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The validity of the face-selective ERP N170 component during simultaneous recording with functional MRI

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Despite the wide interest in the neural mechanisms of face processing and numerous event-related potential (ERP) and functional MRI (fMRI) studies of face-selective neural responses, no study, to date, has collected these two measures simultaneously. The main reason for the absence of such an investigation is that MRI data acquisition generates major artifacts, which completely conceals the EEG signal. Recently, artifact removal algorithms have been developed. Our goal was to examine the validity of the face-selective ERP component N170 and its functional effects such as category selectivity and hemispherical laterality, when recorded simultaneously with functional MRI. In our experiment, half of the scans were collected during fMRI acquisition and half without fMRI acquisition. The validity of the N170 was then measured for its amplitude, latency, face selectivity (the difference between the amplitude to faces and objects), laterality (the difference between the amplitude to faces over the right and the left hemispheres) and the laterality of the face selectivity effect, by correlating these measures across subjects between data collected without fMRI and with fMRI data acquisition, after applying artifact removal procedures. We found high validity coefficients for all N170 measures. Furthermore, ERP data collected outside the scanner on a different day were highly correlated with data collected during MR acquisition for the N170 amplitude, latency, and selectivity index but moderate for laterality indices. Our study demonstrates that face-selective ERP effects are preserved in simultaneous recording with fMRI. These findings will hopefully encourage researchers to combine the two complementary neuroimaging techniques in future research.

Introduction

Faces elicit a robust and reliable neural response in temporal-occipital regions of the human brain. Specifically, event-related potential (ERP) studies have revealed an early temporal-occipital component that peaks around 170 ms after stimulus onset, which shows larger amplitude for faces than objects (Bentin et al., 1996; for an extensive review see Rossion and Jacques (2008)). Functional MRI studies have revealed regions in the occipital–temporal cortex that show a much higher response for faces than objects (Kanwisher et al., 1997; McCarthy et al., 1997; for review see Kanwisher and Yovel (2006)). These findings from human neuroimaging are consistent with single cell recording studies with monkeys, which have reported neurons in the inferior temporal cortex and superior temporal sulcus that show a highly face-selective response (Desimone et al., 1984; Tsao et al., 2006).

The two most prevalent human neuroimaging techniques – functional MRI (fMRI) and ERPs – provide complementary information about spatial and temporal aspects of the neural response, respectively. In particular, functional MRI reveals the brain regions that show a strong face-selective response with relatively high spatial resolution (millimeters) but very poor temporal resolution due to the slow hemodynamic response. In contrast, ERPs measured over the scalp provide an electrophysiological signal of high temporal resolution (milliseconds), but poor information about the exact location of its neural sources. Surprisingly, despite the hundreds of studies that have been published on the neural response to faces with fMRI and ERP and the complementary information they provide about the brain response to faces, only a few studies, to date, have attempted to assess the correlations between the ERP and fMRI response to faces when collected in different sessions (Henson et al., 2003; Horovitz et al., 2004) and, to the best of our knowledge, no study has measured both face-related signals simultaneously.

Simultaneous EEG–fMRI data collection is advantageous to separate recording sessions in several ways. (i) The environments of fMRI and EEG experimental settings are fundamentally different and may generate differences in the brain response to the stimulus or task manipulation that will decrease the correlations between them. (ii) The subject response to the task may differ

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across sessions and if one is interested in the correlations between the signal and the subject trial-by-trial response, simultaneous recording is mandatory. (iii) If an identical task is used in the two sessions, learning effects may generate different brain responses across the two sessions. (iv) Direct correlations between the task-induced modulation of the EEG and fMRI signal that are time-locked to one another (for review see Debener et al. (2007)) will be maximal when they are collected simultaneously. Thus, more robust and valid correlations between the two signals can be revealed when they are collected simultaneously.

The main reason for the absence of such simultaneous fMRI–EEG investigation is that artifacts generated by the MRI mask the EEG signal. In particular, MR gradient switching produces high amplitude artifacts, which completely conceal the EEG signal (see Fig. 1A). Furthermore, because of the high magnetic field, additional artifacts are induced by heart pulses – ballistocardiogram (BCG) artifacts – and further distort the EEG signal (see Fig. 1B). To avoid the artifacts of the MR gradient on the EEG signal, some simultaneous EEG–fMRI studies have used the method of interleaved fMRI data acquisition (e.g. Bonmassar et al., 1999, 2001;

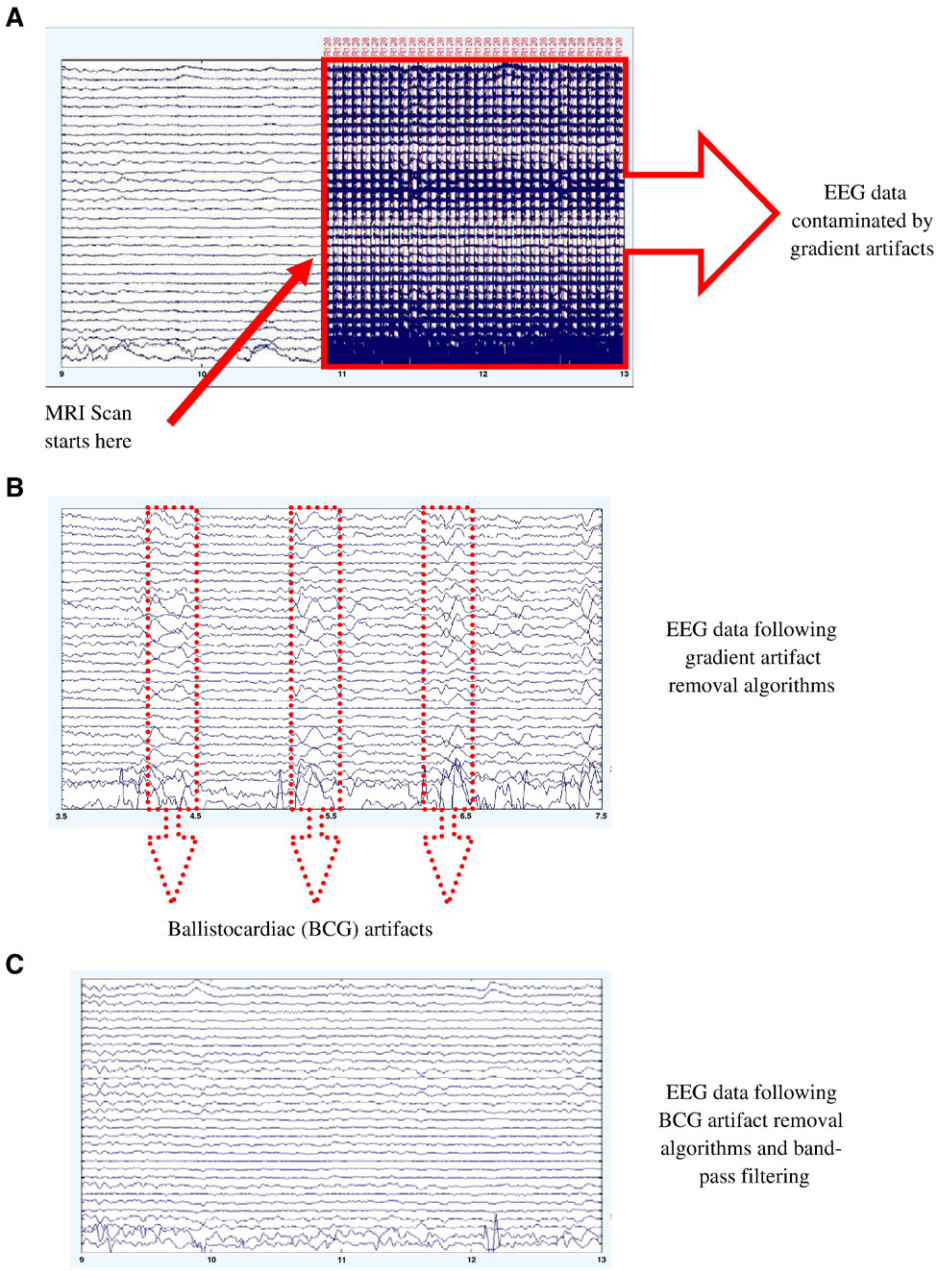

Fig. 1. Steps of artifact removal from an EEG signal collected simultaneously with fMRI. A. Four seconds of EEG data contaminated with artifacts due to switching of magnetic gradients. B. EEG data after removal of gradient artifacts by FASTR algorithm. Artifacts due to cardiac pulses are seen. C. Clean EEG data, after removal of ballistocardiogram (BCG) artifacts and bandpass filtering 0.5–45 Hz.

Mulert et al., 2005; Otzenberger et al., 2005). Because the hemodynamic response peaks about 6 s after stimulus onset, whereas relevant ERP data can be collected within 1 to 2 s after stimulus onset, fMRI data collection can be done starting 2 s after stimulus onset and still provide event-related signals for the same events. The main disadvantage of this method is that the interstimulus interval should not exceed the time course of the hemodynamic response (10–16 s). Thus, the rate of stimulus presentation is very low and the number of stimuli that can be presented in a given recording session is limited. Because the signal-to-noise ratio of fMRI and ERP data increases as the number of trials increases, rapid event-related data collection, which allows many more trials to be presented in a given session is more desirable. Such rapid presentation, however, requires continuous EEG–fMRI recording and an effective method to remove the gradient artifacts that are generated during MRI data acquisition.

Fortunately, MR gradients elicit a predicted and relatively constant pattern of distortion in the EEG signal. Effective algorithms for MR artifact removal (Fig. 1B) as well as algorithms for detection and removal of BCG artifacts (Fig. 1C) have been recently developed, which allow recovery of the EEG signal offline (Allen et al., 2000; Iannetti et al., 2005; Niazy et al., 2005). For example, a recent study reported high validity for the amplitude and latency of the P1 and N1 response to colored words after the removal of gradient and BCG artifacts in a 1.5 T MR scanner (Comi et al., 2005). However, no study, to date, has examined whether the functional characteristics or the experimental effects associated with an ERP component are preserved after the removal of these artifacts. In particular, before embarking on an investigation of the relationship between face-related neural mechanisms using simultaneous ERP–fMRI methods, it is critical to determine that the known functional characteristics of the face-related ERP component N170, such as its category selectivity and hemispheric asymmetry, can be reliably recovered after artifact removal algorithms are applied.

The present study examines whether the ERP response to faces that is recorded simultaneously with BOLD acquisition yields reliable evoked responses, which preserve the basic features of the face-selective N170 response. We first asked whether the amplitude and the latency of the N170 are preserved after the application of artifact rejection algorithms. More importantly, we also confirmed that the well-established functional characteristics of an ERP component are preserved. In particular, the face-selective N170 has three main functional characteristics: 1) The N170 amplitude is significantly larger for faces than non-face objects (e.g. Bentin et al., 1996; Rossion and Jacques, 2008). 2) The N170 amplitude is larger over the right than the left temporal–occipital electrodes (e.g. Bentin et al., 1996; Yovel et al., 2003). 3) The magnitude of the N170 face selectivity is larger over the right than the left hemisphere (Bentin et al., 1996; Rossion et al., 2003).

To assess the validity of the face-selective N170, ERPs for faces and non-face objects (chairs) were recorded while subjects lay in a 3 T MR scanner. Most previous studies of simultaneous EEG–MRI recording were done in 1.5 T scanners (e.g. Becker et al., 2005; Garreffa et al., 2004; Garreffa et al., 2003; Laufs et al., 2003; Lazeyras et al., 2001) so validation of ERP data in a 3 T scanner, which provides better signal-to-noise fMRI data, but also produces twice as large BCG artifacts in the EEG signal, is important. On half of the scans, ERPs were collected during fMRI acquisition and, on the other half, without fMRI acquisition, when subjects were lying in the static magnetic field. We then performed correlational analyses across subjects between data collected during fMRI scanning and without fMRI scanning to assess the validity of each of the five N170 measures. In addition, our subjects returned for another session outside the magnet and we assessed the correlations with data we collected inside the MRI. To the best of our knowledge, the correlations between the N170 measures that were recorded on separate sessions have never been reported, even for data collected in standard settings.

Materials and methods

Subjects

Eleven subjects (age: 22–30, eight females, two left handed) participated in a simultaneous recording of ERP and fMRI. Left-handed subjects were not excluded from our sample as is often the case in face perception studies, in order to increase the variance in our laterality measures and avoid low correlations due to restricted range. Two right-handed subjects, one female and one male, were excluded due to technical problems in recordings. Eight of the nine remaining subjects returned for another ERP recording session outside the MRI. All subjects gave informed consent to participate in the study, which was approved by the ethics committee of the Tel Aviv Sourasky Medical Center.

Apparatus

EEG recording

For EEG recording we used an MR compatible, 32-channel, battery-operated amplifier (Brain Products, GmBH, Germany). The signal was amplified, and sampled at 5000 Hz. Such a high sampling rate is necessary for gradient artifact correction, which are removed offline. The amplifier was located at the back of the scanner. The EEG data were transmitted from the scanner room via an optical fiber to a PC in the control room. The exact timing of stimulus onset and MRI scanner gradient switching was transmitted to the EEG amplifier and recorded together with the EEG signal. Thirty Ag/AgCl nonmagnetic electrodes were positioned on an elastic cap according to the standard 10/20 system, with a frontocentral reference. The wires were braided and connected to the amplifier located at the back of the bore. One electrode was placed under the left eye for EOG and one on the upper-left part of the back for EKG recordings. The EKG data are required to detect the BCG artifacts in the EEG signal, which were removed offline.

Functional MRI recording

MRI data was collected in a 3 T MRI scanner. Echo planar imaging sequence was used to collect fMRI data with TR = 2 s, TE = 35 ms, flip angle: 90°, 30 slices per TR, slice thickness: 4 mm no gap, matrix 64 × 64, FOV 256 mm. On each scan we collected 126 volumes with a total scan time of 4:12 min. The first six volumes were presented during a blank screen and discarded from the analysis.

Stimuli

Visual stimuli were four grayscale images of faces and four grayscale images of chairs. Stimuli were presented with Matlab (psychtoolbox, Brainard, 1997). The stimuli were projected to a screen located at the back of the scanner through a projector. The

subjects viewed the stimuli through a mirror that was placed on the upper part of the head coil in front of the subjects' eyes.

Procedure

The experiment consisted of six runs of EEG recordings: three runs were collected during fMRI scanning and three without fMRI data acquisition. Runs with and without fMRI acquisition were collected in an interleaved manner. Each run included 48 faces and 48 chairs, and 24 null events that were presented in a pseudo-randomized order that allows deconvolution of rapid event-related fMRI response (http://surfer.nmr.mgh.harvard.edu/optseq/). Each of the acquisition conditions, MR and no-MR, included a total of 144 face and 144 chair presentations. Each trial lasted 2 s, during which one stimulus was presented for 250 ms. The stimulus onset was shifted by a random jitter sampled from a uniform distribution between 0 and slice duration time (66.67 ms), to prevent time-locking of the evoked response to the gradient switching. The subjects were asked to press a key each time an image was repeated twice in a row (a one-back task), which occurred every eight trials on average.

A second ERP session outside the scanner

Eight of the nine subjects returned for a follow-up experiment two to six months after the MRI session. The experiment took place in our ERP laboratory, using the same Brain Products EEG system as in the combined ERP–fMRI session. Subjects were seated in front of a 17-inch CRT monitor (60 Hz), at a distance of about 50 cm. The experiment design was identical to the design described above. Subjects were presented with the three runs of faces and chairs that we presented in the scanner and again performed a similar one-back task.

Data analysis

Artifact removal. Fig. 1 shows the EEG data before (Fig. 1A) and after gradient (Fig. 1B) and BCG artifact (Fig. 1C) removal. In order to remove these artifacts we used the FMRIB plug-in for EEGLAB, provided by the University of Oxford Centre for Functional MRI of the Brain (FMRIB) (Iannetti et al., 2005; Niazy et al., 2005).

MR gradient artifacts. Artifacts related to MR gradient switching were removed from all EEG data sets using the FASTR algorithm implemented in the FMRIB plug-in. The FASTR algorithm first corrects for possible minor jitters in the gradients occurrence delays by slightly shifting the slice artifacts to obtain the optimized correlation between each of them and the first artifact. Then, an average template of the artifact is computed and subtracted from the signal (Allen et al., 2000). Following this process, residual artifacts are reduced using subtraction of optimal basis set (OBS) constructed of first, most meaningful, PCAs automatically determined from the plot of ordered eigenvalues of the artifact matrix. The signal is then low-pass filtered.

BCG artifacts were also removed using the FMRIB plug-in in two stages: BCG artifact detection is performed on the EKG channel using combined adaptive thresholding (Christov, 2004) and the Teager energy operator (Kim et al., 2004), followed by a correction algorithm, which aligns all events and corrects for false positives and negatives. An average artifact template is computed. In the pulse artifact removal stage an artifact template is subtracted from the signal. The template for subtraction is constructed with the optimal basis algorithm, similar to the one used to remove the gradient residuals. For some subjects Gaussian-weighted mean artifact subtraction was used to remove the artifacts, due to failure of the optimal basis algorithm to operate on them.

As BCG artifacts are not time-locked to stimulus onset and are much smaller than the gradient artifacts, we also examined whether simple averaging of time-locked EEG segments will effectively remove these artifacts.

ERP analyses

Following artifact removal, the EEG signal was down-sampled to 250 Hz. The data were then filtered with a 0.5–45 Hz bandpass filter. Epochs of −100 ms before stimulus onset and 600 ms after stimulus onset were averaged separately for faces and chairs.

The N170 amplitude and latency were measured at the maximum negative peak of the ERP for faces and chairs within 140–200 ms. The face selectivity of the N170 was a normalized index for the difference in N170 amplitude for faces and chairs.

$$\text{Face selectivity} = \frac{\text{face}_{\text{N170}} - \text{chair}_{\text{N170}}}{\text{face}_{\text{N170}} + \text{chair}_{\text{N170}}}$$

The laterality of the N170 to faces was the normalized difference between the amplitude to faces at the right temporal–occipital electrode (P8) and the left temporal–occipital electrode (P7).

$$\text{Laterality} = \frac{\text{right}_{\text{N170}} - \text{left}_{\text{N170}}}{\text{right}_{\text{N170}} + \text{left}_{\text{N170}}}$$

Finally, we computed the laterality index of the face selectivity effect, by subtracting the face selectivity index at P7 from the face selectivity index at P8.

In a few subjects, the N170 amplitude to chairs was of a positive value. Thus, calculation of the index score in these cases generated values larger than 1, whereas the ratio index of selectivity/laterality scores is meaningful only within the −1 to 1 range. To avoid that we subtracted a constant value (5.5) that was slightly higher from the larger positive amplitude in our sample such that, all amplitude scores had a negative value and all indices value ranged from −1 to 1 (see also Simmons et al. (2007) for a similar baseline correction of a ratio index of an fMRI response).

Correlational analysis

For each subject we computed the amplitude, latency, face selectivity at the right temporal–occipital site (P8) and left temporal–occipital site (P7), laterality of the N170 response for faces, and the laterality of the selectivity effect, for data collected during MR acquisition and without MR acquisition. To measure the validity of these measures when collected simultaneously with fMRI we computed the correlations across subjects between data collected with MR and without MR for each of these N170 measures. A similar correlation analysis of data collected simultaneously with fMRI was also performed with data collected outside the scanner in a separate session two to six months after the scan.

Finally, the effectiveness of applying the BCG artifact removal algorithms (see above) was assessed in comparison to the standard averaging that is used to compute ERPs. As BCG artifacts are not time-locked to stimulus onset, time-locked averaging may suffice

Table 1
Group average of peak amplitudes (within 140–200 ms) and their latencies

		BCG artifact removed		BCG artifact not removed	
Without fMRI		Faces	Chairs	Faces	Chairs
Amplitude (μV)	P7	−7.51	−3.83	−7.47	−4.36
	P8	−7.67	−5.00	−8.60	−6.75
Latency (ms)	P7	160	169	164	169
	P8	159	168	165	170
During fMRI					
Amplitude (μV)	P7	−5.94	−2.74	−4.82	−3.14
	P8	−6.29	−2.64	−7.21	−4.76
Latency (ms)	P7	162	175	161	175
	P8	158	172	157	172

Each condition included 144 trials. Data was computed for EEG data collected with or without simultaneous collection of fMRI data and with or without BCG artifact removal algorithms (see Materials and methods).

to remove their distorting effect. To reveal whether averaging is an effective BCG artifact removal, we measured the correlations between the N170 that were obtained with and without MR acquisition, without applying algorithms for BCG artifact removal.

For all correlation analyses we used Cook's Distance score to exclude outlier data points. Cook's Distance score for a given observation reflects the change in the magnitude of the correlation that results from excluding this observation (Cook, 1979). An outlier was defined as Cook's Distance score larger than 3 standard deviations (excluding the outlier score). In none of our correlational analyses was more than one subject excluded due to high Cook's Distance values.

Results

Group average N170 response to faces and chairs

Amplitude

To assess the pattern of the N170 response for faces and chairs in temporal–occipital electrodes with and without MR acquisition we performed a three-way repeated measure ANOVA with MR condition (MR, no-MR), Hemisphere and Category (face, chair) as repeated measures and amplitude or latency as dependent measures. Our analyses reveal no difference between the pattern of response to faces and chairs at the right and left occipito-temporal electrodes during MR recording and without MR recording. The amplitude of the N170 was larger for faces than objects [$F(1,8)=27.7$, $p<0.001$] and the MR condition did not interact with Hemisphere [$F(1,8)<1$], Category [$F(1,8)<1$], or both [$F(1,8)<1$]. The overall amplitude of the N170 tended to be smaller for the data collected with MR than without MR [$F(1,8)=3.9$, $p=0.08$] (see also Comi et al. (2005)).

Table 1 presents the values of the amplitude and latency of the N170 for faces and chairs at the temporal–occipital electrodes P8 and P7, where the face-selective response is maximal (Rossion and Jacques, 2008). Fig. 2 shows a group average ERP to faces and chairs at a representative electrode P8 across all face and chair trials that were collected without MR gradients (A,C) and with MR gradients (B,D), when BCG artifacts were removed (A,B) or not removed (C,D).

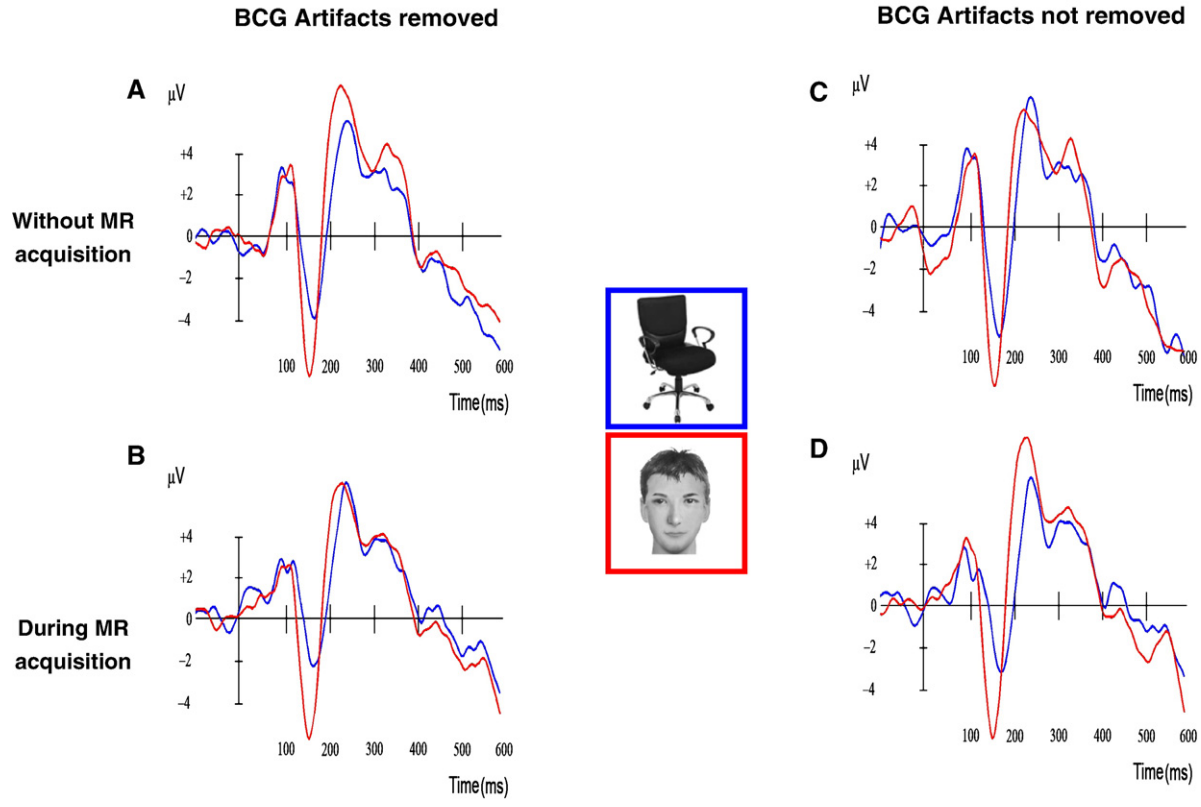

Fig. 2. Grand average ERP of nine subjects at a representative temporal–occipital electrode P8, without (A,C) and with (B,D) MR acquisition when BCG artifacts are removed (A,B) or not removed (C,D).

Latency

The latencies of the N170 for faces and chairs were very similar in the two conditions (MR: right=158 ms, left=162 ms; no-MR right=161 ms, left=161 ms). A two-way ANOVA with MR condition and Hemisphere as repeated measures revealed no difference in latency between the MR and no-MR conditions ($F(1,8)=2.3$, $p=0.17$) and no significant interaction of MR condition with Hemisphere ($F(1,8)=2.7$, $p=0.13$).

Analysis of variance showed that MR artifacts did not distort the pattern of the N170 amplitude and latency to faces. To further assess whether the data collected in the scanner is a valid measure of the N170 response to faces, we performed correlational analyses across subjects for each of the five N170 measures.

Validity analyses

The main goal of the current investigation was to assess the validity of the N170 that was collected simultaneously with fMRI. To that effect, we computed the correlations across subjects between ERP collected with and without MR gradients for the following five measures: amplitude to faces, latency to faces, face selectivity, laterality for face amplitude, and laterality of the face selectivity.

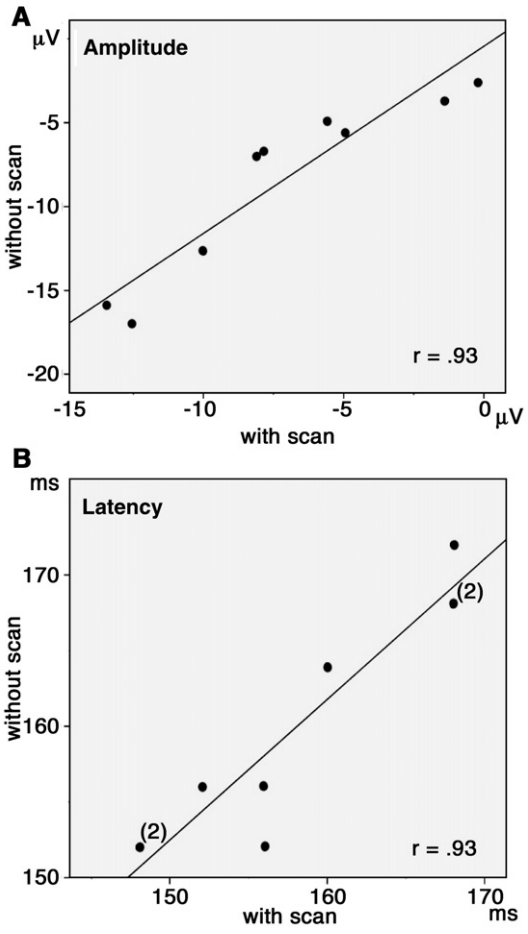

Fig. 3. Correlations across subjects for the N170 peak amplitude (A) and latency (B) to faces at electrode P8, reveal very high correlations between data collected with and without MR acquisition. The symbol "(2)" indicates a dot that represents overlapping data points of two subjects.

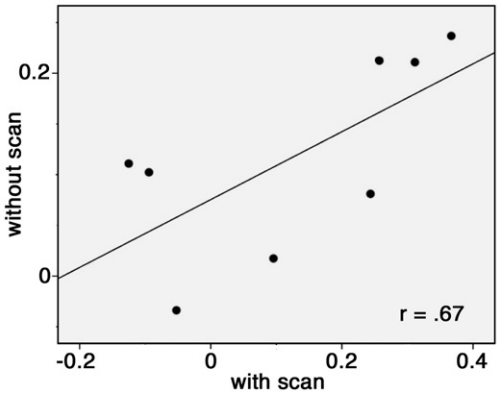

Fig. 4. Correlation across subjects for the N170 face selectivity at electrode P8 between data collected with and without MR. Face selectivity index is computed with the following formula:

$$\frac{face_{N170} - chair_{N170}}{face_{N170} + chair_{N170}}$$

N170 amplitude to faces

The Pearson correlation coefficients between the amplitude of the N170 to faces with and without fMRI data acquisition were very high at the temporal–occipital electrodes over the right hemisphere (P8) and the left hemisphere (P7) (P8: $r(7)=0.93$, $p<.001$; P7: $r(7)=.76$, $p<0.05$). Fig. 3A shows the scatterplot of the correlation between the amplitude of the N170 collected with and without MR at P8 where the N170 face response is maximal.

N170 latency to faces

The correlations between the latency of the N170 peak response to faces with and without fMRI data acquisition were very high at the temporal–occipital electrodes over the right hemisphere (P8) and the left hemisphere (P7) (P8: $r(6)=0.93$, $p=0.001$; P7: $r(7)=0.94$, $p<0.001$). Fig. 3B shows the scatter plot of the correlation between the N170 latency with and without MR acquisition for P8. One subject who had a Cook's D of more than 3 standard deviations above the mean Cook's D score (Mean=0.07, SD=0.06, outlier Cook's D=8.79) at the P8 latency analysis was excluded.

N170 face selectivity

To measure the magnitude of face selectivity for each subject we computed a ratio index of the N170 amplitude to faces and chairs (see Materials and methods). We found a relatively high correlation for this selectivity index between data collected during MR acquisition and data collected without MR acquisition at electrode P8 ($r(6)=.67$, $p=0.07$). The scatter plot shown in Fig. 4 depicts the correlation for right temporal electrode P8. The correlation of the selectivity score for P7 was positive but much lower ($r(6)=.23$, ns). One subject at each electrode analysis, who had a Cook's D score of more than 3 standard deviations above the mean Cook's D score (at P8: Mean=0.07, SD=0.05, Cook's D=7.12, at P7: Mean=0.07, SD=0.08, Cook's D=8.23) was excluded.

Laterality of the N170 amplitude to faces

Another important feature of the N170 component is its higher amplitude to faces over right than left temporal–occipital electrodes (e.g. Bentin et al., 1996). To assess whether this laterality is preserved in data collected during MR acquisition, a laterality ratio

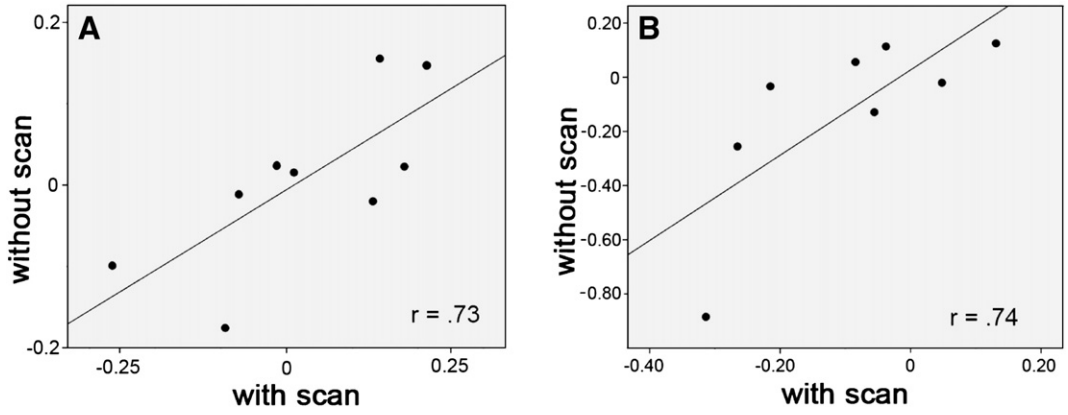

Fig. 5. A. Correlation across subjects of the laterality of the N170 peak amplitude between data collected with and without MR. Laterality index is calculated with the following formula: $(N170_{P8}-N170_{P7})/(N170_{P8}+N170_{P7})$. P8 is the right temporal–occipital electrode, and P7 is the left temporal–occipital electrode. B. Correlation across subjects of the laterality of the N170 face selectivity effect between data collected with and without MR. It is calculated by subtracting the face selectivity index (see Fig. 4) at electrode P7 from electrode P8.

index was computed in which we divided the difference between the N170 amplitude to faces over the right and left hemispheres by the sum of these measures. Analyses revealed a high correlation between the laterality indices for ERP collected with and without MR gradients ($r(7)=0.73$, $p<0.05$) (Fig. 5A).

N170 Laterality of the face selectivity effect

For each subject we computed a normalized face-selective score for each electrode (see selectivity index above) and then subtracted the value at P7 from P8. This measure reflects two important features of the face-selective mechanisms: its robust response to faces relative to objects and its right hemisphere dominance. The correlation between this measure for ERP data collected with and without MR was $r(6)=0.74$, $p<0.05$ (Fig. 5B). One subject who had a Cook's D of more than 3 standard deviations above the mean Cook's D score (Mean=0.11, SD=0.25, Cook's D=13.28) was excluded.

In summary, the high correlations that we revealed between the N170 that we measured with and without effects of MRI demonstrate that the reduction in amplitude following gradient artifact removal is equivalent across subjects, and that the functional effects examined above were also preserved in spite of this overall amplitude reduction.

Correlations with data collected outside the scanner

The results presented above concern a set of correlations between data collected across different scans within the same session inside the scanner. Both data sets were collected in a high magnetic field. To complete our investigation of the validity of ERPs collected in a simultaneous EEG–fMRI setup, we collected data with a similar paradigm in a standard ERP environment outside the scanner. To that end, eight subjects who participated in the fMRI session returned for a second session two to six months after the MRI session.

Despite the long time interval and the markedly different experimental settings, test–retest correlation coefficients were very high. The N170 peak amplitudes as recorded during the scan and in the retest session correlated for electrode P8 $r(6)=0.88$, $p<0.01$ (see Fig. 6), and for P7, $r(6)=0.80$, $p<0.05$. The latencies of the N170 component for face stimuli were highly correlated for electrode P7 ($r(5)=0.78$, $p<0.05$ after exclusion of one outlier) and showed a trend for P8 ($r(6)=0.64$, $p=0.09$). The correlation was also high for the face selectivity measure in electrode P8: $r(6)=0.79$, $p<0.05$ but not for P7 ($r(6)=0.1$, ns), as was the case with the data collected inside the MRI scanner (with vs. without MR acquisition). Positive but lower correlation coefficients were found for the laterality measures ($r(6)=0.41$, ns for the laterality normalized ratio index, and $r(6)=0.57$, ns for the laterality of the face selectivity effect). Taken together, the high correlations that were revealed for the amplitude and latency measures suggest that the data that were collected simultaneously with fMRI are highly reliable even when retesting is done several months after the fMRI scan in completely different settings. The somewhat lower correlations for the laterality measures may suggest that these measures are more sensitive to variance between sessions and highlight the importance of collecting these measures simultaneously with fMRI rather than at separate sessions. One caveat, however, should be mentioned when lower correlations are revealed and coefficients are compared. The correlations reported here are based on a relatively small sample size of 8–9 subjects. Thus, non significant correlations for a given measure may reflect low power to detect a correlation that may exist

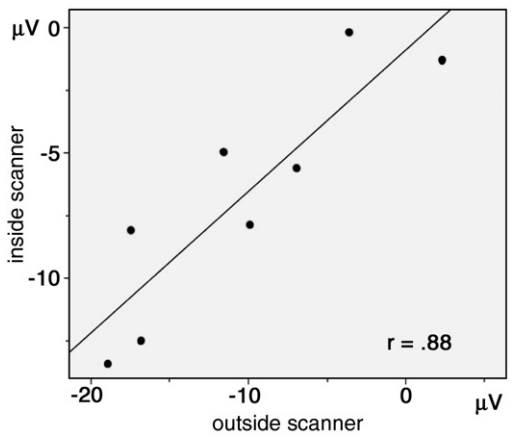

Fig. 6. Correlations across subjects of the N170 peak amplitude at electrode P8 between data collected simultaneously with MR acquisition following gradient and BCG artifact removal, and data recorded outside the scanner two to six months after the scan.

in the population, rather than an absence of a relationship. Importantly, most of the correlations we report are very high despite the small sample size, which reflects the high validity of the N170 data collected with MRI.

The importance of ballistocardiogram (BCG) artifact removal

Finally, we were interested in examining the importance of removing BCG artifacts from ERP data with the algorithms that were specifically designed to detect and subtract these artifacts. As these artifacts are not time-locked to the stimulus, averaging that is time-locked to the onset of the stimulus may provide a good enough artifact removal procedure. Indeed, examination of the grand average ERPs when BCG artifacts are not removed (Figs. 2C, D) seem to show a very similar pattern to ERP data, in which specific detection and subtraction algorithms were applied (Figs. 2A, B).

To evaluate whether this is indeed the case, the same correlations were measured across subjects between the N170 with and without MR, but this time without applying algorithms for BCG artifact removal. Our findings show that correlations when BCG artifacts were not removed were lower than when BCG artifact removal algorithms were applied: amplitude — P8: ($r(7)=0.84$), P7: $r(7)=0.57$); latency — P8: $r(7)=0.81$), P7: $r(6)=0.47$); face selectivity — P8: $r(7)=0.62$), P7: $r(7)=0.21$); laterality for faces ($r(6)=0.12$); and laterality of face selectivity ($r(7)=0.38$). These findings suggest that despite the apparently intact appearance of the waveform (see Figs. 2C, D), BCG artifact removal provides cleaner and more reliable data.

Discussion

We report the results of the first study of the face-selective ERP component (N170) that was collected simultaneously with functional MRI. To determine whether the well-established face-selective characteristics of the N170 are preserved during simultaneous fMRI data acquisition, we examined the validity of the N170 peak amplitude, latency, selectivity to faces, laterality to faces, and laterality of its face selectivity measure. Our data reveal high validity scores for all five N170 measures when collected simultaneously with MRI.

Our validity calculations were performed with data obtained during the same session in the scanner without fMRI acquisition. To further validate the data we obtained in the scanner, our subjects returned for a second session in a standard EEG recording setting outside the scanner two to six months later. To the best of our knowledge, such correlations between N170 measures collected in separate sessions have never been reported, even for data collected in standard settings. Interestingly, we found very high correlations between the N170 amplitude and latency that were collected outside the scanner and during MR acquisition, as well as for the face selectivity feature of the N170 waveform. These findings are remarkable given the long period of time elapsing between the two measures and the markedly different environments during fMRI acquisition and outside the magnet. Importantly, however, the correlations of the laterality scores were somewhat lower across the two sessions, which suggests that they may be more sensitive to the differences across sessions and highlights the importance of simultaneous data collection, if these features of the N170 are the focus of a combined fMRI–ERP investigation.

The correlational analyses are of special importance given the trend of reduction in the N170 peak amplitude in the MR condition relative to the no-MR condition. That is, after applying algorithms of detection and removal of the massive artifacts generated by the scanner, the peak amplitudes to faces and chairs were reduced to a certain degree. Nevertheless, the high correlations across subjects of the N170 peak amplitude that we obtained suggest that the small reduction of amplitude was constant across subjects. Furthermore, individual differences of the N170 characteristics (e.g. face selectivity, face laterality) were also well preserved following artifact removal.

When conducting a simultaneous ERP–fMRI experiment, a complicated and expensive procedure by itself, one may not only want to make sure that the ERP waveforms keep their known appearance and that the components are preserved, but also that experimental effects can be reliably obtained in the MRI scanner. Thus, the validity test of the selectivity and the laterality effects for faces goes beyond the validity of the ERP waveform per se and examine its functional aspect as a face-sensitive ERP response. Selectivity and laterality effects were computed as numerical indices driven from the peak amplitudes of the N170 across conditions or across locations. These ratio indices normalize the variance of the peak amplitude of the ERPs that is likely to reflect technical and/or neuroanatomical/neurophysiological parameters rather than individual differences in cognitive functions. For example, slight individual differences in the cortical folds, giving rise to variations in the precise location of the source dipole within the folds of the cortex, may modulate its orientation (see Luck (2005) for elaboration of this issue). Other physiological or technical idiosyncratic factors include skin conductivity, the exact electrode location on the scalp, the electrode resistance, or the scalp thickness. These factors may influence the absolute magnitude of the amplitude for a given stimulus but are factored out when indices are used. Thus, the high correlation that we report for category selectivity and hemispheric laterality are likely to reflect the functional characteristic of the N170 as a face-related neural marker.

Of particular interest is an insight that we gain about the importance of the removal of artifacts derived from cardiac activity inside the scanner. BCG artifact removal is, at present, debated. Several methods of BCG artifact removal exist (see e.g. Debener et al. (2007)), and some authors consider that removing the pulse artifacts is of small or no significance (Becker et al., 2005). Removing BCG artifacts may mistakenly appear to us as an optional operation, as the procedure of averaging is capable of dissolving this artifact by itself. A support for this claim can be seen in Fig. 2, where both ERPs that did not undergo BCG artifact removal, show typical P1 and N170 waveforms and are very similar to ERPs that did undergo removal with algorithms that specifically detect and subtract artifacts. Furthermore, specific effects such as the face selectivity of the N170 component are detected in the group-averaged ERPs that have not gone through the removal procedure of cardiac artifacts. Nevertheless, an examination of the correlations across subjects reveals that when BCG artifacts are not removed from the raw data, the validity measures of EEG data recorded simultaneously with MR acquisition are lower than when cardiac artifacts are removed, as in some cases the correlations dropped below significance level. Thus, in the framework of a combined ERP–fMRI study of face perception, when testing effects that standard ERP experiments have demonstrated repeatedly in the past, such as hemispherical laterality or category selectivity, outcomes will be more consistent and reliable when BCG artifacts are detected and subtracted, even if grand averaged ERPs may keep their normal shape without applying these procedures.

In summary, our study shows that a highly reliable N170 response to faces can be obtained during simultaneous MR data acquisition in a 3 T scanner after effective gradient and BCG artifact removal. Our data show that not only the amplitude and the latency of the N170 peak response to faces is reliable but also the well-known functional effects reflected in the face-specific N170, such as the hemispherical laterality and the category selectivity. Furthermore, we revealed very high correlations of the N170 amplitude and laterality between data collected during fMRI acquisition and data collected in a different session outside the scanner. Now that the foundations for simultaneous ERP–fMRI studies of face perception are established, it will be of great interest to explore the relationship between the fMRI and ERP response to faces in future investigations that will combine the two complementary neuroimaging techniques.

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