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EEG phase synchronization during emotional response to positive and negative film stimuli

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Abstract

In the present study the patterns of interdependency between different brain regions were investigated as volunteers looked at emotional and non-emotional film stimuli. The main goal was to evaluate the emotion-related differences and to check their consistency during the elaboration of the same type of stimuli in repeated presentations. A measure called synchronization index (SI) was used to detect interdependencies in EEG signals. The hypotheses were that emotional-information processing could involve variation in synchronized activity and that two valence-specific emotions – happiness and sadness – differ from each other. The SI obtained was compared among the various experimental conditions and significant changes were found. The results demonstrated an overall increase of SI during emotional stimulation and, in particular, during sadness, which yielded a pattern involving a large exchange of information among frontal channels. On the other hand, happiness was associated with a wider synchronization among frontal and occipital sites, although happiness itself was less synchronized. We conclude that the SI can be successfully applied for studying the dynamic cooperation between cortical areas during emotion responses.

Keywords: EEG; Phase synchronization; Emotion

Neural assemblies provide a conceptual framework for the integration of distributed neural activity [21]. We can define neural assemblies as distributed networks of neurons transiently linked by reciprocal dynamic connections. The intricate connectivity among functionally specialized groups of neurons is an outstanding characteristic of mammalian brains, which are primarily characterized by the ability to integrate information [20]. However, the specific nature of such interactions remains a point of debate. There are various modes of reciprocal interaction. One of these is phase synchronization among the participating neuronal groups. Direct evidence supporting synchrony as a basic mechanism for brain integration has recently been provided in relation to memory [10,12], learning [17], visual perception [14], binding processes [18], selective attention [11,19] and musical hearing [6]. Most of the works investigating the role of the synchronized activity focused on cognitive processes. Up to now, affective cortical activation and the effects of different emotions have received little attention in synchronization EEG studies. Signals have been studied while people watched emotional stimuli, both pictures and film clips. Researchers used power spectrum analysis to measure the event-related de-synchronization (ERD) and synchronization (ERS)—in other words, the decrease and the increase in power distribution [13]. Findings supported the evidence that synchronization changes were the result of emotional arousal and valence, as evidenced in the frequency range, and involved hemispheric asymmetries [4]. Very interesting results were gathered by such non-linear measures as dimensional complexity, a measure which is able to characterize specific cortical activity changes related to emotional experiences. Emotional activation was associated with an overall increase of complexity in the interaction among cortical regions. On the other hand, emotional valence could not be clearly associated with specific effects [1,3]. Further studies found that emotional arousal led to more complex and less predictable cortical dynamics, where positive emotions were related to a higher complexity in posterior areas and to a lower complexity in frontal areas than that evidenced with negative emotions [2]. The enhanced information exchanges between widely separated dynamical systems were observed in response to emotionally positive induction. In turn, the negative stimuli were found to involve a dynamical

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decoupling between anterior and posterior cortical regions with a processing center in the left prefrontal region [5].

The present study aimed to investigate the underlying cortical mechanism of emotional processing further, examining the pattern of synchronization between each couple of EEG signals recorded at different cortical sites. In order to achieve this goal, phase synchronization was examined as a measure to investigate the relation between the temporal structures of the signal regardless of signal amplitude. Two signals are said to be synchronous if their rhythms coincide. In its classical sense, the term synchrony has been applied to the signal that had a dominant oscillatory mode around a chosen frequency. To investigate whether two systems show phase synchronization, it is first of all necessary to know their phase variables. This is non-trivial for many non-linear model systems and even more difficult when dealing with noisy time-series of unknown origin. In this work we have followed the analytic signal approach to determine the instantaneous phase of the signal. A good estimator of the degree of phase synchronization between two signals is the synchronization index (SI) defined as:

$$\gamma^2_{n,m} = \langle \cos\, \phi_{n,m}(t) \rangle^2 + \langle \sin\, \phi_{n,m}(t) \rangle^2$$

where the brackets denote the average over time; it varies from 0 to 1. The advantage of this index over other ones is that its computation involves no parameters [15].

Despite the information that SI could provide to EEG studies, there are not any studies that utilize this type of index in the complex world of emotion, to best of our knowledge. In this study the changes of SI patterns were analyzed during responses to emotionally-laden external stimulation, using non-emotional and emotional film stimuli differentiated for valence.

We addressed three principal hypotheses: (i) the synchronization index among different EEG channels increases during the elaboration processing of a stimulus with respect to rest; (ii) a further increment in synchronized activity occurs in responses to emotional stimuli with respect to neutral, due to the recruitment of wider brain resources and a greater exchange of information among interacting areas; (iii) this enhancement of synchronization could take place in a more specific effect of emotional valence, with different SI patterns between positive and negative emotions. Finally, stimuli were presented three times comparing EEG responses to the same stimulus in order to check the consistency of SI pattern related to specific emotional information processing.

Thirty healthy, right-handed student volunteers participated in the experiment (15 males, 15 females), ranging in age from 18 to 26 years (mean 20.7 S.D. 2.17). None of the subjects reported any neurological disorders, psychiatric diseases, or were on medication. All had normal or corrected to normal vision.

Stimuli consisted of three sequences (120 s long) representing different emotional scenarios of happiness, sadness and neutral content extracted from commercial films. The films were edited by cutting any detail from the original sequences that could elicit emotional responses different from the target one. Such details included facial expressions or characters' actions. The stimuli obtained were pre-tested on a sample of judges ($N = 30$), who made self-reports in which they labeled the emotion experienced during the vision of films and rated the pleasantness and arousal level on a Likert scale ranging from 0 to 10. The clips were classified as producing the specific target emotional state, with a high concordance between expected and self-reported emotion (k-Cohen = .89, $p < .001$). The complexity of semantic content, defined as the exact understanding of what was happening in the clips, was assessed by an interview. The happiness sequence depicted lovers' encounters. The sadness sequence depicted the death of a significant person. Finally, the neutral sequence depicted a series of routine actions. All the stimuli were colored, presented without sound and balanced in their depiction of the presence of human beings as well as in the relative complexity of their semantic content.

The subjects were seated in comfortable chairs in the recording room and the experimental procedure was explained. The subjects were told to look at the TV screen placed in front of them and to concentrate on the film. At the end of each clip they had to answer some questions about their emotional experience while they were watching the stimuli.

The experiment began with a 300-s baseline recording of resting EEG, followed by the emotional film clips in random order. Each clip trial consisted of: (1) a brief time (3 s.) when a cross appeared on the screen; (2) the clip presentation for 120 s; (3) a 1-min post-film rest period, and (4) subjective ratings, which assessed the subjects' emotional reactions during the previous film. Subjects were asked to rate the pleasantness level, the arousal level, the intensity level of experienced emotion on a scale from 1 (not at all) to 9 (fully experienced emotion) and to rate the emotional state that they experienced during the trial on a rating scale including five primary emotions in random order: happiness, sadness, anger, fear, and disgust (from 1, indicating that the emotion was not at all present, to 9, indicating that it was felt very strongly). At the end of this first experimental session, the emotional films were repeated two times, counterbalancing the presentation order between subjects. Finally, a second eyes-closed baseline of 300 s was recorded.

EEG was recorded from 19 sites (Fp1, Fp2, F7, F8, F3, F4, Fz, C3, C4, Cz, T3, T4, T5, T6, P3, P4, Pz, O1, O2), which refer to linked earlobes. A ground electrode was attached to the center of the forehead. Vertical EOG was measured with electrodes 2 cm above and below the middle of the right eye in order to facilitate ocular artifact scoring, and remove them from the EEG recordings.

EEG and EOG signals were amplified by a multi-channel bio-signal amplifier (band pass 0.3–70 Hz) and A/D converted at 256 Hz per channel with 12-bit resolution and 1/8-2 μV/bit accuracy. The impedance of recording electrodes was monitored for each subject prior to data collection and the threshold was always kept below 5 kΩ.

EEG data was pre-processed using independent component analysis (ICA) [9] removing artifacts from the traces. ICA is generally applicable for removal of a wide variety of EEG artifacts. It simultaneously separates the EEG and its artifacts into independent components based on the statistics of the data, ICA does this without relying on the availability of one or more reference channels for each type of artifact. This avoids the problem of the potential mutual contamination of regressing and regressed

Table 1
Mean, standard deviation and *F*-test of subjective scores of pleasantness and arousal for neutral (N), sadness (S) and happiness (H) film clips ($N = 31$)

	Condition	Mean (S.D.)	*F*	d.f.	Sig	η^2	Comparison	Mean difference	Sig[a]
Pleasantness	Neutral	5.19 (1.25)	31.65	2.60	0.000	0.513	N–H	−1.16	0.01
	Happiness	6.35 (1.99)					N–S	2.19	0.001
	Sadness	3.00 (2.08)					H–S	3.35	0.001
Arousal	Neutral	2.58 (1.61)	12.67	2.60	0.000	0.297	N–H	−1.81	0.001
	Happiness	4.39 (2.08)					N–S	−1.64	0.001
	Sadness	4.23 (2.35)					H–S	0.16	1.00

[a] Bonferroni correction for multiple comparisons.

channels. We applied the ICA to remove ocular artifacts. We discarded all the distinct artifactual components through visual inspection. After the ICA components removing process, a second stage of visual inspection of the EEG data was conducted. If any further artifact was present, the data was discarded. Then, data was band-pass filtered with a forward reverse filtering algorithm in the following five frequency bands of interest: delta (0.5–3), theta (4–7 Hz), alpha (8–12 Hz), beta (13–30 Hz) and gamma (39–41 Hz). In order to avoid starting and ending artifacts, the first and last 5 s of the EEG data gathered during the experimental conditions were excluded from the analyses.

The subjective ratings of emotional responses to film stimuli confirmed that the subjects were able to induce the expected emotions: the percentage of correct identification was 87.1% for the neutral film, 90.3% for the happiness film and 84% for the sadness film.

A repeated-measure ANOVA was calculated on the score of pleasantness and arousal in relation to happiness, neutral and sadness. The descriptive statistics and the results are depicted in Table 1. Both the analyses yielded highly significant results, confirming that the subjective emotional experience was different for the three experimental conditions. As expected, the happiness film was evaluated as being more pleasant than the sadness film. Meanwhile, there was no significant difference in the arousal level of the two emotional conditions. A further analysis was performed to prove that emotional films elicited the target emotions of sadness and happiness without combining with different primary emotions. The intensity scores reported by subjects for each primary emotion included in the scale were analyzed in repeated-measure ANOVAs for the two emotional film clips (primary emotion as within factor with five modalities). The expectation was that the target emotions of happiness or sadness were experienced more intensely than all the others. Results were highly significant in the overall model both for sadness [$F(4, 120) = 44.193$, $p < 0.01$, $\eta^2 = .6$] and happiness [$F(4, 120) = 59.9$, $p < .01$, $\eta^2 = .66$], as well as in each post-hoc mean comparison ($p < .001$). This data confirmed the validity of the stimuli utilized in the experimental procedure to induce the target emotions and to investigate the correspondence in EEG responses.

The SI was calculated at each frequency band for all the couples of electrodes, obtaining a synchronization matrix for each subject and each condition. The statistical analysis was performed on SI between the couples of channel locations, independently for each frequency band. The data in the synchronization matrices was entered into repeated-measure ANOVAs with condition as the within-subjects factor, with four levels: rest, neutral, sadness and happiness. The main effect for condition was found to be statistically significant for a number of frontal and posterior couples of electrodes (see Table 2). The wider differences involved a variation in synchronized activity between the right and left frontal channels and between the frontal and occipital channels, whereas there were few effects involving the synchronization among ipsilateral electrodes in the same area. In particular, the *F*-test produced significant results at the alpha and beta frequency bands, where it revealed differences in synchronization between the right and left prefrontal electrodes and between the frontal and occipital sites. The synchronization pat-

Table 2
Significant results of *F*-test of synchronization index among the couples of frontal and posterior electrodes (d.f. = 3.78, assuming sphericity)

α ($p < 0.01$)		β ($p < 0.01$)		θ ($p < 0.01$)		γ ($p < 0.01$)	
Fp1-Fp2	$F = 5.8$	O1-O2	$F = 4.1$	O1-O2	$F = 4.1$	Fp1-O1	$F = 2.95$
Fz-F4	$F = 4.56$						
F3-O2	$F = 5.19$						
F8-O2	$F = 7.1$						

α ($p < 0.05$)		β ($p < 0.05$)		θ ($p < 0.05$)		γ ($p < 0.05$)		δ ($p < 0.05$)	
Fp2-F4	$F = 3.7$	Fp1-Fp2	$F = 2.16$	Fp1-Fp2	$F = 2.16$	Fp1-O2	$F = 2.2$	Fp1-F3	$F = 2.97$
Fp1-F3	$F = 2.8$	Fp1-Fz	$F = 2.19$	Fp1-O2	$F = 3$	Fp1-Fz	$F = 2.15$	Fp1-F4	$F = 3.67$
Fz-F7	$F = 2.95$	Fp1-F4	$F = 2.6$	F7-O2	$F = 2.26$	Fp1-F4	$F = 2.2$	Fp1-F8	$F = 3.51$
F4-F8	$F = 3.7$	Fp1-F8	$F = 5.3$	Fz-O2	$F = 2.23$	Fp1-F8	$F = 2.14$	Fz-F8	$F = 2.89$
Fp1-O2	$F = 2.08$	Fp1-O1	$F = 2.52$	F8-O2	$F = 2.35$				
F4-O2	$F = 2.4$								

Table 3
Significant Tukey test ($p < 0.05$) of synchronization index between the couples of frontal and occipital electrodes for the three stimulation conditions (neutral, happiness, sadness) and the rest condition

Condition	Frequency	Channels	q[a]
Neutral–sadness	γ	F7-T3	−3.85
		Fp1-Cz	−4.34
Happiness–sadness	α	Fp1-F3	−4.793
		F3-F4	−3.91
	β	Fp1-F3	−4.642
	γ	Fp2-Fz	−3.914
Rest-neutral	α	Fp1-Fp2	6.175
		Fz-F7	5.115
		Fp2-F4	4.903
		Fz-F4	5.359
		F4-F8	5.079
		Fp1-O2	3.849
	γ	Fp2-Fz	5.032
Rest-happiness	α	Fp1-Fp2	5.721
		Fp2-F4	3.917
		Fz-F4	4.66
		F4-F8	5.062
		F8-O2	−3.897
	β	O1-O2	−4.669
Rest-sadness	α	Fp2-F4	3.981
		F3-O2	−4.154
		F8-O2	−4.127
	β	O1-O2	−5.412
	δ	Fp1-F3	−3.822
		Fp1-F4	−3.808
		Fp1-F8	−4.281
		Fz-F8	−4.280

[a] Critical $q = 3.68$, $k = 4$, d.f. = 78.

terns also differed among conditions at the theta band in relation to the synchronization within the occipital recording area and especially in relation to the synchronization between frontal and posterior sites. At the gamma band the analyses of variance reached the level of statistical significance for the couples of frontal and occipital electrodes and inside the frontal areas, especially in the left sites. The delta band showed significant variation within frontal sites both within the left hemisphere and between the right and the left ones. In any case, there is a general linear increase as the conditions change from rest to neutral, happiness and sadness.

Post-hoc analyses were performed using Tukey test in order to compare synchronization patterns under the specific conditions of rest, neutral, happiness and sadness and in order to distinguish the contribution of a single type of response to the overall model (see Table 3). Differences between rest and stimulation conditions have been found for numerous couples of frontal and posterior electrodes at each frequency band. In each contrast, emotional conditions turned out to be more synchronized than neutral conditions. There were significant differences in the frontal regions between happiness and sadness and between neutral and sadness. The sadness-related activity was more synchronized than happiness in any significant case.

The last step of analysis was the effort to evaluate the differences in SI occurring between repeated presentations of the same stimulus. SI values were entered in 2×3 repeated-measure ANOVAs and processed to assess the main effect of the factor repetition (with two modalities: first and last presentation) as well as to assess the factor emotion (with three modalities: happiness, sadness and neutral). Synchronization patterns did not differ at all. Comparisons between the repeated presentations of emotional stimuli did not provide any significant results for SI, showing that EEG responses to the same stimulus presented similar synchronization patterns.

The aim of this work was to evaluate the dynamic coupling between EEG channels, considering both local and distal changes of synchronization patterns during non-emotional and valence-specific emotional responses. The main hypothesis regarded an increase in synchronization during emotional processing, in contrast to what happens during non-emotional processing, and specific differences between the two emotions.

Data analyses performed on SI turned out to be significant for numerous couples of frontal and occipital electrodes at the different frequency bands. Within the alpha the most impressive difference involved the stimulation conditions compared with rest, where frontal sites turned out to be more synchronized. Furthermore, the activities related to sadness and happiness showed opposite patterns. Sadness turned out to be more synchronized than happiness, particularly within the left frontal regions. However, happiness tended to be more synchronized within the right hemisphere. Post-hoc analysis reached a high significance level only in the case of the Fp1-F3 activity in the comparison between happiness and sadness. Different patterns of activity emerged between frontal and occipital sites, where synchronization increased during stimulation in respect to rest. In particular, during emotional conditions happiness tended to be more synchronized than sadness in respect to the neutral condition. At the beta band there were several differences in synchronization patterns between frontal and occipital sites, with emotional conditions that exhibited a larger synchronization than rest and neutral ones. As at the alpha frequency band, happiness was less synchronized than sadness. A similar effect was obtained at the theta band, which also showed a greater synchronization during sadness than happiness within frontal left leads and an increased synchronization between frontal and occipital sites during positive emotional responses. At the delta band an effect turned up due to emotional responses during which the synchronized activity increased between right and left frontal sites, particularly in the sadness condition. At the gamma band both happiness and sadness appeared to be more synchronized than the neutral response. However, happiness involved an interaction between the frontal and occipital channels that did not occur in sadness.

Our analyses of EEG synchronization for repeated presentations of the same stimulus suggested that the patterns that emerged in happiness and in sadness were resilient. Results of comparisons between the first and the last presentation showed no significant variation in the synchronization patterns of cortical areas. The consistency of results of SI analysis sustains the hypothesis that there is an association between a specific synchronized activity and the elaboration of a stimulus.

To summarize, the first observation is that sadness always turned out to be more synchronized than happiness at each frequency band. Further, there were also differences in the couples of electrodes involved in the SI changes. Sadness was associated with a wider synchronization between the right and left frontal sites and within the left hemisphere, supporting the theory that there was wider inter-hemispheric communication. In contrast, happiness was associated with a wider synchronization along the rostro-caudal axis, i.e. between the frontal and occipital sites.

Previous literature reported data that supported the theory that cortical activity had a valence-related effect. This was found through the use of Kolmogorov entropy as a measure. It was also found that positive emotions were correlated with a lesser degree of entropy (i.e. a greater synchronization and dynamical complexity), in particular in the frontal region [2,16,7]. In [8] a coherence spectral analysis is conducted to study basic emotions. The authors found a different degree of coherence in the alpha band, a degree larger in happiness than in sadness. These results coincide with ours because there is the same kind of inter-hemispheric interaction. However, our study found that a positive response did not ever turn out to be more synchronized than a negative one. It should be kept in mind that the negative stimuli we used here were completely different from those in the previous research studies (images of burn victims or imagination technique). In our induction procedure we used perceptual stimuli that were not so cruelly shocking. They depicted a situation of loss that was able to elicit a specific emotion of sadness. It is possible that this emotion could involve a wider evaluation process that is reflected in a synchronization enhancement in frontal sites.

Taken as a whole, the present findings were coherent with previous literature that highlighted the role of information exchange during emotional response and was supported by empirical data showing an increase of mutual dimension in cortical dynamics in emotional processing [1]. The mutual dimension is thought to increase as the number of neural networks oscillate synchronously at different frequencies and become interactive. All the outcomes in this field of research have suggested that an increase in mutual dimension in response to affective conditions may be a necessary mechanism for generating emotion. Findings of the present study confirm this hypothesis by identifying the interacting cortical regions that play a core role in emotional processes. Nonetheless, the present work presented a number of limits. First, there were a small number of subjects. Thus, the statistical tests are not strong enough to detect small significant effects (II type error). Second, the experimental conditions did not allow us to elicit a stable emotional response and the elaboration of a complex stimulus could vary during the screening, so that the experimental treatment turned out to be less specific in relation to the aims of the study. This is widely discussed in the research on emotion [16]. Nonetheless, films are one of the most valid tools for inducing an emotion in the laboratory. Furthermore, they allow researchers to collect a data set that is long enough for them to apply particular mathematical procedures, such as the one proposed here.

Our results support the idea that synchronization provides an interesting and useful tool for studying and more deeply understanding the variation in brain activity that occurs during mental and emotional processes. In this work synchronized activity was associated with emotion, suggesting that there were differences between two specific emotional responses. If we consider the complex nature of emotion and the characteristic way emotion involves several biological systems as well as several neural circuits at different cerebral levels, we can conclude that synchronization seems to be a relevant topic for this field of research.

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