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Fractal characterization of internally and externally generated conscious experiences

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ABSTRACT

Although there is an extensive literature on the study of the neural correlates of consciousness (NCC) this is a subject that is far from being considered over. In this paper we present a novel experimental paradigm, based on binocular rivalry, to study internally and externally generated conscious experiences. We called this procedure bimodal rivalry. In addition, and assuming the non-linear nature of the EEG signals, we propose the use of fractal dimension to characterize the complexity of the EEG signal associated with each percept. Analysis of the data showed a significant difference in complexity between the internally generated and externally generated percepts. Moreover, EEG complexity was dissimilar for externally generated auditory and visual percepts. These results support fractal dimension analyses as a new tool to characterize conscious perception.

1. Introduction

Neural correlates of consciousness (NCC) are patterns of activity that accompany a given conscious experience (Rees, Kreiman, & Koch, 2002). Although many efforts have been made in order to characterize the NCC, we are far from a complete characterization of biological bases of conscious experiences. In this study, we introduce a procedure to investigate the EEG characterization of conscious experiences using a non-linear method based on fractal dimension analysis (FD). Since many authors suggest that non-linear approaches are more adequate and may be more powerful to relate brain patterns of activation with cognition than classical lineal analyses (e.g., Klonowsky, 2008; Pereda, Quian Quiroga, & Bhattacharya, 2005), this methodology may extend the understanding of neural bases of conscious states.

There are internally and externally produced conscious experiences. We will refer to externally generated conscious experiences as those subjective percepts elicited directly by sensory information. The other type, internally generated experiences, arise when attention is focused on one's train of thoughts (*mind wandering* – MW).

In this introduction, we briefly review approaches to the study of neural correlates of externally generated consciousness, and MW. Then, we introduce a method to study NCC based on fractal dimension analysis of EEG signals during externally and internally subjective experiences.

1.1. Neural correlates of externally generated conscious experiences

One of the approaches to the study of conscious perception is to investigate sensory inputs that elicit alternating subjective experiences. This methodology allows a decoupling between conscious experience and other functions that may occur during conscious perception such as memory or attention. Most of the research with this method focuses on visual conscious perception and make use of binocular rivalry. In binocular rivalry procedures, two visual inputs are presented independently to each eye producing an alternating perception. Participants reported transitions between percepts by a button press. Since switches between each visual input occur during fixed physical presentation, changes at any physiological measure are attributed to the conscious experience (see Blake & Logothetis, 2002, for a review). There is not a consensus about the level of processing at which competition between visual inputs is overcome. Some authors have proposed that competition between visual inputs is solved early, resulting from mutual inhibition between neurons in primary visual cortex. Experimental results have found neural activity changes in time related with perception in monocular regions of primary visual cortex (e.g., Polonsky, Blake, Braun, & Heeger, 2000). However, experimental results also support the idea that competition between visual inputs takes rise in higher cortical areas after the information from two images has been integrated (e.g.,

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Logothetis, Leopold, & Sheinberg, 1996). This spatial characterization has been qualified by other experiments focused on oscillatory characteristics of large groups of neurons in the above mentioned areas of the cortex. In a classic paper, Crick and Koch (1995) suggested that synchronized oscillations in the high-frequency range (>40 Hz) are the basis of feature integration (binding) and visual awareness.

Although visual NCC have been widely investigated, neural correlates of auditory percepts have also received some attention. In a recent review, Brancucci and Tommasi (2011) suggest that the rationale of binocular rivalry experiments can be successfully used in the auditory domain. They refer to these experiments as binaural rivalry, and they induce bi-stable auditory percepts by means of dichotic listening and stream segregation procedures. In dichotic listening paradigms, two dissimilar stimuli are presented one to each ear, only one being perceived by participants. In stream segregation procedures, acoustic features of the stimuli lead to different perceived streams of sounds. The same auditory input can be interpreted as one or two streams. In an experiment conducted by Gutschalk et al. (2005), the authors found that neural correlates of bi-stable percepts were situated in the auditory non-primary cortex. Hence, non-primary cortices are widely considered the NNC for visual and auditory conscious perception; however, besides this similarity, research suggests that NCC depends on the sensory modality. Thus, some cortical areas involved in visual awareness (e.g., inferior temporal cortex) are not related with auditory NCC. On the contrary, areas like the medial temporal gyrus have never been associated with visual NCC but they are strongly related with auditory percepts (Brancucci, Franciotti, D'Anselmo, Della Penna, & Tommasi, 2011).

1.2. Neural correlates of MW

Conscious perception not only arises from external inputs; self generated states cover the 30% of the waking brain activity (Smallwood, Fishman, & Schooler, 2007). This type of conscious 'mode' has been called MW and may appear during in-attention of an ongoing task or when an individual is not engaged at any task (see Gruberger, Levkovitz, Zangen, Ben-Simon, & Hendler, 2011; Smallwood & Schooler, 2006 for reviews). Neural substrates of MW have been related with the default mode network – DMN, (Gusnard, Akbudak, Shulman, & Raichle, 2001; Spreng, Mar, & Kim, 2009) which is a neural circuit that is activated when participants are in a resting state (Raichle & Snyder, 2007). Smallwood, Brown, Baird, and Schooler (2012) propose that MW is generated by a combination of DMN and the fronto parietal control network (FPN). The FPN would protect internally generated trains of thought from disruption. MW has also been characterized by the examination of oscillatory properties of the EEG. A recent study conducted by Braboszcz and Delorme (2011) recorded the EEG of participants while doing a simple breath cycles counting task. MW states were identified during the task by online reports of participants. Long segments of EEG were analyzed before and after reports aiming to extract the characteristics of brain oscillations associated with MW. The results of Braboszcz and Delorme showed an increased power in delta (2–3.5 Hz) and theta (4–7 Hz) activity and a decrease power in the alpha (9–11 Hz) and beta (15–30 Hz) bands. This study is relevant for two reasons. First, it links specific properties of EEG time series to different types of conscious processing. Second, it uses introspection as a method for EEG functional classification. However, in the study of EEG time series, it has been well documented that linear methodologies, as Fourier Transform used in the mentioned study, may not be adequate for non-periodic and irregular EEG time series (Gao et al., 2006; Klonowsky, 2008).

1.3. Non-linear fractal dimension analysis

The fundamental assumption of non-linear methods is that EEG signals are generated by deterministic processes reflecting non-linear associations between neuron assemblies (Jansen, 1991; Pereda et al., 2005). One of the applications of the theory of non-linear dynamics to the study of EEG has relied in the use of the fractal dimension (FD) to characterize chaos variations under different conditions. In this context, an EEG signal is considered a fractal curve that has the property that each short time segment within the EEG signal follows a pattern of small-scale fluctuations in time and amplitude that are similar in form to the large-scale fluctuations on the whole EEG signal. The FD or "complexity" of an EEG signal is a single number that measures how intricate the pattern of these self-similar fluctuations is. For example, an EEG signal dominated by a single steady rhythm would have a FD close to 1. EEG patterns that appear to be dominated by a more complex time-varying patterns or more apparently "dysynchronized" activity would have FD with fractional (non-integer) values higher than 1. The higher the FD value, the more complex the EEG pattern. In general, different cognitive states might be characterized by different levels of EEG complexity, depending on the specific neurocognitive systems that are engaged in supporting those states.

The FD of EEG series has been already applied to a variety of behavioral and cognitive tasks and populations. FD has been shown to be sensitive to a wide variety of cognitive functions as mental task loading (Gregson, Britton, Campbell, & Gates, 1990; Lutzenberger, Birbaumer, Flor, Rockstroh, & Elbert, 1992), general intelligence (Lutzenberger, Elbert, Birbaumer, Ray, & Schupp, 1992), sleep stages (Röschke & Aldenhoff, 1991), or mental or neurological disorders as Alzheimer's disease or schizophrenia (Jeong, 2004; Müller, Mika, Rätsch, Tsuda, & Schölkopf, 2001; Light & Braff, 2003). Although these studies suggest that EEG complexity reflects important properties of the functional organization of cortical structures, it has not been used to characterize NCC. To our knowledge, the paper we present is the first one focused on the EEG complexity of conscious states.

Among all algorithms developed to calculate FD to time series data, Higuchi's algorithm (HFD, Higuchi, 1988) produces the more accurate estimation (Abásolo, Hornero, Gómez, García, & López, 2006; Gómez, Mediavilla, Hornero, Abásolo, & Fernández, 2009). In addition, this method can be applied to stochasctic, non-stationary and chaotic signals (Klonowsky, 2009). Another advantage of this algorithm is that HFD may be computed with relatively short time series extracted from long segments of the EEG (see Appendix A for the HFD algorithm details).

1.4. Goal, experimental strategy and predictions

The main goal of this research was to study whether EEG complexity, measured with HFD, can be used to characterize NCC. In addition, we wanted to explore whether binocular rivalry and MW procedures can be successfully combined to extend previous investigations about NCC.

Our method, which we call bimodal rivalry, produces non-stable percepts between visual and auditory modalities during presentation of a short video clip. In order to combine binocular rivalry and MW procedures, participants watched a video that did not match in visual and auditory inputs. Although they were receiving simultaneous visual and auditory information, they obviously could not integrate audio and video into a single percept. Hence, auditory and visual modalities were mutually exclusive as bi-stable percepts in binocular rivalry experiments. Moreover, when participants watched the video, they could be mind wandering, neither attending to auditory nor to visual stimuli. This possibility was considered as another experimental condition in the