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Effects of a multi-sensory environment on brain-injured patients: Assessment of spectral patterns

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ABSTRACT

Snoezelen® multi-sensory (SMS) environment has been commonly applied as a therapeutic strategy to alleviate the symptoms associated to a wide variety of pathologies. Despite most studies have reported a wide range of positive revealed short-term changes associated to SMS intervention, little has been done to systematically quantify its effects. The present study examined electroencephalographic (EEG) changes in 18 individuals with brain-injury and 18 healthy controls during SMS stimulation. The experimental design included a multi-sensory stimulation session carried out in a Snoezelen® room, preceded and followed by a 5 min quiet rest condition. Spontaneous EEG activity was analyzed by computing the relative power in conventional EEG frequency bands. The results suggest that SMS stimulation induces a significant increase ($p < 0.05$, Wilcoxon sign-ranked test) of relative power for low frequency bands (i.e., theta and alpha bands) and a significant decrease ($p < 0.05$, Wilcoxon sign-ranked test) for fast rhythms (i.e., beta1, beta2 and gamma bands). In addition, statistically significant differences ($p < 0.05$, Mann–Whitney U-test) between both groups were found in relative power of theta band. Our findings suggest that the slowing of EEG oscillatory activity may reflect the state of relaxation induced by the SMS stimulation. Furthermore, this study presents a new strategy to assess the short-term effects of SMS stimulation therapy in comparison to previous studies using subjective observations and qualitative data.

1. Introduction

Multi-sensory therapy is an activity which usually takes place in a specially equipped room aiming to stimulate the primary senses through light, sound, touch and smell. Snoezelen® multi-sensory (SMS) rooms contain tactile, visual, olfactory, auditory, vestibular and proprioceptive sensory equipment, such as mirror light balls, aromatherapy oils, optic fiber bundles, calming music, bubble tubes and other nominal sensory stimuli [1]. These stimuli can be presented in isolation or in combination, intensified or reduced and shaped for passive or active interaction [2]. A SMS environment is designed to create a feeling of comfort and safety, where the individual can relax, explore and enjoy the surroundings [3]. This environment has been applied to a wide range of conditions, such as aged people with dementia [4–7], mental health service recipients [8], adults with profound mental retardation [1,2], people with intellectual disabilities [9,10], individuals with autism [2,11], breastfeeding women [12] and children with Rett disorder [13] and severe brain injury [14], among others.

Although some authors have revealed negative outcomes when SMS therapy is applied [11], most studies have shown a wide range of positive effects. Preliminary investigations have suggested that multi-sensory therapy is beneficial for people with sensory and learning disabilities [9]. Moffat et al. revealed positive short-term benefits in people with dementia exposed to SMS environments, which experienced positive mood states such as happiness and calmness [5]. In other study, van Weert et al. observed that Snoezelen® rooms improved the nonverbal and verbal communication in nursing home residents with dementia during morning care [7]. Lotan and Shapiro suggested that regular visits to a SMS environment may provide a partial solution in management the difficulties of young children with Rett disorder [13]. Studies that measured physiological data also suggested the benefits of SMS therapy. In this sense, Hotz et al. analyzed the heart rate and muscle tone in children recovering from severe brain injury after SMS stimulation [14]. Their results revealed significant decreases in heart rate and muscle tone in all affected extremities for each subject, suggesting that SMS therapy produces a beneficial use in this population. Baillon et al. conducted a study to assess the effects of Snoezelen® intervention on the mood and behavior of people

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with dementia [15]. They observed that multi-sensory stimulation produced a reduction in agitation behavior and heart rate, though these effects were highly dependent on the analyzed subject. In sum, most of these studies have shown positive benefits of the SMS therapy, although the results are usually based on subjective observation or on qualitative data. These types of information do not provide an objective measure for understanding the mechanisms underlying SMS stimulation and therefore further efforts are required to systematically analyze and quantify the effects of SMS environments.

Multi-sensory stimulation is thought to affect central nervous system by inducing a state of relaxation in participants. This particular state of the brain alters the functional organization of cortical networks [16]. Therefore, the electroencephalographic (EEG) activity can be expected to quantify the changes induced in brain rhythms, since EEG oscillations measure the electrical field produced by the synchronous cortical network activity. To support this approach, several EEG studies have reported changes in the power spectrum during the exposure to a variety of relaxation and meditation techniques, though little is still known about the underlying neural mechanisms in stimulation therapies [16–18].

The purpose of this study was to describe the changes induced in the EEG brain oscillations by a SMS environment on individuals with brain-injury and healthy controls. The experimental protocol involved a multi-sensory stimulation session, where several auditory and visual stimuli were presented to the participants. In addition, a previous and a posterior 5 min quiet rest condition, where participants were asked to relax, close their eyes and remain awake, were applied. EEG activity was analyzed by computing the relative power in conventional EEG frequency bands before and after the multi-sensory stimulation session. The spectral patterns were compared to assess the spectral changes induced by a multi-sensory environment in brain dynamics. Furthermore, self-reported measures related to the level of relaxation and the global level of satisfaction with the SMS stimulation session were correlated with the observed changes in relative power. To sum up, we wanted to test the hypothesis that SMS stimulation elicits measurable changes in the EEG activity of brain-injured patients and to determine whether they can be related to a state of relaxation.

2. Materials

2.1. Participants

Informed consent was obtained from all participants and all patients' guardians prior to enrolling in the study. Likewise, all enrolled subjects and patients' guardians were previously informed about the background of the study, therapeutic techniques and experimental protocol. The study protocol was approved by the Ethics Committee at the "Centro de Referencia Estatal (CRE) para la Atención a Personas con Grave Discapacidad y Dependencia" (San Andrés del Rabanedo, Spain). A total of forty-one participants were initially selected to participate in the study. However, the final inclusion of participants was based on the following inclusion and exclusion criteria:

- Inclusion criteria: (1) age ranged between 25 and 50 years; (2) brain-injured patients showing evidence of pathologic condition on computed tomography (CT) or magnetic resonance imaging (MRI) scan; (3) Glasgow coma scale (GCS) score > 3; (4) collaborative in the EEG recording procedure; (5) ability to complete a full length neuropsychological evaluation; (6) ability to participate in the SMS stimulation session; (7) participants were not taking any drug that could affect the EEG recordings at the time of study.
- Exclusion criteria: (1) absence of neuroimaging data in patients; (2) secondary head trauma, penetrating brain injury or brain injury as result of child abuse; (3) psychiatric problems, neurological disorders, history of a chronic disease for the preceding 6 months, or pre-existing physical, neurological, psychiatric or developmental disorders; (4) mental retardation; (5) pregnancy; (6) presence of a pacemaker or other implanted medical device that may interfere with the EEG equipment.

Twenty-three participants with mild to severe brain injury from a National Reference Center for people with severe disabilities named "CRE para la Atención a Personas con Grave Discapacidad y Dependencia" (Spain) were initially included in the study. However, five of them were excluded due to excessive electromyographic activity and to the lack of attention during SMS stimulation session. Therefore, eighteen brain-injured patients (11 men and 7 women, age = 38.4 ± 5.1 (29–46) years, mean ± standard deviation M ± SD (range)) were finally included in the study.

Eighteen volunteers (9 men and 9 women, age = 37.6 ± 5.6 (30–48) years, M ± SD (range)) were also enrolled in the study as a control group among the staff of the "CRE para la Atención a Personas con Grave Discapacidad y Dependencia". They were cognitively normal controls with no history of neurological or psychiatric disorders. Additional sociodemographic data for brain-injured patients and controls are presented in Table 1. Non-significant differences were observed in the mean age ($p > 0.05$, Mann–Whitney U-test) or gender ($p > 0.05$, Mann–Whitney U-test) of both groups.

Brain injury diagnosis was made on the basis of exhaustive medical, physical and neuropsychological examinations, which were performed at the "CRE para la Atención a Personas con Grave Discapacidad y Dependencia" (Spain). Table 2 summarizes diagnostic information for the brain-injured patients. As indicated in Table 2, patients displayed a wide range of lesion distribution patterns, though a bilateral location of brain damage is the most common (61.1%). Nine of the patient's hospital records reported direct bilateral occipital lobe damage as part of their injury, whereas two indicated bilateral frontal lobe damage. Six patients also exhibited damage in frontal, parietal and occipital lobes (four in right hemisphere and two in left hemisphere), while one subject suffered damage in left temporal and parietal areas.

Neuropsychological testing was performed on all participants. A summary of test performance is presented in Table 3. Mini-Mental State Examination (MMSE) was used as the screening test to assess the cognitive deficit [19]. Brain-injured patients and controls obtained a mean MMSE score of 27.6 ± 0.7 points (range 27–29) and 30.0 ± 0.0 points (range 30–30), respectively. In addition, a neuropsychological examination was applied to analyze higher-level cognitive functions. For that purpose, 9 subtests of the Spanish

Table 1
Summary of the sociodemographic data of brain-injured patients and controls.

Characteristics	BI	C
Gender (no. of subjects)		
Male	11	9
Female	7	9
Age (years)		
Mean ± SD (range)	38.4 ± 5.1 (29–46)	37.6 ± 5.6 (30–48)
Occupation pre-injury (no. of subjects)		
Full time	8	14
Part time	0	2
Casual	5	0
No employment	5	2
Education (years)[a]		
Mean ± SD (range)	11.0 ± 2.3 (8–15)	16.8 ± 4.2 (10–21)

BI: brain-injured patients; C: controls; SD: standard deviation.
[a] Since 6 years.

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Table 2
Summary of the clinical characteristics of brain-injured patients.

Characteristics	Brain-injured patients' data
Brain injury severity (no. of subjects)	
Mild/Moderate (GCS = 9–15/15)	15
Severe (GCS = 3–8/15)	3
Time since injury (no. of subjects)	
0.5–4 years	2
4–8 years	4
>8 years	12
Neurosurgery (no. of subjects)	
Yes	6
No	12
Location of lesion (MRI/CT scan) (no. of subjects)	
Left	3
Right	4
Bilateral	11

GCS: glasgow coma scale; MRI: magnetic resonance imaging; CT: computed tomography.

neuropsychological test battery Luria-DNA ("Diagnóstico Neuropsicológico de Adultos") were used to assess visual-spatial skills (visual perception and spatial orientation), language area (expressive and receptive speech), memory functioning (immediate and logical memory), intellectual skills (comprehension of thematic pictures and texts, as well as discursive processes) and attention [20]. It is noteworthy that most patients (83.3%) were classified as having mild/moderate brain injuries according to GCS.

2.2. The Snoezelen® room

The study was conducted in the Snoezelen® room situated in the "CRE para la Atención a Personas con Grave Discapacidad y Dependencia". The Snoezelen® room measures 4 m × 5 m with walls painted in white, white floor tiles, ceiling in white fabric and windows with opaque glass. It is fully ventilated and composed of an array of multi-sensory equipment that provides stimulation in different modes to create a relaxing but also stimulating atmosphere.

The stimuli used in the study included: auditory (stereo system to play relaxing sounds of nature, like birds chirping) and visual (colored bubble tubes, optic fiber bundles, rotating mirror ball and projector with revolving disk showing moving pictures of clouds across an open sky) sensory equipment.

Table 3
Summary of the neuropsychological data of brain-injured patients and controls.

Characteristics	BI	C
	Mean ± SD (range)	Mean ± SD (range)
9 subtests of the Spanish neuropsychological test battery Luria-DNA[a]		
Visual perception	45.8 ± 6.9 (20–50)	54.2 ± 3.5 (50–60)
Spatial orientation	45.6 ± 3.8 (35–50)	52.5 ± 2.6 (50–55)
Expressive speech	45.6 ± 7.8 (25–55)	54.2 ± 3.9 (50–60)
Receptive speech	46.7 ± 3.4 (40–50)	54.7 ± 4.4 (50–65)
Immediate memory	40.0 ± 5.1 (30–45)	52.2 ± 3.1 (50–60)
Logical memory	38.6 ± 4.8 (30–45)	54.4 ± 4.2 (50–65)
Comprehension of thematic pictures and texts	39.8 ± 3.6 (35–45)	52.5 ± 3.1 (50–60)
Discursive processes	38.6 ± 4.1 (35–45)	52.8 ± 3.1 (50–60)
Attention	46.7 ± 3.4 (40–50)	54.4 ± 4.8 (50–65)
MMSE	27.6 ± 0.7 (27–29)	30.0 ± 0.0 (30–30)

BI: brain-injured patients; C: controls; SD: standard deviation; MMSE: mini-mental state examination.
[a] T-score.

2.3. Procedure

A Snoezelen® treating therapist administered a one-to-one 18 min treatment session, using several pieces of equipment. The stimuli were introduced slowly, in order not to overload the participant and no intellectual or physical demands were placed on the individual. In addition, the SMS stimulation session was preceded and followed by a 5 min quiet rest condition, during which the EEG activity was recorded with subjects in a relaxed state, awake and with eyes closed. EEG recordings were continuously monitored by an expert. Although the expert electroencephalographist and the treating therapist stayed in the room during the SMS stimulation session, only the therapist was involved with the subject's exposure to the Snoezelen® environment by guiding and promoting the experience and any related effects. For those subjects that were dependent for ambulation and sitting, the therapist moved their wheelchairs near the sensory equipment or the subject was carried to the sensory stimuli being evaluated. The SMS stimulation involved an internal session structure: introduction to the session, acquisition of 5 min of spontaneous EEG activity, carrying out the SMS intervention through the presentation of the stimuli, winding the session down and acquisition of 5 min of spontaneous EEG activity. The length of each session was the same for each participant. A detailed description of the session protocol used in the Snoezelen® room is shown in the following lines:

(1) Prior to entering the Snoezelen® room, the auditory and visual stimuli were turned off and the light was turned on.
(2) The subject was brought into the room and 19 EEG sensors were placed according to the recommendations of the international 10–20 system.
(3) After sensor placement, the subject was informed about the stimuli that will be shown during the SMS session.
(4) The subject was asked to stay relaxed, awake and with eyes closed and 5 min of spontaneous EEG activity were recorded from 19 EEG derivations.
(5) After 1 min, the light was turned off, the bubble tubes were turned on and the therapist described the colored bubbles rising in the tubes.
(6) After 5 min, the bubble tubes were turned off, the optic fiber bundles were turned on and the therapist described the spray of optic fibers, which change color in a rhythmical manner.
(7) After 5 min, the optic fiber bundles were turned off, the bubble tubes and the gyratory mirror ball were turned on, sound wall was turned on with relaxing sounds of nature and the subject was asked to concentrate on the changing colored spotlights that were projected on the wall.
(8) After 4 min, the bubble tubes ant the gyratory mirror ball were turned off, the wheel projector that slowly rotates to display images of the movement of clouds across the sky on the wall was turned on and the subject was asked to concentrate on the shape and movement of the clouds.
(9) After 4 min, the SMS equipment was turned off, the light was turned on and 5 min. of spontaneous EEG activity were recorded with subject relaxed, awake and with eyes closed.
(10) Finally, the subject was asked about her/his sensations and feelings during the SMS stimulation session.

2.4. EEG recordings

EEG signals were recorded from 19 derivations of the international 10–20 system (channels Fp1, Fp2, Fz, F3, F4, F7, F8, Cz, C3, C4, T3, T4, T5, T6, Pz, P3, P4, O1 and O2) with a common average reference using a Neurofax JE-912A (Nihon Khoden). Five minutes of spontaneous EEG activity were acquired preceding and

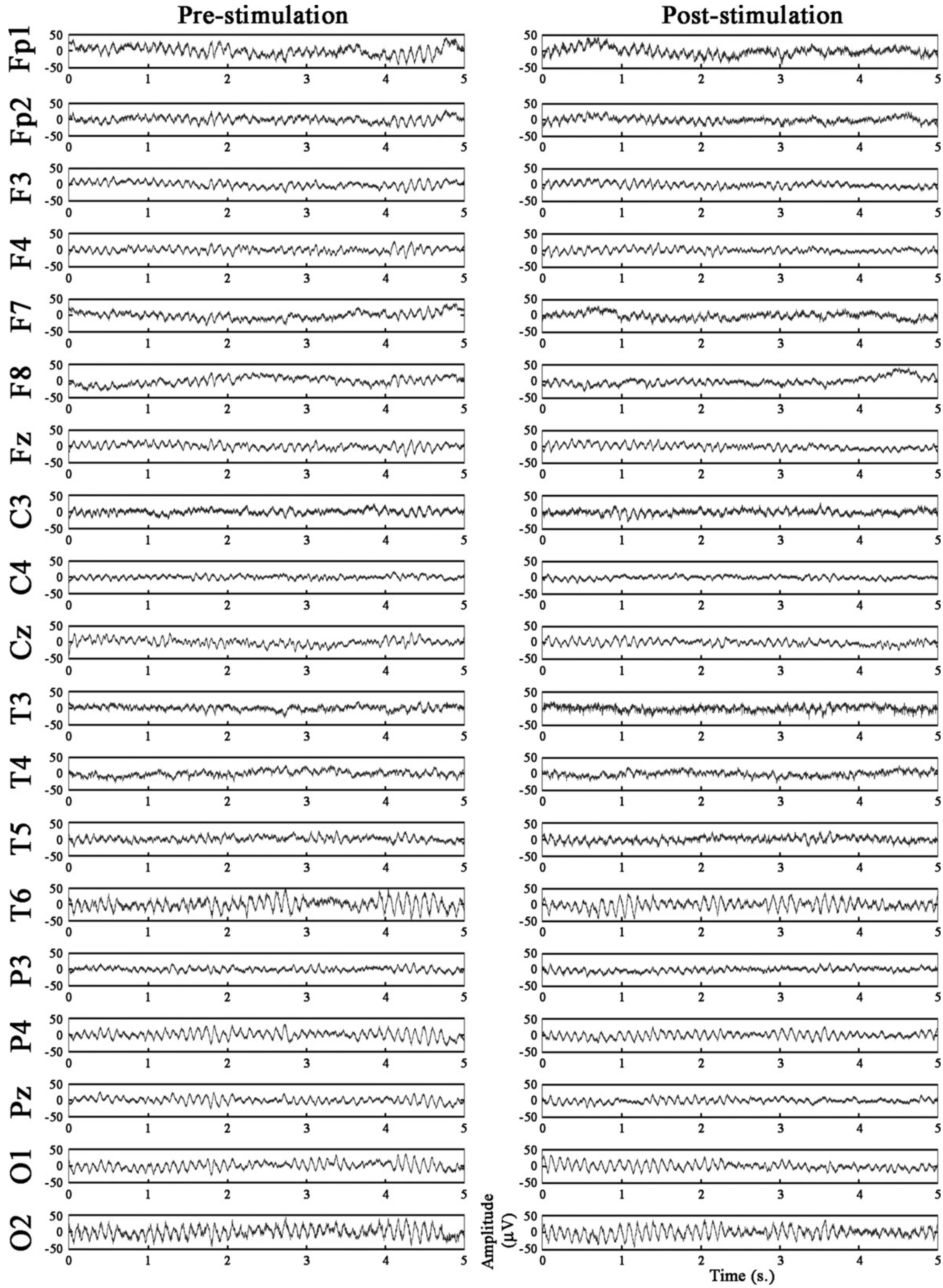

Fig. 1. 5 s EEG epochs from 19 acquisition sensors (channels Fp1, Fp2, Fz, F3, F4, F7, F8, Cz, C3, C4, T3, T4, T5, T6, Pz, P3, P4, O1 and O2) for a brain-injured patient: (a) pre-stimulation; (b) post-stimulation.

following the SMS stimulation session with participants in a relaxed state, awake and with eyes closed. Vigilance was continuously monitored in order to prevent drowsiness. EEG recordings were sampled at 500 Hz and processed with a 0.08–120 Hz band-pass filter and a 50 Hz notch filter.

Each EEG signal was divided into epochs of 5 s (2500 samples) and judged by visual inspection to be free from electrooculographic and movement artifacts, as well as to exclude episodes of drowsiness (25.4 ± 9.8 artifact-free epochs per channel and participant, M ± SD). Figs. 1 and 2 display 5 s EEG epochs from 19 derivations

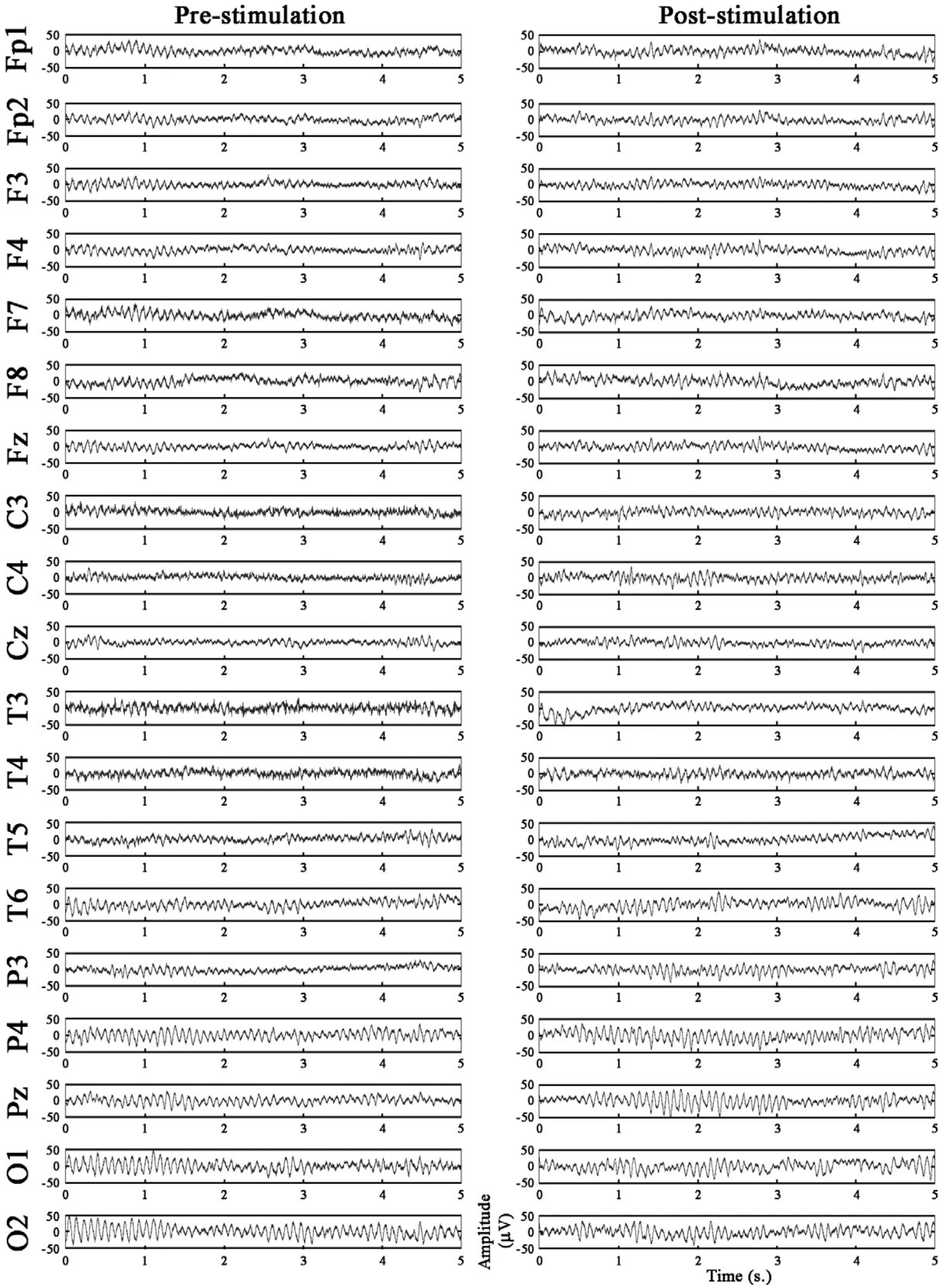

Fig. 2. 5 s EEG epochs from 19 acquisition sensors (channels Fp1, Fp2, Fz, F3, F4, F7, F8, Cz, C3, C4, T3, T4, T5, T6, Pz, P3, P4, O1 and O2) for a healthy control: (a) pre-stimulation; (b) post-stimulation.

preceding and following the SMS intervention for a patient with brain injury and for a control subject, respectively. Finally, each EEG signal was filtered using a FIR (finite impulse response) band-pass filter with a Hamming window and cut-off frequencies at 1 and 40 Hz.

3. Methods

3.1. Spectral analysis

In order to analyze the changes in the spectral content of EEG recordings, the relative power (*RP*) was calculated. This measure represents the relative contribution of several oscillatory components to the global power spectrum. In comparison to absolute power, relative power provides independent thresholds from the recording equipment and decreases inter-subject variability [21].

To calculate relative power, the power spectral density (PSD) was computed for each EEG epoch, as the Fourier transform of the autocorrelation function. The PSD was then averaged for each channel and participant. Finally, the definition of relative power was obtained by summing the contribution of the desired spectral components. Relative power was calculated in the conventional EEG frequency bands:

(1) Delta band (1–4 Hz): *RP*(delta).
(2) Theta band (4–8 Hz): *RP*(theta).
(3) Alpha band (8–13 Hz): *RP*(alpha).
(4) Beta1 band (13–19 Hz): *RP*(beta1).
(5) Beta2 band (19–30 Hz): *RP*(beta2).
(6) Gamma band (30–40 Hz): *RP*(gamma).

3.2. Statistical analysis

Initially, a descriptive analysis was carried out to explore the distribution of the relative power values. Kolmogorov–Smirnov and Shapiro–Wilk tests were applied to evaluate the normality of the distributions. In addition, Levene test was used to assess the homoscedasticity. We observed that the relative power values did not meet the parametric test assumptions. Owing to this issue, differences between pre and post relative power values were analyzed using the nonparametric Wilcoxon signed-rank test (statistical significance $\alpha = 0.05$), whereas the nonparameteric Mann–Whitney U-test was used to assess the statistical differences in relative power values between both groups ($\alpha = 0.05$).

In addition to the statistical analysis, notched boxplots were calculated to analyze the variations in relative power (post-stimulation–pre-stimulation) averaged over all channels.

Signal processing and statistical analyses were performed using the software packages Matlab (version 7.8.0; Mathworks, Natick, MA) and PASW Statistics (version 18.0; SPSS Inc, Chicago, IL).

4. Results

4.1. Global analysis

In a first stage, we analyzed the global changes in relative power values averaged over all channels. The relative power was computed in the conventional EEG frequency bands for each 5 s EEG epoch and the results were averaged over all sensors to obtain a quantitative measure per participant.

The relative power values reflected a general increase in low frequency bands (theta) and a general decrease in high frequency bands (beta1, beta2 and gamma) for patients with brain injury. Relative power values for controls indicate a global decrease in both low (i.e., delta) and high frequency bands (i.e., beta1, beta 2, gamma), though a general increase was observed in alpha band. These results can be seen in Fig. 3 and Table 4, where the boxplots and the statistical results corresponding to the changes in the relative power after and before the SMS stimulation are depicted for each group. Brain-injured patients showed a statistically significant increase of *RP*(theta) ($Z = -2.983$, $p = 0.003$) and statistically significant decreases of *RP*(beta2) ($Z = -3.113$, $p = 0.002$) and *RP*(gamma) ($Z = -2.547$, $p = 0.011$). A slight decrease in *RP*(beta1) was also found, though it did not show statistically significant differences ($Z = -1.894$, $p = 0.058$). On the other hand, controls obtained statistically significant decreases of *RP*(delta) ($Z = -2.243$, $p = 0.025$), *RP*(beta1) ($Z = -2.069$, $p = 0.039$) and *RP*(beta2) ($Z = -2.853$, $p = 0.004$), together with a statistically significant increase of *RP*(alpha) ($Z = -2.112$, $p = 0.035$).

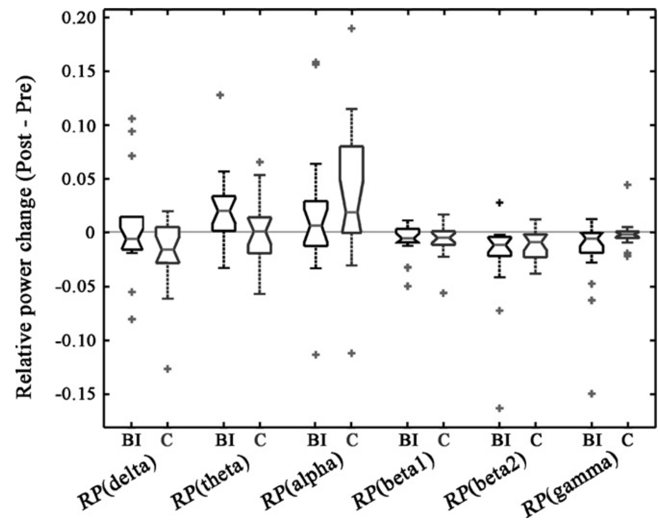

Fig. 3. Notched boxplots displaying the distribution of the differences in mean relative power values (Post-stimulation–Pre-stimulation) averaged over all channels at each frequency band. BI: brain-injured patients; C: controls.

Fig. 3 and Table 4 also show some differences in the pattern of change for relative power between brain-injured patients and controls. As can be seen in Table 4, statistically significant differences between both groups were only found in *RP*(theta) ($Z = -2.294$, $p = 0.022$). Fig. 3 shows that patients with brain injury reached a significantly higher increase of *RP*(theta) than healthy controls. No significant differences were found in the other frequency bands.

The internal consistency was checked to assess whether the observed spectral patterns are homogeneous through the individuals from both groups. The intraclass correlation coefficient (ICC) was estimated from a two-way random effect model. In addition, 95% confidence intervals (95% CI) were calculated. The ICCs for individuals with brain injury and controls during the pre-stimulation condition were of 0.891 (0.703–0.982, 95% CI) and 0.988 (0.968–0.998, 95% CI), respectively. During the post-stimulation condition, the ICCs were of 0.923 (0.791–0.987, 95% CI) and 0.992 (0.979–0.999, 95% CI) for brain-injured patients and controls, respectively.

As previously mentioned, participants were asked to rate their global satisfaction with the SMS stimulation session and their level of relaxation on a 10-point scale (10 being the highest). Higher scores indicate a high level of satisfaction with the stimulation session or a deep level of relaxation. The following two items were used: (i) "on a scale from 1–10 (10 being the highest), how would you rate the experience?"; (ii) "on a scale from 1–10 (10 being the highest), how would you rate the level of relaxation?".

Brain-injured patients and controls reported a global level of satisfaction of 7.9 ± 1.3 (5–10) (M ± SD (range)) and 8.2 ± 1.3 (5–10) (M ± SD (range), respectively. Regarding the level of relaxation, brain-injured-patients and controls reported scores of 7.6 ± 1.7 (3–9) (M ± SD (range)) and 7.2 ± 1.2 (5–9) (M ± SD (range)), respectively. Significant differences were not found in the global level of satisfaction score ($p > 0.05$, Mann–Whitney U-test) or the level of relaxation ($p > 0.05$, Mann–Whitney U-test) between both groups. Spearman rank correlation was computed to analyze the relationships between self-reported variables and the changes in relative power values. Thus, a slight correlation was only found between the level of satisfaction and *RP*(beta1) ($r = 0.430$, $p = 0.075$) for individuals with brain injury. On the other hand, the level of relaxation was significantly correlated with *RP*(delta) ($r = 0.534$, $p = 0.023$) and *RP*(theta) ($r = 0.575$, $p = 0.013$) for brain-injured patients.

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Table 4
Statistics associated to the Wilcoxon signed-rank tests and to the Mann–Whitney U-tests for the mean relative power values averaged over all channels at each frequency band. The significant values (*p*-value < 0.05) have been highlighted.

	BI		C		BI vs. C	
	Z	*p*	*Z*	*p*	*Z*	*p*
RP(delta)	−0.065	0.947	**−2.243**	**0.025**	−1.471	0.141
RP(theta)	**−2.983**	**0.003**	−0.152	0.879	**−2.294**	**0.022**
RP(alpha)	−1.241	0.214	**−2.112**	**0.035**	1.076	0.282
RP(beta1)	−1.894	0.058	**−2.069**	**0.039**	0.000	1.000
RP(beta2)	**−3.113**	**0.002**	**−2.853**	**0.004**	0.807	0.420
RP(gamma)	**−2.547**	**0.011**	−0.936	0.349	1.614	0.107

BI: brain-injured patients; C: controls; *Z*: *Z*-statistic; *p*: *p*-value.

Likewise, *RP*(gamma) tended to decrease with the level of relaxation, though the correlation was not statistically significant ($r = -0.426$, $p = 0.078$). The correlation of the self-reported level of relaxation with *RP*(alpha) was also statistically significant ($r = 0.515$, $p = 0.029$) for controls, who also obtained a slight correlation with *RP*(theta) ($r = -0.459$, $p = 0.055$).

4.2. Regional analysis

In a second stage, we explored the spatial patterns of the changes in relative power values. Thus, the relative power was computed in the conventional EEG frequency bands for each 5 s EEG epoch to obtain a quantitative measure per participant and channel.

Detailed results for relative power values at each frequency band are shown in Figs. 4 and 5, where the spatial distribution of significant differences can be observed for brain-injured patients and controls, respectively. The results are in agreement with those reported in the global analysis. Thus, an increase of relative power in low frequency bands (theta and alpha) and a decrease in high frequency bands (beta1, beta2 and gamma) can be appreciated again for patients with brain injury. *RP*(theta) showed a spatially widespread pattern of significant increases. Specifically, we observed significant increases of *RP*(theta) in the fronto-centro-temporal and parietal regions over both hemispheres and in the left occipital region. Likewise, *RP*(alpha) also displayed significant increases in the temporal region over both hemispheres, though the changes were more localized than for *RP*(theta). On the other hand, we found significant decreases of *RP*(beta1) in left fronto-temporal and occipital regions. *RP*(beta2) showed a widespread pattern of significant decreases, including the central region, the fronto-temporal region over both hemispheres and the left temporo-parieto-occipital region. Finally, *RP*(gamma) also displayed significant decreases in the temporo-frontal region over both hemispheres and in the left centro-parieto-occipital region.

The spectral patterns obtained by healthy controls also agree with the results reported in the global analysis. Regional analysis shows that *RP*(delta), *RP*(beta1), *RP*(beta2) and *RP*(gamma) are significantly lower in the pre-stimulation condition than in the post-stimulation one, whereas *RP*(alpha) significantly increases after the multi-sensory stimulation session. Specifically, *RP*(delta) showed significant decreases, including the left centro-parietal region, the left frontal region and the right fronto-temporal region. *RP*(alpha) displayed significant increases in the frontal region over both hemispheres, in the left centro-parietal region and in the right fronto-temporal region. On the contrary, *RP*(beta1) showed a more localized pattern of significant decreases in the parieto-occipital region over both hemispheres and in the left temporal region. *RP*(beta2) exhibited a widespread pattern of significant decreases, including the left fronto-central region, the temporo-parieto-occipital region over both hemispheres and the right temporal region. Finally, *RP*(gamma) showed significant decreases in the left frontal and the temporo-parieto-occipital region over both hemispheres.

5. Discussion

In this study, we assessed the changes induced by a SMS environment in the spectral content of the EEG recordings from eighteen individuals with brain-injury and eighteen healthy controls. Significant increases and decreases of relative power in brain-injured patients were found for slow (i.e., theta) and fast (i.e., beta1, beta2 and gamma) rhythms, respectively. Controls displayed a slightly different pattern of changes. Significant increases and decreases of relative power in low (i.e., alpha) and high (i.e., beta1, beta2 and gamma) frequency bands were also observed. However, a significant increase of relative power in delta band was found. These results indicate that SMS stimulation affects central nervous system, so that this kind of therapy induces an overall slowing of EEG oscillatory activity. An increase of the relative power in theta and alpha bands, together with a decrease of the relative power in beta and gamma bands, are commonly observed in subjects during relaxation and meditation states [16–18]. Our findings reinforce the idea that SMS stimulation induces a state of relaxation, since the redistribution of relative power involves a slowing of EEG oscillatory activity. Previous EEG studies analyzing diverse relaxation strategies have also reported a global decrease and increase of power for slow and fast rhythms, respectively [22–24]. Furthermore, in meditation contexts, a general increase of theta activity has been described in a large number of studies independently of the particular meditation technique [17]. Investigations based on music perception like a relaxation strategy have reported increments in the power of theta [22,24] and alpha bands [24], which agrees with our results, though *RP*(alpha) did not achieve significant differences for individuals with brain injury. Likewise, EEG studies analyzing the relaxation response elicited by autogenic training have observed increases in the theta band power, along with decreases in the alpha band power [23]. This neurophysiologic pattern partially agrees with our findings, since *RP*(alpha) did not obtain significant differences in the global comparison for brain-injured patients. Some studies suggest that theta band may be a more reliable marker of the central nervous system effects of relaxation techniques than alpha band [22]. Nevertheless, long-standing evidence supports the idea that alpha band plays an important role in audio-visual stimulation [16], meditation [26] and relaxation contexts [17]. Our findings with healthy controls reinforce this notion. A slight increase of *RP*(theta) was obtained, but significant differences were indeed found in alpha band. Discrepancies between both groups could be due to the brain damage of patients which modifies the spontaneous EEG activity and, as a consequence, the associated spectral patterns. This issue becomes clear in the theta band, where brain-injured patients show a lower lateralization of relative power than controls. As previously mentioned, most patients displayed a bilateral location of brain damage.

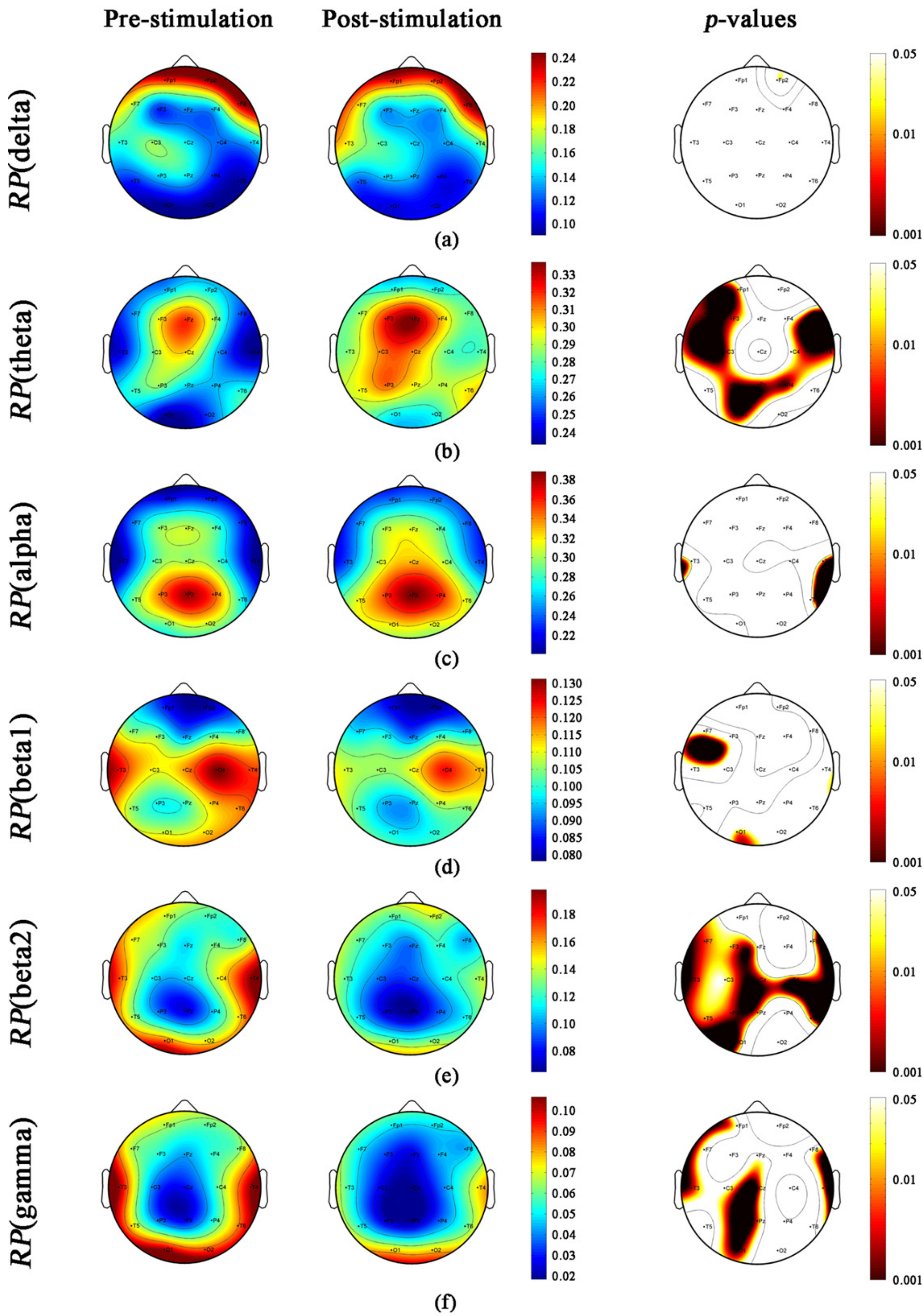

Fig. 4. Sensor layout showing the distribution of the mean relative power values at each frequency band (pre-stimulation and post-stimulation) and the corresponding *p*-values for brain-injured patients: (a) *RP*(delta); (b) *RP*(theta); (c) *RP*(alpha); (d) *RP*(beta1); (e) *RP*(beta2); (f) *RP*(gamma).

Therefore, differences in *RP*(theta) might evidence the abnormal brain dynamics elicited by brain injury. Furthermore, it is worth noting that statistically significant differences in the pattern of change between brain-injured patients and controls were observed in *RP*(theta), but not in the other frequency bands. These results suggest that the SMS stimulation induced, in general, similar changes in the relative power for both groups, although some particular changes in EEG activity can also be found for brain-injured patients.

Regional analyses of relative power agree with those previously reported. An increase of relative power in slow oscillations (i.e., theta and alpha) and a decrease in fast rhythms (i.e., beta1, beta2 and gamma) were found for both groups. Nevertheless, several

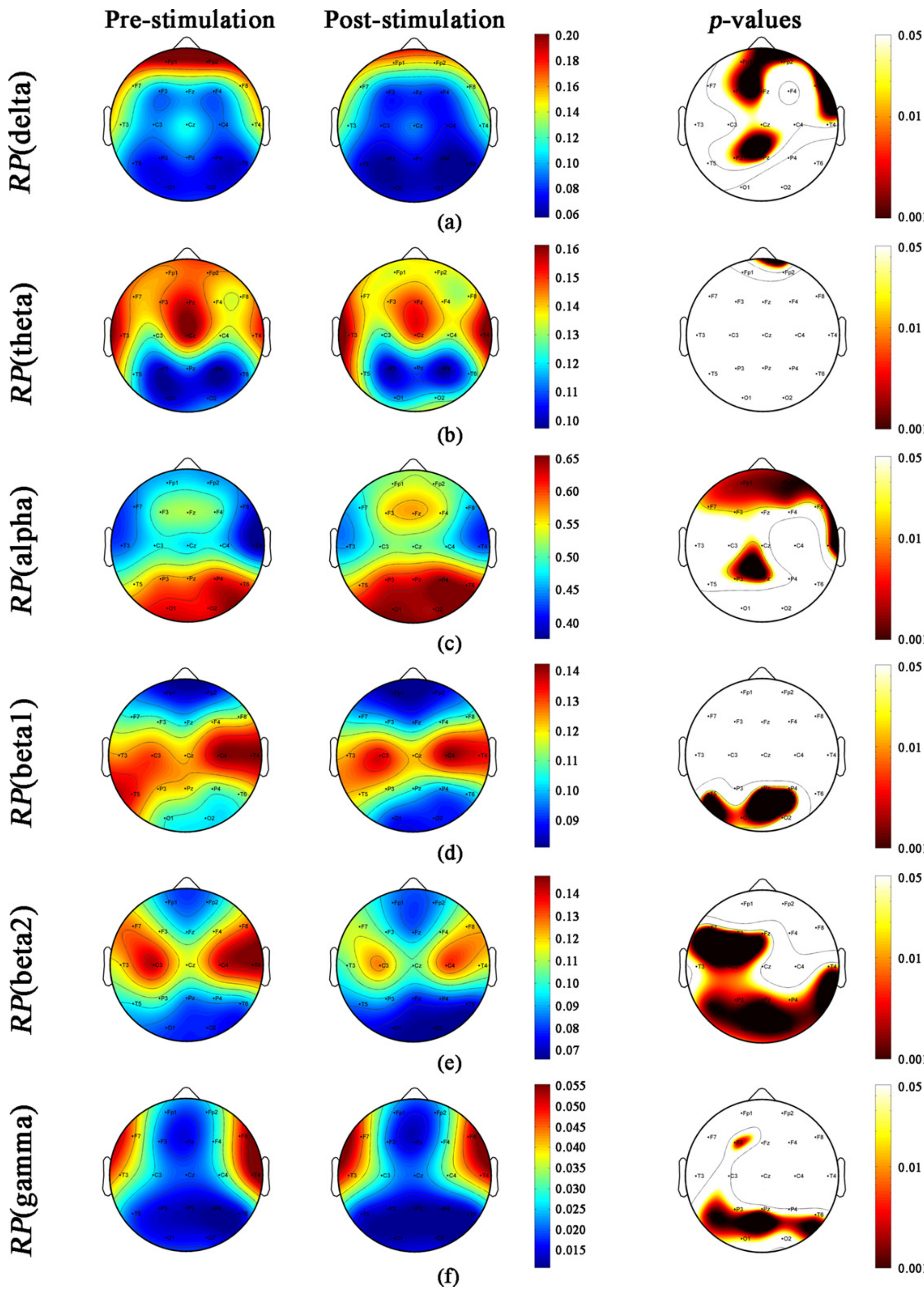

Fig. 5. Sensor layout showing the distribution of the mean relative power values at each frequency band (pre-stimulation and post-stimulation) and the corresponding *p*-values for control subjects: (a) *RP*(delta); (b) *RP*(theta); (c) *RP*(alpha); (d) *RP*(beta1); (e) *RP*(beta2); (f) *RP*(gamma).

differences arise between the patterns of change for theta and alpha bands. A significant increase of *RP*(theta) was found for patients with brain injury, whereas a slight increase was observed for controls. On the contrary, a significant increase of *RP*(alpha) was reached for controls and a slight increase was obtained for brain-injured patients. Detailed results showed significant increases of *RP*(theta) in the fronto-centro-temporal and parietal regions over both hemispheres for brain-injured patients, as well as in the left occipital region. In addition, significant increases of *RP*(alpha) were focused on the right temporal region for both groups, though significant increases in the frontal region over both hemispheres and in the left centro-parietal region were also found for controls. These findings confirm the results obtained in a previous EEG study analyzing the changes in EEG activity due to long-term audio-visual stimulation, where researchers observed a significant increase in the power of theta and alpha bands over the frontal and central cortex [16]. Günther et al. also reported a diffuse hyperactivation in delta and theta frequency bands in schizophrenic males in comparison with a control group after a relaxation procedure based on three music perception tasks [25]. On the contrary, we found a significant decrease of *RP*(delta) for controls in the left centro-parietal, left frontal and right fronto-temporal regions. Discrepancies could be explained due to the particular brain dynamics elicited for each stimulation paradigm. In the case of brain-injured patients, the results of Günther et al. partially agree with the spatially widespread pattern of significant increases in *RP*(theta) observed in the present study, as well as with the significant increases in theta activity over multiple cortical regions reported by Jacobs and Friedman [22]. Similarly, Lagopoulos et al. observed that nondirective meditation is accompanied by significant increases of theta activity over frontal and temporo-central regions, as well as by significant decreases of alpha activity over the posterior region in comparison with the frontal one [26]. In contrast, we observed significant decreases of relative power in beta and gamma bands for both groups. Significant changes of *RP*(beta1) were focused on fronto-temporal and occipito-parietal regions, whereas statistically significant differences for *RP*(beta2) were obtained in the central region, the left frontal region and the temporo-parieto-occipital region. In a previous EEG study carried out by Jacobs et al. [18], several participants listened to relaxing music, whereas a control group listened to a control audiotape. Similarly to our findings, they reported a significant reduction in frontal beta activity. With regard to *RP*(gamma), significant changes for brain-injured patients were observed in the temporo-frontal region over both hemispheres and in the left centro-parieto-occipital region. In the case of controls, statistically significant differences were focused on the left frontal and the temporo-parieto-occipital region. A similar pattern of changes was also reported in a previous EEG study, where gamma band activity in long-term meditators notably differed from that in controls over lateral frontal and parietal electrodes [27]. In summary, results from regional analyses revealed that a particular spatial pattern of change in relative power is associated to SMS stimulation in individuals with brain-injury, which becomes clear in low frequency bands.

A number of studies reported positive effects in several subjective and qualitative variables after the application of a SMS therapy [5,7,9,13]. However, the carryover and the long-term effects of SMS intervention were not evident [33]. Previous studies reported an improvement on physiological, cognitive and behavioral functioning [14], though their findings indicated that SMS intervention needs to be intense and frequent for being effective [2]. Likewise, previous research suggested that SMS therapy could achieve a 'time-limited benefit' [31], whereas no long-term effects were observed in other therapeutic approaches [1,31]. Certainly, the short-term pattern of changes observed using the relative power did not imply per se that SMS therapy elicits a positive benefit in participants, but provide evidence for a characteristic alteration of brain dynamics. It is worth noting that brain-injured patients usually experience a generalized slowing of oscillatory EEG activity due to the brain damage [28]. However, a slowing of EEG rhythms does not necessarily imply an impaired brain function. As previously mentioned, SMS stimulation therapy is useful to ameliorate disruptive behaviors and improve quality of life. Several studies found that a state of relaxation is associated with both a global slowing of EEG activity and diverse positive effects, such as happiness, calmness, reduction of agitation, improvements in the nonverbal and verbal communication, or inhibition of behavioral changes [22–24]. Our findings suggest that SMS stimulation induces a state of relaxation, since the redistribution of relative power involves a slowing of EEG oscillatory activity and the observed spectral changes are related to the self-reported level of relaxation. Nevertheless, some differences between both groups were observed. Brain-injured patients obtained statistically significant correlations in delta and theta bands, whereas correlations were statistically significant in alpha band for controls. Discrepancies could be due to the particular spectral patterns observed for each group. Statistically significant differences for brain-injured patients were found in *RP*(theta). However, a significant increase in *RP*(alpha) was observed for controls. As a consequence, it could be hypothesized that changes in *RP*(theta) might reflect the level of relaxation for brain-injured patients, whereas the relaxation process for controls could be related to the changes in *RP*(alpha). Subjects with negative feedback showed, in general, changes in relative power less important than those observed for subjects with positive feedback. Nevertheless, one of the brain-injured patients self-reported an intermediate level of relaxation (5/10) and the lowest level of satisfaction with the experience, though the pattern of changes in relative power was similar to those observed for the other patients. It is worth noting that the time since injury was of 1 year, which can negatively influence the sensations of this patient. Self-reported variables can be biased indeed by the individual's perception and condition. The two brain-injured patients with negative feedback suffered from severe brain injury. Therefore, the self-reported level of relaxation may not reflect the actual one.

Finally, a number of methodological and technical issues should be further discussed. A slowing of EEG activity has also been reported in other neurophysiologic states, related to abnormal brain function and to the ingestion of drugs [29,30]. Nevertheless, this issue was discarded owing to the well-defined inclusion and exclusion criteria and the fact that none of the participants were taking any medication that could affect EEG activity. It is noteworthy that spectral analyses carried out in the present work have shown immediate post-session changes in the participants' brain activity. These findings confirm the short-term benefits of Snoezelen® intervention suggested in previous studies [2,3,31–33]. However, we have not proved whether these effects are maintained over time. Therefore, future efforts will be addressed to explore the long-term changes produced by SMS stimulation in individuals with brain-injury.

6. Conclusion

In summary, our findings suggest that SMS stimulation therapy elicits significant changes in the relative power from brain-injured patients and healthy controls, which involve a slowing of EEG oscillatory activity. Significant differences were found in the relative power of theta band between both groups, which suggests that SMS stimulation could induce a characteristic pattern of change for brain-injured patients.

The investigation presented in this paper can be considered as the first attempt to systematically quantify EEG changes induced by a SMS environment in individuals with brain-injury and controls, as well as a novel attempt to understand the underlying brain dynamics. Our results extend previous findings where several subjective observations and qualitative data were used to assess the effects of SMS stimulation intervention. Furthermore, the proposed methodology can be useful to quantitatively assess the qualitative changes observed in people with other disorders, such as sensory and intellectual disabilities, dementia, children with Rett disorder, mental retardation and autism, among others, after a SMS intervention.

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Conflict of interest statement

The authors declare that they have no conflict of interest that could inappropriately influence this research work.

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