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Measuring the face-sensitive N170 with a gaming EEG system: A validation study

Peter de Lissa[a,*], Sidsel Sörensen[a], Nicholas Badcock[a], Johnson Thie[b], Genevieve McArthur[a]

[a] Department of Cognitive Science, ARC Centre of Excellence in Cognition and its Disorders, Macquarie University, Sydney, NSW, Australia
[b] School of Electrical and Information Engineering, University of Sydney, Sydney, NSW, Australia

HIGHLIGHTS

- Can a portable, inexpensive gaming EEG system measure the face-sensitive N170?
- Face/object evoked N170 peaks were recorded with research and gaming EEG systems.
- The gaming system ERP's were highly correlated with the research grade ERP's.
- A cheap, portable gaming system can reliably record face-sensitive N170 peaks.

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ABSTRACT

Background: The N170 is a "face-sensitive" event-related potential (ERP) that occurs at around 170 ms over occipito-temporal brain regions. The N170's potential to provide insight into the neural processing of faces in certain populations (e.g., children and adults with cognitive impairments) is limited by its measurement in scientific laboratories that can appear threatening to some people.
New method: The advent of cheap, easy-to-use portable gaming EEG systems provides an opportunity to record EEG in new contexts and populations. This study tested the validity of the face-sensitive N170 ERP measured with an adapted commercial EEG system (the Emotiv EPOC) that is used at home by gamers.
Results: The N170 recorded through both the gaming EEG system and the research EEG system exhibited face-sensitivity, with larger mean amplitudes in response to the face stimuli than the non-face stimuli, and a delayed N170 peak in response to face inversion.
Comparison with existing method: The EPOC system produced very similar N170 ERPs to a research-grade Neuroscan system, and was capable of recording face-sensitivity in the N170, validating its use as research tool in this arena.
Conclusions: This opens new possibilities for measuring the face-sensitive N170 ERP in people who cannot travel to a traditional ERP laboratory (e.g., elderly people in care), who cannot tolerate laboratory conditions (e.g., people with autism), or who need to be tested in situ for practical or experimental reasons (e.g., children in schools)

1. Introduction

The brain has yielded some of its secrets to our technical devices, giving a glimpse of the function and architecture of its operation. Event-related potential (ERP) measures taken from the human scalp have revealed a pattern of neural sensitivity to the perception of faces in comparison to other objects in the visual environment. This face-sensitive ERP, occurring at approximately 170 ms over occipito-temporal brain regions after visual presentation, is known as the N170 (Bentin et al., 1996; Eimer, 1998). The N170 is not only larger in response to faces than to other objects, but is sensitive to structural disruption of faces through face inversion, which significantly delays the N170 latency (Itier et al., 2006; Itier and Taylor, 2004; Linkenkaer-Hansen et al., 1998; Rossion et al., 2000). The N170 is also affected by perception of face-related characteristics, such as race (Vizioli et al., 2010), featural spacing (Maurer et al., 2002), and viewer-related characteristics, such as prosopagnosia (i.e., an impaired in recognising familiar faces) and social impairment (e.g., autism, schizophrenia; Feuerriegel et al., 2014).

* Corresponding author. Tel.: +61 2 9850 4121; fax: +61 2 9850 6059.
E-mail address: peter.delissa@mq.edu.au (P. de Lissa).

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A limiting factor of the N170 as a tool for understanding face processing in humans is that it is typically measured using a research-grade electroencephalograph (EEG) system installed in a laboratory. While this allows for control over environmental factors that might influence the recording of human brain potentials, it limits the type and number of participants that participate in N170 studies. For example, some people with cognitive disorders, such as autism or schizophrenia, find it difficult to tolerate research laboratory conditions. This restricts N170 research to a select subsample of high functioning people with these disorders who are not necessarily representative of the entire population with the disorder.

A potential solution to this problem lies in recent advances in the development of portable and inexpensive EEG headsets for use in gaming environments (e.g., Emotiv EPOC®, Imec's wireless EEG headset, NeuroFocus MyndTM, Neurokeeper's headset, NeuroSky Mindwave®). Another dimension of interest in these devices is that they are relatively inexpensive, which may provide an efficient avenue for research groups to investigate brain potentials in various contexts or paradigms which otherwise may not be suitable or available through research-grade systems. In their commercial form, these gaming devices do not readily allow for the measurement of ERPs, since they are not equipped to "timelock" EEG responses to particular stimuli. However, scientists have been able to modify these commercial devices in appropriate ways that allow the creation of ERPs from EEG data. For example, Debener et al. (2012) found that a modified Emotiv EPOC headset could be used to record an auditory P300 ERP in a quiet office and while walking outdoors, results which were reinforced in a replication study investigating the P300 in outdoor environments using single-trial analyses (De Vos et al., 2014a,b). De Vos et al. (2014a,b) further compared the wireless Emotiv EPOC amplifier with a wired research grade EEG amplifier in a visual P300 paradigm (alternating recording through each amplifier system while utilizing the same electrode setup), finding similar EEG/ERP patterns in both voltage amplitudes and topography. Badcock et al. (2013, 2015) reported that an adjusted Emotiv EPOC headset produced late auditory ERP peaks (i.e., the P1, N1, P2, N2, and P3 peaks) similar in size and morphology to those generated by a research-grade Neuroscan EEG system.

To date, no study has compared visually evoked N170 peaks elicited recorded through a modified gaming EEG device and a research-grade EEG system. Given the potential of gaming EEG devices to generate valid visual ERPs in people who are difficult to test in laboratory settings (e.g. people with autism or schizophrenia) or who are difficult to access (e.g., people confined to hospitals, nursing homes, or home), and the relatively inexpensive nature of these devices, the aim of the current study was to test the validity of the face-sensitive N170 ERP measured with an adjusted gaming EEG system. To this end, we compared the N170 response to upright and inverted faces and objects through simultaneous EEG recordings by a commercial gaming 14-channel Emotiv EPOC EEG headset (the "EPOC system") and a research-grade Neuroscan EEG system with a 14-channel Easycap Ag-AgCl electrode array (the "Neuroscan system").

2. Materials and methods

The Human Ethics Committee at Macquarie University approved the methods used in this study. All participants gave their informed and written consent to participate in the study.

2.1. Participants

Fourteen Macquarie University undergraduate students took part in the study. One participant was excluded due to heavy EEG contamination from facial movements. The participants (8 females, 11 right-handed) were aged between 16 and 27 years (mean age = 20.8 years) and had normal or corrected-to-normal vision.

2.2. Stimuli

The stimuli were upright and inverted gray-scale images of wrist-watches and emotionally-neutral Caucasian faces, cropped within a standard-sized oval frame where only internal face parts were visible. There were 75 unique identities/watches in each of four conditions (upright faces, upright watches, inverted faces, inverted watches), yielding a total of 300 images presented per testing session. The face images were obtained from seven databases: NimStim (Tottenham et al., 2002), the Karolinska Directed Emotional Faces (KDEF; Lundqvist et al., 1998), Gur et al. (2002), Computational Vision Archive (courtesy of Caltech), the MIT-CBCL (Weyrauch et al., 2004), the Ekman and Friesen face set (Ekman and Friesen, 1976), and a set from Kieran Lee and David Perrett of St Andrews University. The non-face wristwatch stimuli were sourced from the University of Kansas Information and Telecommunication Technology Centre database.

Each trial began with a white 500-ms fixation cross in the centre of a computer screen that had a black background. This was immediately replaced with a 200-ms upright or inverted face or watch, which was followed by a blank black screen until a response was made. Participants were asked to indicate whether the image was upright or inverted through a binary keyboard response. A response was followed by a 2000-ms "blink" screen before a new trial commenced. The stimuli were presented by Experiment Builder software (ver 1.6.1) on a 19" CRT computer monitor with a refresh rate of 100 Hz at a distance of 50 cm from the participant. As such, each image was $17.4^\circ \times 12.7^\circ$ degrees of visual angle.

2.3. Emotiv EPOC EEG system

As mentioned above, commercial gaming EEG systems are not primarily designed for the measurement of ERPs since they lack a temporally-reliable stimulus event triggering port. This limitation was addressed using a marker-triggering circuit that injected an electrical pulse into two EEG channels (T7 and T8) of the EPOC system at the onset of a stimulus (Badcock et al., 2013; Thie, 2013). The marker-triggering circuit (circuitry and function outlined in Thie, 2013) was connected to the EPOC headset through two electrical wires, which were screwed underneath the left T7 and right T8 electrodes. As per the requirements of the marker-triggering circuit, these trigger channels were then biased to the right DRL channel by connecting them with electrical wires to a 4.7 kΩ resistor, which was then wired into the DRL electrode (Figs. 1 and 2).

The marker circuit was activated in each trial by a phototransistor placed over a small corner section of the stimulus display monitor. Accordingly, each trial involved a concurrent 200-ms presentation of a critical visual stimulus (an upright or inverted face or watch) and a small white square presented under the phototransistor. The marker circuit involved a consistent 24-ms delay between detection of the signal from the phototransistor and the onset of the electrical pulse in the triggering channels. This latency was removed from each of the event-markers, after a pulse-detection algorithm determined the timing of the onset of the trigger-pulses in the EEG recording offline. The onset times of these electrical spikes were co-registered with the stimulus presentation sequence to provide a reliable index of the timing of each stimulus event.

A limitation of the EPOC system as a tool for measuring the face-sensitive N170 in particular is the use of the left CMS (Common

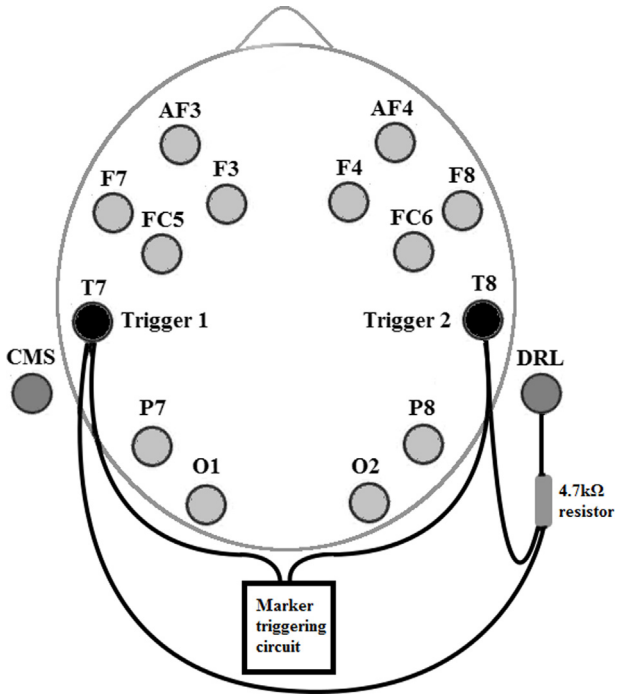

Fig. 1. The electrode sensor array of the Emotiv EPOC, and wiring modifications incorporating the marker-triggering circuit.

Mode Sense) reference point at either the left P3 electrode or the left mastoid electrode (M1). Studies investigating early face-sensitive brain potentials have shown that the choice of reference site strongly modulates the face-sensitive N170. Specifically, use of a common average reference (i.e., the mean of all scalp electrodes) generates a relatively large N170 over occipito-temporal areas, while use of mastoid references generates a relatively large vertex positive peak (VPP) over central/frontal regions (i.e., the positive part of the dipole eliciting the occipito-temporal N170; see Joyce and Rossion, 2005 for a review). However, the use of a common average reference is problematic for the EPOC system as the number and positioning of the electrodes may not yield a balanced

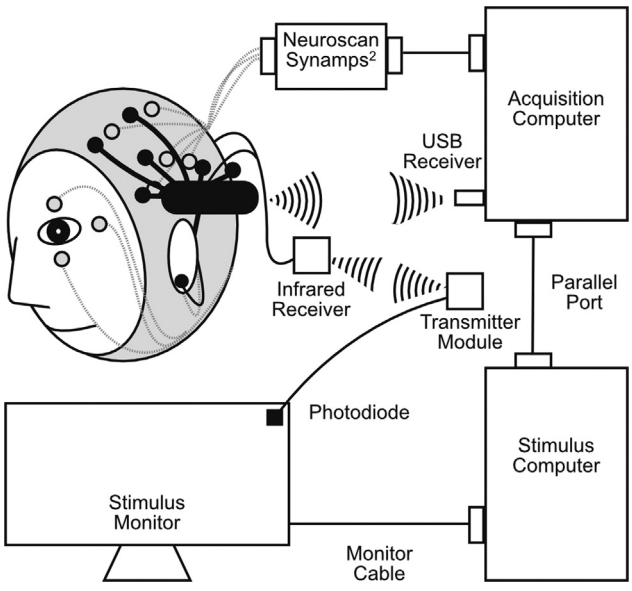

Fig. 2. The recording system setup for the EPOC and Neuroscan EEG systems that includes the event triggering system of the adapted EPOC EEG system.

and comprehensive array (Luck, 2005). The use of the left mastoid alone as a reference would, in turn, lead to a face-sensitive effect in mid-frontal regions not specifically sampled by sensors. The earlobes, however, have been found to be a reliable reference point from which to record occipito-temporal N170 peaks, leading to face sensitivity manifesting in both the N170 and VPP peaks (Joyce and Rossion, 2005). For these reasons, we therefore re-routed the left (CMS) and right (DRL) sensors of the EPOC system to the participants' left and right earlobes by wiring Ag–AgCl Easycap electrodes into the fixed M1 and M2 sensors. The use of reference electrodes of different materials to the scalp sensors constitutes a deviation from standard practice in EEG, potentially leading to an imbalance of DC offsets due to such differences (Gutberlet et al., 2009). This compromise was made in the current study to allow for the positioning of the reference electrodes in a manner that was tailored to addressing the question of N170 sensitivity, which may otherwise have been picked up and thus distorted through mastoid references.

2.4. EEG online recording

EEG data was simultaneously recorded via the EPOC and Neuroscan systems. The location of each set of scalp electrodes was defined by the Neuroscan system, which used an Easycap electrode cap with 16 electrodes (including references) placed according to the international 10–20 system (FC3, FC4, F3, F4, FT7, FT8, F7, F8, T7, T8, P7, P8, O1, O2, M1 (online reference at left earlobe), & M2 (offline reference at right earlobe). Holes were cut into the Easycap to allow the electrodes of the EPOC system to be placed on scalp regions immediately adjacent to the Easycap electrodes (i.e., at AF3, AF4, F3, F4, FC5, FC6, F7, F8, T7, T8, P7, P8, O1, O2, CMS (left earlobe), and DRL [right earlobe]). The left and right earlobes were used as online and offline references for the Neuroscan system, whereas the Emotiv system used the left earlobe as an online reference, and the right earlobe for the DRL sensor. Thus, four electrodes were attached to the earlobes of each participant. This was achieved by placing the EPOC references on one inner and one outer earlobe, and vice-versa for the Neuroscan system. This pattern was alternated between participants to counterbalance any possible systematic effect such placement might introduce. Electrode impedances for electrodes in the research system were kept below 5 kΩ, while the EPOC system uses a proprietary impedance value system.

For the Neuroscan system, Ag/AgCl sintered electrodes were connected with the scalp using a research-grade non-abrasive saline/chloride gel. For the EPOC system, the gold-plated (coated in an electrochemically-active material infused polymer) electrodes were connected with the scalp via cotton pads soaked in sodium chloride saline solution (as is typical for gaming systems) plus a small amount of the saline gel added to sensor scalp sites to better equate the conductive mediums between the EPOC and Neuroscan systems. The amount of gel was not sufficient to form a bridge between neighbouring EPOC and Neuroscan system electrodes. The gel did not make physical contact with the EPOC electrodes, and the cotton-pads were removed from the electrodes after each testing session.

EEG signals detected by the EPOC electrodes were pre-processed within the headset (programmed by the manufacturer), passing through a 0.16-Hz high-pass filter pre-amplification process, as well as an 83-Hz low-pass filter, before being digitized at 2048 Hz. Two notch filters were then applied at 50 and 60 Hz before further low-pass filtering was performed with a 43-Hz cut-off. The signal was then down-sampled to 128 Hz and transmitted to a recording computer via a proprietary wireless signal. In contrast, EEG signals detected by the Neuroscan system electrodes were sampled through a Synamps II amplifier at a sampling rate of 1000 Hz, with an online band-pass filter of 1 to 100 Hz, and a notch filter at 50 Hz.

2.5. EEG offline processing

The EEG data from both systems was processed offline with EEGLAB version 11.0.4.3b software (Delorme and Makeig, 2004). In order to match the sampling rate of the EPOC system, EEG data from the Neuroscan system was down-sampled to 128 Hz. The EEG data from the Neuroscan system was then re-referenced offline to the mathematically linked left and right earlobe electrodes, while the EPOC system incorporated the left earlobe as an online common-mode sense reference point online. EEG data from both systems were filtered through a band-pass of 0.1–30 Hz with a 12 dB/octave roll-off. EEG artefacts were excluded by visual analysis and then ocular artefact correction was performed through independent component analysis (ICA; Vigario, 1997; Delorme and Makeig, 2004). The cleaned EEG data was imported into Neuroscan Edit 4.5 software and then converted into condition-specific −102 to 602 ms epochs. Trials containing EEG signals exceeding ±150 μV were excluded from analysis.

For each system, the accepted EEG epochs for each participant were averaged together to produce ERPs at each scalp site to upright faces, inverted faces, upright watches, and inverted watches. Individuals' ERPs were averaged together to create grand average ERPs for each of the four experimental conditions. Visual analysis of the grand average waveforms of the four conditions confirmed the presence of a strong occipito-temporal negativity at P7 and P8 electrodes in both systems at approximately 170 ms, similar to the results of a recent study investigating the face-sensitive N170 using these sets of stimuli while recording through a 32-channel Neuroscan system (de Lissa et al., 2014) and in accord with previous studies (see Rossion and Jacques, 2007, for a review). Similarly, a distinct positive peak similar in morphology to a vertex positive peak (VPP) was observed over central frontal electrode sites at approximately 170 ms, maximally at the F3 and F4 electrodes. The VPP is thought to reflect the frontal–central part of the dipole producing the bilateral N170 peak, and is commonly represented as a central ERP waveform (Joyce and Rossion, 2005). Thus, as well as measuring the N170, we computed an average waveform from the F3 and F4 electrodes to represent the VPP.

2.6. Data analysis

The similarity of the N170 (at P7 and P8) and the VPP (at F3 and F4 combined; "F3/F4") measured by the EPOC gaming system and the Neuroscan research system was measured in three ways. First, intra-class correlations (ICCs; Fisher z corrected) were used to index the degree of similarity of the N170 and VPP waveforms (−100 ms to 600 ms) measured by each system (Badcock et al., 2013; Bishop and McArthur, 2005; Cassidy et al., 2012; McArthur et al., 2009, 2010; McArthur and Bishop, 2005; Shrout and Fleiss, 1979). We used 95% confidence intervals to determine if the ICCs of participants were statistically significantly greater than 0.

Second, the size of the N170 and VPP peaks were indexed using mean amplitudes that were calculated from a time window of 145 ms to 195 ms (centred around the N170/VPP peaks in the grand average waveform). Repeated measures ANOVAs were used to test the main effects of system (EPOC versus Neuroscan), stimulus type (faces versus watches), stimulus orientation (upright versus inverted), and hemisphere (P7 versus P8 for N170 only).

Third, the timing of the N170 and VPP peaks were indexed using peak latency measures that were indexed within a 50-ms time window that flanked the N170 and VPP peaks in the grand average waveforms (120–220 ms). A limitation of peak latency measures is that their validity depends upon the presence of clear peaks in the defined time interval for each participant. We tested the validity of our peak latency measures by comparing them to each participant's N170 and VPP waveforms. This revealed that the N170 and VPP peaks of many participants to watches were so small and indistinct that the peak detection algorithm did not produce valid peak latency scores. In one respect this was a positive outcome since it confirmed that our N170 and VPP ERPs were face-sensitive (i.e., these peaks were markedly smaller to non-face stimuli (i.e., watches) than face stimuli, which produced large peaks). However, it also meant that we could not include peak latency scores for watches in our analyses. Thus, we used repeated measures ANOVAs to test the peak latency data for main effects of system (EPOC versus Neuroscan), stimulus orientation (upright versus inverted), and hemisphere (P7 versus P8 for N170 only).

Due to the difference of a left-earlobe only reference in the Emotiv EPOC system compared with the common linked-earlobe reference in the Neuroscan system, an intra-class correlation analysis comparing the data obtained from the Neuroscan system using a linked-earlobe reference to a left earlobe only reference was conducted, to clarify potential differences in the brain potential data due to referencing system differences.

Levene's Tests for Normality ascertained that the distributions of ERP measures for upright and inverted faces and watches were normally distributed. The threshold for statistical significance was defined as $p \leq .05$.

3. Results

3.1. The N170

3.1.1. ICCs

Fig. 3 compares the N170 waveforms produced by the EPOC and Neuroscan systems, along with ICCs with 95% confidence intervals. The ICCs were strong (all at least 0.79). None of the confidence intervals included zero, and hence the ICCs for N170 for each type of stimulus were statistically significant.

3.1.2. Mean amplitude

Fig. 4 illustrates the same data as Fig. 3 rearranged to directly compare the N170 waveforms generated by faces versus watches (top) and upright faces versus inverted faces (bottom) by the EPOC and Neuroscan systems. Table 1 illustrates the N170 mean amplitudes (with standard deviations; SD) produced by the EPOC and Neuroscan systems for each condition at each electrode site. The repeated measures ANOVA revealed significant main effects of system, $F(1, 12) = 10.60$, $p = .01$, $\eta^2 = .47$, with larger overall mean amplitudes recorded by the EPOC system; and also stimulus type, $F(1, 12) = 30.87$, $p < .001$, $\eta^2 = .72$, because faces elicited larger N170 mean amplitudes than watches. Interactions were found between stimulus type and hemisphere, $F(1, 12) = 5.41$, $p = .04$, $\eta^2 = .31$, and between system, stimulus type, and hemisphere, $F(1, 12) = 6.13$, $p = .03$, $\eta^2 = .34$. Further ANOVAs were performed for each system separately to determine the source of the interactions. These revealed a significant main effect of stimulus type for both the Neuroscan system, $F(1, 12) = 31.89$, $p < .001$, $\eta^2 = .73$, and the EPOC system, $F(1, 12) = 28.47$, $p < .001$, $\eta^2 = .70$, reflecting larger mean amplitudes for faces than watches (see Fig. 4). An additional interaction between stimulus type and hemisphere was found for the EPOC system, $F(1, 12) = 6.28$, $p = .03$, $\eta^2 = .34$. Post-hoc t-tests revealed that the N170 was (1) significantly larger to faces than watches at both P7 at P8, $t(12) = -4.49$, $p = .001$ and $t(12) = -4.92$, $p < .001$, respectively; (2) significantly larger to faces at P8 than P7, $t(12) = 2.22$, $p = .046$, and (3) did not differ in size at P7 and P8 for watch stimuli, $t(12) = 0.38$, $p = .71$.

Additional analyses conducted on the Neuroscan ERP data referenced only to the left earlobe revealed the same patterns of face-sensitivity, $F(1, 12) = 26.99$, $p < .001$, $\eta^2 = .69$, with larger N170 amplitudes to faces than watches at both P7 at P8, $t(12) = -3.85$,

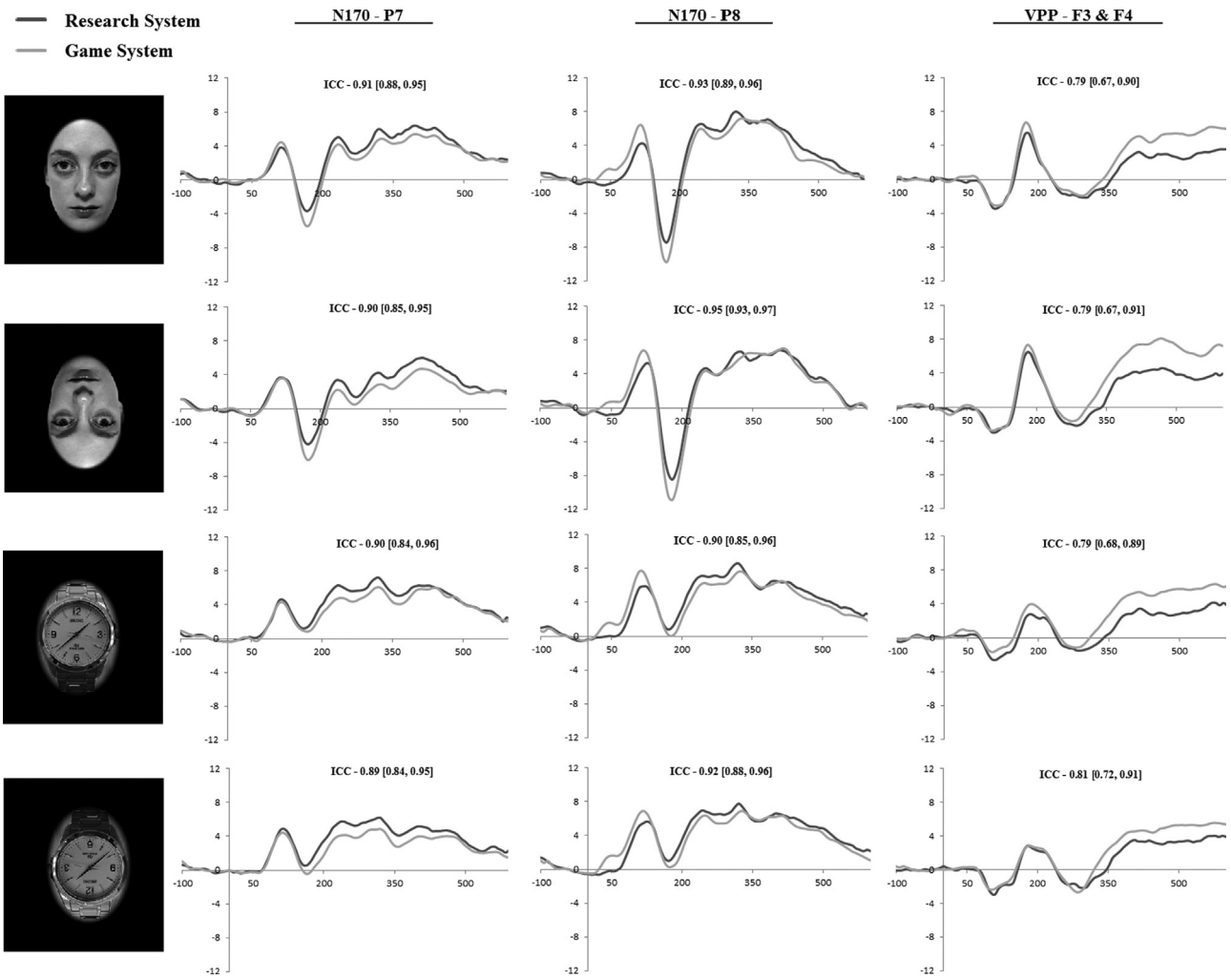

Fig. 3. N170 (negative peak at around 170 ms) and VPP (positive peak at around 170 ms) event-related potential (ERP) waveforms recorded by the EPOC gaming system (light grey lines) and the Neuroscan research-grade system (black lines). Fisher z intra-class correlation coefficients (ICC; with 95% confidence intervals) indicated a strong correspondence between waveforms produced by the two systems in all conditions (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

$p = .002$ and $t(12) = -4.49$, $p < .001$. There was also a significant main effect of system, $F(1, 12) = 8.03$, $p = .015$, $\eta^2 = .40$, with greater N170 amplitudes recorded through the EPOC system than the left-only referenced Neuroscan system. These results, coupled with a .96 correlation between the waveforms of data referenced to the linked earlobes and a left-only earlobe in the Neuroscan system suggests a left-earlobe only reference may be used to obtain reliable patterns of face-sensitivity (Fig. 5).

3.1.3. Peak latency

Table 1 illustrates mean N170 peak latency measures (with standard deviations; SD) produced by the EPOC and Neuroscan

Table 1
Means (*M*) and standard errors (SE) for mean amplitude (MA; in microvolts; mV) and peak latency (PL; in milliseconds; ms) measures for the N170 (at P7 and P8) and vertex positive peak (VPP; at F3 and F4) event-related potential (ERP) peaks produced by the Neuroscan research-grade system and the EPOC gaming system. NA = not applicable since latency measures were not valid for watch stimuli (see Results).

System	ERP	Site	Measure	Faces		Watches	
				Upright *M* (SE)	Inverted *M* (SE)	Upright *M* (SE)	Inverted *M* (SE)
Neuroscan	N170	P7	MA (mV)	−2.3 (1.2)	−2.6 (1.1)	2.0 (1.0)	1.5 (0.9)
			PL (ms)	169 (5)	177 (5)	NA	NA
		P8	MA (mV)	−4.9 (1.5)	−5.3 (1.8)	1.8 (0.8)	2.0 (0.9)
			PL (ms)	174 (4)	183 (3)	NA	NA
	VPP	F3/F4	MA (mV)	3.5 (1.2)	3.9 (1.0)	1.4 (0.7)	1.4 (0.6)
			PL (ms)	180 (4)	180 (3)	NA	NA
EPOC	N170	P7	MA (mV)	−3.7 (1.4)	−4.1 (1.4)	1.4 (1.0)	0.3 (0.9)
			PL (ms)	171 (5)	177 (5)	NA	NA
		P8	MA (mV)	−6.8 (1.8)	−7.2 (2.0)	1.2 (1.0)	1.2 (1.0)
			PL (ms)	175 (4)	181 (3)	NA	NA
	VPP	F3/F4	MA (mV)	4.6 (1.3)	4.8 (0.9)	2.7 (1.1)	1.7 (1.0)
			PL (ms)	178 (3)	182 (4)	NA	NA

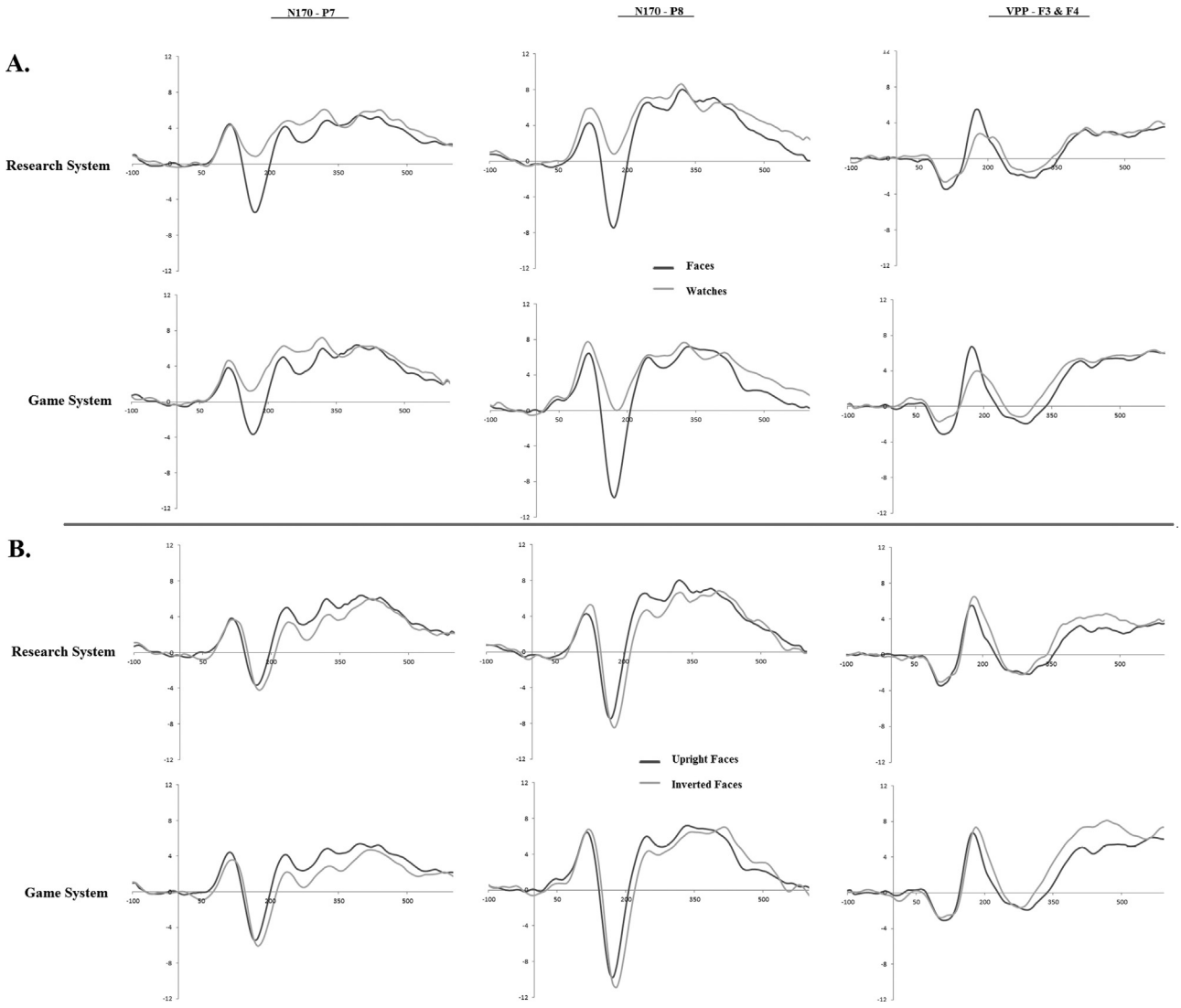

Fig. 4. (A) Event-related potential (ERP) waveforms to faces (black lines) and watches (grey lines) produced by the EPOC gaming system and Neuroscan research-grade system. (B) ERP waveforms to upright faces (black lines) and inverted faces (grey lines) produced by the EPOC gaming system and Neuroscan research-grade system (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

systems for each condition at each electrode site. The repeated measures ANOVA revealed a significant main effect of face orientation, $F(1, 12) = 40.75$, $p < .001$, $\eta^2 = .77$, because inverted faces elicited a later N170 peak (180 ms) than upright faces (172 ms). However, this significant main effect was qualified by an interaction with system, $F(1, 12) = 6.26$, $p = .03$, $\eta^2 = .34$. Pairwise comparisons showed that while face inversion significantly delayed the N170 peaks in both systems (Neuroscan: $t(12) = 4.37$, $p < .001$; EPOC: $t(12) = 4.88$, $p < .001$, this delay was significantly larger in the Neuroscan system than the EPOC system $t(12) = 2.50$, $p = .03$. It should

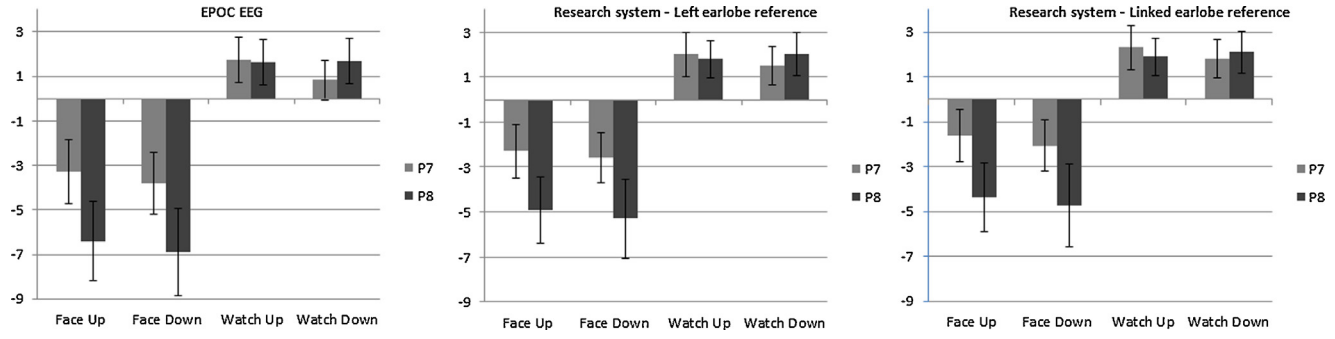

Fig. 5. ICC comparisons of voltages in the ERP waveforms produced in the Neuroscan EEG system when referencing to linked earlobes or left-only earlobes revealed minimal differences, with an average correlation of .96.

be noted that this measured delay (8 ms) approximately equals one time sample (7.8 ms) for the EPOC system, and is therefore of uncertain accuracy.

3.2. The VPP

3.2.1. ICCs

Fig. 3 compares the VPP waveforms produced by the EPOC and Neuroscan systems, along with mean ICCs with 95% confidence intervals. The ICCs were all strong (all at least 0.79). None of the confidence intervals included zero, and hence the ICCs for VPP for each type of stimulus were statistically significant.

3.2.2. Mean amplitude

Fig. 4 compares the VPP waveforms generated by faces versus watches (top) and upright faces versus inverted faces (bottom) by the EPOC and Neuroscan systems. Table 1 illustrates the VPP mean amplitudes (with standard deviations; SD) produced by the EPOC and Neuroscan systems for each condition at each electrode site. The repeated-measures ANOVA revealed a significant main effect of stimulus type, $F(1, 12) = 27.93$, $p < .001$, $\eta^2 = .70$, with larger amplitudes elicited by faces than watches. There was no main effect of system, $F(1,12) = 1.58$, $p = .23$, or stimulus orientation, $F(1,12) = 0.09$, $p = .77$. However, there was an interaction between system and stimulus orientation, $F(1, 12) = 8.27$, $p = .014$, $\eta^2 = .41$, because the VPP was larger to inverted than upright stimuli (i.e., across faces and watches) for the Neuroscan system, while the opposite pattern was observed for the EPOC system.

3.2.3. Peak latency

Table 1 illustrates mean VPP peak latency measures (with standard deviations; SD) produced by the EPOC and Neuroscan systems for each condition at each electrode site. The repeated-measures ANOVA found no main effects of system or face orientation, $F(1, 12) = 0.10$, $p = .76$, and $F(1,12) = 1.88$, $p = .20$, respectively, and no significant interaction, $F(1,12) = 1.93$, $p = .19$.

4. Discussion

The aim of the current study was to test the validity of the face-sensitive N170 ERP measured with an adapted EPOC gaming system. The ICC measures revealed that the N170 and VPP ERP waveforms produced by the EPOC system were very similar to those produced by the Neuroscan system in all conditions. Critically, the N170 and VPP ERPs recorded by both systems exhibited face-sensitivity, with larger mean amplitudes in response to the face stimuli than the non-face stimuli (i.e., watches), as well as delayed N170 and VPP peaks in response to face-inversion. Thus, both the EPOC and Neuroscan EEG systems in this study successfully replicated two key effects reliably found in ERP studies of face processing (Itier et al., 2006; Rossion et al., 2000). Combined with the positive outcomes of a previous validation of the EPOC system for measuring auditory ERPs (Badcock et al., 2013), these results support the use of an adapted EPOC EEG system as a valid alternative (or complement) to research-grade EEG systems for measuring both face-sensitive ERPs and late auditory ERP peaks in situations where a research-grade system is untenable or inappropriate.

Two interesting and unexpected outcomes of this study were that the EPOC system produced larger N170 and VPP peaks than the Neuroscan system (see Fig. 3), and that the EPOC system–but not the Neuroscan system—detected an enhanced face sensitivity in the right hemisphere, as has been reported by previous N170 studies (for review see Rossion and Jacques, 2007). This may have resulted from slight differences in electrode placement. As outlined in the Methods, the electrodes for the EPOC and Neuroscan systems were placed adjacent to each other on participants' heads. It is possible that the electrodes for the EPOC system were inadvertently placed in slightly more appropriate locations for indexing N170 and VPP brain potentials. Since the electrodes for the research-grade Neuroscan system were placed according to the 10–20 international system, such a finding may simply reflect the imperfect nature of electrode placement when measuring any brain potential over the scalp. However, studies utilizing such gaming EEG systems in future would benefit from having a structured system of electrode placement to prevent headset movement or inter-participant variability in placement.

In sum, the current study aimed to evaluate the suitability of the EPOC EEG headset as a tool to investigate the face-sensitivity of the N170 and VPP peaks. The premise was that if such a device were able to reliably record these face-sensitive patterns of neural activity, the portability and ease of use of these headsets might further expand the horizons of research in this area to permit ERP testing of participants of various characteristics in various contexts. With the advent of relatively inexpensive gaming EEG systems, the use of such systems as alternatives to research-grade systems requires validation before their accuracy in laboratory and non-laboratory settings is accepted. The results of this study suggest that face-sensitivity of the N170 can be recorded through such a device with a reliability comparable to a research-grade system, though with modifications tailored to specific research-questions and methodologies. Thus, the use of such devices may prove a useful neuroscientific tool for investigating the neural correlates of face processing in populations of people who cannot attend, or cannot tolerate, ERP research laboratories.

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References

Badcock NA, Mousikou P, Mahajan Y, de Lissa P, Thie J, McArthur GM. Validation of the emotiv EPOC® EEG gaming system for measuring research quality auditory ERPs. PeerJ 2013;1:e38, http://dx.doi.org/10.7717/peerj.38.

Badcock NA, Preece KA, de Wit B, Glenn K, Fieder N, Thie J, et al. Validation of the emotiv EPOC EEG system for research quality auditory event-related potentials in children. PeerJ 2015;01(2015):3, http://dx.doi.org/10.7717/peerj.907.

Bentin S, Allison T, Puce A, Perez E, McCarthy G. Electrophysiological studies of face perception in humans. J Cogn Neurosci 1996;8(6):551–65, http://dx.doi.org/10.1162/jocn.1996.8.6.551.

Bishop DVM, McArthur GM. Individual differences in auditory processing in specific language impairment: a follow-up study using event-related potentials and behavioural thresholds. Cortex 2005;41:327–41, http://dx.doi.org/10.1016/S0010-9452(08)70270-3.

Cassidy S, Robertson IH, O'Connell RG. Retest reliability of event-related potentials: evidence from a variety of paradigms. Psychophysiology 2012;49(5):659–64, http://dx.doi.org/10.1111/j.1469-8986.2011.01349.x.

Debener S, Minow F, Emkes R, Gandras K, de Vos M. How about taking a low-cost, small, and wireless EEG for a walk? Psychophysiology 2012;49:1617–21, http://dx.doi.org/10.1111/j.1469-8986.2012.01471.x.

de Lissa P, McArthur G, Hawelka S, Palermo R, Mahajan Y, Hutzler F. Fixation location on upright and inverted faces modulates the N170. Neuropsychologia 2014;57:1–11, http://dx.doi.org/10.1016/j.neuropsychologia.2014.02.006.

Delorme A, Makeig S. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. J Neurosci Methods 2004;134:9–21, http://dx.doi.org/10.1016/j.jneumeth.2003.10.009.

De Vos M, Gandras K, Debener S. Towards a truly mobile auditory brain–computer interface: exploring the P300 to take away. Int J Psychophysiol 2014a;91(1):46–53, http://dx.doi.org/10.1016/j.ijpsycho.2013.08.010.

De Vos M, Kroesen M, Emkes R, Debener S. P300 speller BCI with a mobile EEG system: comparison to a traditional amplifier. J Neural Eng 2014b;11(3):036008, http://dx.doi.org/10.1088/1741-2560/11/3/036008.

Eimer M. Does the face-specific N170 component reflect the activity of a specialized eye processor? Neuroreport 1998;9(13):2945–8, http://dx.doi.org/10.1097/00001756-199809140-00005.

Ekman P, Friesen WV. Pictures of facial affect. Palo Alto, CA: Consulting Psychologists Press; 1976.

Feuerriegel D, Churches O, Hofmann J, Keage HAD. The N170 and face perception in psychiatric and neurological disorders: a systematic review. Clin Neurophysiol 2015;126(6):1141–58, http://dx.doi.org/10.1016/j.clinph.2014.09.015.

Gur RC, Sara R, Hagendoorn M, Marom O, Hughett P, Macy L, et al. A method for obtaining 3-dimensional facial expressions and its standardization for use in neurocognitive studies. J Neurosci Methods 2002;115:137–43, http://dx.doi.org/10.1016/S0165-0270(02)00006-7.

Gutberlet I, Debener S, Jung. , Makeig T-PS. Techniques of EEG recording and preprocessing. In: Tong S, Thakor NV, editors. Quantitative EEG analysis methods and applications. MA: Artech House Publishers; 2009.

Itier RJ, Latinus M, Taylor MJ. Face, eye and object early processing: what is the face specificity? NeuroImage 2006;29(2):667–76, http://dx.doi.org/10.1016/j.neuroimage.2005.07.041.

Itier RJ, Taylor MJ. N170 or N1? Spatiotemporal differences between object and face processing using ERPs. Cereb Cortex 2004;14(2):132–42, http://dx.doi.org/10.1093/cercor/bhg111.

Joyce C, Rossion B. The face-sensitive N170 and VPP components manifest the same brain processes: the effect of reference electrode site. Clin Neurophysiol 2005;116:2613–31, http://dx.doi.org/10.1016/j.clinph.2005.07.005.

Linkenkaer-Hansen K, Palva JM, Sams M, Hietanen JK, Aronen HJ, Ilmoniemi RJ. Face-selective processing in human extrastriate cortex around 120 ms after stimulus onset revealed by magneto- and electroencephalography. Neuroscience Letters 1998;253:147–50, http://dx.doi.org/10.1016/S0304-3940(98)00586-2.

Luck SJ. An introduction to the event-related potential technique. Cambridge, MA: The MIT Press; 2005.

Lundqvist D, Flykt A, Öhman A. The Karolinska directed emotional faces—KDEF, CD ROM from department of clinical neuroscience, psychology section. Karolinska Institutet; 1998, ISBN 91-630-7164-9.

Maurer D, Le Grand R, Mondloch CJ. The many faces of configural processing. Trends Cogn Sci 2002;6(6):255–60, http://dx.doi.org/10.1016/S1364-6613(02)01903-4.

McArthur G, Atkinson C, Ellis D. Atypical brain responses to sounds in children with specific language and reading impairments. Dev Sci 2009;12:768–83, http://dx.doi.org/10.1111/j.1467-7687.2008.00804.x.

McArthur GM, Atkinson C, Ellis D. Can training normalise atypical passive auditory ERPs in children with SRD or SLI? Dev Neuropsychol 2010;35(6):656–78, http://dx.doi.org/10.1080/87565641.2010.508548.

McArthur GM, Bishop DVM. Speech and non-speech processing in people with specific language impairment: a behavioural and electrophysiological study. Brain Lang 2005;94:260–73, http://dx.doi.org/10.1016/j.bandl.2005.01.002.

Rossion B, Gauthier I, Tarr MJ, Despland P, Bruyer R, Linotte S, et al. The N170 occipito-temporal component is delayed and enhanced to inverted faces but not to inverted objects: an electrophysiological account of face-specific processes in the human brain. NeuroReport 2000;11(1):69–74, http://dx.doi.org/10.1097/00001756-200001170-00014.

Rossion B, Jacques C. Does physical interstimulus variance account for early electrophysiological face sensitive responses in the human brain? Ten lessons on the N170. NeuroImage 2007;39(4):1959–79, http://dx.doi.org/10.1016/j.neuroimage.2007.10.011.

Shrout PE, Fleiss JL. Intraclass correlations: uses in assessing rater reliability. Psychol Bull 1979;86:420–8, http://dx.doi.org/10.1037/0033-2909.86.2.420.

Thie J. A wireless marker system to enable evoked potential recordings using a wireless EEG system (EPOC) and a portable computer. PeerJ PrePrints 2013;1:e32v1, http://dx.doi.org/10.7287/peerj.preprints.32v1.

Tottenham N, Borscheid A, Ellertsen K, Marcus DJ, Nelson CA. Categorization of facial expressions in children and adults: establishing a larger stimulus set. J Cogn Neurosci 2002;14(Suppl.):S74.

Vigario RN. Extraction of ocular artifacts from electroencephalography using independent component analysis. Electroenceph Clin Neurophysiol 1997;103:395–404.

Vizioli L, Foreman K, Rousselet GA, Caldara R. Inverting faces elicits sensitivity to race on the N170 component: a cross-cultural study. J Vis 2010;10(1):1–23, http://dx.doi.org/10.1167/10.1.15.

Weyrauch B, Huang J, Heisele B, Blanz V. Component-based face recognition with 3D morphable models. In: First IEEE Workshop on Face Processing in Video; 2004, Washington, DC.