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EEG reveals the effect of fMRI scanner noise on noise-sensitive subjects

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One drawback of fMRI is that subjects must endure intense noise during testing. This may be annoying to some people and acceptable to others. The aim of this study was to examine, by means of event-related potentials (ERPs), the possible influence of this noise on brain activity while performing a mental reasoning task. Subjects carrying out tasks in a silent environment were compared with two groups executing the same tasks in an "fMRI-like" noisy environment, one of which consisted of subjects who were annoyed by the noise and the other of subjects who tolerated it easily. Subjects who were annoyed performed less well (i.e., produced more errors compared to the "no noise" group) and "not annoyed" subjects showed a speed-accuracy trade-off (i.e., reacted faster but made more errors compared to "no noise" subjects).

Noise led to more pronounced N1 and P2 peaks but attenuated N2. As early ERP components are influenced by attention, this observation most likely reflects different attentional requirements. The slow cortical negative shift during task processing was significantly attenuated with "annoyed" subjects compared to "not annoyed" subjects. Emotion-related subcortical structures may be responsible for the observed difference.

These findings suggest that individual reactions to fMRI scanner noise should be taken into account when designing fMRI studies and interpreting results.

Keywords: fMRI acoustic noise; EPI; EEG; Slow cortical potential, SCP; Event-related potential, ERP; Noise annoyance; Cognition; Emotion

Introduction

Functional imaging using fMRI with EPI-BOLD sequences usually produces very intense acoustic noise. Current flowing in gradient coils causes Lorenz forces to act on them in the presence of the main magnetic field, and the direction of these forces varies with the rapid switching of these currents in EPI, causing them to vibrate noisily. "Silent" MRI sequences have been developed (Hennel et al., 1999) which reduce noise by using sinusoidal gradient slopes, the longest possible slope duration and the minimum number of slopes. These offer significantly lower performance, particularly in a reduction of spatial and temporal resolution, and truly mute sequences are suitable only for noise-intolerant subjects, for instance in some pediatric and psychiatric applications (Marcar et al., 2002).

Scanner noise present during the presentation of tasks is one of many unusual environmental variables in fMRI that may affect brain activation. Others are the supine position of subjects, which has been postulated to influence cerebral perfusion, and the psychological effect of the confinement of the MR scanner bore. Subject discomfort and the unusual environment of the horizontal MR scanner were at least partial motivations behind the development of a 7 T vertical primate scanner (Pfeuffer et al., 2004), and interest in the difference in activation between supine and upright fMRI, the specific reason for the construction of a 3 T vertical human scanner (Nakada and Tasaka, 2001). Nakada and Tasaka find no significant differences between the shape of brain structures between upright and supine MR and have yet to report results regarding perfusion or activation. It seems likely that scanner noise is the most important environmental disparity between everyday environments in which cognitive tasks are solved and the fMRI setting.

Several studies have been performed to assess the influence of fMRI noise on brain activity through direct and cognition-related indirect pathways (for an overview see Moelker and Pattynama, 2003). The direct adverse effects are most apparent in auditory tasks, as MR-related acoustic noise induces a BOLD response in the auditory cortex (Hall et al., 1999; Talavage et al., 1999; Bandettini and Cox, 2000). Further evidence for altered brain activity during auditory tasks comes from EEG research: Novitski et al. (2001),

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showed that, in event-related potentials (ERPs) evoked by tones and chords, P1, N1 and P2 peak latencies were prolonged and the amplitude of N2 was reduced in response to standard sounds by fMRI background noise compared to no background noise conditions. Functional MRI noise may influence higher cognitive processing through indirect effects which are based on altered attention. Focusing attention on a specific modality implies that the modality-specific cortical area shows increased activity. Increasing the attentional load required to process the task in the presence of a distracting noise may lead to increased activity in attentional (Mazard et al., 2002) and task-relevant areas (Brechmann et al., 2002), respectively. On the other hand, it is also possible that fMRI signal decreases are attributable to exhaustion and loss of attention in the presence of MR noise (Cho et al., 1998).

From a psychological perspective, an emotion-related indirect influence on brain activity is also conceivable. It is obvious that noise can lead to emotional reactions: noise annoyance has been linked to a variety of emotions including anger, aggression, rage, displeasure, exasperation, fear, disquiet, helplessness, resignation, depression, etc. (Breier et al., 1987; Guski et al., 1999). Each of these may be caused by separate, although perhaps partly overlapping brain networks (for reviews, see e.g., Phan et al., 2002; Wager et al., 2003). Thus, emotional reactions to fMRI-scanner noise could also influence brain activity during an fMRI session. Furthermore, emotions have been shown to interfere with cognition (e.g., Ellis et al., 1984; Jackson and Smith, 1984; Conway and Giannopoulos, 1993; Perlstein et al., 2002). Impairments in cognitive task performance when fMRI noise is presented, as revealed by higher error rates (Mazard et al., 2002; Lamm et al., 2001) and longer response times (Lamm et al., 2001), may be linked to both MR noise-related attentional distraction and emotional reactions. As individual factors influence noise annoyance (e.g., Fields, 1993; Miedema and Vos, 1999), fMRI noise may be annoying or distracting to some subjects but acceptable to others. We hypothesized that brain activity may systematically differ between healthy subjects who were annoyed and those who were not annoyed by fMRI noise.

The purpose of the current study was to clarify the possible effect of background fMRI scanner noise on brain activity during higher cognitive processing and whether there is a difference in brain activation between subjects who become annoyed by the noise and those who do not. To explore these effects, the impact on cognitive processing of playing recorded fMRI noise to subjects was investigated using slow cortical potential (SCP; Bauer, 1998) recording.

Methods

Subjects

Forty right-handed healthy female subjects, aged between 18 and 29 years (mean 23 years), volunteered for this study. Written informed consent was obtained from all subjects prior to their participation. The experiment was approved by the Ethics Committee of the Medical Faculty of the University of Vienna. Since brain activity may differ with gender in respect of emotions (e.g., Oliver-Rodriguez et al., 1999; Klein et al., 2003; Royet et al., 2003), only female participants were investigated. Of the 40 subjects, 15 were chosen at random for the “no noise” group. The remaining 25 subjects were assigned to the “noise” group. According to a post-experimental questionnaire, subjects from the “noise” group were categorized into those who were “annoyed” and “not annoyed”. In total, 13 subjects had to be excluded from the analyses, 10 on the basis of excessive EEG artifacts and 3 due to incomplete post-experimental questionnaires. In total, 9 subjects remained in the “no noise” group, 9 in the “annoyed” and 9 in the “not annoyed” group.

Stimuli

The stimuli were 50 number completion items which were presented in a random order for each subject. With each task item, subjects were presented with a series of numbers arranged according to some mathematical rule and asked to choose the number which continued the sequence correctly from 4 alternatives (see the example below) by pushing the corresponding button of a 4-button response box. The multiple choice format (one correct and 3 plausible looking numbers) was chosen to minimize the number of correct answers arrived at by chance.

The sample below is given in the presentation format used (the correct choice is underlined here):

3	5	9	15	23	33	45
		55	57	58	59	

All of the task items used in the experiment had been pre-tested extensively and were solvable in a median time of 18 s.

In order to familiarize subjects with the task, they had extensive training approximately 1 week before EEG recording. Immediately prior to the data acquisition, subjects were also given 20 items to ensure familiarity with the tasks and confidence in their ability to answer them correctly.

Item presentation was for a maximum of 43 s but was terminated by subjects' answers. Immediately after each response subjects were shown the message “correct” or “incorrect” for 2 s. Subjects were then asked to estimate the likelihood that they would solve the next item correctly on a 4 point scale (‘very high’, ‘high’, ‘low’ and ‘very low’). This question was presented for a maximum of 5 s. Crosshairs were presented between tasks for a random period of 6 to 10 s to allow the electrophysiological signal to return to baseline.

EEG recordings

The EEG data set used in the analysis was collected via 20 electrodes attached to the scalp according to the International 10–20 System at Fp1, Fp2/F7, F3, Fz, F4, F8/T3, C3, Cz, C4, T4/T5, P3, Pz, P4, T6/O1, Oz, O2. All channels were referenced to the noncephalic ‘sterno-vertebral’ site, i.e., to the common end of an adjustable voltage divider that connected skin locations above the 7th vertebra and the right manilum sternum (Stephenson and Gibbs, 1951). In order to control for eye movements, the vertical and horizontal electrooculogramm (EOG) was recorded bipolarly. Calibration trials in which subjects performed voluntary vertical and then horizontal eye movements were stored for regression-based EOG correction (Bauer and Lauber, 1979). 3D coordinates of all scalp-electrode locations were measured by means of a photogrammeric 3D scanner (Bauer et al., 2000).

All signals were recorded within a frequency range of DC to 30 Hz and sampled at 125 Hz for digital storage. The recording system was a DC-amplifier BDS 3064 (Ing. Zickler Ges.m.b.H, 2511 Pfaffstatten, Austria).

Experimental setting and procedures

Subjects were seated in front of an 18″ TFT-monitor in a comfortable chair in a sound-attenuated, dimly lit room equipped with an intercom, enabling communication with the experimenter.

The "noise" group was presented with digitally recorded fMRI scanner noise via a surround sound system during EEG recording. Scanner noise was switched on before the first task was presented and switched off after the last task was solved, i.e., in a similar manner to an fMRI experiment. Noise was also present during the interstimulus interval.

The sound used in EEG was that produced by a Bruker 3 T Medspec S300 MR scanner with whole-body gradients (BGA-55) providing a maximum of 45 mT/M in <300 μs, executing a single-shot blipped gradient-recalled echo-planar sequence with a 128 × 128 matrix and receiver bandwidth of 200 kHz, running continuously with a slice acquisition time of 167 ms (i.e., a frequency of EPI "beeps" of 6 Hz) (Robinson et al., 2004). This was recorded with a digital audiotape (DAT) using two nonmagnetic microphones separated by 25 cm sited inside the scanner bore.

The scanner noise was played back during EEG experiments via a PC over a Dolby 5.1 surround sound system. Subjects generally wear ear protection in fMRI (in the case of our laboratory, earplugs) but not in EEG. As a consequence, the same noise level in the two environments could not be achieved under these two conditions via sound levels measured with a calibrated microphone or a noise level meter. The noise level in EEG without earplugs was instead matched to that experienced in fMRI with earplugs via a two-stage subjective comparison. In the first stage, a single test person wearing earplugs was placed in the MR scanner and subjected to the EPI sequence described for 3 min. This person, still wearing earplugs, listened to the DAT recording of the sequence over headphones immediately after coming out of the scanner, and adjusted the playback volume to that which they judged to give the same sound level. This process was repeated until the person was satisfied that the volume levels were the same. In the second comparison, the sequence was again played over headphones at this volume to the test person, still wearing earplugs, but this time seated in the EEG laboratory. The sequence was then played to the test person without earplugs via the surround system, the volume of which was adjusted to give the same sound level. This volume was used for playback for all EEG measurements.

The sound level in the EEG setting was measured with a single omnidirectional condenser microphone (Behringer 8000, Behringer International GmbH, Willich, Germany), connected to the DAT recorder described and calibrated with a 94 dB tone at 1 kHz issued from a Cirrus 511 E calibrator (Cirrus Research PLC, Hunmanby, UK) before and after recording the scanner sequence at the playback volume. The microphone was sited in the transverse plane, with the tip at the usual position of a subject's left ear. The DAT recording was transferred to a PC and analyzed for peak sound pressure level (SPL).

Subjects of the "noise" group were seated in the center of the 5.1 surround sound system without earplugs during EEG recording. Subjects were informed that – in addition to the EEG experiment – an fMRI experiment with the same tasks was to be carried out, and that fMRI scanner noise would be presented during the whole EEG recording to ensure optimum comparability.

Post-experimental questionnaire

Subjects were asked to complete a questionnaire immediately after the experiment, covering the subjects' general motivation and the perceived difficulty of the tasks. For the "noise" group, additional questions addressed the emotional impact of the noise (presence and strength of feelings of anger, aggression, dejection, demotivation and apathy) and the possible impact of the noise on concentration and whether the noise was disturbing. All ratings were given on a 4 point scale (+ +, +, −, − −).

Analyses

EEG data processing and averaging

Prior to any processing of the data, weighted vertical and horizontal EOG signals were subtracted from each EEG channel, trial by trial, in order to compensate for eye movement artifacts.

Table 1
Latencies of the selected ERP components

	"no noise" group	"noise" group
N1	Not observed	Average over 16 ms centered at the minimum value between 140 and 200 ms post-stimulus (p.s.) at Oz
P2	Not observed	Average over 16 ms centered at the maximum value between 180 and 240 ms p.s. at Oz
N2	Average over 16 ms centered at the minimum value between 170 and 270 ms p.s. at Oz	Average over 16 ms centered at the minimum value between 220 and 280 ms p.s. at Oz
P3a	Average over 16 ms centered at the maximum value between 280 and 380 ms p.s. at Cz	Average over 16 ms centered at the maximum value between 300 and 400 ms p.s. at Cz
P3b	Average over 16 ms centered at the maximum value between 380 and 530 ms p.s. at Pz	Average over 16 ms centered at the maximum value between 400 and 550 ms p.s. at Pz
SCP1	Average over 50 ms centered at 1000 ms p.s.	Average over 50 ms centered at 1000 ms p.s.
SCP2	Average over 200 ms centered at 1900 ms p.s.	Average over 200 ms centered at 1900 ms p.s.
SCP3	Average over 200 ms centered at 2900 ms p.s.	Average over 200 ms centered at 2900 ms p.s.
SCP4	Average over 200 ms centered at 3900 ms p.s.	Average over 200 ms centered at 3900 ms p.s.
SCP5	Average over 200 ms centered at 4900 ms p.s.	Average over 200 ms centered at 4900 ms p.s.

Subject- and channel-specific weights, separated for the vertical and the horizontal EOG, were calculated as the ratio of the covariance of the EEGs and EOGs and the variance of the EOGs. Additionally, trials were skipped if judged by visual inspection to contain artifacts.

For each subject, artifact-free single-trial data of items 1–50 were averaged. Five early components (N1, P2, N2, P3a and P3b) and 5 SCP components (SCP1, SCP2, SCP3, SCP4 and SCP5) were chosen for further analyses (see Table 1 and Fig. 1). Mean signal

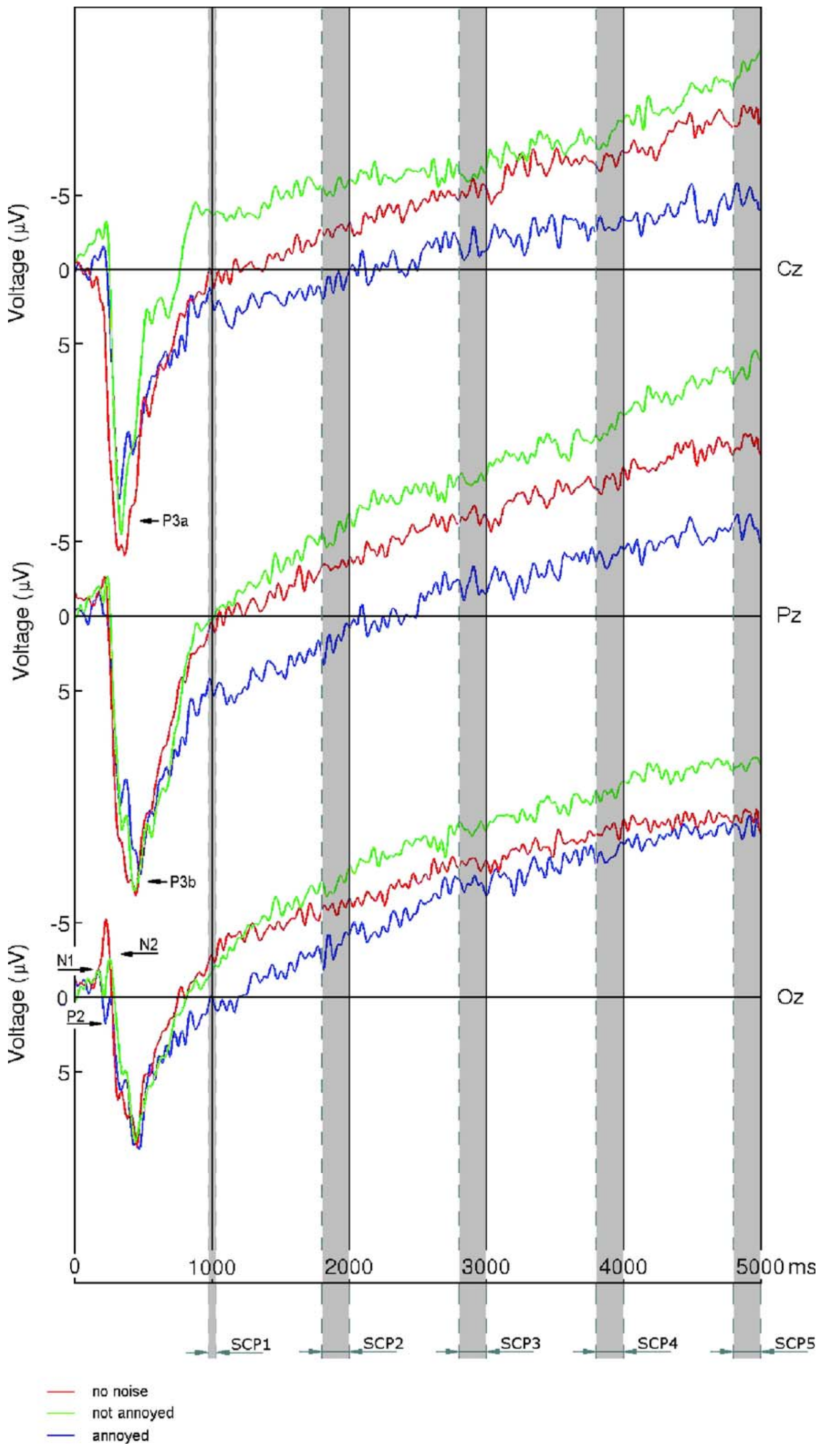

Fig. 1. ERP components of the grand means of the groups without noise (red) and with noise, the latter divided into "not annoyed" (green) and "annoyed" (blue) subjects. The EEG time courses for the first 5 s of task processing at selected electrode positions are shown. N2, P3a, P3b and the slow cortical potential shift can be identified clearly with and without noise. N1 and P2 are only observable when noise was presented. 5 time points were chosen within the slow potential shift (SCP1–SCP5).

Table 2
Assessment of the post-experimental questionnaire

	No noise		Not annoyed		Annoyed	
	Mean	SD	Mean	SD	Mean	SD
Importance of overall good performance	3.07	0.80	3.00	0.50	2.89	0.78
Difficulty of tasks	1.53	1.06	1.11	0.33	1.22	0.67
The presented noise led to feelings of:						
Anger			1.56	0.53	3.00	1.22
Aggression			1.11	0.33	2.67	1.32
Dejection			1.44	0.73	3.78	0.44
De-motivation			1.44	0.73	3.56	0.73
Apathy			1.33	0.71	3.22	1.10
Noise impacted on concentration			1.89	1.05	3.33	0.71
Noise was disturbing			2.22	0.67	3.11	0.78

1 = total disagreement, 4 = total agreement.

values over 200 ms preceding task presentation served as prestimulus baselines. Time windows for the identification of the peak for each endogenous component were chosen according to the grand mean of the three groups (Table 1). Because no clear N1 and P2 could be identified with the "no noise" group and the other early components had an earlier onset, time windows were different between the "no noise" and "noise" groups. Furthermore, analyses for N1 and P2 were only carried out for the "annoyed" and "not annoyed" group.

Statistical analyses

Introspective data

Questionnaire responses were converted to numbers between 1 and 4, with 1 = '– –' being equivalent to complete disagreement, 2 = '–' moderate disagreement, 3 = '+' moderate agreement and 4 = '+ +' total agreement. To allow assessment of clusters of emotional reactions to the fMRI noise (i.e., becoming slightly angry or reacting somewhat dejectedly), a factor analysis was computed with the data of the "noise" group. Questionnaire data were also subjected to descriptive statistics and group differences were analyzed by means of Mann–Whitney *U* test and Kruskal–Wallis tests.

Behavioral data

Descriptive statistics were applied to the reaction time data and to error rates, whereas group inference-statistics were investigated using the Pearson Chi-Square test and Mann–Whitney *U* test.

Physiological data

ERP data were analyzed by means of a repeated measures analysis of variance (ANOVA). Analyses were performed on raw and z-scaled data (McCarthy and Wood, 1985; Haig et al., 1997), because overall amplitude differences as well as differences in topographical patterns were of interest. Nonsphericity adjustment of degrees of freedom was performed with the Greenhouse–Geisser correction (level of significance: $P < 0.05$). Latencies were analyzed by means of univariate analysis of variance (ANOVA). Tukey's HSD tests were used for post hoc analyses of significant main effects and interactions of between-subjects factors.

Table 3
Response times and percentage of correct answers

	No noise	Not annoyed	Annoyed
Median of response times	14.1 s	12.8 s	13.9 s
Correct answers	96%	90%	90%

Results

Sound pressure level

The sound pressure level to which subjects in the "noise" group were subjected was 88 dB.

Introspective data

According to the post-experimental questionnaire, all subjects were highly motivated and performance oriented (see Table 2) and the items were considered to be easy.

The results of the factor analysis of the post-experimental questionnaire revealed that three factors (eigenvalue > 1) explain approximately 79% of the total variance. Factor 1 (eigenvalue = 4.64) had high loadings in all "emotion" questions, the question concerning the "impact of the noise on concentration" and the "noise disturbance". This factor was labeled "annoyance". The second factor (eigenvalue = 1.34) had a high negative loading in the item "perceived difficulty of the tasks" and the third factor (eigenvalue = 1.14) had a high loading in the "general motivation" item.

The categorization into "annoyed" ($N = 9$) and "not annoyed" ($N = 9$) subjects was solely according to the factor "annoyance".

A Mann–Whitney *U* test comparing questionnaire scores of the 9 "annoyed" and 9 "not annoyed" subjects reached significance with the pooled data according the factor "annoyance" ($P < 0.001$).

Table 4
Results of ANOVA for repeated measurements of each ERP component with factors: Noise ("no noise", "not annoyed", "annoyed") × Location (20)

	N2	P3a	P3b	SCP1	SCP2	SCP3	SCP4	SCP5
Factor	*P*	*P*	*P*	*P*	*P*	*P*	*P*	*P*
Raw data								
Noise	n.s.	n.s.	n.s.	n.s.	0.005	0.045	0.028	0.023
Noise × Location	0.004	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
z-scaled data								
Noise	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Noise × Location	0.006	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

n.s. = not significant.

Kruskal–Wallis tests comparing the groups “no noise”, “annoyed” and “not annoyed” neither reached significance for the question “importance of overall good performance” nor for the question “difficulty of items”.

Behavioral data

The “no noise” group achieved 96% correct answers on average. Both “not annoyed” and “annoyed” subjects solved 90% of tasks on average (see Table 3). A Pearson Chi-Square test comparing all these groups revealed a significant difference ($P < 0.002$). The median response time for the “no noise” group was 14.1 s, for “not annoyed” subjects 12.8 s and for the “annoyed” 13.9 s (see Table 3). Mann–Whitney U tests revealed a significant difference between “no noise” and “not annoyed” groups ($P < 0.002$) and between “annoyed” and “not annoyed” groups ($P < 0.001$).

EEG changes

In order to identify differences between the three groups, ANOVAs for repeated measures [factors: Noise (“no noise”, $N = 9$, “not annoyed”, $N = 9$, “annoyed”, $N = 9$) × Location (20)] were performed with raw and z-scaled data for each ERP component (see Table 4) except N1 and P2. These two components were subjected to an ANOVA for repeated measures with the factors: Annoyance (“not annoyed”, $N = 9$, “annoyed”, $N = 9$) × Location (20).

Analyses of N2 raw and z-data revealed significant interactions for Noise × Location (raw data: $F_{(38,456)} = 3.928$, $P < 0.004$; Greenhouse–Geisser $\varepsilon_{GG} = 0.126$; z-data: $F_{(38,456)} = 2.688$, $P < 0.006$; $\varepsilon_{GG} = 0.247$). As shown by significant a priori linear and a posteriori interaction contrasts (Boik, 1979; a posteriori significance level was Bonferoni-corrected with $\alpha' = 0.016$), this significant interaction was mainly due to a more pronounced N2 over occipital areas without noise, with higher negative values at occipital sites and more positive values at frontal sites (see Fig. 2 and Table 5).

ANOVA for latencies [Noise (“no noise”, $N = 9$, “not annoyed”, $N = 9$, “annoyed”, $N = 9$) × Latency] revealed a significant difference for the N2 ($P < 0.002$, $F_{(2,24)} = 8.128$). Noise prolonged latencies, as shown by Tukey’s HSD [“annoyed” (mean latency $L = 255$ ms) vs. “no noise” ($L = 220$ ms): $P < 0.002$; “not annoyed” ($L = 244$ ms) vs. “no noise”: $P < 0.034$]. No difference was found between the noise groups [Tukey’s HSD “annoyed” vs. “not annoyed” did not reach significance].

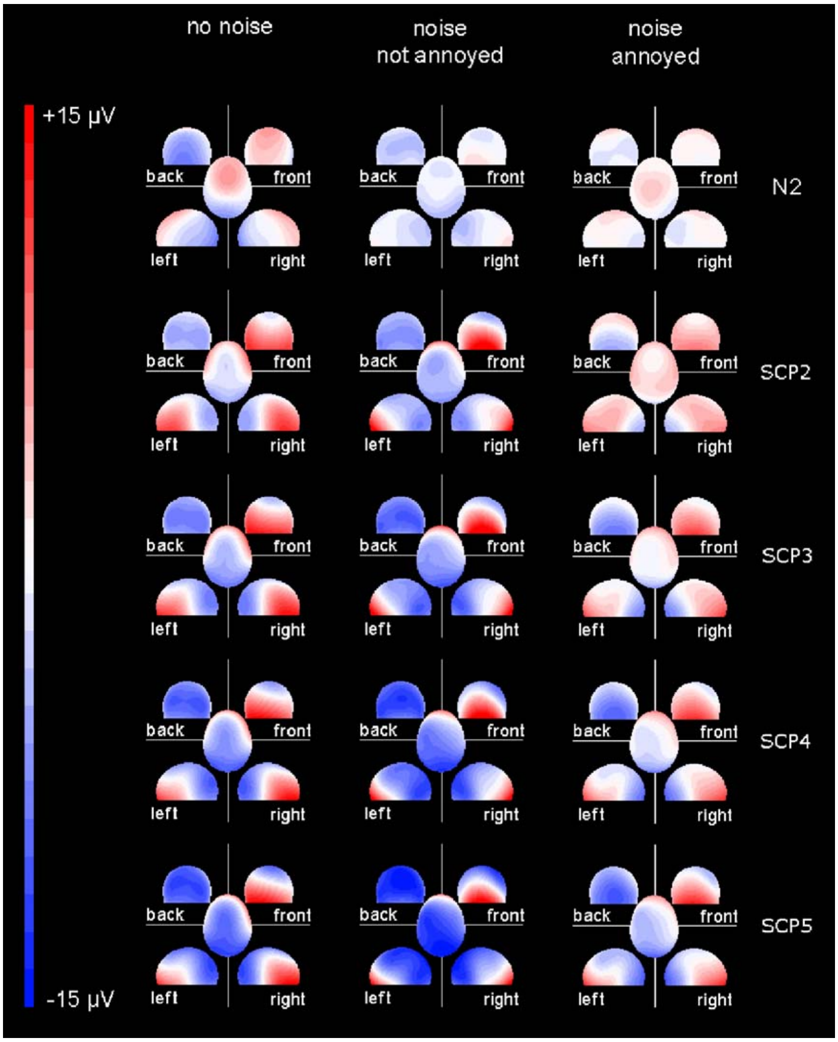

Fig. 2. Maps of grand means of significant components. Noise reduced the N2 component and shifts towards negative amplitude values were generally reduced when subjects became annoyed.

Table 5
A priori and a posteriori contrasts for the significant ANOVA interaction "Noise × Location" of N2

	Raw data at locations		z-data at locations	
	O1, Oz, O2		O1, Oz, O2	
	P	$F_{(1,24)}$	P	$F_{(1,24)}$
A priori contrasts				
"annoyed" vs. "not annoyed"	n.s.	n.s.	n.s.	n.s.
"annoyed" vs. "no noise"	0.016	6.730	0.031	5.219
"not annoyed" vs. "no noise"	n.s.	n.s.	0.017	6.522
	Raw data at locations		z-data at locations	
	F3, Fz, F4 vs. O1, Oz, O2		F3, Fz, F4 vs. O1, Oz, O2	
	P	$F_{(1,24)}$	P	$F_{(1,24)}$
A posteriori interaction contrasts				
"annoyed" vs. "not annoyed"	n.s.	n.s.	n.s.	n.s.
"annoyed" vs. "no noise"	0.003	11.120	0.004	7.833
"not annoyed" vs. "no noise"	0.002	11.621	0.010	10.283

vs. = versus; n.s. = not significant.

Analyses of SCP2, SCP3, SCP4 and SCP5 showed significant main effects for the factor "Noise" with raw data (SCP2: $F_{(2,24)} = 6.779$, $P < 0.005$; SCP3: $F_{(2,24)} = 3.538$, $P < 0.045$; SCP4: $F_{(2,24)} = 4.144$, $P < 0.028$; SCP5: $F_{(2,24)} = 4.422$, $P < 0.023$) indicating a topographic pattern with a generally smaller negative-going shift with "annoyed" subjects compared to "not annoyed", as supported by Tukey's HSD ("annoyed" vs. "not annoyed" during SCP2: $P < 0.004$, mean difference for SCP2: 4.65 μV; SCP3: $P < 0.040$, 4.52 μV; SCP4: $P < 0.027$, 5.43 μV; SCP5: $P < 0.020$, 6.59 μV). Although mean differences were also large between "annoyed" and "no noise" subjects (from 3.03 μV for SCP2 up to 4.42μV for SCP5), Tukey's HSD did not reveal any significance. Likewise, Tukey's HSD did not reveal any significant difference between the "not annoyed" and "no noise" groups (see Table 6). Neither ANOVA of z-scaled data of these SCP components, nor ANOVA of latencies as well as raw and z-data for P3a and P3b amplitudes yielded any significant result.

Repeated measures ANOVA for N1 and P2 [factors: Annoyance ("not annoyed", $N = 9$, "annoyed", $N = 9$) × Location (20)] showed no significance either for latencies, or for raw or z-scaled data. As has been mentioned, these two components were not identifiable for "no noise" subjects, so a separate ANOVA was calculated.

Discussion

As our study included only female subjects, results and interpretations cannot be generalized for gender. According to the introspective data, all subjects were highly motivated and considered the tasks to be easy. Individual differences were found when fMRI scanner noise was played back as background noise: some of the subjects accepted the noise, others became annoyed and the noise evoked negative feelings. By means of a factor analysis, we attempted to establish if a specific type of emotion (e.g., anger or dejection) was preferentially evoked in reaction to scanner noise or if subjects experienced a diffuse pattern of negative feelings. We identified just one factor which had high loadings in all questions concerning emotions and distraction of concentration. Thus, fMRI noise seems to induce a general negative affect and subjects are not able to clearly identify an emotion to which this should be assigned. This result reflects the broad extent of the noise annoyance concept, as a negative evaluation of environmental conditions, but with connotations that are rather diverse (Guski et al., 1999). However, the weak selectivity may also be partly due to the method. No time course of feelings was measurable with the applied post-experimental questionnaire. It is feasible that subjects reacted with anger or aggression at the beginning of the experiment but fell into a state of "helplessness" with feeling similar to those associated with depression or passivity, when they experienced a loss of control over the noise for an extended period of time. Given the available data, subjects had to be simply classified as having been annoyed or not annoyed. Response times were shorter for "not annoyed" subjects than for the "no noise" group and did not differ between the groups of "annoyed" and "no noise". Error rates were more than twice as high in the noisy environment as in the silent. According to the "annoyed" subjects, these behavioral observations clearly indicate that their performance was worse. Explanations for the so-called 'speed-accuracy trade-off' of the "not annoyed" group, i.e., why subjects trade speed for accuracy, remain somewhat speculative. When and why people respond quickly or accurately has been a fundamental question since the beginning of experimental psychology (Woodworth, 1899). Given the extensive research on this topic, it is surprising that the basic processes underlying these decisions are still poorly understood (for a review see Forster et al., 2003). One explanation may be that processing the task in the presence of a distracting noise entails increased attentional load. This may serve two purposes;

Table 6
Tukey's HSD for significant ANOVA main factor "Noise" of SCP2, SCP3, SCP4 and SCP5

	SCP2	SCP3	SCP4	SCP5
	P	P	P	P
"annoyed" vs. "not annoyed"	0.004	0.040	0.027	0.020
"annoyed" vs. "no noise"	n.s.	n.s.	n.s.	n.s.
"not annoyed" vs. "no noise"	n.s.	n.s.	n.s.	n.s.

vs. = versus; n.s. = not significant.

to allow the task to be performed under such conditions and, quite separately, to block noise. The additional resources allocated to processing the task may have led to shorter reaction times here. Shorter reaction times are often related to lower accuracy (Forster et al., 2003). In the present study, the additional cognitive effort required to block noise was perhaps responsible for this impaired performance. Interestingly, people who became annoyed did not show this speed-accuracy trade-off. Their mean response time did not differ significantly from the "no noise" group, but they made more mistakes. It is possible that they were not able to make additional attentional resources available for task processing because some of the attentional resources were used for dealing with the evoked emotions (see e.g., Drevets and Raichle, 1998). As "not annoyed" and "annoyed" subjects had the same error rates but the "annoyed" subjects took longer to find an answer, the reported differences in the literature between performance recorded off-line and during fMRI (Lamm et al., 2001; Mazard et al., 2002) may not only be due to distracted attention but to cognitive-emotional interference as a result of noise annoyance. Other factors may contribute to differences between cognitive processing in the fMRI environment and in everyday circumstances, such as subjects' supine position and the narrow confines of the MR scanner. By analyzing cognitive processing with fMRI noise in EEG, however, we have been able to separate noise effects from the other potential confounds of the fMRI setting.

Acoustically, typical EPI noise experienced in fMRI is not a broadband noise but rather a complex sound, with characteristic beep-beep-beep-... noise bursts, with beeps corresponding to each acquisition of a slice. The aim of the study was to assess the influence of the noise that is usually present in an fMRI experiment. Noise was switched on at the beginning of EEG recording and switched off after recording was stopped, without stimulus-locking of the presentation of the noise. Thus, averaging the data should have eliminated evoked potentials elicited by single noise bursts. However, fMRI scanner noise influenced very early stages (N1, P2, N2) of processing of the visual presented tasks. Additionally, different reactions to the noise (being annoyed vs. being not annoyed) resulted in distinct brain activity during later stages of task processing, i.e., from 2 s post-stimulus until the end of the analyzed time interval.

N1 and P2 were only identifiable with background noise, whereas, in agreement with Novitski et al. (2001), N2 was more pronounced without noise. As early ERP components are influenced by attention (besides physical task features; e.g., Groves and Eason, 1969; Oakley and Eason, 1990; Johannes et al., 1995), and cross-modal attention has been shown to modulate event-related brain potentials (e.g., Eimer, 2001; Hotting et al., 2003), the observed heterogeneity in distribution was probably caused by different attentional requirements. It is obvious that the blocking out of distracting fMRI noise is necessary for successful processing of the reasoning task under noise conditions. Thus, an additional cognitive effort is required, even if this blocking is highly automated, leading to altered task performance and perhaps also to the divergent ERP's observed. Prolonged peak latency of N2 under noise fits with this interpretation.

The slow cortical negative shift during task processing was significantly attenuated for "annoyed" subjects compared to "not annoyed" subjects. As there was no significant interaction with the location factor, topographies of the two groups differed only in strength. Thus, the same cortical areas might have been activated, but with different intensities. The EEG method used collects mainly cortical brain activity, but emotions are also related to limbic and subcortical structures (e.g., LeDoux, 1992; Charney and Deutch, 1996; Lang et al., 1998; Cardinal et al., 2002), which may be responsible for the observed difference. Actually, there are some hints of a reciprocal suppression of brain activity during emotional vs. higher cognitive processing. Drevets and Raichle (1998), showed in a review that when brain regions putatively involved in performing memory, language, or visuospatial tasks become activated, brain regions involved in emotional processing become less active, and vice versa. They suggest that "the deactivation of particular regions may be consistent with a 'limited capacity' model of cognitive processing, in which the excessive amounts of information available to the brain necessitate a variety of attentional mechanisms that select among competing mental processes". In this context, our results could be interpreted as the different SCPs of the groups reflecting different attentional mechanisms that allocate processing resources during task performance. SCPs of "annoyed" subjects were not as negative as those of the "not annoyed", perhaps due to an allocation of attentional resources for dealing with the emotions which arose. The poorer performance of this group is in agreement with this interpretation.

Our findings have several implications for the design and interpretation of fMRI studies. Firstly, we have shown that fMRI background noise can influence attention-related neuronal activity as reflected in the early ERP components of visual processing, probably causing different task performance. The BOLD response for cognitive tasks of longer duration is usually recorded with repetition times (TR) of 2 s and longer. Thus, very short duration early brain activity as measured via N1, P2 or N2 may not be apparent in fMRI data. However, these early processes are perhaps accompanied by longer lasting activation of other attention-related areas which should be detectable by fMRI. Activity in one of these areas, the anterior cingulate cortex (ACC) has already been shown to increase during cognitive task processing when fMRI noise was presented compared to a silent condition (Mazard et al., 2002).

Secondly, fMRI noise may lead to annoyance and emotional reactions in some but not all subjects. Annoyed subjects differ systematically from not annoyed subjects in both brain activity and performance in the reasoning task (with the annoyed subjects needing about 1 s longer to solve a task). The same would be expected to be the case with other complex mental tasks. It has been demonstrated that emotional reactions to scanner noise could be a confounding variable when studying the emotions with fMRI. This could pose a particular problem when studying patients suffering from affective disorders, because they are potentially particularly susceptible to the emotional reactions described. This could confound matched control investigations in both cognition and emotion studies.

Our results suggest that individual reactions to fMRI noise should be taken into account when designing fMRI studies, interpreting results and making comparisons with EEG studies employing the same stimuli in quiet surroundings.

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