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A novel method for the determination of the EEG individual alpha frequency

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ABSTRACT

The individual alpha frequency (IAF) is one of the most common tools used to study the variability of EEG rhythms among subjects. Several approaches have been proposed in the literature for IAF determination, including the popular peak frequency (PF) method, the extended band (EB) method, and the transition frequency (TF) method. However, literature techniques for IAF determination are over-reliant on the presence of peaks in the EEG spectrum and are based on qualitative criteria that require visual inspection of every individual EEG spectrum, a task that can be time consuming and difficult to reproduce. In this paper a novel *channel reactivity based* (CRB) method is proposed for IAF computation. The CRB method is based on quantitative indexes and criteria and relies on task-specific alpha *reactivity* patterns rather than on the presence of peaks in the EEG spectrum. Application of the technique to EEG signals recorded from 19 subjects during a cognitive task demonstrates the effectiveness of the CRB method and its capability to overcome the limits of PF, EB, and TF approaches.

1. Introduction

Since the first EEG recording (Berger, 1929), evidence that particular mental activities or states are reflected by EEG rhythmic patterns at specific frequencies has led to the introduction of the conventional and widely utilised frequency intervals (bands): delta (δ, 0.1 − 3.5 Hz), theta (θ, 4–7.5 Hz), alpha (α, 8–13 Hz), beta (β, 14–30 Hz), and gamma (γ, >30 Hz); see Niedermeyer (2005) and Sanei and Chambers (2007) for reviews. Depending on the inter-individual differences, EEG rhythms can differ in their frequencies from subject to subject (Başar et al., 1997; Klimesch et al., 2000; Niedermeyer, 2005). Since the early attempts to capture these individual features of EEG rhythms and correlate them with individual behavioural states and cognitive traits, the speed of alpha oscillations, the so-called alpha frequency, has turned out to be a meaningful index of inter-individual variability (Başar et al., 1997; Doppelmayr et al., 1998; Hadley, 1941; Klimesch et al., 1993; Klimesch, 1999; Knott, 1938; Niedermeyer, 2005; Osaka, 1984; Pfurtscheller and Lopes da Silva, 1999). In the following we will discuss the most well-known approaches to investigation of the alpha frequency at the individual level and some open issues which motivate the development of a new method.

1.1. Literature methods for individual alpha frequency (IAF) determination and margins for improvement

1.1.1. The peak frequency (PF) method

It is well-known that the alpha rhythm is clearly seen under conditions of physical relaxation and relative mental inactivity (IFSECN, 1974). In fact, at resting conditions, the EEG spectrum usually shows a visible peak in the alpha range. Historically, the first method proposed to characterise the individual alpha frequency (IAF) is the so-called peak frequency (PF) method, which consists of localising the frequency f_p at which this peak occurs. As an example, panel (a) of Fig. 1 shows a representative EEG spectrum at rest, with f_p represented as a vertical solid line and the alpha range highlighted by two vertical dotted lines.

The PF method has been widely applied in several studies, for instance to show that the mean alpha frequency is 10.2 ± 0.9 Hz in an adult (Petersén and Eeg-Olofsson, 1971), increases from childhood to puberty (Epstein, 1980) and decreases for the rest of the lifespan (Köpruner et al., 1984; Saletu and Grünberger, 1985), is related to head size (Nunez et al., 1978), is lower in demented subjects compared to age matched normal subjects (Coben et al., 1985), predicts age-related decline in working memory (Clarka et al., 2004), is influenced by genetic factors (Smit et al., 2006), and correlates with the amplitude of visual evoked potential and haemodynamic response (Koch et al., 2008). Besides being directly investigated, the frequency f_p has also been utilised as an anchor point to determine the frequency intervals corresponding to theta and alpha bands (Babiloni et al., 2004, 2010; Capotosto et al., 2009; Doppelmayr et al., 2005; Klimesch et al., 2004).

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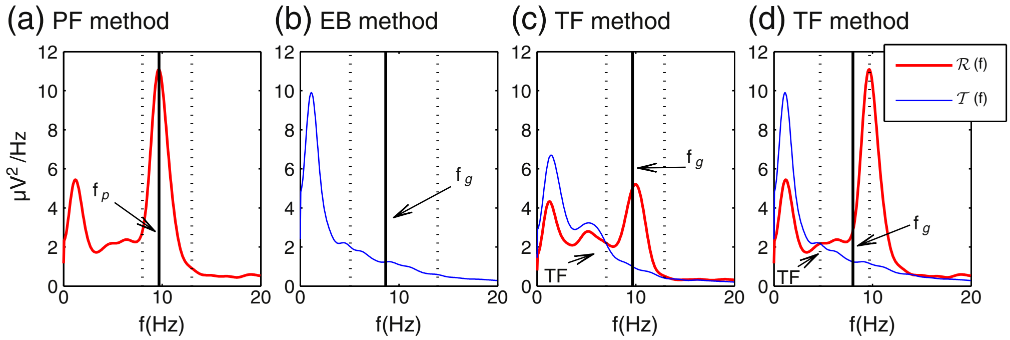

Fig. 1. Representative cases of resting (red) and test (blue) EEG spectra. Panel (a) illustrates an example of peak frequency (PF) f_p determination by the PF method. In the picture, two vertical dotted black lines delimit the (8, 13) Hz alpha range and the vertical solid line is drawn in correspondence with f_p. Panel (b) shows an example of gravity frequency f_g determined by the extended band (EB) method for a representative test spectrum that is quite flat in the alpha range. In the picture, a vertical solid line is drawn in correspondence with f_g and the interval on which it was computed (the extended alpha band) is delimited by two vertical dotted lines. Panels (c) and (d) show two examples of gravity frequencies f_g determined by the transition frequency (TF) method. The panels depict two representative cases of superimposed resting and test spectra with the relative TFs. For both images, vertical dotted lines delimit the interval from TF toTF + 5 Hz and the vertical solid line is drawn in correspondence with f_g.

1.1.2. The centre of gravity frequency concept

Drawbacks of the PF method comprise the fact that the definition of f_p does not cope with cases such as EEG spectra with multiple peaks or EEG spectra that are quite flat in the alpha range. In these cases, which are common when the EEG spectrum is not relative to the resting condition, a more appropriate approach is the one that employs the centre of gravity frequency, that is, the weighted sum of spectral estimates divided by the total alpha power (Klimesch, 1999). This quantity reflects the central tendency of the alpha power and is therefore more representative of the average activity of the alpha population. The determination of the gravity frequency requires the definition of the interval on which the gravity centre will be computed. However, when the EEG spectrum shows multiple peaks or is quite flat, the definition of such an interval is not trivial and deserves further development.

1.1.3. The extended band (EB) method

A method that utilises the extended alpha band to compute the gravity frequency, concisely denoted as the extended band (EB) method, was introduced by Klimesch et al. (1990). The procedure can be summarised as follows. First, by visually inspecting each individual EEG recording, subjects without a clearly detectable alpha peak in the resting spectrum are discarded. Then, for each of the remaining subjects, an extended alpha band is determined as follows. First, leads with an evident peak in the alpha interval of the EEG spectrum at rest are selected on a qualitative basis by visual inspection. Then, for each of these leads the frequency interval (f_1, f_2) is determined by localising, by visual inspection, the starting point of the ascending edge, f_1, and the ending point of the descending edge of the alpha peak, f_2. Finally, the extended alpha band for the subject is obtained by averaging the boundaries of these intervals. Klimesch et al. (1990) called the IAF the frequency that is obtained by utilising the extended alpha band to compute, for each selected lead, the gravity centre of the EEG spectrum relative to the temporal interval under investigation. Either the resting interval or an interval in which the subject is performing the task (test interval) can be utilised. As an example, panel (b) of Fig. 1 shows a representative EEG spectrum computed during a test interval. In the graph, the IAF, denoted by f_g and computed as the gravity frequency over the extended alpha band delimited by the two vertical dotted lines, is represented as a solid vertical line. The computation of the average IAF over all of the selected leads yields a single frequency for each subject.

Since its first definition, the term "IAF" has been utilised to also denote this average and later any alpha frequency computed on an individual basis. Several results have been published on the relationship between IAF and memory performance. In particular, Klimesch et al. (1990) found that good memory performers have an IAF about 1 Hz higher than bad memory performers, and hypothesised that this result was an indicator of faster retrieval of information from memory (Klimesch, 1997). IAF has also been utilised as an anchor point to determine the alpha and theta bands as frequency intervals with a fixed (Klimesch, 1997) or percentage (Doppelmayr et al., 1998) width.

The EB method for the IAF determination has some open issues. For instance, when the computation of the IAF is relative to a test interval, the gravity centre of the EEG spectrum is computed over a frequency band that is obtained by exploiting the resting spectra dynamics. This could prevent the capture of the alpha rhythms that are in reality modulated by the mental process relative to the task. Moreover, discarding data relative to subjects with spectra that do not show a clear alpha peak could result in a loss of information about broader aspects of the phenomenon under investigation. Finally, the need for visual inspection of every individual EEG spectrum and the lack of a proper formalisation to assess the presence of peaks in the spectra can make the results difficult to reproduce.

1.1.4. The transition frequency (TF) method

Another method for IAF computation was reported by Klimesch (1999). The approach is based on the crucial finding that in most cases when the task demand increases theta synchronises whereas alpha desynchronises (Capotosto et al., 2009; Doppelmayr et al., 1998; Gevins et al., 1997; Grabner et al., 2007; Klimesch et al., 1997; Klimesch, 1999; Lopes da Silva, 1992; Raghavachari et al., 2001; Rugg and Dickens, 1982; Schacter, 1977). In other words, theta power increases (synchronises) during a test interval with respect to a resting interval, whereas the alpha power decreases (desynchronises). As a consequence of this pattern, by superimposing the resting and test spectra, it can be seen that there is a frequency at which the two spectra intersect and the theta synchronisation gives way to alpha desynchronisation. This frequency is defined as the transition frequency (TF) (Klimesch et al., 1996; Klimesch, 1999) and is shown in panel (c) of Fig. 1, where representative resting (red) and test (blue) EEG spectra are reported. TF marks the transition between the alpha and theta bands. Accordingly, the IAF is defined as the peak or gravity frequency of the spectrum over the individual interval (f_1, f_2) in which f_1 corresponds to TF, and f_2 is set on an empirical basis (Klimesch, 1999). For instance, a reasonable value for f_2 was suggested to be TF + 5 Hz. In Fig. 1(c) the interval (f_1, f_2), determined as suggested above, is shown by two dotted vertical lines. In the same picture, the IAF, determined as the gravity frequency of the interval and denoted as f_g, is represented as a solid vertical line. The