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Effect of language experience on selective auditory attention: An event-related potential study

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ABSTRACT

Dual language experience has typically been shown to improve various executive control functions. We investigated with event-related brain potentials (ERPs) recorded from early (natively) bilingual speakers and control participants whether it also affects auditory selective attention. We delivered to our participants two tone streams, one to the left and one to the right ear. Both streams consisted of standard tones and two types of infrequent deviant tones which had either an enhanced duration or intensity. The participants were instructed to attend either to the right or left stream and to detect longer-duration deviants in the attended stream. The results showed that the early bilinguals did not outperform the controls in target detection accuracy or speed. However, the late portion of the attention-related ERP modulation (the negative difference, Nd) was larger over the left hemisphere in the early bilinguals than in the controls, suggesting that the maintenance of selective attention or further processing of selectively attended sounds is enhanced in the bilinguals. Moreover, the late reorienting negativity (RON) in response to intensity-deviant tones was larger in the bilinguals, suggesting more efficient disengagement of attention from distracting auditory events. Hence, our results demonstrate that brain responses associated with certain aspects of auditory attention are enhanced in the bilingual adults, indicating that early dual language exposure modulates the neuronal responsiveness of auditory modality.

1. Introduction

There is extensive evidence that representations of two native languages in the brains of bilinguals are active simultaneously even when only one of the languages is currently in use (e.g., Bijeljac-Babic et al., 1997; Marian and Spivey, 2003a, 2003b; Marian et al., 2003; Blumenfeld and Marian, 2007; Thierry and Wu, 2007; Van Heuven et al., 2008; Martin et al., 2009). This cross-linguistic competition has been found both at the phonological (e.g., Marian and Spivey, 2003a, 2003b; Marian et al., 2003; Blumenfeld and Marian, 2007) and semantic (Thierry and Wu, 2007; Martin et al., 2009) level, and it was suggested to be automatic and unconscious (Thierry and Wu, 2007; Martin et al., 2009).

Co-activation of two languages in bilinguals has also been proposed to lead to enhanced domain-general executive control skills that contribute also to performance in visual tasks, such as the Simon and the Stroop tasks (e.g., Green, 1998; Bialystok, 2009, 2011; Hilchey and Klein, 2011; Bialystok et al., 2004; Bialystok et al., 2008; Costa et al., 2008). The Simon task measures whether irrelevant spatial information (location of a colour cue indicating the direction of motor response) affects participants' responses to task-relevant non-spatial (colour cue) information. On congruent trials, the response key for colour is typically on the same side as the stimulus, whereas on incongruent trials, the correct response key is on the opposite side. Bilinguals were shown to be faster than monolinguals both on congruent and incongruent trials and exhibit a smaller Simon effect (increased time needed to respond to the incongruent items) than monolinguals (Bialystok et al., 2004). In the Stroop task, bilinguals had a lower error rate than monolinguals when naming the ink colour that conflicted with the word meaning (e.g., the word “blue” written in red; Bialystok et al., 2008). In the

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attention network task (ANT), bilinguals suffered less interference from incongruent stimulation, switching cost was lower in bilinguals than in monolinguals, and bilinguals took more advantage of the alerting cues (Costa et al., 2008). All this evidence proposes that dual language use contributes to domain-general enhancement in executive functions, such as inhibitory control, switching, and conflict monitoring. Bilingual advantage in executive functions has been, however, recently questioned, and dual language exposure has been suggested to have beneficial effects only in specific, but undetermined, circumstances (e.g., Duñabeitia et al., 2014; Paap et al., 2014, 2015).

Furthermore, most of the evidence on bilingual advantage in executive functions has been obtained using visual tasks, whereas less is known on this advantage in the auditory domain. In one of the few studies, Krizman et al. (2012) compared the performance of high-school aged bilinguals to that of monolinguals in a sustained selective attention task during which the participants were asked to respond when the number 1 (not 2) was heard or seen. To study attention in an ecologically valid setting, the participants were tested in a high-school environment. The results showed that bilinguals were significantly more accurate than monolinguals in their task performances both in visual and auditory modalities. Furthermore, Krizman and colleagues showed that auditory brainstem potentials to fundamental frequencies of syllables were more robust in early bilingual than monolingual participants and that this brainstem activity correlated positively with the level of performance in an attention task (Krizman et al., 2012, 2014, 2015). In another study, it was shown that bilinguals outperformed monolinguals in the Simon task, but not in a version of the Stroop task that involved a linguistic-auditory conflict between a word's meaning (low or high) and pitch of voice uttering the word, suggesting that bilingual advantage does not extend to the auditory domain (Bialystok and DePape, 2009).

To investigate whether the age of acquisition (AoA) of the second language modulates processing of sound changes (duration, frequency, silent gap, and frequency modulation), Ortiz-Mantilla et al. (2010) compared the event-related potentials (ERPs) of mono- and (early and late) bilinguals. The results showed that the mismatch negativity (MMN) and P3a ERP responses to deviant tones were enhanced in bilinguals who had started to use their second language later (AoA > 10 years) in life compared with early (AoA < 10 years) bilinguals and monolinguals. These findings suggest that acoustic change processing might be enhanced in late bilinguals since learning a language later in life might have increased the demands for perceptual attention to auditory input and consequently these mechanisms are less automatized in late than in early bilinguals.

Altogether, previous research has evidenced beneficial effects of bilingualism on inhibitory, switching, and monitoring control functions but these effects might be restricted to certain circumstances (e.g., modality, task, AoA). In the present study, our aim was to further investigate the influence of dual language exposure on selective attention in the auditory modality using the ERP technique. The ERP technique provides an excellent tool to investigate online different attentive processes, by means of distinct ERP parameters, associated with the performance of a selective attention task. In particular, we aimed to investigate whether ERPs associated with involuntary and voluntary attention are differentially modulated by bilingual experience. All participants were presented with two streams of tones, one to each ear, and were instructed to direct their attention either to the right or to the left stream and to detect longer-duration deviant tones (while not responding to intensity deviant tones) in the attended ear. Occasionally, the attended ear was switched as indicated by an arrow on a screen viewed by the participant. Auditory selective attention is associated with a negative difference (Nd) between ERPs to attended and unattended sounds over frontal and central scalp locations (e.g., Hansen and Hillyard, 1980; Näätänen et al., 1992; Alho et al., 1994). This negative displacement consists of two parts: the early Nd (Nde), typically peaking at 100–200 ms from sound onset, is largest over the frontal-central scalp positions, whereas the late Nd (Ndl), peaking at latencies longer than 300 ms, has usually a more frontal scalp maximum. The Nde reflects selection of attended sounds in the auditory cortex (e.g., Näätänen, 1990) on the basis of their common physical features, such as location or pitch, or both, not shared by the other sounds (e.g., Alho et al., 1989). The Ndl, which has been localized to the auditory cortex (Hari et al., 1989; Degerman et al., 2008), in turn, has been suggested to reflect further processing of the attended sounds or maintenance of a selective tuning of the auditory cortex with sensory support from each attended sound (Näätänen, 1990). Attention-related modulation of ERPs in response to standard tones has been shown to develop gradually but rapidly: the modulation is stronger after only a few stimulus presentations following focusing of attention to particular sounds, suggesting that it takes some time to focus attention effectively to a new auditory stream (e.g., Donald and Young, 1982; Hansen and Hillyard, 1988).

Additionally, we measured the ERPs in response to intensity-deviant tones both in attended and unattended locations. Several ERP components, such as MMN, P3a, and late negativity, have been associated with change detection in the auditory environment. The MMN component, appearing usually around 100 ms to 250 ms after deviant tone onset, was shown to reflect pre-attentive change detection processes and it is elicited even when attention is directed to another task (Näätänen et al., 1978; Näätänen and Alho, 1997; Näätänen and Winkler, 1999). The mechanisms underlying the MMN can, however, redirect attention to subsequent deviants in the auditory stream and a difficult discrimination task on attended location increases the MMN amplitudes (Alho et al., 1992). The P3a, occurring around 300 ms after deviant tone onset, has been associated with involuntary orienting of attention towards a novel or a deviant stimulus (Escera et al., 2000). Subsequent to the P3a, a late negativity, also named as a reorienting negativity (RON) and occurring around 400 to 600 ms after distractive deviant tone onset, has been suggested to reflect re-allocation of attention back to the task after a momentary distraction and compensation for the distraction when active reorienting is necessary for accomplishing the task (e.g., Schröger and Wolff, 1998; Berti and Schröger, 2001; Escera et al., 2001; Escera and Corral, 2007). In addition, we measured the P3b component, associated with task-relevant rare events in a stimulus sequence (e.g., Friedman et al., 2001; Duncan et al., 2009) in response to longer-duration deviant tones in the attended ear. Altogether, two ERP components (MMN, and P3a) are associated with mechanisms of involuntary detection of, and orienting of attention to changes in the auditory environment while the negative difference (Nd), P3b, and the RON reflect processes that are associated with allocation of voluntary attention, target detection, and active reorienting, respectively.

We hypothesized that if the early bilinguals are capable of maintaining their attention more efficiently and selectively to the attended stream due to their dual language experience, they would show a stronger modulation of Nd than monolingual controls. Accordingly, if the early bilinguals are better in re-allocating their attention after distractive stimulation, they are expected to exhibit more pronounced RON than the control participants. Additionally, we hypothesized that cognitive processes associated with voluntary rather than involuntary attention are enhanced in the early bilinguals, and consequently, MMN, and P3a, reflecting these involuntary processes, were expected to be more similar in both groups.

2. Material and methods

2.1. Participants

The final participant sample included seventeen early (natively) bilingual Finnish-Swedish speakers (12 females, age range 20–28 years, mean 24 years, SD = 2.7) and seventeen control participants with Finnish as their native language (12 females, age range 20–41 years, mean 28 years, SD = 6.6). Even though the difference in age between the language groups was significant ($F(1, 33) = 6.94$, $p = 0.013$), age did not correlate with ERP amplitude measures (all correlations $p > 0.05$). All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of neurological, psychiatric, or hearing disorders. The participants gave a written informed consent. Eight other participants (four controls and four bilinguals) were tested but their data were rejected because they were not able to detect the target sounds, and thus, perform the task (three participants in both language groups) or their EEG recording was too noisy (one participant in each group).

All early bilingual participants had started learning and using both of their native languages at home before the age of three years. However, both the early bilingual and control participants had learned other non-native languages at school; both groups had started learning English at the age of 9 years and the control participants had started learning Swedish after the age of 13 years. The participants estimated their daily language use as follows: The control participants estimated to use Finnish 91.5%, English 7.3%, and Swedish 0.7% of their time; the early bilingual participants estimated to use both Finnish and Swedish quite equally (47.5% and 46.3%), respectively and English 5.2% of their time. The controls estimated their native Finnish as excellent, second language, English, as good or excellent, and their third language, Swedish as fair. The early bilinguals estimated both of their native languages as excellent and their third language, English, as good or excellent. Five controls and five early bilinguals had formal music training (e.g., playing an instrument or singing in a choir) > 10 years and five controls and seven early bilinguals < 10 years, while seven controls and five early bilinguals did not have any musical training apart from that received in primary school. All participants were studying for, or had obtained a Bachelor's or a Master's degree. Ethical Review Board of the Institute of Behavioural Sciences, University of Helsinki approved the experimental protocol.

2.2. Stimuli

Auditory stimuli were harmonic tones constructed by Adobe Audition program (version 3.0, San Jose, CA, USA). The rise and fall times of the tones were 10 ms. The tones were delivered to the right and left ear in oddball sequences. The fundamental frequencies of tones delivered to the opposite ears were different (261 Hz and 349 Hz) to ease discrimination between the two streams. The frequencies were counterbalanced across the ears during the experiment. In each ear, standard tones (probability, $p = 0.8$) had the duration of 75 ms. Two different deviant tones were used in each ear. One of them ($p = 0.1$) had the same duration as the standard tones (75 ms) but its intensity was 15 dB higher than that of the standard tones. The participants were asked not to respond to these deviants. The other deviant tones ($p = 0.1$) had the same loudness as the standard tones but their duration was 110 ms. The participants were asked to respond to these deviants in the attended stream by pressing a response button with their right index finger (Fig. 1). Responses were defined as hits if they occurred within 175–1200 ms from target onset in the attended ear. Responses were defined as false alarms if they occurred within 175–1200 ms from target onset in the unattended ear. The proportions of hits and false alarms were calculated by dividing them by the total number of targets in attended and unattended ear, respectively. The stimulus onset asynchronies (SOAs) varied randomly (20-ms steps, an even distribution) between 200 and 600 ms, and thus the sounds in the two streams never overlapped. The ear of sound delivery varied randomly but there were never more than four tones presented successively to one ear. The ear to be attended changed randomly every 10, 15, or 20 s. During 500 ms before and after the arrow cue instructing an attention switch no deviant or target tones were delivered, and during 4800 ms after a switch there were never more than two tones presented successively to one ear. During the data analysis, the ERP epochs were

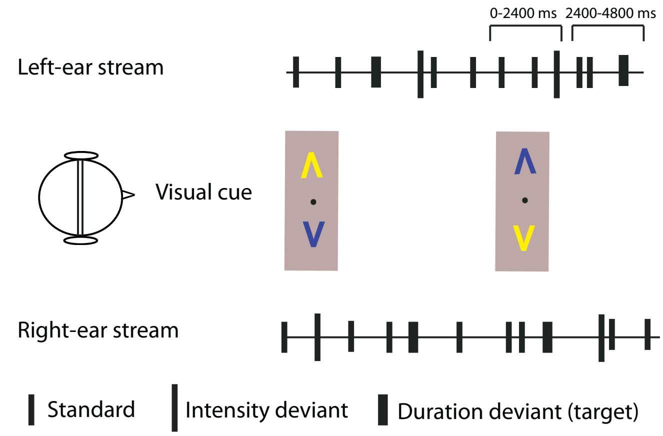

Fig. 1. Participants' task was to attend to the left or the right ear stimuli as indicated by the visual cue (blue arrow) and to press a response button when a longer-duration deviant sound ($p = 0.1$) occurred in the attended stream. Participants were asked not to respond to intensity-deviant sounds ($p = 0.1$). The SOAs varied randomly between 200 and 600 ms, and thus the sounds in the two streams never overlapped. The ear to be attended changed randomly every 10, 15, or 20 s. To obtain ERPs, the epochs were averaged separately for the attended and unattended standard and deviant tones, and also separately for standard tones in an earlier (≤2400 ms) and a later (> 2400 ms–4800 ms) time windows after an attention switch. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

averaged separately for standard tones in an earlier (≤2400 ms) and a later (> 2400 ms – 4800 ms) time windows after an attention switch. Because of variable SOAs and sound durations, there were on average six standard sounds (three for each ear) in each 2400-ms time window. Sound stimuli were presented via headphones (Sony MDR-7506, Park Ridge, NJ, USA).

Visual stimuli, that were two (blue and yellow) arrowheads (20 mm × 20 mm) pointing to the left and right, were shown constantly on a grey background in the centre of a computer screen facing the participants at a distance of 150 cm. The fixation dot (5 × 5 mm) was located in the middle of the display to which the participants were asked to fixate their gaze. The distance between the dot and tips of the arrows was 30 mm. The blue arrow indicated which auditory stream, left or right, the participant was to attend (Fig. 1).

2.3. Experimental procedure

The participants were seated in an electrically and acoustically shielded room. Before the experiment, a comfortable intensity level of 60 dB above individual hearing threshold was determined for each participant. Stimulus presentation was controlled through a script written in Presentation software (Neurobehavioral Systems Inc., Berkeley, CA, USA). The participants were allowed to practice the task until they felt ready to begin the experiment. Their task was to attend to the left or the right ear stimuli as indicated by the visual cue and to press a response button (Cedrus RB, Cedrus Corporation, San Pedro, CA, USA) when a longer-duration deviant sound occurred in the attended stream. Six experimental blocks were presented and each of them lasted about 10 min. There were 39 attention switches during each block, and thus, 234 switches during the whole experiment. In the whole experiment, there were 9000 tones (half of them to be attended and the other half to be ignored) including 7200 standard tones, and 900 deviant tones of each type.

2.4. EEG recordings and analysis

EEG was recorded using a 64-channel active-electrode recording system (Biosemi ActiveTwo, Biosemi, Amsterdam, The Netherlands) with a sampling rate of 512 Hz and bandwidth of DC-104 Hz. The electrodes were positioned in an electrode cap according to the Biosemi

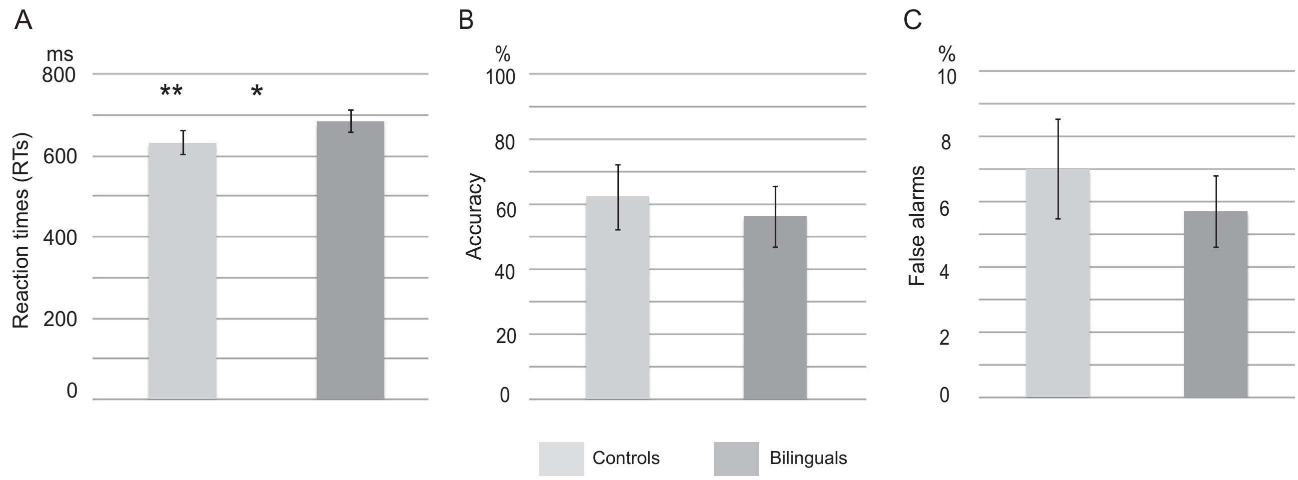

Fig. 2. A. Reaction times (RTs) to correctly detected target tones (longer duration deviant tones in the attended stream). B. Percentages of correct responses to target tones. C. Percentages of false alarms to longer duration tones in the stream to be ignored. Light grey bars: control participants, dark grey bars: early bilinguals. Vertical bars indicate SDs. *$p < 0.05$.

ABC-system. In addition, left and right mastoid electrodes, and a nose electrode were attached. Eye movements and blinks were detected primarily with an external electrode attached below the left eye. The data were pre-processed using a BESA Research program (version 5.3, MEGIS Software GmbH, Gräfelfing, Germany). The data were filtered off-line (0.01–45 Hz) and re-referenced to the average of mastoids.

Eye-movement and blink-related variance was subtracted from the data by principal component analysis (Ille et al., 2002). After that, the data were segmented to 900 ms epochs starting 100 ms before each stimulus onset, the mean voltage over the 100-ms prestimulus period serving as a baseline for amplitude measurements. Thereafter epochs in which the amplitude exceeded ± 100 μV were excluded. To obtain ERPs, the remaining epochs were averaged separately for the attended and unattended standard and deviant tones, and also separately for standard tones in an earlier (≤2400 ms) and a later (> 2400 ms–4800 ms) time windows after an attention switch. ERP components were quantified from individual difference waves by subtracting 1) ERPs to attended standard from ERPs to unattended standard tones (Nde and Ndl), 2) ERPs to intensity deviant from ERPs to standard tones (MMN, P3a, and the RON), and 3) ERPs to target deviants from ERPs to standards in the attended ear (P3b). The maximum peak for each component was determined individually in each participant at Cz electrode, where typically all these components show large amplitudes. The peak latencies for each component were identified from the individual ERP difference waves explained above in the following windows after tone onset: Nde: 100–200 ms, Ndl: 300–600 ms, MMN: 100–200 ms, P3a: 200–350 ms, and RON: 400–800 ms. These time-windows of ERP components were chosen based on previous literature (see, Introduction; Duncan et al., 2009). The amplitudes were measured from a 100-ms window centred at the mean of individual peak latencies. This 100-ms time-window was chosen in accordance with previous literature (see, e.g., Escera et al., 2002; Berti and Schröger, 2001). The P3b amplitude was quantified from ERP difference waves as the mean amplitude between 500 and 700 ms from tone onset.

Based on previous findings, we also analysed the Nde and Ndl for standard tones in an earlier (≤2400 ms) and a later (> 2400–4800 ms) time window after an attention switch to study gradual development of these components (cf., Donald and Young, 1982; Hansen and Hillyard, 1988). Because of variable SOAs and stimulus durations, and also due to an additional rule that never more than two tones were presented successively to one ear during these two time windows after the attention switch, approximately three standard tones to each ear were delivered during each time window.

2.5. Statistical analysis

A one-way analysis of variance (ANOVA) was used to test the effect of Language group on the behavioural results (hit reaction times and the proportions of hits and false alarms). Amplitudes of ERP components measured from each participant's difference waveforms at 25 channels were subjected to the following statistical analyses. The fixed-model $5 \times 5 \times 2$ ANOVA included two within-subject factors: Frontality and Laterality of electrode. Frontality had 5 levels from a frontal to parietal electrode lines: frontal (F3-F1-Fz-F2-F4), fronto-central (FC3-FC1-FCz-FC2-FC4), central (C3-C1-Cz-C2-C4), centro-parietal (CP3-CP1-CPz-CP2-CP4), and parietal (P3-P1-Pz-P2-P4), and Laterality of electrode location ha 5 levels from left to right: left lateral (F3-FC3-C3-CP3-P3), left medial (F1-FC1-C1-CP1-P1), midline (Fz-FCz-Cz-CPz-Pz), right medial (F2-FC2-C2-CP2-P2), and right lateral (F4-FC4-C4-CP4-P4). Language Group (controls versus early bilinguals) was included as a between-subject factor. *Time from switch* (early phase versus late phase after an attention switch) was included as a within-subject factor in the analyses in which switch effects were studied. Bonferroni correction was applied to post-hoc tests when sources of significant ANOVA effects having multiple within-subject comparisons were calculated. If an interaction by language group was significant, an independent sample *t*-test was performed. The statistical analyses were conducted using the SPSS statistical package (SPSS Statistics, version 20, IBM, Armonk, New York, NY, USA) and ANOVA results were Greenhouse–Geisser corrected for non-sphericity when appropriate. However, even in this case, the original degrees of freedom are reported for the F-values.

3. Results

3.1. Behavioural results

Mean reaction times (RTs) to target sounds were 631 ms (SD 60 ms) and 683 ms (SD 53 ms) in the control participants and in the early bilinguals, respectively (Fig. 2A). The controls were significantly faster than the early bilinguals in responding to targets ($F(1, 32) = 7.18$, $p = 0.012$, $d' = 0.92$). Mean RTs to the first target sound after an attention switch were 640 ms (SD 72 ms) and 695 ms (SD 61 ms) in the control participants and in the early bilinguals, respectively, also this difference being statistically significant ($F(1, 32) = 5.71$, $p = 0.023$, $d' = 0.83$). There was no statistically significant between-group differences in the accuracy of target detection ($F(1, 32) = 0.86$, $p = 0.360$, Fig. 2B) or in the ratio of false alarms to duration-deviant sounds presented to the ear to be ignored ($F(1, 32) = 1.76$, $p = 0.195$, Fig. 2C).

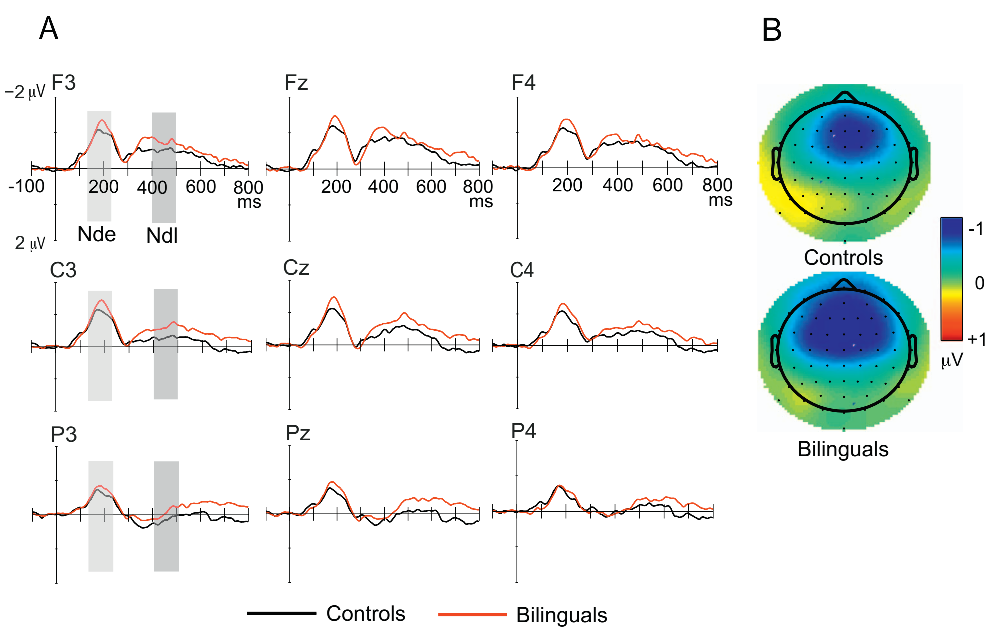

Fig. 3. A. Difference waves obtained by subtracting grand-average ERPs to standard tones in the unattended ear from grand-average ERPs to standard tones in the attended ear (data averaged across the left and right ears) in control participants and early bilinguals. Vertical lines indicate tone onset. The light and dark grey boxes indicate the time windows for Nde (137–237 ms) and Ndl (403–503 ms) amplitude analyses, respectively. B. Scalp distributions of Ndl (average amplitudes measured from difference waves over a 100-ms window centred at the peak latency) in the control and early bilingual participants.

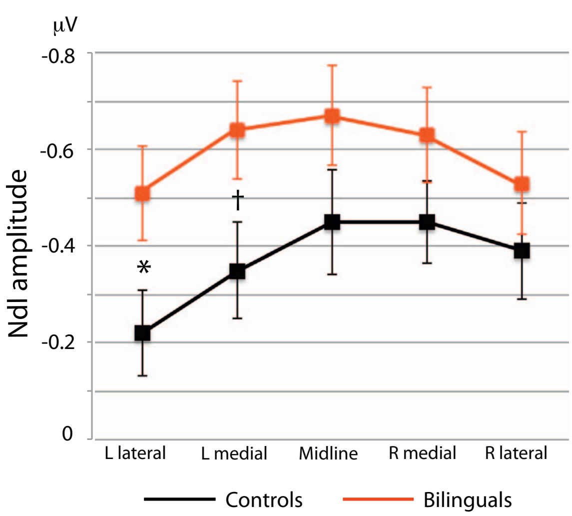

Fig. 4. Mean difference wave amplitudes for Ndl over a 100-ms window centred at the peak latency in the control and early bilingual participants over the left lateral (F3, FC3, C3, CP3, and P3), left medial (F1, FC1, C1, CP1, and P1), midline (Fz, FCz, Cz, CPz, and Pz), right medial (F2, FC2, C2, CP2, and P2), and right lateral (F4, FC4, C4, CP4, and P4) recording sites. Vertical bars indicate SEMs. Group difference, *t*-tests: *$p < 0.05$, †$p = 0.05$.

3.2. Voluntary attention: Nde and Ndl to standard tones

Nde, calculated over all standard tones, began around 100 ms from tone onset and reached its maximum amplitude over the frontal-central recording sites between 100 and 200 ms (Fig. 3). The mean peak latency of Nde was 185 ms (SD 34 ms) for the control group, and 189 ms (SD 23 ms) for the early bilingual group. The difference in the latencies between the groups was not significant ($t(32) = -0.348$, $p = 0.104$). The amplitudes of Nde were the largest over the anterior recording sites (Laterality × Frontality: $F(16, 152) = 5.88$, $p = 0.001$, Laterality: ($F(4, 128) = 5.85$, $p = 0.005$, Frontality: $F(4, 128) = 53.84$, $p = 0.001$). Post-hoc analyses indicated that the amplitudes were significantly more negative over the frontal (mean amplitude $-1.07\,\mu V$, SD 0.53, $d' = 0.65$), fronto-central ($-1.12\,\mu V$, SD 0.55, $d' = 0.71$), and central ($-1.05\,\mu V$, SD 0.51, $d' = 0.63$) than over the parietal ($-0.64\,\mu V$, SD 0.41) recording sites (all p values < 0.004). Post-hoc analyses did not show any significant differences between the levels of Laterality factor (all $p > 0.05$). The main effect of Language Group was not significant ($F(1, 32) = 0.968$, $p = 0.33$) and there were no significant interactions with Laterality ($F(4, 128) = 0.352$, $p = 0.847$) or Frontality ($F(4, 128) = 0.308$, $p = 0.737$) with the Language Group.

Ndl, calculated over all standard tones, started around 300 ms from tone onset and continued until 600 ms with maximum amplitudes over the frontal and central sites (Fig. 3). The mean peak latency of Ndl was 444 ms (SD 68 ms) for the control group and 462 ms (SD 44 ms) for the early bilingual group. The difference in the latencies between the groups was not significant ($t(32) = -0.899$, $p = 0.062$). The Ndl amplitudes were largest over the anterior recording sites (Laterality × Frontality: $F(16, 152) = 4.72$, $p = 0.001$, Laterality: ($F(4, 128) = 22.07$, $p = 0.001$, Frontality: $F(4, 128) = 50.76$, $p = 0.001$). Post-hoc analyses indicated that the amplitudes were significantly more negative over the frontal (mean amplitude $-0.79\,\mu V$, SD 0.47), fronto-central ($-0.76\,\mu V$, SD 0.47), and central ($-0.56\,\mu V$, SD 0.44) than over the centro-parietal ($-0.28\,\mu V$, SD 0.46) and parietal ($-0.04\,\mu V$, SD 0.51) recording sites (all $p < 0.001$, $d' = 0.44$ to 1.08). Post-hoc analyses did not show any significant differences between the levels of Laterality factor (all $p > 0.05$). The interaction of Language Group and Laterality was significant ($F(4, 128) = 4.25$, $p = 0.020$) indicating that Language Group contributed to the Ndl amplitudes differentially depending on the lateral location of the recordings. According to *t*-tests, the early bilinguals had larger Ndl amplitudes than the controls at the left lateral ($t(32) = 2.20$, $p = 0.035$, $d' = 0.53$) and left medial ($t(32) = 2.04$, $p = 0.050$, $d' = 0.49$) recording sites (Fig. 4). Participants' age or current daily language use of Finnish, Swedish, or English did not correlate with the magnitudes of Ndl in either Language group (all correlations $p > 0.05$).

3.3. Voluntary attention and switching efficiency: Nde and Ndl to standard tones during the early and late phase after the switch

The main effect of Time from Switch was significant on the amplitudes of both Nde ($F(1, 32) = 14.51$, $p = 0.001$) and Ndl ($F(1, 32) = 4.19$, $p = 0.049$). Larger amplitudes were obtained during the late (mean amplitude $-1.11\,\mu V$, SD 0.74) than the early ($-0.5\,\mu V$, SD 0.65) phase after the attention switch ($t(33) = 3.85$, $p = 0.001$). The interaction of Time from Switch and Frontality was significant for Nde amplitudes ($F(4, 128) = 5.06$, $p = 0.021$) and almost significant for Ndl

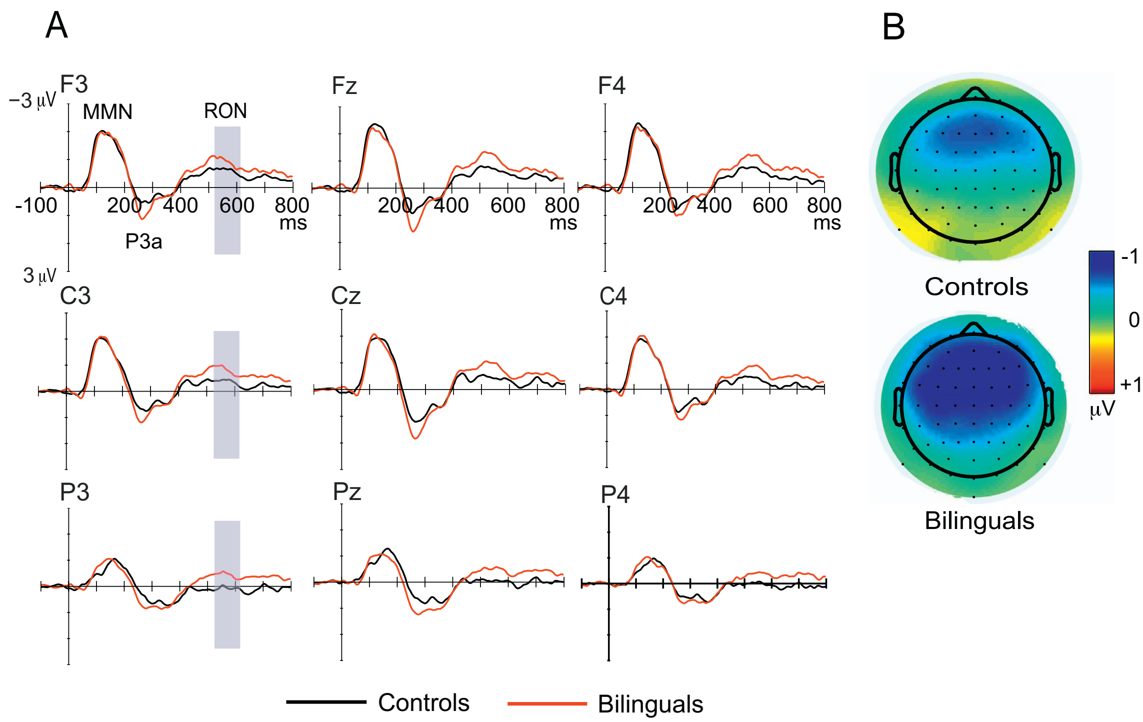

Fig. 5. A. Difference waves obtained by subtracting grand-average ERPs to intensity deviant tones from grand-average ERPs to standard tones (both in attended and unattended conditions; data averaged across the left and right ears) in the control and early bilingual participants. The light grey boxes indicate the time window for late negativity (518–618 ms) amplitude analyses. B. Scalp distributions of late negativity (average amplitudes measured from difference waves over a 100-ms window centred at the peak latency) in the controls and early bilingual participants.

amplitudes (F(4, 128) = 2.66, p = 0.078). Larger amplitudes for Nde during the late phase were observed over the frontal (−1.26 μV, SD 0.76), fronto-central (−1.32 V, SD 0.72), and central (−1.23 μV, SD 0.69) than over the parietal (−0.75 μV, SD 0.63) recording sites (p = 0.05–0.01, d′ = 0.51 to 0.60). Interactions of Language Group and Time from Switch were not significant for the amplitudes of Nde (F(1, 32) = 0.360, p = 0.553) and Ndl (F(1, 32) = 0.810, 0.375).

3.4. Involuntary attention, reorienting of attention, and target detection: ERPs in response to intensity- and duration-deviant (target) tones

Intensity-deviant tones elicited MMN (deviance detection), P3a (involuntary attention orientation), and RON (reorienting of attention) components both in the attended and unattended ear (Fig. 5). The mean peak latency of MMN was 141 ms (SD 24 ms) for the control group and 137 ms (SD 26 ms) for the early bilingual group. The difference in the latencies between the groups was not significant (*t*(32) = 0.417, p = 0.523). There was a significant main effect of Attention (F(1, 32) = 14.0, p = 0.001). The MMN amplitudes were larger to the attended intensity deviants (mean − 1.76 μV, SD 0.93) than unattended intensity deviants (−1.27 μV, SD 0.75). The main effect of Language Group was not significant (F(1, 32) = 0.023, p = 0.882) and there was no significant interaction of Attention and Language Group (F(1, 32) = 0.041, p = 0.841).

The mean peak latency of P3a was 276 ms (SD 30 ms) for the control group and 273 ms (SD 31 ms) for the early bilingual group. The difference in the latencies between the groups was not significant (*t* (32) = 0.116, p = 0.736). There was a significant main effect of Attention on P3a amplitude (F(1, 32) = 17.26, p = 0.001): The P3a amplitudes were larger to intensity deviants among attended tones (mean 0.99 μV, SD 1.10) than to those among unattended tones (0.48 μV, SD 0.84). However, the main effect of Language Group was not significant (F(1, 32) = 1.1, p = 0.303) and there was no significant interaction of Attention and Language Group (F(1, 32) = 1.94, p = 0.173).

Intensity-deviant tones elicited also larger RON over the anterior and posterior recording sites (Fig. 5). The mean peak latency of RON was 565 ms (SD 123 ms) for the control group, and 571 ms (SD 122 ms) for the early bilingual group. The difference in the latencies between the groups was not significant (*t*(32) = 0.036, p = 0.850). There was an interaction of Frontality and Attention (F(4, 128) = 5.77, p = 0.017) on the RON amplitude. The mean RON amplitudes were more negative to intensity deviants among the attended than to those among the unattended tones and this effect was larger over the frontal and fronto-central than over the parietal recording sites (all p-values < 0.05) and over the central than over the parietal recording sites (p = 0.05). The main effect of Frontality was significant (F(4, 128) = 30.84, p = 0.001). The RON amplitudes were larger over the frontal (mean − 0.81 μV, SD 0.62) and fronto-central (−0.81 μV, SD 0.85) than over the parietal (−0.22 μV, SD 0.65) recording sites (p = 0.01, d′ = 0.66 and 0.56, respectively). The interaction of Attention and Language Group was not significant (F(1, 32) = 0.020, p = 0.889), but there was a significant main effect of Language Group (F(1, 32) = 4.17, p = 0.049, d′ = 0.46): the mean amplitude was −0.77 μV (SD 0.69) in the early bilinguals and − 0.34 μV (SD 0.62) in the controls. Participant age or current daily language use of Finnish, Swedish, or English did not correlate with the magnitudes of RON in either Language group (all correlations p > 0.05).

Target tones (duration deviants in the attended stream) elicited also a P3b component (target detection). The P3b amplitudes were the largest over the posterior recording sites (Frontality: F(4, 128) = 52.15, p = 0.001). Post-hoc analyses indicated that the P3b amplitudes were significantly larger over the centro-parietal (mean amplitude 1.92 μV, SD 1.72) and parietal (2.10 μV, SD 1.68) than over the frontal (0.42 μV, SD 1.11) and centro-frontal (0.75 μV, SD 1.36) recording sites (all p = 0.05–0.001, d′ = 0.54 to 0.85). The effect of Language Group was not significant (F(1, 32) = 1.73, p = 0.198).

4. Discussion

In the present study, we investigated whether exposure to two native languages in early childhood influences attention-related modulations of ERPs in a selective listening task in adulthood. The results showed that in both early bilingual and control groups, the Nde and Ndl components were elicited by attention, which corroborates previous research showing a link between these components and spatial attention to a particular auditory stream (e.g., Alho et al., 1989; Hari et al., 1989; Näätänen, 1990; Degerman et al., 2008). Moreover, we found that the Ndl and RON components – associated with maintenance of attention or further processing of attended sounds and reorienting of attention, respectively – were enhanced in bilinguals. More particularly, our ERP results showed that the Ndl amplitudes were more pronounced in the early bilinguals than in the controls over the left scalp sites. However, no differences between language groups were found for the Nde amplitudes. In addition, we observed that the RON associated with intensity-deviant tones was larger in the early bilinguals than controls, suggesting that deviant-tone induced distraction is compensated more efficiently in bilinguals. The magnitudes of MMN and P3a to these deviant sounds were not different between the language groups, suggesting that in both groups deviant sounds caught involuntary attention (deviance detection and involuntary orienting of attention) similarly. Altogether, our results on Ndl and RON suggest that allocation of attention to auditory information is modulated in adults exposed to two languages in their early childhood.

Both early bilingual and control participants performed comparably in the task requiring detection of longer-duration target tones in the attended tone stream. In addition, the early bilingual participants were somewhat slower than the controls in target detection. While duration cues are important both in the Finnish and Swedish (Lehtonen, 1970; McAllister et al., 2002), there are more possible quantity contrasts in Finnish than in Central Standard Swedish (Helgason et al., 2013). Although Fenno-Swedish (Swedish spoken in Finland) spoken natively by our early bilingual participants has more durational distinctions than Central Standard Swedish (Helgason et al., 2013), Finnish is nevertheless even richer in durational contrasts influencing word meaning. Such more extensive exposure of our control than bilingual participants to durational contrasts might have speeded their reaction times to duration targets. Namely, for example, a previous study showed that native Finnish speakers are behaviourally and neurally more accurate in tone duration discrimination than native German speakers, in whose language sound duration contrasts have a minor role (Tervaniemi et al., 2006).

Despite the lack of behavioural benefits in our bilingual participants, there were several differences in the ERP responses between the groups suggesting that cognitive processes associated with attention differ according to language experience. An overt behavioural response, such as reaction time or accuracy, reflects an end product of multiple cognitive processes and it does not provide a direct means to assess processes that occur between sensory stimuli and a motor response (e.g., Luck et al., 2000; Luck, 2005). In contrast, the ERPs provide a temporally sensitive and a direct measure of underlying cognitive process allowing us to determine which processes between a stimulus and a response are influenced by experimental manipulations. Moreover, the ERPs provide an online measure of cognitive processing even when an overt reaction is not required or when stimulation is presented outside the focus of attention. This was true also in our study: the language group effects were found for Ndl and RON components in response to standard and deviant sounds, respectively, which did not require any behavioural response. Additionally, there are some examples of studies showing that even though the ERPs are sensitive to experimental or participant group manipulations, the effects are not found behaviourally (e.g., Kozou et al., 2005; Sokka et al., 2016) suggesting that the combination of the two measures (behavioural and ERP) might provide a more complete picture of the underlying processes.

Although we found that the Ndl amplitudes were larger in the early bilinguals than in the controls over the left hemisphere scalp sites, no group differences were found for Nde. It has been proposed that while Nde is caused by a selection process based on a physical difference or differences separating the attended and unattended sounds the Ndl reflects voluntary maintenance of selective tuning for attended sounds or their further processing (Näätänen, 1990). Thus, the present results are indicative of enhanced maintenance of selective attention or further processing of attended sounds in the early bilinguals rather than improved attentional selection. However, both Nde and Ndl have been suggested to originate, at least in part, from the temporal cortex (Hari et al., 1989; Degerman et al., 2008). Stronger axonal connections have been observed between the left and right hemispheres in early bilingual than in monolingual adult participants (García-Pentón et al., 2014) and stronger left-hemisphere language-related white matter trajectories have been found in early than late young adult bilinguals (Hämäläinen et al., 2017). Therefore, the left-hemispheric enhancement of Ndl in our early bilingual participants suggests that native bilingualism might also enhance the involvement of left-hemisphere temporal areas in further processing of, or maintenance of attention to, non-linguistic sounds.

Consistent with our initial hypothesis that cognitive processes associated with involuntary attention are not enhanced in early bilinguals, our results showed that the MMN and P3a, reflecting these processes, were similar in both language groups. We also hypothesized that the RON, associated with reorienting processes, would be enhanced in bilinguals. This was indeed what we observed: the RON in response to intensity-deviant tones was larger in the early bilinguals than in controls. Hence, our early bilinguals seem to be more efficient in disengaging their attention from attention catching and distracting auditory events and re-allocating it back to the task (see, Schröger and Wolff, 1998; Berti and Schröger, 2001; Escera et al., 2001; Escera and Corral, 2007). The frontally distributed RON is typically larger for more attention capturing sounds (i.e. for the novel sounds) than for the deviant sounds (Escera et al., 2001). In the light of that evidence, our results might reflect a higher efficiency in the early bilinguals than in the controls in reorienting their attention back to the auditory stream they were originally attending to. This implies that the early bilinguals may have developed more enhanced reorienting skills than the controls to compensate for distraction. This finding is in the accordance with previous evidence suggesting that bilinguals might have better attention disengagement skills (e.g., Mishra et al., 2012; Grundy et al., 2017). The bilingual participants' performance was shown to be less influenced by previous trial congruency, and this was reflected in both behavioural and ERP results (Grundy et al., 2017). Our study suggests that a larger RON to distractive sounds might represent a similar measure for better disengagement skills.

To summarize, we observed a stronger modulation of Ndl in response to attended standard sounds for the bilingual group, suggesting *enhanced maintenance of selective attention or enhanced processing of attended sounds* in the early bilinguals. In addition, we found that there was a lack of group differences in the magnitudes of MMN and P3a to intensity-deviant sounds, suggesting *similar involuntary* orienting of attention to deviant sounds in both groups. However, RON to tones after disruptive deviant sounds was enhanced in the bilinguals, indicating more efficient *reorienting of their attention as* compared to the controls. Taken together, our results suggest that the experience on multiple languages influences not only the language-related functions but also non-linguistic cognitive processes such as attention. Our results also suggest that bilingual language experience may contribute to specific attention processes such as maintenance and reorienting of attention.

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