Alain et al’s findings (Alain et al, 2001; Alain and McDonald, 2007) we hypothesized that mistuning alone would be processed similarly by young and middle-aged adults. On the other hand, we expected to see age differences for IPD processing. As the P2 has been implicated in concurrent sound segregation and in aging effects evoked by IPD processing of pure tones, we expected the age effect to be most prominent in the P2 component. We chose to include middle-aged adults rather than older adults to focus on early normal aging, thereby minimizing the impact of sensory factors (i.e., decline in hearing acuity) on the findings.

MATERIALS AND METHODS

Participants

Ten young (age: \bar{x} = 25.4 yr; range = 21–35) and 11 middle-aged (age \bar{x} = 52.46 yr; range = 48–57) adults participated in the study. Participants were recruited from the faculty and student population at Montclair State University and the local community. All participants had normal hearing bilaterally (≤ 20 dB HL) at octave frequencies from 250 to 8000 Hz and normal

middle ear function. Participants had no known auditory processing or neurological problems. All participants provided informed consent in accordance with the Montclair State University Institutional Review Board.

Stimuli

We constructed a 3000 msec complex tone consisting of five harmonics of equal amplitude. The fundamental frequency was 250 Hz (f). A 40 Hz sinusoidal 100% amplitude modulation was applied to the harmonic complex. During the first 1500 msec of the stimulus, all harmonics were in tune and interaurally in phase. At 1500 msec after stimulus onset, we manipulated the phase and/or frequency of the second harmonic ($2f$; 500 Hz) while keeping the other harmonics of the complex unchanged. The frequency manipulation involved shifting $2f$ downward by 2, 4, or 8%. The frequency mistuning was presented diotically and was maintained until the end of the stimulus. The IPD was created by shifting the phase of $2f$ by 180° in the right ear. The phase shift occurred at the minimum point of the amplitude modulation to avoid the detection of an abrupt change in the stimulus at the point of the phase reversal. Like the frequency mistuning, the IPD occurred throughout the second 1500 msec of the stimulus. The stimulus labels in Table 1 represent the mistuning and IPD characteristics of the second harmonic.

Presentation Levels

Stimuli were delivered to participants through earphones in a sound attenuated booth. Prior to the actual testing, the detection threshold of the harmonic complex (with all five harmonics in tune) was determined separately for the left and right ear of each subject. During testing the stimuli were presented at 30 dB SL re: the individual ear threshold. This resulted in a maximum difference in presentation levels between the ears of 2 dB (except for one young adult who had a 4 dB difference).

Passive Listening

A passive listening procedure was used to record AEPs. To reduce body movements and attention to the sound stimuli during the AEP recordings, each participant watched a muted, subtitled movie of their choice. Participants were instructed to ignore the sounds and focus on the movie. To confirm compliance, subjects were monitored from the control room. AEPs were recorded in three, 35 min blocks of trials. One hundred fifty trials were randomly delivered for each of the seven stimulus types (Table 1) with an interstimulus interval varying between 2800 and 3200 msec.

Active Listening

Active listening was evaluated to ensure that all participants could detect the stimulus changes. Active

Table 1. Stimulus Labels Reflecting the Acoustic Features of the Second Harmonic from the 1500–3000 msec Interval Post-Stimulus Onset

| | | IPD | |
|-----------|----|---------------|-------------|
| | | Present | Not Present |
| Mistuning | 0% | $IPD2f_{0\%}$ | n/a* |
| | 2% | $IPD2f_{2\%}$ | $2f_{2\%}$ |
| | 4% | $IPD2f_{4\%}$ | $2f_{4\%}$ |
| | 8% | $IPD2f_{8\%}$ | $2f_{8\%}$ |

* $2f_{0\%}$ does not evoke a change AEP because the characteristics of the second harmonic are the same as the first half of the stimulus.

listening always followed passive listening. AEPs were not recorded. In addition to the seven stimuli used during passive listening there was a stimulus with no change at 1500 msec post-stimulus onset (i.e., $2f_{0\%}$). Participants were asked to press the response button when they heard the stimulus change from one to two sounds. Participants were familiarized with the task prior to data collection. Percent correct scores were acquired for each stimulus type.

AEP Recording and Analysis

Scalp electroencephalographic activity was recorded at a sampling rate of 1000 Hz and with analog filter settings from 0.15 to 70 Hz (slope -12 dB/octave) from 63 sintered silver-silver electrodes attached according to a modified version of the International 10–20 system. The nose electrode served as reference and AFZ as ground. Sweep duration extended from -200 to 1000 msec relative to the change in the auditory stimulus at 1500 msec. Offline signal averaging was carried out after artifact rejection (based on VEOG waveform exceeding $\pm 50 \mu\text{V}$), linear detrending procedures, low-pass digital filtering at 20 Hz with a filter slope of -48 dB/octave, and baseline correction procedures (based on the first 200 data points). Averaged AEPs were based on a minimum of 90 sweeps per stimulus type. For each participant, the AEPs in response to all stimulus types contained a comparable number of sweeps.

RESULTS

Description of Grand Averaged Waveforms and Behavioral Accuracy Scores

Grand averaged waveforms based on all subjects ($n = 21$) for all seven stimulus types are shown in Figure 1. A clear N1-P2 complex to stimulus change at 1500 msec post-stimulus onset was evoked for all stimuli except for $2f_{2\%}$. The range of accuracy scores obtained in the active listening condition was between 85 and 100% for all stimulus changes except $2f_{2\%}$ (range 0–100%). The AEP activation in response to $2f_{2\%}$ was absent in those subjects who were able to perceive the stimulus change. Therefore, AEPs to $2f_{2\%}$ were excluded from further analysis.

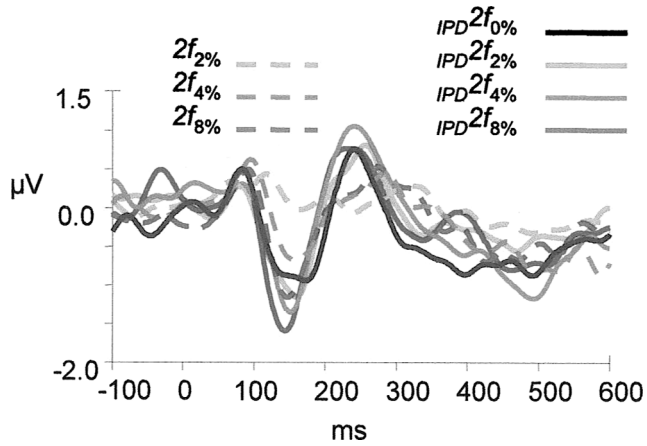


Figure 1. Grand averaged AEP at electrode FCZ, averaged across all subjects (n = 21).

As can be seen in Figure 2, AEPs in response to stimuli with IPDs *and* mistuning had a clearer morphology than the stimuli with mistuning only. This was true in young and middle-aged adults alike. However, when comparing the AEPs for each of these stimuli between young and middle-aged adults, it appears that the slope toward P2 and P2 peak in response to the stimuli containing IPD occur later in middle-aged adults than young adults.

Temporospatial Principal Component Analysis

A two-step principal component analysis (PCA) was conducted; a temporal PCA was followed by a spatial PCA. The purpose of the temporospatial PCA is to extract distinct components describing the variance contributions of temporally and spatially overlapping AEP components that are difficult to distinguish with traditional AEP measures (Kayser et al, 2001). Because we were mainly interested in the N1 and P2 components, we limited the analysis time window to 0–350 msec after change onset. PCA analysis settings (Promax rotation, Kappa = 3, Kaiser normalization) were based on a recently established standard protocol that was shown to yield the best results for AEP datasets (Dien et al, 2005).

The input to the temporal PCA consisted of 350 variables (time points) × 7938 observations (21 participants × 63 electrodes × 6 stimulus types). First, a covariance matrix was formed reflecting the covariance between each pair of time points. Then temporal factors (or linear combinations of time points) were extracted for a Promax rotation. Fourteen temporal factors with an eigenvalue greater than 1 were extracted, explaining 99.59% of the variance. The factor scores of the 14 temporal factors were subsequently used in the spatial PCA. The input to the spatial PCA consisted of 62 variables (electrodes; VEOG electrode excluded) × 1764 observations (21 participants × 14 temporal factors × 6 stimulus types). Five spatial factors (or linear combinations of electrodes) with an eigenvalue greater than 1 were extracted, explaining 90.54% of the variance.

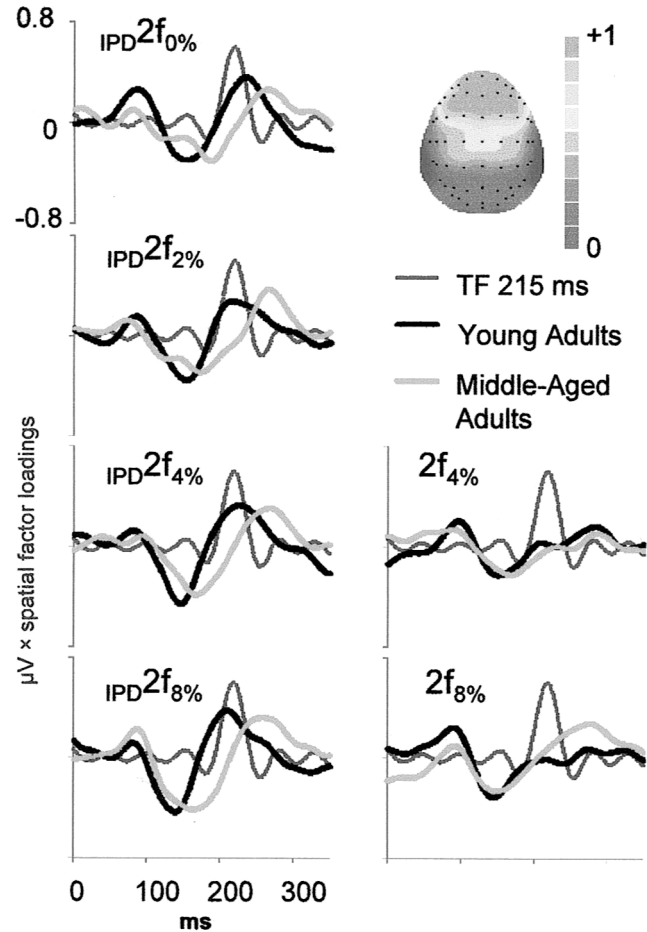


Figure 2. Topographic map and time waveforms of Spatial Factor 1 (SF1). TF 215 msec is added to illustrate the time window that differentiates IPD processing between young and middle-aged adults.

Five temporal factors were located within the N1-P2 time window (100 to 240 msec); TF 108 msec (peak latency at 108 msec), TF 140 msec, TF 190 msec, TF 215 msec, and TF 240 msec. Two spatial factors (SF1, fronto-central electrode sites, SF5, central electrode sites) represented the scalp distribution typically observed for the N1 and P2 components (Fig. 2).

Mixed-Design ANOVA

Spatial factor scores of individual spatial factors (SF1, SF5) were the dependent variable in separate mixed-design ANOVAs for each temporal factor of interest. Stimulus type (*IPD2f0%*, *IPD2f2%*, *IPD2f4%*, *IPD2f8%*, *2f4%*, *2f8%*) was the within-subject independent variable and age group (young, middle-aged) was the between-subject independent variable. Only significant findings pertinent to age effects for neurophysiologic processing of IPDs (as supported by polynomial within-subject contrasts) are reported. In a mixed-design ANOVA for the P2 component, with SF1 spatial factor scores at TF 215 msec as the dependent measure, a significant interaction effect of stimulus type × age

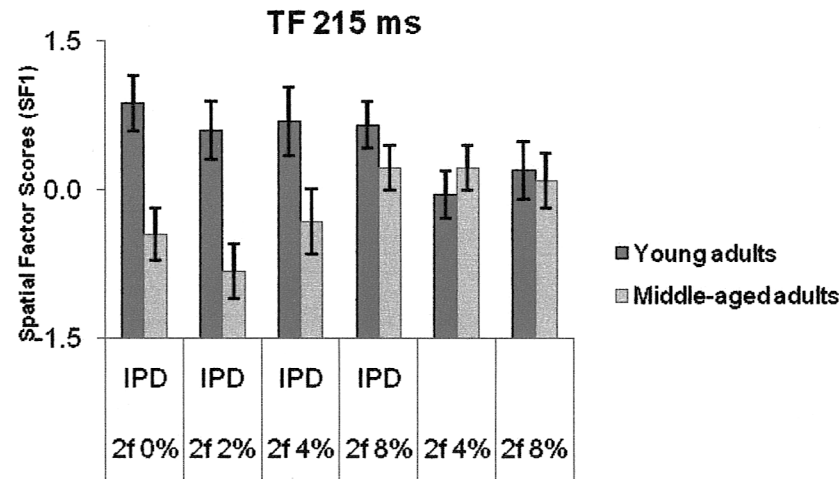


Figure 3. Linear trend for TF 215 msec at SF1. Error bars indicate one standard error of the mean.

group was found, $F(5,95) = 4.396$, $p = .001$. Within-subject polynomial contrasts indicated a significant linear trend for stimulus type \times age group, $F(1,19) = 17.887$, $p < .001$ (Fig. 3). Spatial factor scores of SF1 at TF 215 msec were different between young and middle-aged adults in response to $IPD2f_0\%$, $IPD2f_2\%$, and $IPD2f_4\%$. The time waveforms of SF1 shown in Figure 2 are based on the grand averaged AEP for each stimulus and age group and represent the average of all electrodes multiplied by their respective factor loadings.¹ As can be seen in the grand averaged waveforms in Figure 2, even though a clear P2 response was evoked, the P2 latency was delayed in middle-aged compared to young adults. For the remaining three stimuli, $IPD2f_8\%$, $2f_4\%$, and $2f_8\%$, the spatial factor scores were similar for the middle-aged and young adults. The grand averaged waveforms for $2f_4\%$ and $2f_8\%$ did not reveal differences in the P2 component at 215 msec between young and middle-aged adults.

Although in Figure 2 the waveform evoked by $IPD2f_8\%$ appears different for young and middle-aged adults, this difference was remarkably smaller than for the other stimuli containing IPDs. The P2 evoked by this stimulus occurs slightly earlier in both age groups; therefore, the temporal factor may not have covered the P2 peak completely. However, even the earlier temporal factor (TF 190 msec) did not reveal a significant age effect for the $IPD2f_8\%$ stimulus.

DISCUSSION

The results of this study indicate that IPDs presented alone or in conjunction with mistuning evoke strong AEPs. This is in contrast to behavioral studies which indicate that an IPD is not a strong cue for auditory grouping in simultaneous sound segregation (Buell and Hafter, 1991; Culling and Summerfield, 1995). This is likely due to the fact that in the

behavioral studies minimally detectable IPDs were measured. But, to be certain that the IPD would be perceived by the young and middle-aged adults and evoke a clear AEP, a large (180°) phase shift was used in the present study. Also, in this study we did not measure IPD processing in isolation but evaluated its role when a sudden phase shift occurred in an ongoing stimulus. Because sound rarely occurs in isolation in a natural auditory environment, our methodology sheds light on IPD processing in typical listening situations.

Neurophysiologic studies have shown that AEPs can be used to examine concurrent sound segregation (Alain, 2007). Typically, these studies evoke an onset AEP to complex sounds with one auditory object and to complex sounds with two concurrently occurring auditory objects to obtain an AEP difference wave, the object-related negativity (ORN) (Alain, 2007). We elicited a change AEP rather than an onset AEP and, due to the nature of our stimuli, we did not elicit responses to a harmonic complex with one auditory object. Therefore, we do not have data available to evaluate the presence of an ORN.

Regardless, we demonstrated neurophysiologic differences in young and middle-aged adults when IPDs were available as a grouping cue for concurrent sound segregation in an ongoing stimulus. The upward slope and peak of the P2 component were delayed in middle-aged adults compared to young adults when a phase shift occurred in the second harmonic as long as that harmonic was not mistuned or was mistuned by less than 8% (Figs. 2–3). Our middle-aged adults (range 48–57 years) were slightly older than Alain and McDonald's middle-aged participants (range 40–50 years) (Alain and McDonald, 2007); yet, our data confirm the lack of an age effect for concurrent sound segregation based on mistuning alone. Moreover, no age effects were found for the AEP elicited by $IPD2f_8\%$.

To interpret these findings, we turn to a recent study by McDonald and Alain (2005). They showed that mistuning the third harmonic by 2% only yielded an ORN if the remaining harmonics of the complex were presented at a different spatial location (sounds presented from loudspeakers at $\pm 45^\circ$). They also observed AEP changes between 150 and 250 msec after sound onset when the in-tune third harmonic was presented from a different spatial location than the remaining harmonics. For 16% mistuning, changing the spatial location of the third harmonic relative to the remaining harmonics did not modify the AEP. Behaviorally, participants were more likely to report hearing two sounds when the third harmonic was presented from a different loudspeaker if the sound was in tune or mistuned by 2%, but not when the sound was mistuned by 16%. In other words, the location cues played a more important role when mistuning was either absent or near threshold. It is of note that in our study evidence of neurophysiologic aging was only present in response to stimuli with a phase shift and, like McDonald and Alain, became more apparent when the percent of mistuning decreased or was absent, so that IPD was likely the primary grouping cue. Hence, we conclude that our findings reflect neurophysiologic aging for IPD processing in concurrent sound segregation.

As mentioned earlier, neurophysiologic aging in binaural hearing has been confirmed in change AEPs elicited by a sudden phase shift in a pure tone (Ross et al, 2007). Of particular interest is the aging effect noted by Ross et al when the change AEP was elicited by a sudden phase shift in a 500 Hz pure tone. Ross et al reported that P2 latency was significantly prolonged in older adults relative to young and middle-aged adults, but the change AEP did not differ substantially between young and middle-aged adults. However, the morphological change in the P2 of their older adults strongly resembles our findings in middle-aged adults.

The functional significance of the P2 has not been determined. However, Ross and colleagues (2007) suggested that "P2 may be related to the termination of the stimulus evaluation process. Thus, the prolonged interval between N1 and P2 in the change response may indicate the greater time needed for binaural processing in older adults" (p. 11178). Our findings suggest that more time is needed for processing at an even earlier age when binaural cues are used for concurrent sound segregation in a complex sound environment.

In conclusion, neurophysiologic aging was demonstrated when IPDs functioned as the single or primary grouping cue in concurrent sound segregation. This was evidenced by a delay in the upward P2 slope and the P2 peak latency to a sudden phase shift in the second harmonic of a harmonic complex in middle-aged adults compared to young adults. This AEP difference increased as mistuning (as a second grouping cue) decreased and remained evident when the IPD was the only grouping cue.

NOTE

1. For each $x, y = ((\mu V_{\text{electr1}} * \text{spatial factor loading}_{\text{electr1}}) + (\mu V_{\text{electr2}} * \text{spatial factor loading}_{\text{electr2}}) + (\mu V_{\text{electr3}} * \text{spatial factor loading}_{\text{electr3}}) + \dots + (\mu V_{\text{electr62}} * \text{spatial factor loading}_{\text{electr62}}))/62$.

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