

Aging: A Switch From Automatic to Controlled Processing of Sounds?

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In this article, the authors show that aging differentially affects peoples' ability to automatically and voluntarily process auditory information. Young, middle-aged, and older adults matched behaviorally in an auditory discrimination task showed similar patterns of neural activity indexing the voluntary and conscious detection of deviant (i.e., target) stimuli. In contrast, a negative wave indexing automatic processing (the mismatch negativity) was elicited only in young adults for near-threshold stimuli. These results indicate that aging affects the ability to automatically register small changes in a stream of homogeneous stimuli. However, this age-related decline in automatic detection of small changes in the auditory environment can be compensated for by top-down controlled processes.

Age-related changes in the peripheral auditory system are, in large part, responsible for the difficulties that older adults experience in detecting, locating, and recognizing sounds in the complex acoustic environments typical of everyday listening situations (e.g., Abel, Krever, & Alberti, 1990; Fitzgibbons & Gordon-Salant, 2001; Schneider & Pichora-Fuller, 2001). Presumably, such losses in peripheral sensitivity result in impoverished and noisy signals being delivered to the central nervous system, illustrating an inefficiency of automatic (data-driven) processes. In addition, studies using positron emission tomography or functional magnetic resonance imaging have found age-related declines in blood flow in many cortical brain areas, including the prefrontal cortex and medial temporal lobe (for reviews see Grady & Craik, 2000; Raz, 2000). Such changes could also contribute to older adults' difficulties in processing auditory information by generally slowing down perceptual and cognitive operations (Salthouse, 1996) or by interfering with inhibitory control mechanisms (Hasher & Zacks, 1988). Thus, age-related changes in both peripheral and central auditory systems could affect automatic processing by reducing the fidelity of the signal delivered to higher cognitive systems, by reducing the speed at which stimuli are automatically processed, or by failing to inhibit the processing of irrelevant material.

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Many theorists have argued that when stimulus degradation or other factors result in an impoverished signal, performance can be improved by exerting top-down control (e.g., by focusing attention on the stimuli, by inhibiting irrelevant material, etc.; Just & Carpenter, 1987; Stanovich & West, 1979). Hence, we might expect older adults to rely more heavily on controlled processing if they are subject to age-related declines in automatic processing.

Recording of event-related brain potentials (ERPs) provides a powerful tool for examining the effect of age on controlled and automatic processing because it can be performed for the same stimuli when they are both task relevant and task irrelevant. The conscious identification of rare deviant (i.e., target) stimuli embedded in a stream of standard stimuli has been associated with a negative and a positive wave maximum over the central and parietal scalp regions. The negative wave, referred to as the N2b, indexes stimulus classification processes (Ritter, Simson, Vaughan, & Friedman, 1979; Ritter, Simson, Vaughan, & Macht, 1982), whereas the positive wave, referred to as the P3b, indicates the completion of target evaluation (Kutas, McCarthy, & Donchin, 1977) and context updating (Donchin & Coles, 1988). In comparison, when the same stimuli are presented while participants perform some other task (e.g., reading or watching a video), the detection of rare deviant stimuli generates a mismatch negativity (MMN) wave that is maximum at the frontocentral scalp region (Näätänen, 1992; Picton, Alain, Otten, Ritter, & Achim, 2000). The MMN amplitude and latency are related to auditory discriminability (Picton, Alain, et al., 2000; Tiitinen, May, Reinikainen, & Näätänen, 1994), with highly salient deviant stimuli relating to both larger and earlier peak amplitude relative to less salient deviant stimuli.

The MMN is particularly well-suited for studying automatic processing because it is elicited in paradigms in which overt attention and behavioral responses are not required. Its generation reflects a neural mismatch between the deviant stimulus and a representation of the standard stimulus held in sensory memory,

and it depends on a frontotemporal network in which the prefrontal cortex modulates the amplitude of the MMN response generated in the auditory cortex (Alain, Woods, & Knight, 1998; Alho, Woods, Algazi, Knight, & Näätänen, 1994).

Although some studies have examined age effects on controlled and automatic processing of sounds (e.g., Fabiani & Friedman, 1995; Ford & Pfefferbaum, 1991; Ford et al., 1997), to our knowledge this is the first comparison that uses stimuli that are equally discriminable to all participants, irrespective of age. When the same physical stimuli are presented to young and old participants, age-related differences in cortical activity could be due to either (a) age-related differences in the peripheral processing of the stimuli or (b) age-related changes in the central processing of the stimuli. By making the stimuli equally discriminable to all participants, we minimize the possibility that any observed age effects result from differences in peripheral processing or from differences in task difficulty.

Method

Participants

Ten young (mean age = 27 years, $SD = 4$, range = 21–31; 5 men), 10 middle-aged (mean age = 47 years, $SD = 7$, range = 37–58; 4 men), and 10 older (mean age = 69 years, $SD = 5$, range = 60–78; 4 men) adults took part in an active and a passive listening experiment. All participants had pure-tone thresholds less than or equal to 30-dB hearing level in the range of 250 to 2000 Hz and were within the normal, clinical range for these frequencies. Nevertheless, there were age effects on audiometric thresholds, with young adults having the lowest thresholds ($M = 2.75$), middle-aged adults having intermediate thresholds ($M = 7.63$), and older adults having the highest audiometric thresholds ($M = 16.13$, $F(2, 27) = 21.67$, $p < .001$ (all pairwise comparisons at $p < .05$). In the active listening condition, data from 1 older adult were discarded because of ocular-related artifacts. All but 2 participants were right-handed. The young adults were recruited from local colleges, whereas middle-aged and older adults were recruited from the community and local volunteer groups.

Stimuli and Task

Stimuli were produced by multiplying a 2-kHz pure tone by a temporal window created by summing a series of Gaussian envelopes ($SD = 0.5$ ms) spaced 0.5 ms apart. Two short tones marked the beginning and end of the gap. These tonal markers were created by multiplying a pure tone by an envelope consisting of the sum of six Gaussians (see Figure 1). The duration of each marker (defined as the time between the centers of the first and last Gaussians in the envelope) was 2.5 ms. The duration of the gap (Δt) was defined as the time between the last Gaussian in the leading marker and the first Gaussian of the lagging marker (Δt ranged from 3 to 13 ms). The comparison stimulus (a tone whose duration and energy were equal to that of the two markers defining the gap) was created by filling in the missing Gaussians between the two markers.

Participants were presented with sequences of sounds comprised of deviant (two tone pips separated by a gap; probability = 15%) and standard stimuli (continuous tones matched in duration and energy to the gap stimuli). Gap durations remained fixed within a block of trials. Age-related changes in gap-detection thresholds were taken into account by increasing the gap duration for the middle-aged and older age groups, based on Schneider and Hamstra (1999). Young adults were presented with gap durations of 3, 5, 7, 9, and 11 ms. Middle-aged adults were presented with gap durations of 4, 6, 8, 10, and 12 ms. Older adults were presented with gap durations of 5, 7, 9, 11, and 13 ms. Stimuli were presented with a fixed interstimulus interval (500 ms) at 80-dB sound-pressure level through

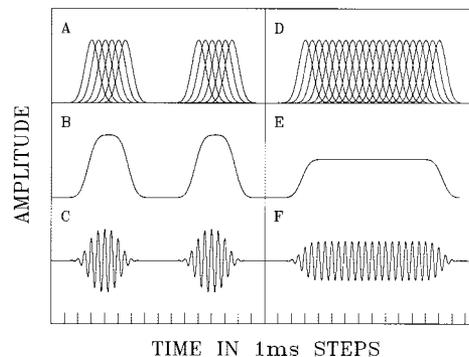


Figure 1. A: Each marker envelope is formed by summing six Gaussians ($SD = 0.5$ ms) spaced 0.5 ms apart. Marker duration (2.5 ms) is defined as the time between the centers of the first and sixth Gaussians. Gap duration (5 ms in this example) is defined as the time between the center of the last Gaussian in the leading marker and the center of the first Gaussian in the lagging marker. B: The envelope formed by summing the Gaussians shown in A. C: The envelope in B was multiplied by a 2-kHz sinusoid in cosine phase to form two 2.5-ms short tones separated by a 5-ms gap. D: The envelope of the continuous comparison tone was constructed by adding Gaussian envelopes spaced 0.5 ms apart to fill in the gap between the two markers. E: The envelope formed by summing the Gaussians in D was rescaled so that the area under the squared envelope in E equaled the area under the squared envelope in B. F: The continuous comparison tone is formed by multiplying the envelope in E by the 2-kHz tone. In this way, the energy in the continuous tone becomes equal to the total energy in the two short tone markers. (See Schneider & Hamstra, 1999, for further details.)

EARlink 3A insert earphones. To remain consistent with previous research on gap detection as well as keep the time required for recording auditory-evoked potentials at a reasonable level, we delivered stimuli only to the left ear of participants. Presentation order of the 10 trial blocks (2 for each gap duration) was randomized across gap durations and participants. A total of 5,100 standards and 900 deviants (180 deviants per gap duration) were presented to each participant.

The same stimulus sequences were presented in two separate recording sessions. In the first session, participants were instructed to ignore the auditory stimuli and to perform a concomitant visual serial-choice reaction-time task (passive listening condition). The visual stimuli were five lights on a response box. On each trial, one light turned on and participants turned it off by pressing the button corresponding to the light. The next light turned on after a response-stimulus interval (RSI) of 200 ms. This serial-choice reaction-time task, with rapid RSI, provided a measure of continuous task performance during the presentation of irrelevant auditory stimuli. The second session was conducted on a separate day at which time participants were instructed to pay attention to the stimuli (active listening condition) and to respond as quickly and as accurately as possible by pressing a button whenever they heard a stimulus with a silent gap (target).

Recording and Analysis of ERPs

The electroencephalogram was recorded from an array of 64 electrodes, including those from the standard 10–20 placements. Vertical and horizontal eye movements were recorded with electrodes at the outer canthi and at the superior and inferior orbit. Electrophysiological signals were digitized continuously (bandpass 0.05–50 Hz; 250-Hz sampling rate) via NeuroScan SynAmps and stored for offline analysis. During the recording, all electrodes were referenced to midline central electrode (Cz); for data analysis, they were re-referenced to an average reference, and the electrode Cz was reinstated.

ERP epochs were extracted offline and included a 200-ms prestimulus baseline and 500 or 800 ms of poststimulus activity for the passive and active listening experiments, respectively. The epochs were chosen to encompass the ERP components of interest in both passive and active listening experiments. Trials contaminated by excessive peak-to-peak deflections ($\pm 150 \mu\text{V}$) at the channels not adjacent to the eyes were automatically rejected before averaging. The ERPs were then averaged separately for each site, stimulus type, and listening condition. For each individual average, ocular artifacts (e.g., blinks and lateral movements) were corrected by means of ocular source components (Berg & Scherg, 1994; Picton, van Roon, et al., 2000). ERPs were digitally lowpass filtered to attenuate frequencies above 15 Hz, and amplitudes and latencies were analyzed in selected latency regions with respect to the 200-ms prestimulus period. The effects of age on ERP components were examined in a subset of electrodes where these components showed the maximal activity. The N2b peak amplitude and latency was defined as the maximum negativity between 175 and 375 ms after target onset at central electrodes (i.e., C1, Cz, C2). Similarly, the P3b peak amplitude and latency were defined as the maximum positivity between 250 and 600 ms after target onset at parietal electrodes (i.e., P3, Pz, P4). The MMN was quantified in the difference waveform between ERPs elicited by standards and the corresponding deviant stimuli. Its peak amplitude and latency were defined as the maximum negativity at frontocentral electrodes (F1, Fz, F2, FC1, FCz, FC2) between 100 and 300 ms after stimulus onset.

Results

In this study, we selected gap durations based on previous data so that similar performance in young, middle-aged, and older adults would be generated (Schneider & Hamstra, 1999). The validity of this assumption was tested by comparing the hit rate among young, middle-aged, and older adults as a function of the gap duration. The analysis of variance (ANOVA) yielded a gap size effect, $F(4, 104) = 17.34, p < .001$, with the shortest gap duration generating the lowest hit rate as compared with the other gap durations ($p < .001$ in all cases). There was no significant difference between young ($M = 91.9\%$), middle-aged ($M = 94.7\%$), and older ($M = 89.7\%$) adults in hit rate, $F(2, 26) = 0.97, p = .39, \eta^2 = 0.07, 1 - \beta = 0.20$, nor was the Group \times Gap Size interaction significant, $F(4, 104) = 1.55, p = .22, \eta^2 = 0.11, 1 - \beta = 0.35$. Therefore, the selected gap durations produced equivalent performance in all three age groups. To examine whether there were ERP differences for these equivalent levels, we first averaged across gap duration within each group and then compared the mean ERP amplitude across age groups.

In all participants, the conscious detection of target stimuli was associated with large negative and positive deflections, peaking at about 230 and 400 ms after target onset (Figure 2, see also Appendix A). The age effect on N2b latency was marginally significant, $F(2, 26) = 3.25, p = .06, \eta^2 = 0.20, 1 - \beta = 0.57$. A planned comparison revealed a delayed N2b in older adults ($M = 273$ ms) as compared with young ($M = 241$ ms) or middle-aged ($M = 240$ ms) adults ($p < .05$). Although middle-aged ($M = -0.96 \mu\text{V}$) and older adults ($M = -1.47 \mu\text{V}$) showed greater N2b amplitude than young adults ($M = -0.58 \mu\text{V}$), these differences were not statistically reliable, $F(2, 26) = 0.42, p = .66, \eta^2 = 0.03, 1 - \beta = 0.11$. Consistent with previous articles (e.g., Goodin, Squires, Henderson, & Starr, 1978; Pfefferbaum, Ford, Roth, & Kopell, 1980), the P3b latency increased with age, $F(2, 26) = 9.58, p < .001, \eta^2 = 0.42, 1 - \beta = 0.97$, with the P3b being delayed in older adults ($M = 485$ ms) in comparison to young

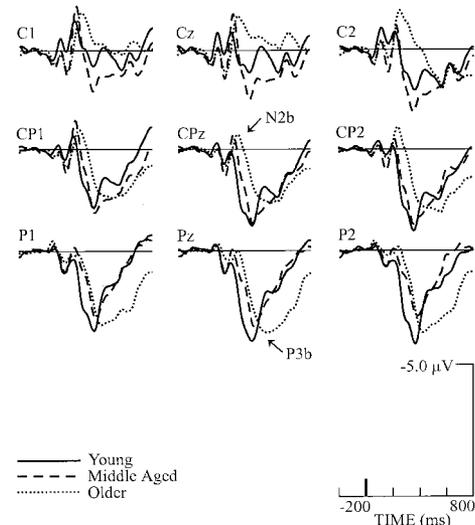


Figure 2. Group mean event-related brain potentials (ERPs) elicited by correctly identified targets during the auditory discrimination task in young (solid line), middle-aged (dashed line), and older (dotted line) adults. The ERPs were averaged across gap size within each group. Negativity is plotted upward. The taller vertical line on the scale indicates stimulus onset. C1 = left central; Cz = midline central; C2 = right central; CP1 = left centralparietal; CPz = midline centralparietal; CP2 = right centralparietal; P1 = left parietal; Pz = midline parietal; P2 = right parietal.

($M = 379$ ms) and middle-aged ($M = 390$ ms) adults ($p < .001$). There was no significant difference in P3b latency between young and middle-aged adults ($p = .68$). The effects of age on P3b amplitude were not significant (group mean amplitude = 2.78, 2.09, and 2.62 μV for young, middle-aged, and older adults, respectively), $F(2, 26) = 0.35, p = .75, \eta^2 = 0.03, 1 - \beta = 0.10$.

Performance at the Visuomotor Task

Young, middle-aged, and older adults correctly responded on 96%, 98%, and 99% of the trials, respectively, indicating their compliance with the instructions. However, there was a significant effect of age on accuracy, $F(2, 26) = 8.10, p < .01$, with young adults pressing the wrong button more often than middle-aged or older adults ($p < .01$). There was also an age effect on response times, $F(2, 26) = 23.32, p < .001$, with young adults having the fastest pace ($M = 409$ ms), the middle-aged adults having the intermediate pace ($M = 453$ ms), and the older adults having the slowest pace ($M = 552$ ms). The data from 1 middle-aged participant were lost because of a technical error.

When participants were asked to ignore the auditory stimuli and perform the visuomotor task, the same deviant stimuli (averaged across gap size within each group) generated a reliable MMN wave in all three age groups (Figure 3; see also Appendix B). The MMN latency increased with age, $F(2, 27) = 4.46, p < .05, \eta^2 = 0.25, 1 - \beta = 0.72$. Pairwise comparisons revealed that the MMN peaked earlier in young ($M = 185$ ms) than in older ($M = 215$ ms) adults ($p < .005$). The MMN latency was intermediate in middle-aged adults ($M = 197$ ms) and did not significantly differ from the young or older adults. The MMN peak amplitude was also affected by age, $F(2, 27) = 4.59, p < .05, \eta^2 = 0.25, 1 - \beta = 0.73$, with

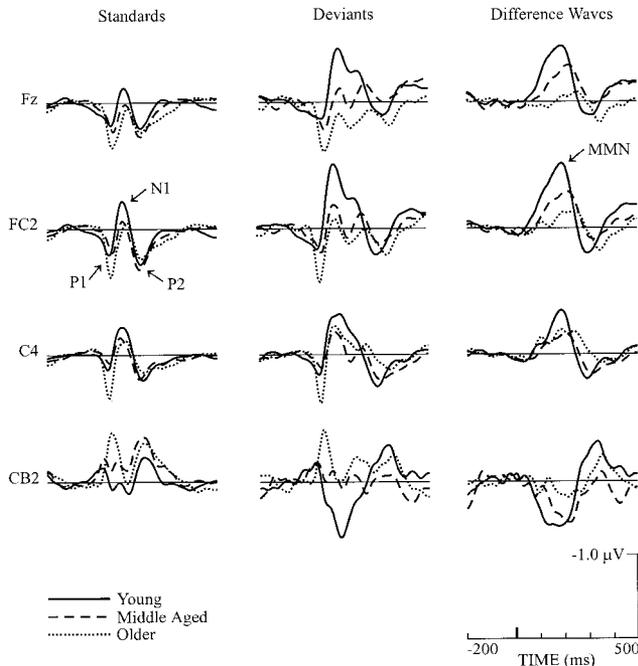


Figure 3. Event-related brain potentials (ERPs) averaged across all gap sizes. Group mean ERPs elicited by standard and deviant stimuli over the midline frontal (Fz), right frontocentral (FC2), right central (C4), and right cerebellar (CB2) scalp region in young (solid line), middle-aged (dashed line), and older (dotted line) adults. The corresponding difference waves between ERPs elicited by standard and deviant stimuli are illustrated under Difference Waves. MMN = mismatch negativity wave.

the largest ($M = -1.02 \mu\text{V}$), intermediate ($M = -0.75 \mu\text{V}$), and smallest ($M = -0.50 \mu\text{V}$) amplitude for young, middle-aged, and older adults, respectively. A planned comparison revealed that the MMN amplitude was larger in young than in older adults ($p < .005$). The MMN in middle-aged adults did not differ from those recorded in young or older adults ($p > .12$ in both cases).

Age Effects on Brain Response Elicited by a Near-Threshold Stimulus

In the following analyses, we used the shortest gap duration that produced a hit rate within 2% of the asymptotic value reached by the psychometric function, relating hit rate to gap duration. This analysis takes into consideration the individual differences in reaching asymptote performance and therefore provides a more precise evaluation of age effects on brain responses elicited by equally discriminable stimuli. The asymptotic gap threshold was estimated by fitting the following psychometric function to the hit rate: $c + (1 - a) / (1 + \text{Exp}[-s(d - m)])$, where c and a are both required to be greater than or equal to 0, d is the gap duration, s determines the slope of the psychometric function, and m is the point on the psychometric function where the slope reaches its maximum value. The parameter c is an estimate of the false-alarm rate, and $(1 - a)$ is the asymptotic value of the psychometric function.

Young, middle-aged, and older adults reached asymptotic performance at 97%, 98%, and 91% accuracy, respectively. Only the

middle-aged adults differed significantly from the older adults with respect to asymptote, $t(17) = 2.11$, $p = .05$. This group difference was due to the presence of two older adults showing asymptotes in the 70% to 80% range.¹ The gap duration eliciting asymptotic performance varied between 3 and 7 ms in young adults ($M = 5.4$ ms, $SD = 1.3$ ms), between 4 and 8 ms in middle-aged adults ($M = 5.8$ ms, $SD = 1.1$ ms), and between 5 and 9 ms in older adults ($M = 7.0$ ms, $SD = 1.0$ ms). Note that older adults required a significantly longer gap duration than young and middle-aged adults to reach asymptotic performance, $t(17) > 2.43$, $p < .05$, in both cases, a result consistent with those of previous studies (Schneider & Hamstra, 1999; Schneider, Pichora-Fuller, & Kowalchuk, 1994). There was no significant difference in gap duration between young and middle-aged adults.

The age effects on the N2b and P3b responses were similar to those observed in the former analysis with the exception of the N2b latency, which was not significantly affected by age when the participants were behaviorally matched by using the smallest gap size to reach asymptotic performance, $F(2, 26) = 2.26$, $p = .12$, $\eta^2 = 0.15$, $1 - \beta = 0.42$ (see Figure 4). Age differences in N2b amplitude were not statistically reliable, $F(2, 26) = 0.45$, $p = .64$, $\eta^2 = 0.03$, $1 - \beta = 0.12$. Although the N2b tended to be broader in duration in older than in young or middle-aged adults, these differences in amplitude were also not statistically reliable: For the 250–350 ms interval, $F(2, 26) = 1.98$, $p = .16$, $\eta^2 = 0.13$, $1 - \beta = 0.37$. There was an effect of age on the P3b latency, $F(2, 26) = 9.63$, $p < .001$, $\eta^2 = 0.43$, $1 - \beta = 0.97$. The P3b peak latency was delayed in older adults ($M = 492$ ms) compared with the P3b recorded in young ($M = 365$ ms) or middle-aged ($M = 400$ ms) adults ($p < .005$ in both cases). There was no significant difference in P3b latency between young and middle-aged adults ($p = .24$). The effect of age on peak or mean P3b amplitude at parietal sites was not significant, $F(2, 26) = 0.58$, $p = .57$, $\eta^2 = 0.04$, $1 - \beta = 0.14$. However, a visual inspection of the data revealed that middle-aged adults showed a more frontally distributed P3b than young or older adults (see Appendix A). An ANOVA with group and electrode (i.e., Fz, FCz, Cz, Pz, Oz) yielded a significant interaction, $F(8, 104) = 3.18$, $p < .05$. Pairwise comparisons confirmed that the P3b was more frontally oriented in middle-aged than in young or older adults, $F(4, 104) > 4.14$, $p < .05$ in both cases. There was no difference in P3b amplitude distribution between young and older adults.

Figure 5 shows the MMN response to the gap duration that elicited the asymptotic performance in all participants. First, we examined whether the deviant gap stimulus generated a significant MMN response in each group by comparing six consecutive 50-ms intervals starting at 100 ms poststimulus. Deviant stimuli generated a reliable MMN response only in young adults, $F_s(1, 9) = 9.93$ to 26.81 ($p < .05$ in all cases), despite during active listening the same gap durations produced equivalent response amplitudes and equivalent detectability in all age groups. No significant MMN response could be detected in middle-aged, $F_s(1, 9) = 0.25$ to 1.62 , $p > .23$, or older, $F_s(1, 9) = 0.36$ to 4.10 , $p > .07$, adults. We also compared the mean ERP amplitude between 100 and 200

¹ Removing the two older adults with asymptotes in the 70%–80% range did not change the outcome of the ANOVAs for the electrophysiological data.

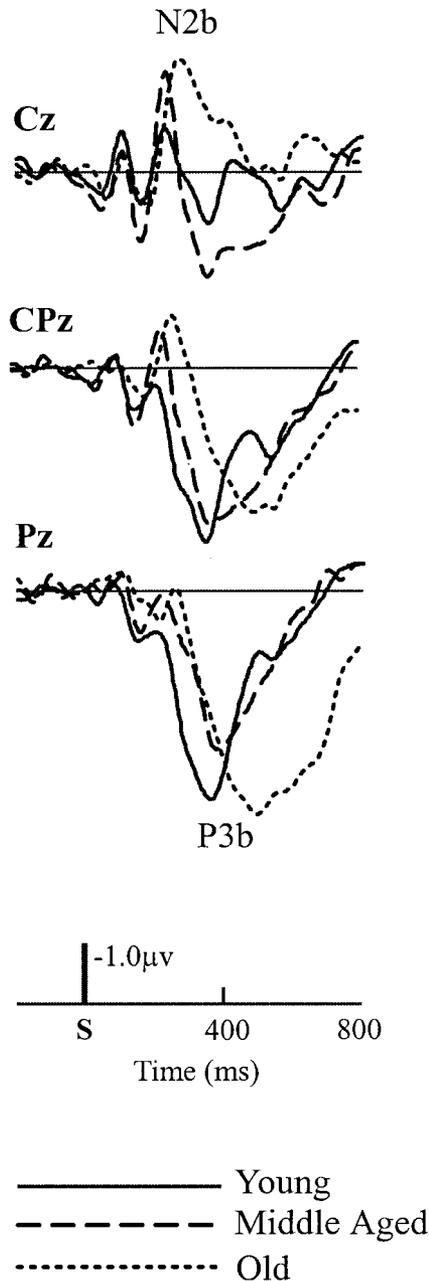


Figure 4. Near-threshold target stimuli. Group mean event-related brain potentials (ERPs) elicited the shortest gap duration that produced a hit rate within 2% of the asymptotic value reached by the psychometric function relating hit rate to gap duration. The ERPs are shown for the midline central (Cz), centralparietal (CPz), and midline parietal (Pz) scalp regions in young (solid line), middle-aged (dashed line), and older (dotted line) adults.

ms elicited by the standard and deviant stimuli in young, middle-aged, and older adults. The ANOVA yielded a significant Stimulus Type \times Group interaction, $F(2, 27) = 5.81, p < .01$, indicating greater MMN amplitude in young ($M = -0.52 \mu\text{V}$) than in middle-aged ($M = -0.11 \mu\text{V}$) and older ($M = -0.09 \mu\text{V}$) adults. This interaction was explored further by examining the effects of

age on ERPs elicited by the standard and deviant stimuli separately. The age effects on ERPs elicited by the deviant stimuli were significant, $F(2, 27) = 6.87, p = .004, \eta^2 = 0.34, 1 - \beta = 0.89$, whereas the age effects on ERPs elicited by standard stimuli were not, $F(2, 27) = 1.52, p = .24, \eta^2 = 0.10, 1 - \beta = 0.30$. This indicates that the age effect on MMN was driven primarily by age-related changes in processing deviant stimuli presented at near-threshold levels.

Discussion

In this study, we presented neurophysiological evidence of reduced automatic processing in middle-aged and older adults, coupled with an increased reliance on controlled processing to compensate for losses in early and automatic perceptual processes. When older, middle-aged, and younger adults were equated behaviorally, as evidenced by the hit rate for all gap sizes or by selecting the gap level at which each individual reached asymptotic performance, age differences in amplitude of the neurophysiological responses were virtually absent when attention was focused on the auditory stimuli. The similarities in amplitude of both the N2b and P3b across age groups suggest that controlled processing produced equal response strengths in all age groups. Power

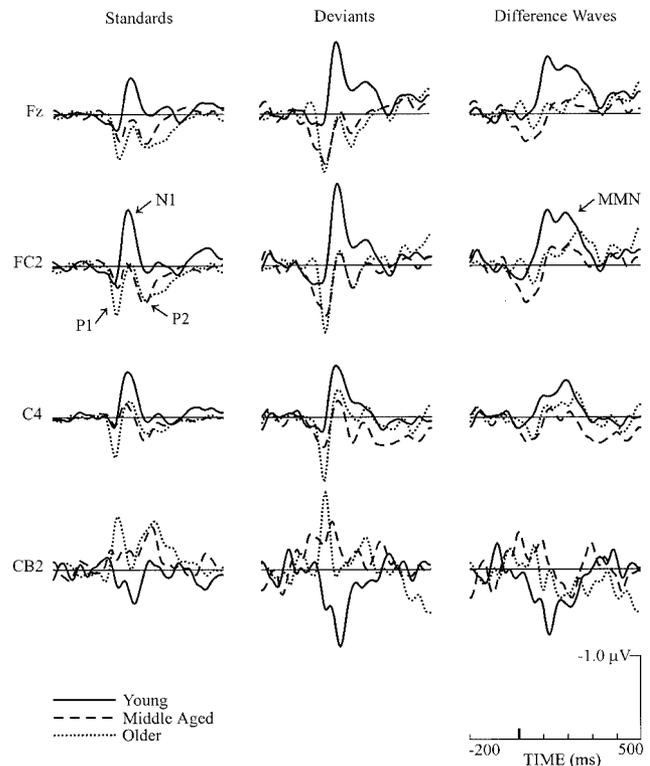


Figure 5. Event-related brain potentials (ERPs) at asymptotic detection. Group mean ERPs elicited by standard and deviant stimuli that produced the asymptotic performance in all participants. The ERPs are shown for the midline frontal (Fz), right frontocentral (FC2), right central (C4), and right cerebellar (CB2) scalp region in young (solid line), middle-aged (dashed line), and older (dotted line) adults. The corresponding difference waves between ERPs elicited by standard and deviant stimuli are illustrated under Difference Waves. MMN = mismatch negativity wave.

estimates indicate a small effect size that may be difficult to detect even with a large sample of participants. However, the N2b wave was broader in duration in older adults (although not statistically reliable) and the P3b was much more frontal in middle-aged adults (see Appendix A), suggesting that differential brain processing allows the middle-aged and older adults to do the task as well as young controls. In addition, the effects of age on the P3b latency are consistent with previous research (Ford et al., 1979; Iragui, Kutas, Mitchiner, & Hillyard, 1993; Pfefferbaum, Ford, Wenegrat, Roth, & Kopell, 1984; Verleger, Neukater, Kompf, & Vieregge, 1991) and may reflect differences in processing time needed to complete target evaluation and context updating. The present study supports and extends earlier reports of delayed P3b in older adults by showing that these age differences remain even for stimuli that are equally discriminable in young and older adults.

When the same stimuli were presented while the participants were engaged in a visual task so that attention was not focused on the auditory stimuli, MMN to the infrequent gap stimuli at near-threshold durations was found in young adults but not in middle-aged or older adults. Hence, when attentional focus is relaxed, and/or attentional resources are allocated to the visual domain, there is no neurophysiological evidence that a near-threshold deviant stimulus is recognized by the brains of middle-aged and older adults. Our results indicate that the automatic processing of sounds is affected by age (e.g., Alain & Woods, 1999; Bertoli, Smurzynski, & Probst, 2002) and that this effect can take place as early as in the 5th decade of life.

In this study, we found a reliable MMN response in middle-aged and older adults when suprathreshold deviant stimuli were included in the analysis, albeit smaller in amplitude and delayed in latency relative to the MMN response in young adults. This finding is consistent with many studies showing age effects on MMN amplitude and/or latency (Alain & Woods, 1999; Bertoli et al., 2002; Gaeta, Friedman, Ritter, & Cheng, 1998; Pekkonen, Jousmaki, Partanen, & Karhu, 1993; Verleger et al., 1991; Woods, 1992). However, the MMN could not be reliably detected in middle-aged and older adults when only the gap duration that elicited asymptotic detection performance was included in the analysis. The lack of MMN response to very small deviant stimuli has been reported previously (e.g., Bertoli et al., 2002; Gaeta et al., 1998), and like our near-threshold stimuli, it may have been more difficult to perceive when participants were engaged in a continuous visuomotor task.

Age-related decline in hearing sensitivity has been proposed to account for the speech reception problems commonly observed in older individuals. By making the stimuli equally discriminable to all participants, we minimized the possibility that any observed age effects result from differences in peripheral processing or from differences in task difficulty. Of particular importance is that stimuli equally discriminable to all participants generated differential age differences in the automatic and controlled processing of sounds. When attention is allocated to a visuomotor task, the processing of sounds is degraded in older adults to such an extent that stimulus differences are not as prominent as they are in younger adults and therefore not as easily registered. In contrast, when attention is focused on the sounds, older adults appear to be able to use top-down processing, mediated presumably by the prefrontal cortex, to clean up the signal so that it becomes detectable. Thus, the present results provide behavioral and neurophys-

iological evidence that older adults can compensate for age-related losses in automatic processing by mobilizing and focusing their controlled processing resources on the task at hand. The effects of age on perceptual processes differ from those observed for cognitive processes, such as memory, because controlled cognitive processes appear to be more vulnerable to the aging process (Jennings & Jacoby, 1993). Together, our findings, coupled with those on aging and memory, suggest that the effects of age on automatic and controlled processes differ across perceptual and cognitive domains.

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(Appendixes follow)

Appendix A

ERPs to Target Stimuli

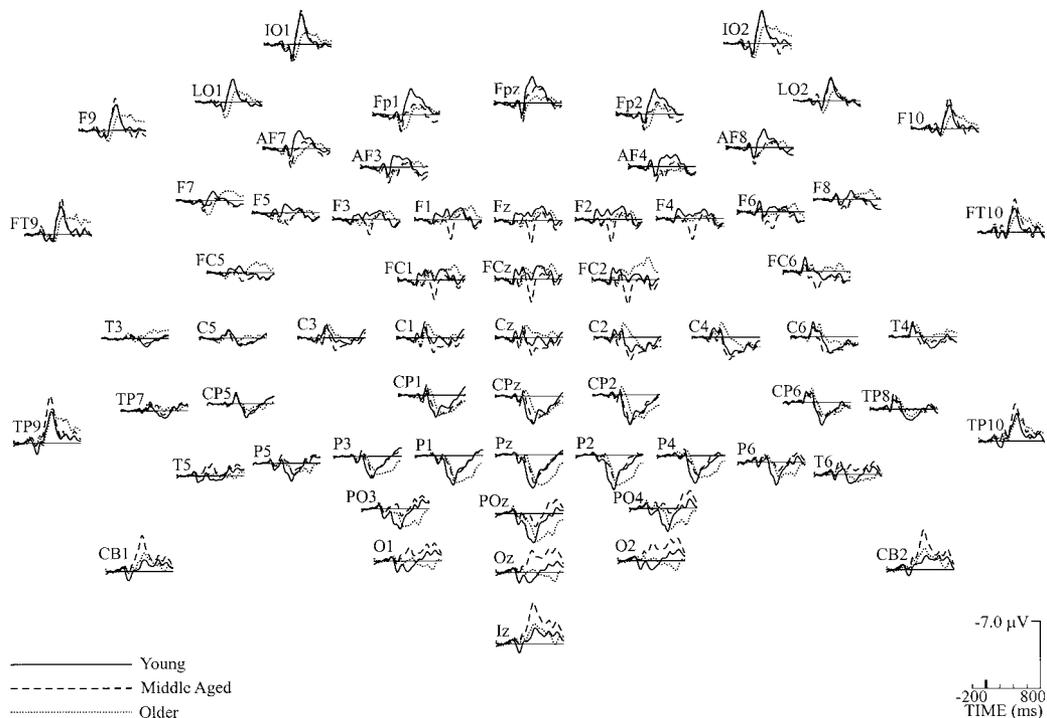


Figure A1. Group mean event-related brain potentials (ERPs) elicited by correctly identified auditory targets presented during the auditory discrimination tasks. The ERPs were averaged across gap levels. All participants generated clear N1, P2, N2b, and P3b waves that were maximal at frontal, central, frontocentral, and parietal scalp regions, respectively. Although N2b and P3b amplitude were comparable among the three age groups, the N2b wave was much broader in duration in older (dotted line) adults than in young (solid line) or middle-aged (dashed line) adults (see electrode C2 and C4). In addition, the P3b was much more frontal in middle-aged adults than in young and older adults. The odd number refers to electrode placed over the left hemisphere, whereas the even numbers refer to electrodes placed over the right hemisphere. F = frontal; C = central; P = parietal; O = occipital; I = inion; T = temporal; Fp = frontopolar; AF = anterior frontal; FC = frontocentral; CP = centroparietal; PO = parieto-occipital; TP = temporoparietal; IO = inferior orbital; LO = lateral orbital; CB = cerebellar.

Appendix B

Mismatch Negativity

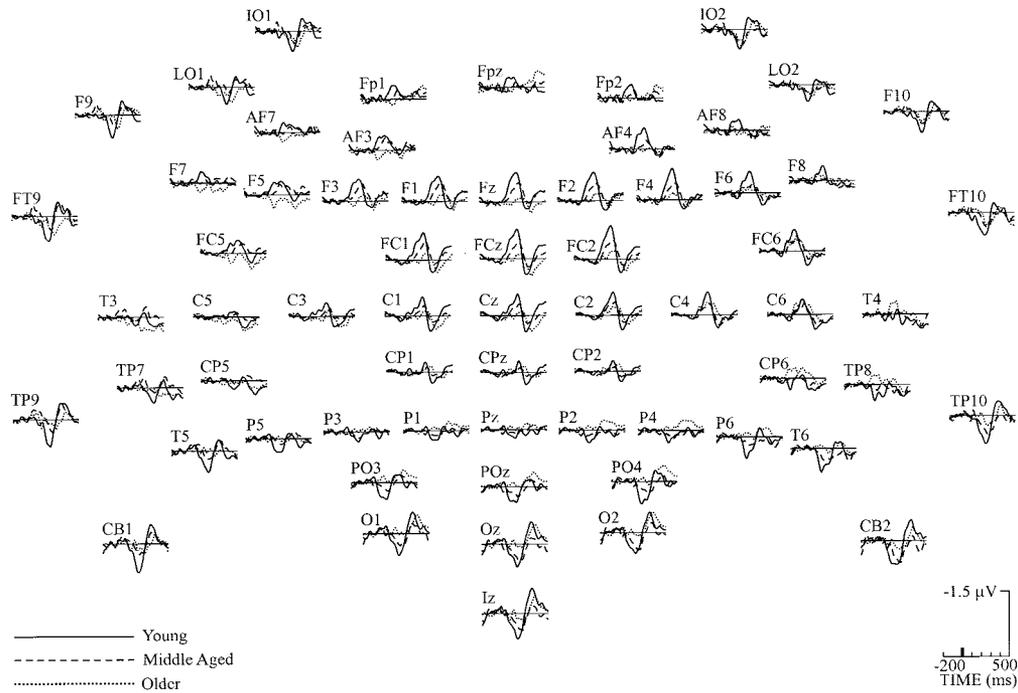


Figure B1. Group mean difference waves between event-related brain potentials (ERPs) elicited by the standard and the deviant stimuli. The group mismatch negativity (MMNs) waves were averaged across gap size. In all three groups, the MMN polarity was inverted between frontal (e.g., Fz) and temporoparietal sites (TP9/10), consistent with generators located in the planum temporale along the Sylvian fissure. F = frontal; C = central; P = parietal; O = occipital; I = inion; T = temporal; Fp = frontopolar; AF = anterior frontal; FC = frontocentral; CP = centroparietal; PO = parieto-occipital; TP = temporoparietal; IO = inferior orbital; LO = lateral orbital; CB = cerebellar. Solid line = young adults; dashed line = middle-aged adults; dotted line = older adults.

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