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Event-related potentials associated with auditory attention capture in younger and older adults

Cassandra Morrison [a,b], Farooq Kamal [a,b], Kenneth Campbell [a], Vanessa Taler [a,b,*]

[a] School of Psychology, University of Ottawa, Ottawa, Canada
[b] Bruyère Research Institute, Ottawa, Canada

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ABSTRACT

A deviant-related negativity (DRN), mismatch negativity (MMN), and P3a are electrophysiological measures thought to reflect processes involved in the involuntary switching of attention to a task-irrelevant stimulus. The purpose of this article was to determine whether healthy older adults involuntarily detect unattended auditory stimuli as efficiently as younger adults. To test this, 20 younger adults (aged 18–30 years) and 20 older adults (aged 65+ years) were presented with to-be-ignored auditory sequences consisting of frequently presented 80 dB SPL standards and rarely presented increments (+10 dB) and decrements (−20 dB). The MMN to the decrement did not differ between the 2 groups. On the other hand, the DRN to the increment was significantly reduced in the older adults. Importantly, the P3a was also significantly reduced in the older adults. This reduced P3a may reflect a deficit in the involuntary shift of attention from current cognitive demands to a potentially more critical event.

1. Introduction

For the purposes of survival, it is critical that acoustic change from a homogenous past be detected and an appropriate action undertaken. Certain acoustic changes, which are potentially highly relevant, can trigger a switch of attention from the task at hand to the processing of the potentially more relevant stimulus. This stimulus-driven control of attentional resources is called attention capture or passive (involuntary) attention (James, 1890). The purpose of the present study is to examine differences in attention capture between younger and older adults.

In the classic Näätänen model, attention capture in the auditory system results from activation of 1 of 2 systems (Näätänen, 1990), both of which are claimed to operate relatively automatically, in the absence of attention. The first system, the transient detection system, detects—as its name implies—brief transient changes to a rarely-occurring auditory stimulus, such as the onset or offset of the stimulus. Unique to the Näätänen model is the use of event-related potentials (ERPs) to quantify the extent of passive processing of the to-be-ignored auditory stimulus. Quantifying the extent of processing of a to-be-ignored stimulus is difficult. However, the output of the first system within the Näätänen model varies directly with the rate of stimulus presentation and the energy (intensity) of the stimulus. Thus, its output increases when stimuli are presented very slowly or when stimulus intensity is high. This output can be monitored by a negative ERP component, N1, which peaks about 100 ms after stimulus onset (Näätänen and Picton, 1987). The amplitude of the N1 will be larger to a high- than a low-intensity stimulus (Näätänen and Picton, 1987). An increase in intensity (a stimulus increment) would therefore result in an increase in the output of the transient detector system, whereas a decrease in intensity (a stimulus decrement) would result in a decrease in its output.

Changes in intensity are also detected by a second system, the change detector system, which detects change in any feature, including pitch, location, duration, and intensity. Acoustic change is often studied using the oddball paradigm. The participant is presented with a frequently occurring "standard" stimulus, and at rare (or "odd") times, a feature of the standard is changed to form a "deviant." The features of all incoming stimuli are compared against the features of the previously presented standard stimulus stored in sensory memory. When a deviant is presented, its features fail to match those stored in sensory memory and acoustic change is detected. The output of this system, as monitored by the mismatch negativity (MMN), varies with the extent of change. The MMN is a negative-going ERP occurring between 100 and 250 ms after stimulus onset (Näätänen, 1990). Importantly, the operations of both the transient and change detector systems occur

* Corresponding author at: School of Psychology, University of Ottawa, Vanier Hall, 136 Jean Jacques Lussier, Ottawa, Ontario K1N 6N5, Canada. Tel.: +1 613-562-6262 ext 1096; fax: +1 613-562-6099.
E-mail address: vtaler@uottawa.ca (V. Taler).

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independently of attention and consciousness. For example, Muller-Gass et al. (2006) demonstrated that the amplitude of the MMN occurring to auditory deviants was not affected by whether the participant attended to a very easy or a difficult visual task. For this reason, the MMN is usually recorded while participants are engaged in another task while ignoring the auditory stimuli.

When the output of either system reaches a certain critical level, an interrupt signal is sent to the central executive, controlling the allocation of attentional and cognitive resources. Attention to ongoing cognitive tasks is then halted and switched to the auditory channel, and the contents of sensory memory are probed for further possible perceptual processing. The switching of attention is thought to be reflected by another ERP component, the P3a, a frontocentral component peaking from 250 to 300 ms after stimulus onset (Escera et al., 1998). More recently, others have argued that the P3a should be viewed as part of a process leading to attention capture (see Parmentier, 2014; Wetzel et al., 2013 for reviews). The particularly large P3a is even elicited during rapid eye movement sleep (Macdonald et al., 2008).

Increases in intensity (an "increment") will activate both the transient and change detector systems. In the oddball paradigm, an increment deviant will elicit a larger N1 than the standard. It will also elicit the MMN because it signals a change from the previous presentations of the standard stimuli. The increased negativity that is observed for the increment is thus a composite N1+MMN. This composite negativity has been labeled a deviant-related negativity (DRN). By contrast, a decrease in intensity (a "decrement") will elicit a smaller N1 than the standard. However, because the decrement signals change from the past, it will elicit the MMN. The negativity that is observed after the presentation of the decrement is thus a "true" MMN because it activates only the change detector system.

These 2 systems have been examined in younger and older adults to determine whether these automatic processes change with age. Although a decline in the amplitude of the MMN has been associated with aging (Nowak et al., 2016; Rimmele et al., 2012; Tsolaki et al., 2015), others have failed to observe this decline (Fabiani et al., 2006; Gaeta et al., 2001). Similarly, a reduced P3a amplitude has been reported in older adults (Nowak et al., 2016; Tsolaki et al., 2015; Tusch et al., 2017), with some studies reporting an absent P3a in older adults compared with younger adults (Rimmele et al., 2012; Tsolaki et al., 2015). On the other hand, Berti et al. (2013) did not observe a P3a difference between younger and older adults.

In general, it would appear that either the MMN does not change in older adults or its amplitude is reduced. The amplitude of the P3a has generally been found to be reduced in older adults. Unfortunately, stimulus parameters vary widely across studies, making it difficult to generalize results between studies. Although almost any stimulus change will elicit the MMN, the P3a will only be elicited by stimulus change that is determined to be potentially highly relevant (Escera et al., 1998). It is possible that the threshold for interrupting the central executive is set to be particularly high in older adults. A stimulus change that is known to elicit a particularly large P3a is an abrupt increase in intensity (Shestopalova et al., 2018). Rinne et al. (2006) noted that the amplitude of the P3a increased with increasing stimulus intensity, whereas a gradual decrease in intensity did not elicit a P3a even for the largest decrement (−9 dB). A similar result was observed by Shestopalova et al. (2018) employing a ±5 dB change in intensity. Muller-Gass et al. (2007) also noted that an increment (+10 dB) elicited a large P3a. On the other hand, a 20 dB decrement also elicited a P3a, but its amplitude was quite small (Muller-Gass et al., 2007). An increment will even elicit a P3a during sleep, whereas a decrement will not (Macdonald et al., 2008). An increase in intensity might be particularly effective in eliciting a P3a because of its effects on both the transient and the change detector systems, whereas the decrement only results in increased activation of the change detector system.

Although previous studies have generally indicated that the P3a is reduced in older adults, it is possible that the deviant stimuli used in previous studies were not deemed by older adults to be sufficiently relevant to warrant a switch of attention from current task demands. Changes in the intensity or spectral content of the auditory stimulus will affect decisions about the apparent distance to the source (Shestopalova et al., 2018). Detecting increases in intensity is thus particularly crucial for survival and may serve as an auditory warning cue. This is because an increase in stimulus intensity is experienced as approaching the observer and is thus potentially threatening. Increases in intensity elicit a fear response in animals and thus activate the amygdala (Bach et al., 2008). A variety of psychophysical measures, including loudness change estimates, discriminability of motion speed, and judgments of duration, are affected by whether the sound is increasing or decreasing in intensity (Baumgartner et al., 2017; Neuhoff, 1998, 2016; Stecker and Hafter, 2000), reflecting an attentional bias toward rising compared to falling sounds (Ghazanfar et al., 2002). The present study thus examines the effects of increasing the intensity of a stimulus. A decrease in intensity is experienced as retreating and is thus not threatening (Bach et al., 2008; Maier and Ghazanfar, 2007). The present study therefore also examines the effects of an equivalent decrease in intensity on the P3a in younger and older adults.

2. Methods

2.1. Participants

A total of 45 participants were initially recruited for the study. Five were excluded from analysis because of "noisy" electroencephalography (EEG) data (see Section 2.3). A total of 40 participants' data were analyzed: 20 younger (10 females; mean age 23.4 ± 3.1) and 20 healthy older adults (12 females; mean age 72.5 ± 4.9). All participants were right-handed, with no history of neurological or psychiatric conditions, were not taking medications that influenced the central nervous system, and had not suffered any major head injuries. All participants reported normal hearing. We completed pure tone audiometry with older adults. Hearing thresholds were below 40 dB at 500, 1000, and 2000 Hz, in both ears. The hearing test was a simple response task where the participants were to identify when they perceived a tone. In addition, the older participants completed the Montreal Cognitive Assessment to screen for cognitive decline (Nasreddine et al., 2005). All participants scored between 25 and 30 on the Montreal Cognitive Assessment ($M = 27.45$, $SD = 1.50$). This study was approved by the University of Ottawa and Bruyère Research Institute ethics boards. Participants provided informed written consent before starting the study, and an honorarium was given as compensation for participation.

2.2. Stimuli and procedure

Participants were seated in a sound-attenuated room and were instructed to watch a silent subtitled video while ignoring concurrently presented auditory stimuli. These auditory oddball stimuli were presented binaurally through headphones. The frequently occurring standard was an 80 dB SPL 1000 Hz pure tone with a duration of 55 ms (5 ms rise/fall time). The standard occurred on 85% of trials. Two types of deviants were also presented, each occurring on 7.5% of trials. The "increment" and "decrement" deviants had intensities of 90 dB SPL and 60 dB SPL, respectively. Order of presentation of the standards and deviants

was pseudorandomized. The auditory sequence started with a minimum of 4 consecutive standards, and deviants were separated by at least 3 standards. The stimulus-onset asynchrony varied from 354 to 454 ms. The task lasted approximately 9 minutes and was completed twice to ensure an optimal signal-to-noise ratio. A brief rest period was provided between blocks.

2.3. EEG data recording and analysis

EEG was recorded from 32 active silver-silver chloride electrodes attached to an electrode cap (Brain Products, GmbH, Munich, Germany) placed according to the international 10–20 system. A reference electrode was placed on the nose, with an electrode placed on the infraorbital ridge of the left eye to record vertical eye movements. The EEG was sampled at rate of 500 Hz. A 20-Hz low-pass digital filter was later applied to the data. Independent component analysis was used to identify eye movement and blink artifacts that were independent of EEG activity. The artifacts were partialled out of the EEG. The EEG was reconstructed into 700 ms epochs starting 100 ms before stimulus onset and then baseline corrected. Trials containing EEG activity exceeding ±100 μV were rejected from the averaging. Five participants (3 younger adults and 2 older adults) were removed from the analysis because more than 25% of trials contained artifact.

2.4. ERP analysis

The DRN and P3a were identified in a difference wave, computed by subtracting the standard from the deviant waveforms. The subtraction routine removes processing that is common to both the standard and deviant stimuli, leaving processing that is unique to the deviant.

The P3a was particularly small after the presentation of the decrement. Moreover, in older adults, a distinct P3a peak was not visible after the increment or decrement. A mean amplitude method is often used to quantify ERP components when distinct peaks are not apparent (Luck, 2014; Picton et al., 2000). The DRN and P3a were identified in the grand average (average of all participants' averages) of the difference waves. The DRN and P3a were measured relative to the zero-voltage prestimulus baseline as the mean of all data points within ±25 ms of this peak. The mean amplitude was measured from 75 to 125 ms for the N1, 150 to 200 ms for the decrement MMN, and 95 to 145 ms for the increment DRN. The P3a after the increment was measured from 200 to 250 ms in younger adults and 220 to 270 ms in older adults, whereas after the decrement, it was measured from 235 to 285 ms in younger adults and from 310 to 360 ms in older adults. A late positivity occurring at about 300 to 350 ms, maximal over parietocentral areas of the scalp, was also apparent after the increment in younger adults. It was absent in older adults and was not observed after the decrement in either group. Measuring an "absent" waveform presents methodological problems. For the increment in younger adults, this late positivity occurred about 100 ms after the P3a. The late positivity was therefore quantified 100 ms after the P3a. Again, the mean amplitude occurring within ±25 ms of this time period was computed. This peak was thus measured at the following times: for the increment at 300 to 350 ms in younger adults and 320 to 370 ms in older adults and for the decrement from 335 to 385 ms in younger adults and 410 to 460 ms in older adults.

Electrode sites were grouped into regions of interest (ROIs). Mean amplitudes were computed separately for frontal (Fz, F3, F4) and central (C3, Cz, C4) ROIs. A 3-way analysis of variance with a single between-subjects factor, Group (Younger, Older), and 2 within-subject factors, Deviant (Decrement, Increment) and Electrode (Left, Midline, Right), was computed on the DRN and P3a. Separate analyses of variance were run for each ROI (central and frontal). The P3b was computed separately for parietal (P3, Pz, P4) and central (C3, Cz, C4) ROIs. All data were analyzed with the Statistical Package for the Social Sciences (v.22) (SPSS).

3. Results

3.1. Standard N1

Because the DRN and P3a were measured in a difference wave, an assumption was made that the processing of the standards is constant across all conditions. This assumption was tested by comparing the N1 elicited at about 100 ms by the standard stimulus for both groups (Fig. 1). The N1 at frontal and central sites was quite small (less than 1 μV) because of the rapid rate of stimulus presentation. Its amplitude did not significantly differ at frontal sites between younger (−0.17 μV) and older adults (0.060 μV), $F(1,38) = 0.70$, $p = 0.41$, $n_p^2 = 0.02$, nor between the groups at central sites (younger adults: −0.40 μV vs. older adults: −0.35 μV), $F(1,38) = 0.04$, $p = 0.85$, $n_p^2 = 0.04$.

3.2. Mismatch negativity/deviant-related negativity

The deviant-standard difference waves are illustrated in Figs. 2 and 3 for the increment and decrement deviants, respectively. As is apparent, both the increment and decrement elicited a negativity (the DRN/MMN) at about 100–150 ms after both deviants that was maximum over frontocentral areas and inverted in polarity at the mastoids.

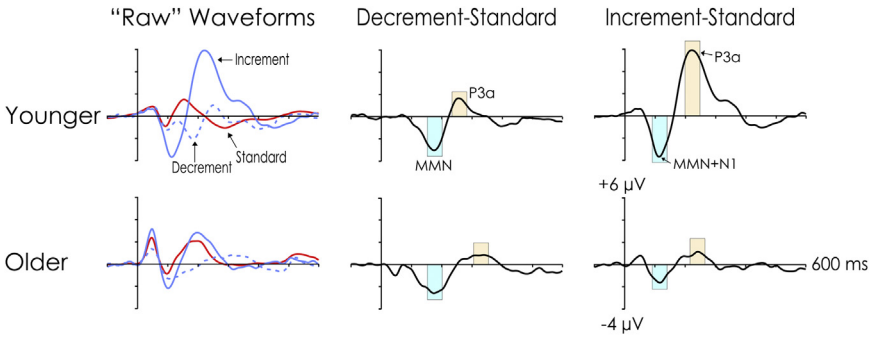

Fig. 1. Raw standard, decrement, and increment ERPs (left column) in younger and older adults. Data are from the Cz electrode site. Positivity in this and all other figures is indicated by an upward deflection. A small negative deflection occurring at about 100 ms is apparent after the presentation of the standard (N1). Its amplitude was not significantly different between younger and older adults. The decrement-standard and increment-standard are illustrated in the center and right columns, respectively. The MMN and P3a are better observed in the difference wave. Abbreviations: ERP, event-related potential; MMN, mismatch negativity.

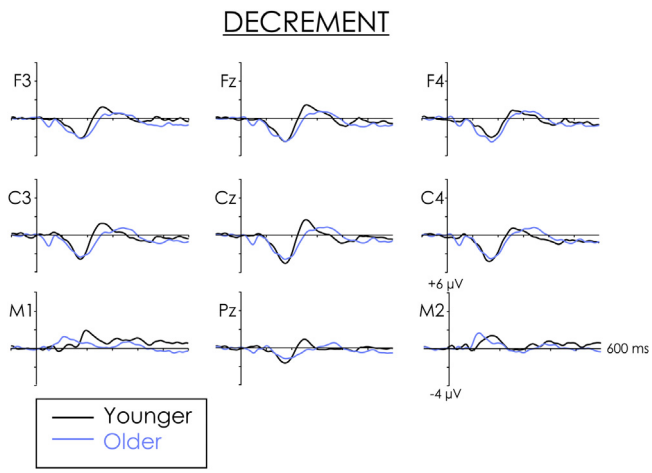

Fig. 2. Decrement-standard difference wave across multiple electrode sites. A frontocentral maximum mismatch negativity that inverted in amplitude at the mastoids is apparent around 100–150 ms. Its amplitude did not differ between the 2 groups. This was followed by a small P3a occurring around 200–300 ms. Its amplitude also did not differ between the 2 groups.

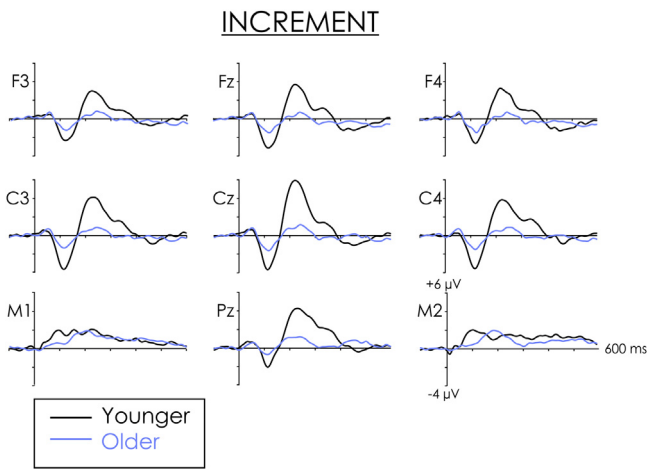

Fig. 3. Increment-standard difference wave across multiple electrode sites. A large composite N1+MMN (deviant-related negativity) was elicited by the increment. Its amplitude was significantly larger in younger than older adults. This was followed by a large P3a. Its amplitude was significantly larger in younger than older adults. A later positivity occurring around 300–350 ms was also apparent for the younger adults but was absent for the older adults.

The frontal region analyses for the MMN and DRN revealed a significant interaction between Deviant and Group, $F(1, 38) = 7.41$, $p = 0.01$, $n_p^2 = 0.16$. The DRN after the increment was significantly larger for younger adults (−2.43 μV) than older adults (−1.19 μV, $p = 0.009$). On the other hand, there were no significant group differences for the MMN after the decrement. There were no significant main effects or interactions involving hemisphere differences.

At central regions, a similar Group × Deviant interaction was observed, $F(1, 38) = 7.77$, $p = 0.008$, $n_p^2 = 0.17$. The DRN after the increment was significantly larger in younger adults (−3.09 μV) than older adults (−1.24 μV, $p = 0.001$). There were no differences in the MMN after the decrement between younger and older adults. Again, there were no significant main effects or interactions involving hemisphere.

3.3. P3a

A positivity, occurring between 200 and 300 ms, and maximum over central regions, was elicited by the 2 deviants. The amplitude of this P3a varied between increment and decrement deviants and between groups. This can be seen in Figs. 2 and 3.

The frontal region analyses for the P3a again revealed a significant interaction between Deviant and Group, $F(1, 38) = 8.29$, $p = 0.007$, $n_p^2 = 0.18$. The P3a after the increment was much larger in younger adults (3.06 μV) than older adults (0.54 μV, $p < 0.001$). A small P3a was elicited by the decrement. Its amplitude did not significantly differ between younger (1.00 μV) and older adults (0.61 μV, $p = 0.36$). For younger adults, the P3a was significantly larger after the increment than the decrement ($p < 0.001$). On the other hand, differences in P3a amplitude between the increment and decrement were not significant for older adults ($p = 0.90$). There were no significant main effects or interactions involving hemisphere.

Similar results were found in the central regions. A significant Deviant × Group interaction was apparent, $F(1, 38) = 15.06$, $p < 0.001$, $n_p^2 = 0.28$. After the increment, the amplitude of the P3a was significantly larger for younger adults (4.41 μV) than older adults (0.83 μV, $p < 0.001$). In addition, the younger adults showed larger amplitudes after the increment than the decrement deviant (4.41 μV vs. 1.05 μV, $p < 0.001$), whereas older adults' P3a amplitude did not differ between the increment and decrement. Again, there were no significant main effects or interactions involving hemisphere.

3.4. Late positivity (P3b)

A later positivity, occurring between 300 and 350 ms, and maximum over parietocentral areas, was elicited only in younger adults after the increment deviant. This P3b can observed in Fig. 3.

At parietal sites, a Group × Deviant interaction was apparent, $F(1, 38) = 5.6$, $p = 0.023$, $n_p^2 = 0.13$. After the increment, the amplitude of the P3b was significantly larger in younger adults (2.06 μV) than older adults (0.18 μV, $p < 0.001$). In addition, the younger adults showed larger amplitudes after the increment than the decrement deviant (2.06 μV vs. −0.35 μV, $p = 0.006$), whereas older adults' P3b amplitude did not differ between the increment and decrement. There were no significant main effects or interactions involving hemisphere.

At central regions, the Group × Deviant interaction failed to attain significance, $F(1, 38) = 3.59$, $p = 0.066$, $n_p^2 = 0.07$. This trend revealed that younger adults had larger P3b amplitudes for the increment (1.54 μV) than the decrement deviant (−0.22 μV, $p = 0.002$), whereas its amplitude did not differ for older adults. The analysis also showed that younger adults had larger P3b amplitudes for the increment than older adults (1.54 μV vs. −0.18 μV, $p = 0.003$), but the groups did not differ for the decrement. Again, there were no significant main effects or interactions involving hemisphere.

4. Discussion

The present study used an oddball paradigm in which deviants were created by increasing or decreasing the intensity of the standard. As expected, both the decrement and the increment deviants elicited a robust negativity, occurring from 100 to 200 ms. Findings from previous studies examining the MMN in younger and older adults are inconsistent, and this was also the case in this study. The MMN to the decrement did not vary between younger and older adults, replicating the findings of Fabiani et al. (2006) and

Gaeta et al. (2001). Interestingly, these studies did not report P3a differences between the groups. In the present study, the decrement elicited a small P3a, but its amplitude also did not differ between younger and older adults. The DRN to the increment was significantly larger in younger than older adults. The P3a was also significantly larger in younger than older adults. Others have also reported a reduced MMN and P3a in older adults (Alain and Woods, 1999; Nowak et al., 2016; Rimmele et al., 2012).

It is possible that the DRN and P3a differences might reflect differences in sensory processing between younger and older adults. However, if this were the case, the processing of the standard stimulus should also have differed between the 2 groups, which we did not observe. The amplitude of the standard N1, much influenced by the perceived intensity of the stimulus, did not differ between younger and older adults. Similarly, the amplitude of the MMN to the lower-intensity decrement did not differ between groups.

Although large DRN and P3a group differences were observed after the increment, group differences were not found for either the MMN or the P3a after the decrement deviant. The ERP group differences as a function of the type of deviant might be a result of differential activation of the change and transient detector systems. As mentioned earlier, an increment will be detected by both the transient and change detector systems, whereas the decrement will be detected only by the change detector systems. It is thus possible that the DRN and P3a group variance might be a result of differential activation of the transient detector system, suggesting that the ability to detect rare transient increases in intensity could be reduced in older adults.

The P3a, which is involved with the "capture of attention", is thought to reflect higher-level processing such as determining whether a stimulus is sufficiently salient to warrant a switch of attention from current cognitive demands (Horváth et al., 2008; Wetzel et al., 2013). The P3a appears to reflect processes that will eventually lead to this switching of attention. The increment elicited a large P3a in younger adults but only a small P3a in older adults. This finding is consistent with previous research that also found an attenuation of the P3a in older adults (Nowak et al., 2016; Rimmele et al., 2012; Tsolaki et al., 2015; Tusch et al., 2017). The capture of attention appears to be largely a stimulus-driven, pre-attentive, automatic process (Muller-Gass et al., 2007). These findings support the hypothesis of diminished attentional orientation in older adults (Fjell and Walhovd, 2004; Rimmele et al., 2012).

A late positivity was also observed after the presentation of the increment, but only in younger adults. This late positivity occurred at about 330 ms and was maximal over parietocentral areas of the scalp. The morphology of this late positivity is very similar to the much-reported P3b (or P300). The P3b is typically only elicited by rarely-occurring stimuli that are actively detected. In the present study, participants were instructed to ignore the auditory channel. However, some studies have indicated that very rare but very loud auditory stimuli will passively elicit an obligatory P3b after the P3a (Cote et al., 2001; Polich, 1989; Putnam and Roth, 1990; Roth et al., 1982, 1984). The P3a probably reflects a pre-attentive process resulting in the switching of attention to the auditory channel, which may lead to additional processing and evaluation of the intruding stimulus event (Escera et al., 1998). It appears that a P3b will only be elicited when the observer becomes conscious of the deviant stimulus, whether this consciousness is internally or externally controlled. The failure to observe a P3b in the older adults after the increment could be because they did not automatically switch attention to the stimulus or could be related to the small amplitude of the P3a, suggesting its relevance was evaluated as low.

The advantage to the attention-switching process is that it does provide a means by which the individual is able to detect sensory input that is critical for survival, regardless of current processing priorities. Most potentially relevant input turns out to be incidental and is not critical for survival. However, the attention switch does come at a cost. Because processing resources have been switched to a task-irrelevant input, performance on the current task may deteriorate, a process labeled as distraction. In this context, the reduced P3a in older adults might also be interpreted as an enhanced ability to ignore task-irrelevant input and maintain attention on the task at hand. As such, the failure to switch attention to the processing of unattended input may serve a protective function, preventing distraction by irrelevant change, especially when older adults may have reduced cognitive resources (see Salthouse et al., 2003; Salthouse, 2009 for a review).

Reductions in P3a and P3b amplitudes suggest that this attention-switching system may be less functional in older adults. There is good evidence that the P3a is generated in widespread areas of the cortex, including the frontal lobes (Knight, 1984; Wronka et al., 2012). For example, those with frontal lobe lesions have an attenuated P3a (Knight, 1984). Frontal regions are especially vulnerable to age-related declines, resulting in decreased functioning and gray matter (for a review, see Fjell et al., 2014; Raz et al., 2005). More specifically, the present study suggests that one of the crucial executive roles of the frontal lobes, the ability to switch attention from current cognitive tasks to the processing of what might be a highly relevant stimulus input, may be compromised in older age.

Disclosure

None of the authors have any conflicts of interest to disclose.

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The data in the manuscript has not been previously published, was not submitted elsewhere, and will not be submitted elsewhere while under consideration at Neurobiology of Aging.

This study was approved by both the University of Ottawa and the Bruyère Research Institute ethics boards.

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