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Validation of the Emotiv EPOC EEG system for research quality auditory event-related potentials in children

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Abstract

Background. Previous work has demonstrated that a commercial gaming electroencephalography (EEG) system, Emotiv EPOC, can be adjusted to provide valid auditory event-related potentials (ERPs) in adults that are comparable to ERPs recorded by a research-grade EEG system, Neuroscan. The aim of the current study was to determine if the same was true for children.

Method. An adapted Emotive EPOC system and Neuroscan system were used to make simultaneous EEG recordings in nineteen 6- to 12-year-old children under “passive” and “active” listening conditions. In the passive condition, children were instructed to watch a silent DVD and ignore 566 standard (1000 Hz) and 100 deviant (1200 Hz) tones. In the active condition, they listened to the same stimuli, and were asked to count the number of ‘high’ (i.e. deviant) tones.

Results. Intraclass correlations (ICCs) indicated that the ERP morphology recorded with the two systems was very similar for the P1, N1, P2, P2, and P3 ERP peaks (r = .78 to .95) in both passive and active conditions, but was poor for the mismatch negativity ERP component (MMN; r < .30). There were few differences between peak amplitude and latency estimates for the two systems.

Conclusions. An adapted EPOC EEG system can be used to index children’s late auditory ERP peaks (i.e. P1, N1, P2, N2, P3) but not their MMN ERP component.

Subjects: Psychiatry and Psychology

Keywords: EEG; ERP; Emotiv EPOC; Validation; Mismatchnegativity; MMN; Intraclass correlation; Methods; Signal processing; Auditory odd-ball; Children

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Introduction

An auditory event-related potential (ERP) is the average pattern of electrical activity generated by neurons in response to a particular auditory event. Auditory ERPs can be measured without a listener's overt attention. Such "passive" auditory ERPs are a useful means of investigating the role of auditory processing in people who find it difficult to pay attention to stimuli, to make decisions about stimuli, or plan overt responses to stimuli. Thus, passive auditory ERPs have proved useful for investigating auditory processing in attention deficit hyperactivity disorder (ADHD; Taylor et al., 1997), schizophrenia (Todd, Michie & Jablensky, 2003); autism (McPartland et al., 2004); developmental dyslexia (McArthur, Atkinson & Ellis, 2009); and specific language impairment (Whitehouse, Barry & Bishop, 2008).

A limitation of passive auditory ERPs is that they are typically measured using research-grade equipment housed in a laboratory. Such settings can be intimidating for many people, particularly children and adults with cognitive disorders. Fortunately, recent research has shown that a commercial "gaming" electroencephalography (EEG) system, called "EPOC" by Emotiv (www.emotiv.com), can be adapted to produce valid ERPs. Badcock et al. (2013) examined auditory ERPs in "passive" (standard and deviant tones are ignored) and "active" (deviant tones are counted) listening conditions in adults, using an adapted EPOC system and a research-grade Neuroscan system. They found high reliability for the "late auditory ERP" peaks (i.e. P1, N1, P2, N2, and P3) but not for the "mismatch negativity" component (MMN; see Näätänen et al., 2004). The EPOC system has also been successfully used to measure the auditory P3 response (Debener et al., 2012; De Vos, Gandras & Debener, 2014) and the visual P3 response (Duvinage et al., 2013; De Vos et al., 2014). Considered together, the outcomes of these seminal studies suggest that the EPOC system can be adapted to record valid auditory P1, N1, P2, N2, and P3 ERP peaks in adults.

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Unfortunately, no study has yet tested if an adapted EPOC system can produce valid auditory ERPs in children. This cannot be inferred from previous validation studies done with adults because children have (1) different ERPs to adults due to cortical and cognitive immaturity (Ponton et al., 2002; Coch, Sanders & Neville, 2005; Mahajan & McArthur, 2012, 2013); (2) "noisier" ERPs than adults (Coch & Gullick, 2012); and (3) more difficultly keeping still during long test sessions than adults, so their EEG (and ERP) responses may be contaminated to a greater degree by electrical noise generated by movement. The aim of the current study was to test the validity of children's passive and active auditory ERPs measured via an adapted EPOC system. In line with an analogous adult study (i.e. Badcock et al., 2013) we predicted that the adapted EPOC system would produce valid ERPs for the highly reliable late auditory ERP peaks (P1, N1, P2, P2, P3) but invalid ERPs for the less reliable MMN component.

Materials and Methods

The Macquarie University Human Research Ethics Committee approved the methods used in this study (approval number: 5201200658).

Participants

Participants were twenty-one children (11 females, 10 males) aged between 6 and 12 years (M = 9.23, SD = 1.80). Parents or guardians of the children provided written informed consent for their child's participation, and children were reimbursed $15 for their time. Participants were required to have normal hearing and vision, and no history of epilepsy. One child was excluded from the study due to a reported hearing loss, and another child was excluded because the EPOC event-markers failed to record. Therefore the final sample included 19 children.

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Stimuli

Presentation (Version 16; Neurobehavioural Systems) was used to deliver tones in passive and active conditions (see below) at a volume that was comfortable for each participant (note: the volume remained fixed across conditions). Each condition consisted of 566, 175-ms, 1000-Hz standard tones (10-ms rise and fall time; 85% of trials) and 100, 175-ms, 1200-Hz deviant tones (10-ms rise and fall time; 15% of trials). Deviant tones were presented after 3 to 35 (randomly allocated) standard tones. The stimulus onset asynchrony was jittered between 900 and 1100 ms to minimize EEG activity related to anticipatory processes. Tones were presented binaurally via Phillips SHS4700/37ear clip headphones fixed to the EPOC headset.

In the passive condition, participants were instructed to watch a silent movie and ignore the tones presented through the headphones. In the active condition, participants were instructed to count the "high" tones whilst watching the silent movie. Participants were asked, and reminded where necessary, to stay as still as possible. Each condition lasted approximately 13 minutes, separated by a short-break.

Neuroscan system

The research-grade EEG system (Neuroscan Version 4.3) used an EEG electrode cap (EasyCap) fitted with 14 Ag-AgCl electrodes located at F3, F7, FC4, FT7, T7, P7, P8, T8, FT8, FC4, F8, F4, M1 (online reference), and M2. Electrodes placed above and below the left eye measured vertical eye movements (“VEOG”), and electrodes placed on the outer side of each eye measured horizontal eye movements (“HEOG”). Please note that the M2 (right mastoid), VEOG, and HEOG electrodes were set up as per standard procedures even though these electrodes were not used in the analysis as EPOC does not provide equivalent measurements. The ground electrode was positioned between FPz and Fz.

During the Neuroscan EEG recording, the EEG was sampled at 1000 Hz. Triggers were inserted into the EEG to indicate the onset of each stimulus. These triggers were generated by Presentation, and were inserted into the EEG via a parallel port.

Adapted EPOC system

The EPOC system used a wireless headset with flexible plastic arms that held gold-plated sensors against the head at 16 sites that aligned with the research EEG headset: AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, FC4, M1 and M2. M1 acted as a ground reference point for measuring the voltage of the other sensors. M2 acted as a feed-forward reference point for reducing electrical interference from external sources.

During recording, the EPOC EEG was sampled at 128 Hz. The onset of each stimulus was marked with an electrical pulse triggered by a wireless transmission system (Thie, 2013). The system consisted of transmitter and receiver units that were linked using infrared (IR) light. The transmitter unit was attached to the audio output of the stimulus presentation computer. The receiver unit was mounted in close proximity to the participant (i.e. taped to their shoulder or resting on a table) with its output wires attached to two of the EEG electrodes (O1 and O2). These electrodes were attached directly to the Driven Right Leg (DRL) through wires and 4700-ohm resistors that mimicked a perfect connection with the scalp. The transmitter unit was made up of a microcontroller board (Arduino Uno) and an interface board. This "shield" amplified the audio stimuli and fed it to the Arduino's analogue input. The receiver waited for a number from the transmitter to trigger a 100-ms-wide pulse. There was a 19-ms delay (accounted for the trigger processing) between the onset of the stimulus and the onset of the marker pulse due to the buffering of the audio signal in order to determine its frequency and the transmission of the 8-bit number.

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Procedure

Neuroscan was setup first and adjusted until sensor impedance was below 5 kOhms. The EPOC headset was fitted over the EasyCap (for a detailed description, see Badcock et al., 2013). This allowed simultaneous measurements of EEGs by the Neuroscan and EPOC systems (see Fig. 1). EPOC electrode connectivity was tested using the TestBench software. Sensors were adjusted until connectivity reached the “green” level, which represented impendences less than 220 kOhms (measured using a resistor between an electrode and the DRL, M2 in the current setup). The total setup time was approximately 55 minutes.

Insert Figure 1 about here

Offline EEG processing

Both Neuroscan and EPOC EEG recordings were processed in the same way using EEGLAB version 11.0.4.3b (Delorme & Makeig, 2004). Large artefacts in each EEG were first excluded by eye. The Neuroscan EEG data were then downsampled to 128 Hz in order to match the sampling rate of the EPOC system. The EEG data were then bandpass filtered from 0.1 to 30 Hz, separated into epochs that started -102 ms before the onset of each tone and ended 500 ms after the onset of each tone, and baseline corrected between -102 and 0 ms. Any epochs with an amplitude in excess of +/- 150 µV were excluded.

Ocular artefact removal was attempted using Independent Components Analysis in EEGLAB (note: channels capturing the eye-movements for Neuroscan were not included in this process to maintain equivalent processing between the systems). This process failed to identify any eye-blink related components for any individual dataset. Therefore eye-blinks were either not consistent or strong enough to meaningfully affect the data.

For each child, the accepted epochs were averaged together to produce late auditory ERP waveforms that comprised P1, N1, P2, and N2 peaks for the standard and deviant tones,

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in the passive and active conditions. Accepted epochs to standard and deviant tones in the passive condition were averaged separately and then subtracted (i.e. the ERP to standard tones was subtracted from the ERP to deviant tones) to produce a mismatch negativity (MMN) waveform.

Analysis

In line with the previous EPOC validation study done with adults, the analysis focused on data from frontal sites in the left and right hemispheres: F3 and F4 for Neuroscan, and AF3 and AF4 for EPOC.

The ERPs produced by the two systems were compared in three ways: (1) total number of accepted epochs were used to compare the quality of the Neuroscan and EPOC EEG data, (2) intraclass correlations (ICCs) were used to index the similarity of Neuroscan and EPOC waveforms (between -102 to 500 ms), and (3) peak amplitude and latency measures were used to compare the size and timing of each ERP peak or component. The number of epochs and peak comparison data sets were tested for normality (Shapiro-Wilk) and equal variance (F test). Single- and paired-sample t-tests and Wilcoxon-signed ranks and were used to evaluate the statistical reliability between EEGs systems comparisons and Cohen's d was used to evaluate the magnitude of the effects. We used a criteria of $p < .05$ unless otherwise specified.

Regarding (3), peak amplitude and latency measures were initially calculated using an automated procedure that identified the point of maximum amplitude (positive or negative) within appropriate time intervals, determined by visual inspection of the relevant grand mean ERP waveforms: 50 to 140 ms (P1); 70 to 140 (N1); 140 to 200 ms (P2); 260 to 400 ms (N2); 260 to 400 ms (P3); 140 to 260 (MMN). We then checked the validity of each peak measure for each child by visually inspecting individual waveforms. This revealed that the N1 and P2 peaks were missing in 9 to 13 (47 to 68%) children across all condition, which is

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characteristic of children's auditory ERPs (Ponton et al., 2000; Mahajan & McArthur, 2012, 2013). A further 13% of the measures produced by the automated peak detection were invalid, identifying an end point of the range greater in magnitude that the true peak. Invalid measures were corrected manually to ensure all peak amplitude and latency measures for all children were valid.

Results

Number of accepted epochs

The distributions for the number of accepted epochs were negatively skewed, thus, Wilcoxon Signed Rank Tests were used to compare the two systems. The median number of accepted epochs, inter-quartile range, and Wilcoxon signed ranks statistics are presented in Table 1. There were statistically fewer acceptable epochs for EPOC than Neuroscan in all conditions. Nevertheless, the number of accepted epochs for both the EPOC and Neuroscan systems was more than adequate for waveform generation for all participants.

Insert Table 1 about here

ICCs

P1, N1, P2, and N2

The mean of the group ERP waveforms produced by the Neuroscan and EPOC systems to the standard and deviant tones in the passive and active conditions are displayed in Fig 2 (see Supplementary Figs 1 and 2 for the auditory ERPs of individual children). The ICCs between late auditory ERP waveforms generated by the two systems to standard and deviant tones in the passive and active conditions are presented in Table 2. The range of ICCs for the standard tones was 0.87 to 0.95 and for the deviant tones was 0.78 to 0.87. All of these distributions were negatively skewed; therefore, statistical differences to zero were assessed using single-sample Wilcoxon signed ranks, all of which were significant: all $Z = 4.62$, $p < .001$. These

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results indicate a strong correspondence between the measurements made with the two systems.

Insert Figure 2 and Table 2 about here

P3

The mean of the group late auditory ERP waveforms produced by the Neuroscan and EPOC systems to the deviant tones in the active condition are displayed in Fig 2 (see Supplementary Fig 2 for the auditory ERPs of individual children). The corresponding ICC values are shown in Table 2. The ICCs for F3/AF3 and F4/AF4 were both 0.78, and the negatively skewed distributions were significantly different to zero: single-sample Wilcoxon signed ranks, F3/AF3: Z = 4.48, p < .001; F4/AF4: Z = 4.62, p < .001. These results indicate a strong correspondence between the measurements made with the two systems.

MMN

The mean of the group MMN ERP waveforms produced by the Neuroscan and EPOC systems are presented in Fig 3 (see Supplementary Fig 3 for the MMN ERP waveforms of individual children). The ICCs between the MMN waveforms generated by the Neuroscan and EPOC systems are shown in Table 4. These ICCs were poor: 0.3 for F3/AF3, and 0.04 for F4/AF4. Both distributions were normally distributed and single-sample t-tests determined the ICC for F3/AF3 was statistically different to zero; t(18) = 3.67, p = .001; but the ICC for F4/AF4 was not, t(18) = 0.47, p = .64. Thus, in contrast to the late auditory ERP waveforms, the MMN waveforms were poorly comparable across the two systems.

Insert Figure 3 and Table 4 about here

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Peak amplitude and latency

The descriptive statistics for P1, N1, P2, N2, P3 and MMN peak amplitude and latency measures produced by the Neuroscan and EPOC systems for standard and deviant tones in the passive and active conditions at F3/AF4 and F4/AF4 are reported in Tables 3, 4, and 5. Peak comparisons between the two systems were conducted using paired-samples t-tests and Wilcoxon singed rank tests, depending upon the normality of the data as indicated in the tables. Due to multiple comparisons, statistical tests with p-values less than .01 will be highlighted ($p < .05$ and .001 are also indicated in the tables).

Insert Tables 3, 4, and 5 about here

P1, N1, P2, and N2

For the P1, N1, P2, and N2 late auditory ERP peaks, there were 11 comparisons that differed statistically between the two systems. One of the differences was the N2 amplitude to the standard tone, which was reduced in the EPOC system by 1.2 μ Vs, small in magnitude ($d = 0.34$). Ten of the differences reflected a delay in the latency of the peaks measured by the EPOC system and 9 of these were evident to the standard tone. The average delay for these comparisons was 7.71 ms ($SD = 3.2$) and effect sizes were small to large ($d = 0.27$ to 1.12).

P3

The differences in P3 amplitude between the systems were no significant and small (both $d = 0.14$). The P3 produced by the EPOC system at F3/AF3 was significantly later than that produced by the Neuroscan system by 14 ms (see Table 5). Cohen's d effects sizes were small to moderate ($d = 0.24$ to 0.57).

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MMN

The differences in MMN amplitude between the two systems was non-significant and small (d = 0.21 and 0.24). The MMN latency was significantly delayed in the EPOC system by 10 and 16 ms (see Table 5). Cohen's d effects sizes were small to moderate (d = 0.26 to 0.45).

Discussion

The aim of the current study was to assess the validity of the Emotiv EPOC gaming EEG system as an auditory ERP measurement tool in children. To this end, we simultaneously measured ERPs using a research-grade Neuroscan system and the EPOC system in children aged between 6 and 12 years. Children were presented with standard and deviant tones in both passive (ignore tones) and active (count high tones) listening conditions. The results replicated the findings of Badcock et al.'s (2013) study with adults: ICCs (0.78 to 0.95) revealed that the EPOC and Neuroscan systems produced similar late auditory ERP waveforms in passive and active conditions at F3/AF3 and F4/AF4; and there were few differences between the P1, N1, P2, N2, and P3 peak amplitudes and latencies. The few differences that were found related mostly to peak latency measures, which were sometimes delayed for the EPOC system. Across all of the peaks (i.e., not just those highlighted as significant in the results), the average delay was 7.76 ms (SD = 5.6). This represents a single sample at 128 Hz. Since this delay was small, and occurred in a minority of comparisons, we do not believe it significantly compromises the use of the EPOC system as a measure of auditory P1, N1, P2, N2, or P3 ERPs in children.

Regarding the MMN, the ICCs between the EPOC and Neuroscan waveforms were found to poor (0.04 to 0.3), probably due to the poor reliability of this component (McArthur, Bishop & Proudfoot, 2003; Mahajan & McArthur, 2011; Badcock et al., 2013). There was no significant difference between the size of the MMN produced by the EPOC and Neuroscan systems. However, the MMN measured by the EPOC system was slightly delayed, again

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possibility due to sampling or transmission techniques. These results suggest that, in contrast to the P1, N1, P2, N2 and P3, the Emotiv EOC system should not be used to measure the MMN in children. Recent research suggests that the magnetic acoustic change complex (mACC) may provide a more efficient and sensitive mechanism for investigating auditory discrimination in children (Bardy et al., 2014).

Overall, the findings of the present study paired with Badcock et al. (2013) suggest that EPOC compares well with Neuroscan for investigating late auditory ERPs in children. This opens up new opportunities for conducting ERP studies with children with or without cognitive impairments who find the laboratory settings associated with traditional research-grade EEG systems threatening or uncomfortable. It also paves the way for large-scale studies of the development of typical and atypical ERPs since it allows the measurement of children's ERPs in settings such as schools, childcare centres, hospitals, and private clinical practices.

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Table 1 Median number of accepted epochs for Neuroscan and EPOC by condition and tone type. Median (inter-quartile range) number of accepted epochs for the Neuroscan and EPOC systems in each condition (passive and active) for each tone type (standard, deviant, and total). Wilcoxon Signed Rank Tests (Z) were used to test the difference between systems.

		EEG System		
Condition	Tone	Neuroscan	EPOC	Z
Passive	Standard	540 (12)	525 (19)	2.31*
	Deviant	99 (1)	97 (4)	2.60**
	Total	639 (14)	621 (20)	
Active	Standard	538 (12)	525 (30)	2.62**
	Deviant	99 (2)	98 (2)	2.54*
	Total	638 (10)	623 (30)	

Note: * p < .05, ** p < .01

Table 2 Neuroscan versus EPOC ERP and MMN waveform Intraclass Correlations. Mean intraclass correlations (ICC) (with 95% confidence intervals) between Neuroscan and EPOC late auditory P1, N1, P2, N2, and P3 ERPs and the MMN component at F3/AF3 and F4/AF4 to standard and deviant tones in both passive and active conditions. Single-sample Wilcoxon signed rank test p-values are represented.

Condition	Tone	F3/AF3	F4/AF4
Passive	Standard	0.95 [0.94, 0.96]***	0.91 [0.88, 0.94]***
	Deviant	0.87 [0.81, 0.93]***	0.83 [0.74, 0.92]***
	MMN	0.30 [0.15, 0.45]**	0.04 [-0.11, 0.19]
Active	Standard	0.90 [0.84, 0.96]***	0.87 [0.82, 0.92]***
	Deviant	0.78 [0.66, 0.90]***	0.78 [0.69, 0.87]***

Note: ** p < .01, *** p < .001

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Table 3 Neuroscan versus EPOC ERP peak comparisons: Passive Listening. Descriptive (n, M [lower, upper 95% confidence intervals]) and inferential (t or Z and Cohen's d) statistics for peak (P1, N1, P2, N2) amplitude (μ V) and latency (ms) measures at sties F3/AF3 and F4/AF4 for Neuroscan versus EPOC in the passive condition.

					EEG System			
Tone	ERP	Measure	Electrode	n	Neuroscan	EPOC	stat.	d
Standard	P1	Amplitude	F3/AF3	19	3.37 [2.2, 4.5]	3.36 [2.0, 4.7]	-0.02^	0
			F4/AF4	19	3.57 [2.5, 4.6]	3.32 [2.2, 4.5]	0.96	0.11
		Latency	F3/AF3	19	98 [89, 107]	104 [96, 112]	-3.59^***	0.33
			F4/AF4	19	99 [91, 107]	103 [95, 111]	-2.76^**	0.27
	N1	Amplitude	F3/AF3	10	-0.88 [-1.9, 0.2]	-0.97 [-1.9, -0.0]	-0.19^	0.07
			F4/AF4	10	-0.92 [-1.7, -0.1]	-1.04 [-1.9, -0.2]	0.58	0.1
		Latency	F3/AF3	10	122 [115, 129]	130 [122, 138]	-4.74**	0.76
			F4/AF4	10	120 [114, 126]	127 [121, 133]	-4.57**	0.84
	P2	Amplitude	F3/AF3	10	1.16 [-0.6, 3.0]	1.22 [-0.4, 2.8]	-0.18	0.02
			F4/AF4	10	1.65 [-0.2, 3.5]	1.42 [-0.1, 3.0]	0.68	0.09
		Latency	F3/AF3	10	152 [143, 161]	162 [154, 170]	-2.93*	0.8
			F4/AF4	10	156 [147, 165]	170 [163, 177]	-3.99**	1.12
	N2	Amplitude	F3/AF3	19	-8.95 [-10.5, -7.4]	-8.01 [-9.9, -6.1]	-2.79*	0.26
			F4/AF4	19	-8.59 [-10.3, -6.9]	-8.23 [-10.0, -6.4]	-1.12	0.1
		Latency	F3/AF3	19	266 [254, 278]	274 [264, 284]	-2.87*	0.33
			F4/AF4	19	264 [253, 275]	273 [264, 282]	-3.02^**	0.42
Deviant	P1	Amplitude	F3/AF3	19	3.93 [2.4, 5.5]	3.74 [2.1, 5.3]	-0.57^	0.06
			F4/AF4	19	3.91 [2.5, 5.3]	3.29 [1.9, 4.6]	1.94	0.21
		Latency	F3/AF3	19	97 [89, 105]	103 [95, 111]	-2.7^**	0.37
			F4/AF4	19	100 [90, 110]	102 [94, 110]	-2.07^*	0.09
	N1	Amplitude	F3/AF3	7	-2.31 [-3.4, -1.2]	-1.96 [-3.0, -0.9]	-0.59	0.27
			F4/AF4	7	-1.69 [-2.8, -0.6]	-2.16 [-3.3, -1.0]	0.66	0.35
		Latency	F3/AF3	7	133 [117, 149]	131 [121, 141]	0.36	0.14
			F4/AF4	7	133 [116, 150]	132 [123, 141]	0.14	0.07
	P2	Amplitude	F3/AF3	7	1.24 [-1.1, 3.6]	1.51 [-0.4, 3.4]	-0.42	0.11
			F4/AF4	7	1.01 [-1.7, 3.8]	1.55 [-0.1, 3.2]	-0.75	0.2
		Latency	F3/AF3	7	164 [152, 176]	171 [157, 185]	-0.93	0.45
			F4/AF4	7	167 [153, 181]	163 [148, 178]	0.56	0.25
	N2	Amplitude	F3/AF3	19	-10.28 [-12.3, -8.2]	-9.75 [-12.0, -7.5]	-1.32	0.12
			F4/AF4	19	-9.94 [-11.7, -8.1]	-9.84 [-12.0, -7.7]	-0.2	0.02
		Latency	F3/AF3	19	230 [221, 239]	237 [226, 248]	-2.41^*	0.3
			F4/AF4	19	230 [217, 243]	234 [222, 246]	-1.37	0.15

Note: ^ Wilcoxon Z, * p < .05, ** p < .01, *** p < .001

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Table 4 Neuroscan versus EPOC EEG system ERP peak comparisons: Active Listening. Descriptive (n, M [lower, upper 95% confidence intervals]) and inferential (t or Z and Cohen's d) statistics for peak (P1, N1, P2, N2) amplitude (μV) and latency (ms) measure at sites F3/AF3 and F4/AF4 for Neuroscan versus EPOC in the active condition.

					EEG System			
Tone	ERP	Measure	Electrode	n	Neuroscan	EPOC	stat.	d
Standard	P1	Amplitude	F3/AF3	19	3.34 [2.4, 4.3]	3.63 [2.5, 4.8]	-0.89^	0.13
			F4/AF4	19	3.36 [2.4, 4.3]	3.43 [2.3, 4.6]	-0.14^	0.03
		Latency	F3/AF3	19	97 [89, 105]	103 [97, 109]	-3.06^**	0.41
			F4/AF4	19	98 [89, 107]	103 [96, 110]	-2.57^*	0.28
	N1	Amplitude	F3/AF3	7	-1.15 [-2.0, -0.3]	-1.03 [-2.1, 0.1]	-0.53	0.11
			F4/AF4	7	-1.07 [-2.2, 0.0]	-1.26 [-2.6, 0.1]	0.88	0.13
		Latency	F3/AF3	7	123 [112, 134]	137 [125, 149]	-3.53*	1.06
			F4/AF4	7	122 [109, 135]	134 [121, 147]	-4.65**	0.8
	P2	Amplitude	F3/AF3	7	0.25 [-1.3, 1.8]	0.34 [-1.1, 1.8]	-0.81	0.05
			F4/AF4	7	0.55 [-1.4, 2.5]	0.43 [-0.9, 1.7]	-0.24^	0.06
		Latency	F3/AF3	7	155 [135, 175]	166 [145, 187]	-4.11**	0.43
			F4/AF4	7	161 [144, 178]	172 [156, 188]	-3.59*	0.54
	N2	Amplitude	F3/AF3	19	-8.24 [-9.9, -6.6]	-7.02 [-8.7, -5.3]	-4.18***	0.34
			F4/AF4	19	-7.51 [-9.0, -6.0]	-7.07 [-8.5, -5.7]	-1.35	0.14
		Latency	F3/AF3	19	247 [238, 256]	257 [247, 267]	-5.02***	0.5
			F4/AF4	19	245 [231, 259]	264 [251, 277]	-2.88*	0.61
Deviant	P1	Amplitude	F3/AF3	19	2.69 [1.4, 4.0]	2.59 [1.1, 4.1]	-0.1^	0.03
			F4/AF4	19	2.66 [1.2, 4.2]	2.52 [0.9, 4.1]	-0.41^	0.04
		Latency	F3/AF3	19	90 [83, 97]	95 [87, 103]	-2.68*	0.38
			F4/AF4	19	93 [85, 101]	96 [90, 102]	-1.65^	0.2
	N1	Amplitude	F3/AF3	6	-3.29 [-8.5, 1.9]	-3.92 [-7.8, -0.1]	-0.4^	0.13
			F4/AF4	6	-2.09 [-6.5, 2.3]	-4.44 [-7.8, -1.1]	2.31	0.55
		Latency	F3/AF3	6	124 [101, 147]	121 [107, 135]	0.16	0.11
			F4/AF4	6	123 [105, 141]	132 [116, 148]	-3.66*	0.45
	P2	Amplitude	F3/AF3	6	1.44 [-2.7, 5.6]	-1.03 [-4.4, 2.3]	2.09	0.6
			F4/AF4	6	0.70 [-3.8, 5.2]	-0.66 [-3.6, 2.3]	-0.78^	0.32
		Latency	F3/AF3	6	160 [137, 183]	166 [141, 191]	-1.34	0.22
			F4/AF4	6	161 [135, 187]	166 [138, 194]	-0.28	0.17
	N2	Amplitude	F3/AF3	19	-11.10 [-13.4, -8.8]	-9.76 [-11.8, -7.7]	-2.5*	0.29
			F4/AF4	19	-10.46 [-12.6, -8.4]	-10.32 [-12.2, -8.4]	-0.23	0.03
		Latency	F3/AF3	19	228 [212, 244]	240 [225, 255]	-2.09	0.36
			F4/AF4	19	235 [220, 250]	243 [228, 258]	-2.88*	0.25

Note: ^ Wilcoxon Z, * p < .05, ** p < .01, *** p < .001

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Table 5 Neuroscan versus EPOC EEG system P3 and MMN peak comparisons. Descriptive (n, M [lower, upper 95% confidence intervals]) and inferential (t or Wilcoxon Z and Cohen's d) statistics for peak amplitude (μV) and latency (ms) measures produced by the Neuroscan and EPOC systems at F3/AF3 and F4/AF4 for the P3 ERP peak (to deviant tones in the active condition) and the MMN ERP component (the difference between ERPs to standard and deviant tones in the passive condition).

				EEG System			
ERP	Measure	Site	n	Neuroscan	EPOC	stat.	d
P3	Amplitude	F3/AF3	16	-2.98 [-5.0, -0.9]	-2.20 [-4.0, -0.4]	-1.87	0.21
		F4/AF4	16	-3.62 [-5.9, -1.4]	-2.53 [-4.8, -0.2]	-2.43*	0.24
	Latency	F3/AF3	16	331 [315, 347]	345 [327, 363]	-3.69**	0.41
		F4/AF4	16	328 [308, 348]	348 [331, 365]	-2.63*	0.57
MMN	Amplitude	F3/AF3	19	-4.35 [-5.6, -3.1]	-4.73 [-6.1, -3.4]	1.03	0.14
		F4/AF4	19	-4.87 [-6.2, -3.5]	-5.23 [-6.3, -4.1]	-0.85^	0.14
	Latency	F3/AF3	19	190 [172, 208]	200 [182, 218]	-3.23**	0.26
		F4/AF4	19	188 [170, 206]	204 [188, 220]	-2.99**	0.45

Note: ^ Wilcoxon Z, * p < .05, ** p < .01, *** p < .001

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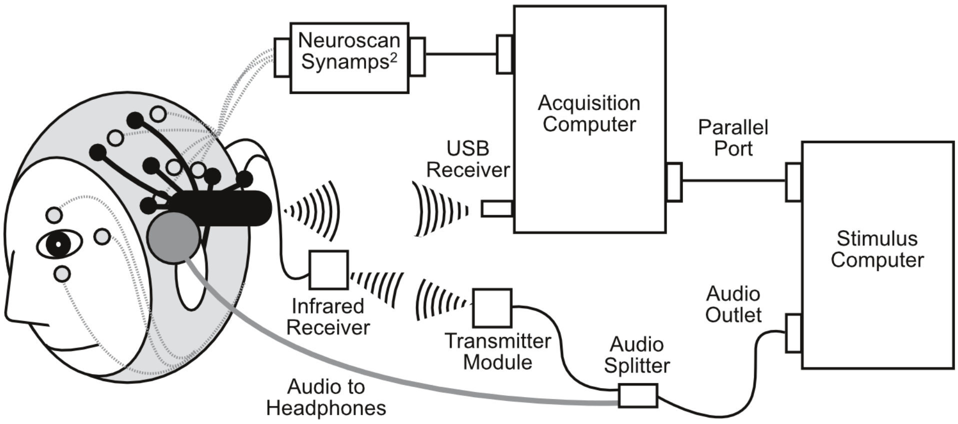

Figure 1 Schematic diagram of simultaneous Neuroscan (in grey) and EPOC (in black) setup, including infrared transmission for EPOC event markers.

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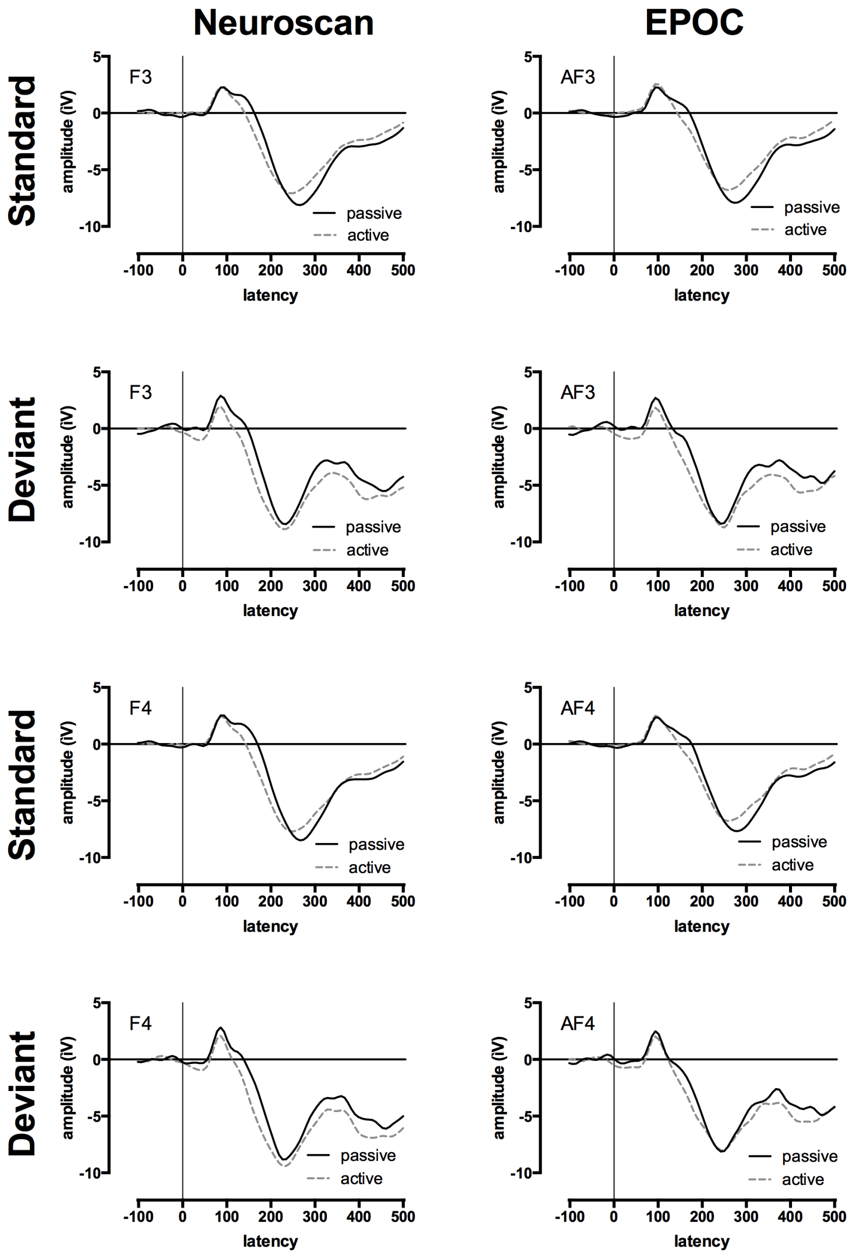

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386 Figure 2 Auditory ERP waveforms for the standard and deviant stimuli in the passive

387 (unbroken line) and active conditions (broken line) for the Neuroscan (left) and EPOC (right)

388 systems.

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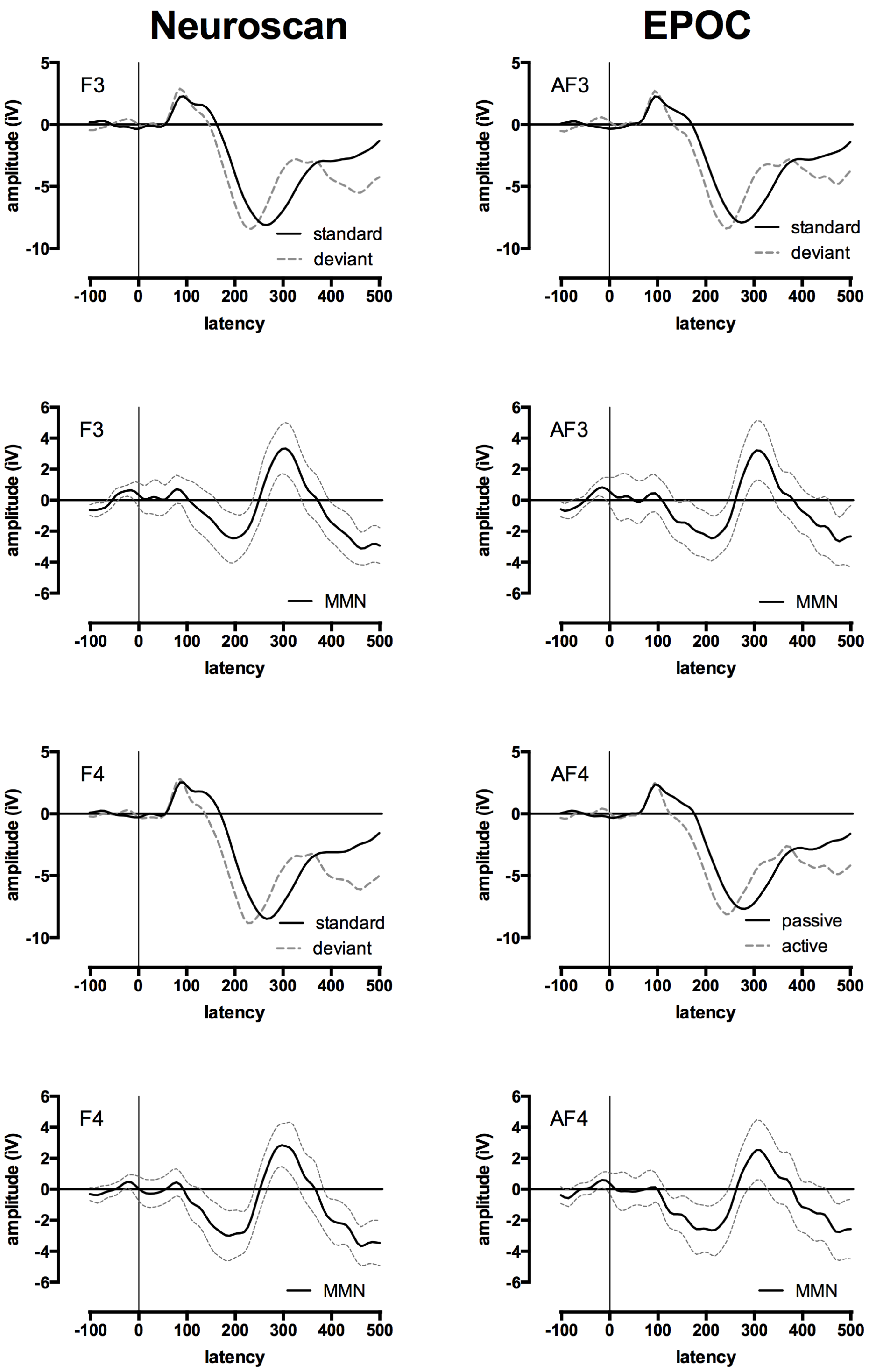

Figure 3 Event-related potential (ERP) waveforms for standard tones (unbroken line), deviant (broken line) tones, and the difference between standard and deviant tones (i.e., the MMN; unbroken line represent the 95% confidence intervals) produced by the Neuroscan (left) and EPOC (right) systems at F3/AF3 (top) and F4/AF4 (bottom).

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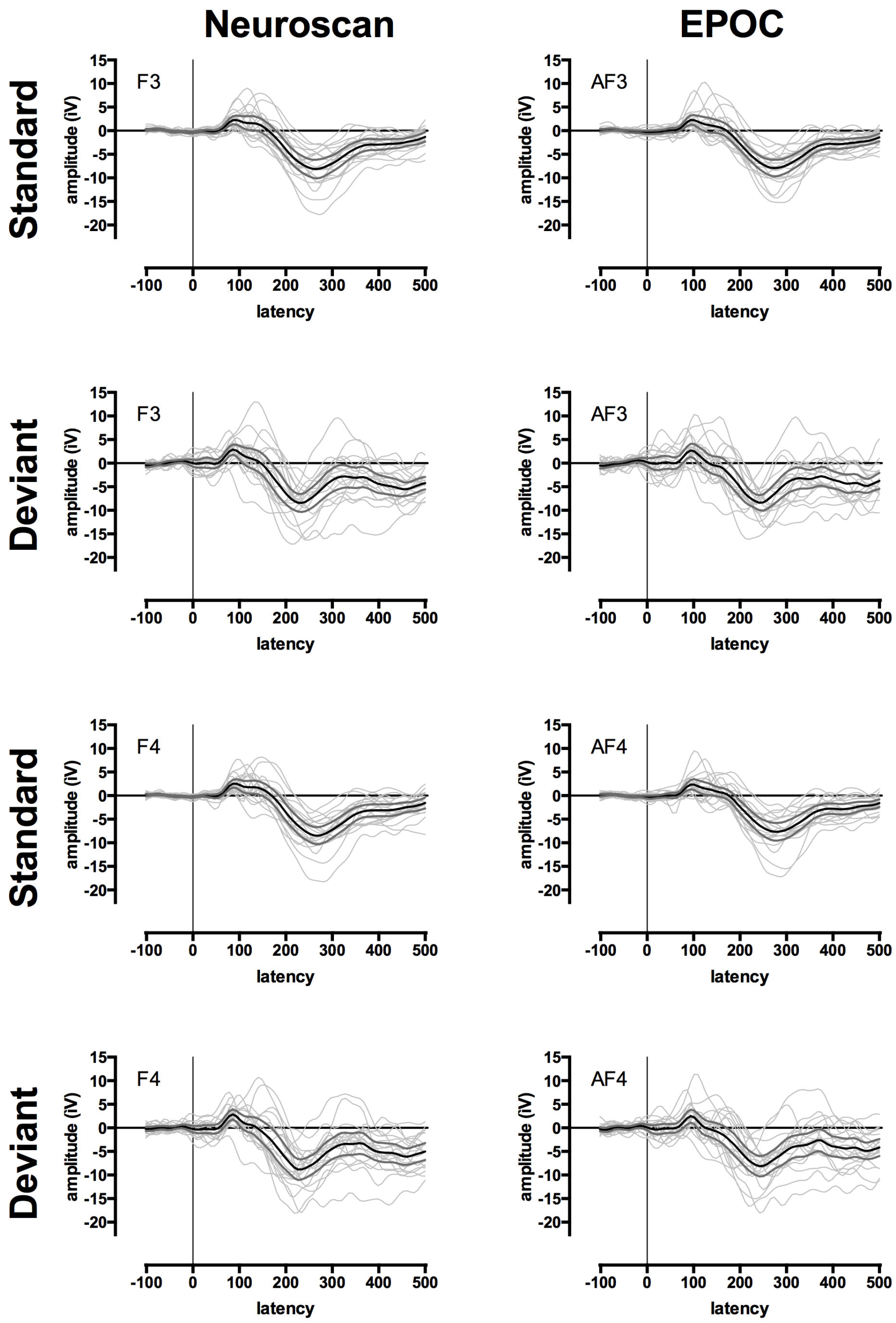

Supplementary Figure 1 The auditory ERP waveforms of individuals (grey lines) at F3/AF3 and F4/AF4 for standard and deviant stimuli in the passive condition for the Neuroscan (left) and EPOC (right) systems. The black line represents mean and the bold grey are the 95% confidence intervals.

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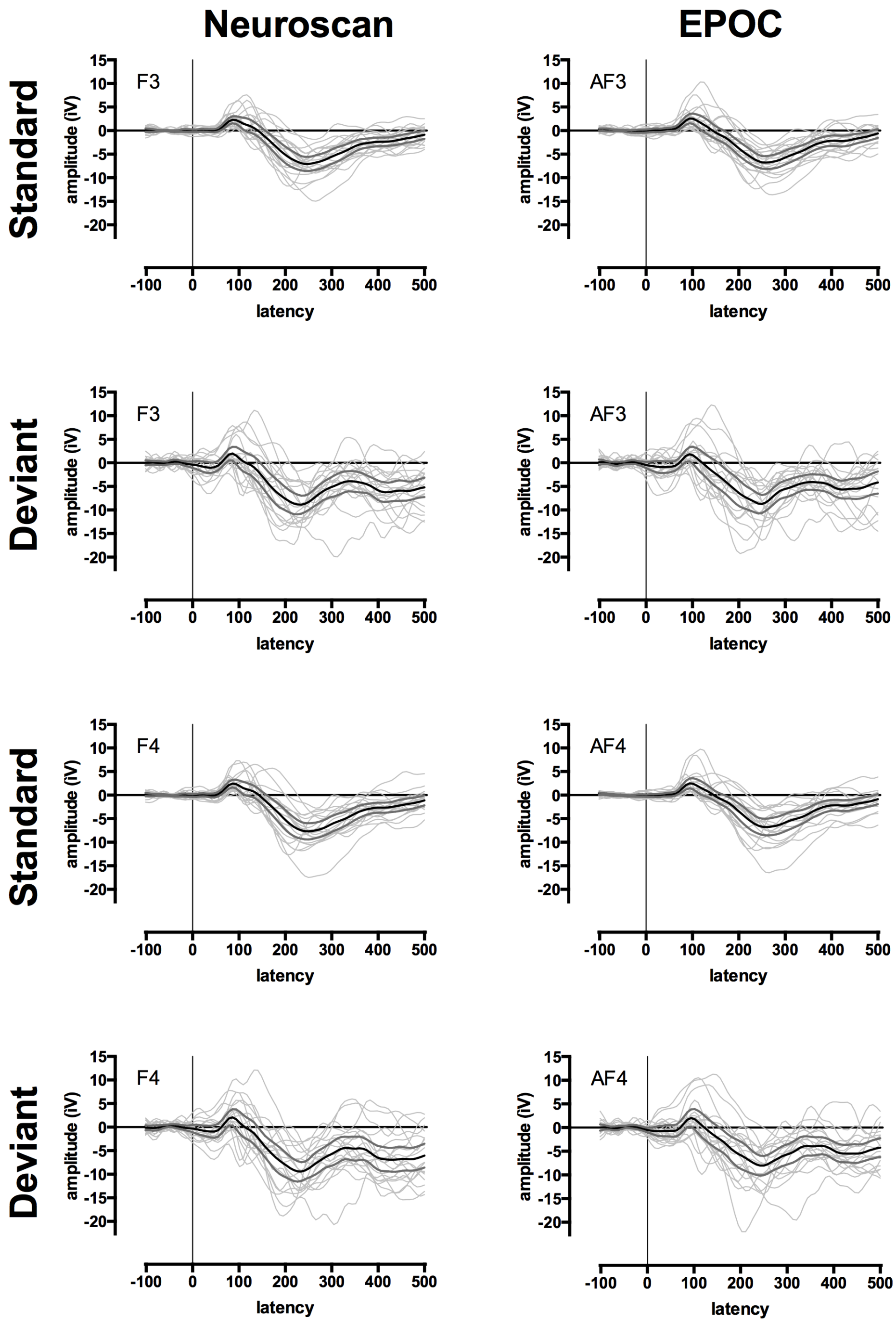

Supplementary Figure 2 The auditory ERP waveforms of individuals (grey lines) at F3/AF3 and F4/AF4 for standard and deviant stimuli in the active condition for the Neuroscan (left) and EPOC (right) systems. The black line represents mean and the bold grey are the 95% confidence intervals.

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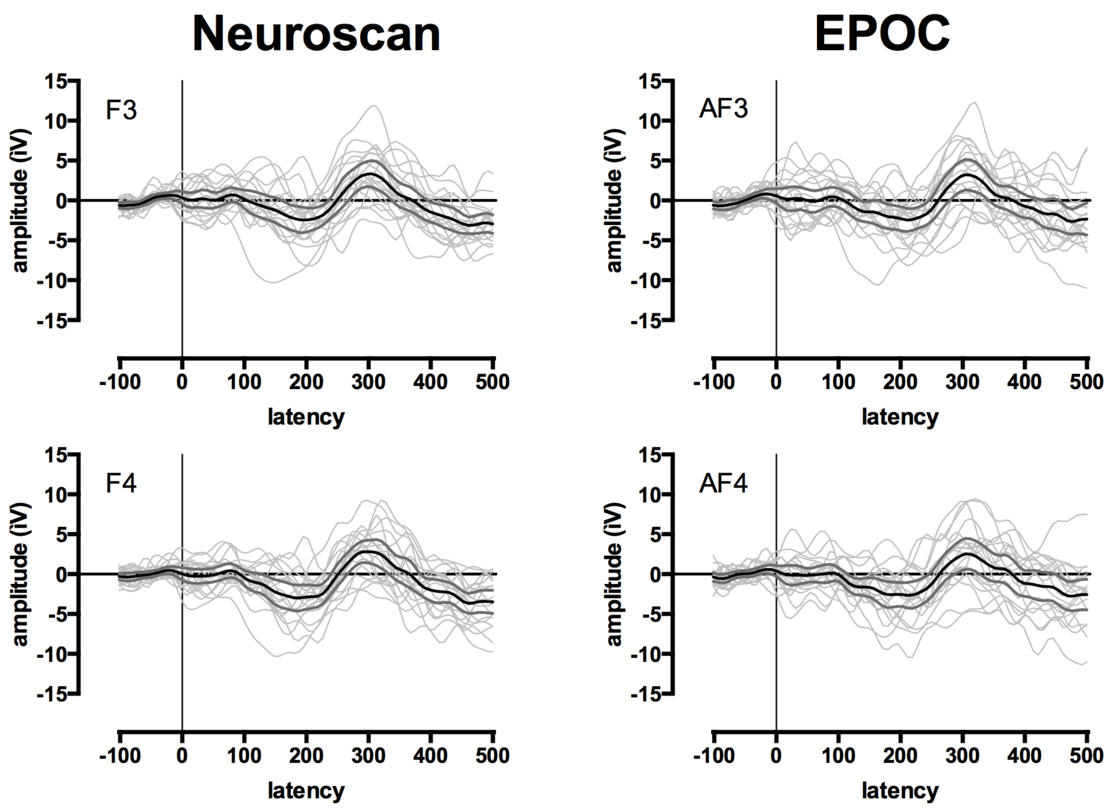

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405 Supplementary Figure 3 The MMN waveforms of individuals (grey lines) at F3/AF3 and

406 F4/AF4 for standard and deviant stimuli in the passive condition for the Neuroscan (left) and

407 EPOC (right) systems. The black line represents mean and the bold grey are the 95%

408 confidence intervals.