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Research Report

A decomposition of electrocortical activity as a function of spatial frequency: A weighted multidimensional scaling analysis

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ABSTRACT

In this study, we examined the usefulness of weighted multidimensional scaling (WMDS) to decompose electrocortical activity of multiple brain sources. This electrocortical activity was evoked by checkerboard stimuli of four different spatial frequencies (0.75, 1.5, 3.0, and 6.0 cpd), presented to 12 participants under passive viewing conditions. Visual evoked potentials (VEPs) were recorded with a high density montage of 60 electrodes. These data were analyzed by using WMDS, resulting in four different dimensions, each of which can be considered equivalent to a potential scalp distribution, i.e. dipole source. The first of these dipole sources, which were determined by brain electrical source analysis (BESA), was predominantly activated by higher spatial frequencies, the second and third were predominantly activated by lower spatial frequencies, while the third and fourth sources were characterized by hemispheric asymmetry. Moreover, the neural activity of these brain sources was characterized by different patterns as a function of spatial frequency and time. The results suggest that visual processing of spatial frequencies comprises relatively separate subsystems with different spatiotemporal response characteristics.

1. Introduction

Within the domain of visual abilities, the ability to perceive spatial structure – shapes, locations, sizes, and orientations of objects in space – is considered one of the most important abilities. Particularly, the phenomenon of spatial frequencies is regarded as central to visual information processing (e.g., DeValois and DeValois, 1990; Graham, 1989; Hughes et al., 1996; Palmer, 1999). This concept accounts for a variety of perceptual and attentional phenomena (e.g., Breitmeyer and Ganz, 1976; Ginsburg, 1984; Robertson and Lamb, 1991). For example, spatial frequencies may play a role in color induction (Smith et al., 2001), may mediate the phenomenon of global and local attention and natural scene recognition (Peyrin et al., 2004; Sasaki et al., 2001), and may guide attention when searching for a target in complex visual patterns (Robertson, 1996).

Electrocortical activity of the visual cortex in response to spatial frequency can be measured by visual evoked potentials (VEPs) (Regan, 1989). Clear evidence has been provided that different spatial frequencies result in different VEPs. The most salient difference occurs between 70 and 120 ms after stimulus onset over occipital–temporal areas, consisting of an increased negative (or decreased positive) amplitude to high as

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compared to low spatial frequencies (e.g., Bodis-Wollner et al., 1992; Harter and White, 1970; Kenemans et al., 1993; Plant et al., 1983; Proverbio et al., 1996, 1993; Reed et al., 1884; Zani and Proverbio, 1995). Several investigators have suggested that these differences in amplitude are related to different brain areas (e.g., Aine et al., 1990; Drasdo, 1980; Hudnell et al., 1990).

Kenemans et al. (2000), who used brain electrical source analysis (BESA), indeed provided evidence that high(er) spatial frequencies activated an equivalent dipole pair that was medially located and tangentially oriented and that low(er) spatial frequencies activated a dipole pair that was laterally located and radially oriented. They suggested that these dipole sources were located in primary and secondary visual cortical areas, respectively. Moreover, for two intermediate frequencies they found two pairs of dipoles with intermediate locations and orientations. Kenemans et al. argued that the dipole sources of the two intermediate spatial frequencies may not have intermediate locations and orientations, compared to those activated by the extreme spatial frequencies. While they argued that the scalp-recorded activity to the intermediate spatial frequencies might reflect the superposition of activity of the lateral-radial and the medial-tangential sources (see Proverbio et al., 1996, for a similar argument), they could neither deny nor confirm that the intermediate spatial frequencies activated anatomically distinct pairs of dipole sources, i.e. different brain regions.

Generally, the spatiotemporal superposition of neural activity as measured by scalp electrodes has been recognized by many authors for many years (e.g., Achim and Marcantori, 1997; Donchin, 1966; Donchin and Heffley, 1978; Glaser and Ruchkin, 1976; Näätänen, 1992; Nunez, 1981; Tucker et al., 1994). Particularly, as exemplified by the indeterminacy of the results of the study of Kenemans et al. (2000), the superposition of neural activity, volume-conducted from multiple regions of brain tissue, can be an important obstacle to localize the generators of evoked potentials (EPs) and can cause significant errors in localization procedures (Dien, 1998; Liu et al., 2002).

A method that is sometimes used to disentangle this superposition of activity is principal components analysis (PCA) (Dien, 1998; Dien et al., 2007, 2003; Duffy et al., 1990; Kavanagh et al., 1976; Skrandies and Lehmann, 1982; Spencer et al., 1999, 2001). Critics, however, have demonstrated a number of caveats of PCA that complicates its interpretation and have made its use controversial. The most notable problem is the rotational indeterminacy of the principal components (e.g., Achim and Bouchard, 1997; Achim and Marcantori, 1997; Dien, 1998; Hunt, 1985; Möcks and Verleger, 1986; Wood and McCarthy, 1984).

In the present study, an attempt was made to disentangle this overlapping electrocortical activity by using another multivariate statistical method, called weighted multidimensional scaling (WMDS; Carroll and Chang, 1970). This method has been reformulated explicitly for EP analysis by Möcks (1988a,b) under the term topographic component model (TCM), but has not received much attention (see, however, Achim and Marcantori, 1997; Field and Graupe, 1991). Formally, multidimensional scaling (MDS) is a technique for the analysis of similarities or dissimilarities between a set of objects with the purpose to understand the essential structure of these objects, smoothing out nonsystematic variance (Borg and Groenen, 1997). Contrary to PCA, WMDS is not subject to rotation problems and does not assume linear relationships between variables. In accordance with Carroll and Chang (1970), we assumed a limited number of dimensions, that can be considered equivalent to a potential scalp distribution, i.e. a dipole source. Each of these dimensions was fixed in location and orientation across the entities time points, experimental

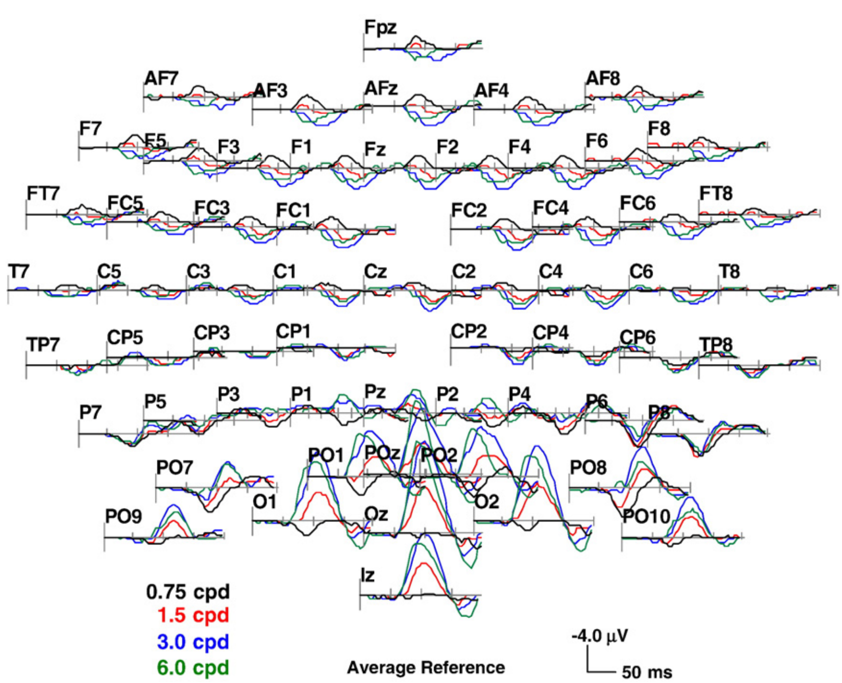

Fig. 1 – Grand-average VEPs to checkerboard stimuli of four different spatial frequencies (0.75, 1.5, 3.0, and 6.0 cpd) at 60 electrode locations. The VEPs were re-referenced to the average of the 60 electrodes with BESA.