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An independent components analysis (ICA) approach to the study of developmental differences in the saccadic contingent negative variation

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Abstract

This study investigated the development of the saccadic CNV in 74 subjects aged 7–18 years, using pro- and anti-saccade tasks, and independent components analysis (ICA) for data analysis. Within the 2-stimulus paradigm, a central fixation point (S1) was followed 2.5 s later by a peripheral cue (S2) presented at 4° to the left or right of S1 in random order. The EEG was recorded from 40 electrodes applied over both hemispheres using a DC amplifier. With increasing age, pro- and anti-saccadic reaction times became faster, this effect being slightly more pronounced during childhood for the anti-saccade task. ICA revealed a lateral-posterior sCNV in younger children, and the known anterior-central sCNV in late adolescents. By contrast, the gaze maintenance negativity (GMNb), an anterior-central negativity accompanying the excursion of the eye, was present in all age groups. Our results underline the importance of topographical approaches in developmental ERP research and the usefulness of ICA. They suggest major task-dependent developmental differences in the spatial modulation of frontal-lobe sensitive ERP components.
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1. Introduction

While the body of research on event-related brain potentials (ERP) *in adults* is immense, only very little is known about these ERP components in *children and adolescents* (Segalowitz and Davis, 2004). This holds also for ERP components that are known to be sensitive to the functional integrity of the frontal lobes. One of these components is the contingent negative variation (CNV), a slow negative potential shift with a topographical maximum around the vertex. The CNV is typically elici-ted within the two-stimulus paradigm, where a first or "warning stimulus" reliably predicts the occurrence of a second or "imperative stimulus" that is associated with a certain task (pre-warned response). The early phase of the CNV is considered to reflect contingency formation, its final phase response preparation (Rockstroh et al., 1989). As the two-stimulus paradigm is an elementary version of the group of delay tasks, which require the formation of cross-temporal contingencies, a frontal origin of the CNV has been suspected (Fuster, 1989). Indeed, Proulx and Picton (1978) have shown that the CNV arises only if a subject apprehends the contingency between WS and IS. Furthermore, cortical recordings in non-human primates (Gemba et al., 1990; Hablitz, 1973; Mauritz and Wise, 1986; Sasaki and Gemba, 1991; Sasaki et al., 1990) and in surgical patients (Hamano et al., 1997; Ikeda et al., 1996; Lamarche et al., 1995) have revealed that *both* self-initiated motor acts (giving rise to the readiness potential) and pre-warned responses are preceded by neuronal activity in supplementary motor area (SMA), primary motor (MI) and primary sensory cortex (SI). Additional activity in premotor and prefrontal cortices could, however, only be registered before pre-warned responses. Finally, in patients with unilateral frontal ablations the CNV is missing over the ablated region (Zappoli et al., 1995).

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Frontal-lobe sensitive ERP components are particularly interesting from a developmental perspective because the frontal lobes have been considered for long to show strong and protracted development during childhood and adolescence (Golden, 1981). Accordingly, at the *behavioural level* several studies have shown, for instance, that parameters derived from pro- and anti-saccade tasks (see below) show patterns of ''developmental fractionation'' (i.e., differential developmental trajectories) that correspond to the assumed protracted development of the frontal lobes (Fischer et al., 1997; Klein and Foerster, 2001; Klein, 2001a,b). However, at the *electro-cortical level* these developmental effects have barely been studied as yet. This holds also for the CNV. Cohen (1973) studied the CNV in 6–18-year-olds and found its amplitude to reach the adult level only with the age of 15 years. Segalowitz et al. (1992) found differences between 12-year-olds and adults only in the early, but not the late CNV. Significant age group differences also for the late CNV were observed by Klorman (1975) in 10-, 14-, and 19-year-olds. Again was the early CNV larger in 19- as compared to 14-year-olds, and the late CNV smallest in 10-year-olds. Using a task in which the WS provided the Go versus Nogo instruction, Segalowitz and Davis (2004) found a clear developmental pattern for the emergence at about 12 years of age of the CNV on Go trials (with no developmental changes on Nogo trials, which elicit limited CNV). This comparison between Go and Nogo trials is particularly interesting because it provides some evidence of functional specificity of the CNV findings which can be related to theories of prefrontal functions. Alternatively to this all-or-none comparison, the degree of involvement of prefrontal cortex functions could be varied experimentally (see below). Major developmental effects have also been reported for a slow negative potential shift that had been suggested to be part of the late CNV: The Bereitschaftspotential (BP; readiness potential). Chiarenza et al. (1993) have shown the BP to be consistently present in children aged 10 years and older.

Although age groups may not only differ in amplitudes or latencies of ERP components, but also in their topographies, multi-channel recordings and the application of modern topographical analysis techniques can only rarely been found in the *developmental* ERP literature. Topographical differences, however, can be expected for a number of reasons. *First*, the age groups may show global or regional differences in cortical anatomy (e.g., Jernigan et al., 1991; Pfefferbaum et al., 1994) or physiology (e.g., Chiron et al., 1992) which give rise to differences in the spatial modulation of ERP components. *Second*, age groups may differ quantitatively (e.g., slower) or qualitatively (e.g., processing styles) in task processing, giving rise to age group differences in the temporal and spatial modulation of ERP components.

A common problem of multi-channel recordings is the complexity of the data set, which typically comprises information along the temporal, spatial, and ''situational'' (different tasks or conditions) dimensions. This general problem is particularly pronounced in cross-sectional developmental research, where various age groups must be compared with respect to the temporal, spatial, and situational aspects of electro-cortical activity. Hence, data reduction as a preparatory step for statistical analyses is mandatory in developmental ERP research. There are, obviously, a number of valuable analysis approaches that provide a considerable reduction in data complexity (e.g., BESA; Scherg and Picton, 1991). Here, we focus on topographical independent components analysis (ICA; Makeig et al., 1999). ICA is a method optimizing a linear transformation of the input matrix (N electrodes $\times$ time) onto the output (N components $\times$ time) such that the resulting component time courses show maximal temporal independence. Since neighbouring EEG electrodes tend to capture similar and therefore highly temporally dependent signals, the transformation into a number of temporally independent components that, taken together, explains all input signals, is a valuable step in the interpretation of EEG or ERP data. Similar to principal component analysis, data reduction is provided by the fact that most of the complex signals observed across all EEG electrodes are can be explained by relatively few strong constituent signals. Since no source model is assumed, the physiological plausibility of the component topographies extracted solely through the temporal relationships of the input is not trivial and therefore lends additional confidence to the results. Finally, due to the linear and complete nature of the optimized transformation, a comparison between electrode-based concepts and ICA representation is possible at any time.

We apply ICA to study developmental differences in the spatial-temporal modulation of the CNV elicited during two tasks that ''challenge'' regions in the frontal lobes in different degrees, the pro- and anti-saccade tasks. While visually-guided ''pro''-saccades are directed at the peripheral cue, ''anti''-saccades are directed at the mirror image position of the peripheral cue (Hallett, 1978). As has been outlined elsewhere (see Klein et al., 2000a,b; Munoz and Everling, 2004), the anti-saccade task challenges a number of so called executive functions, including preparatory set, the inhibition of a peremptory response, a stimulus incompatible response, and the generation of an endogenous saccade. Furthermore, working memory has been suggested to be involved in the execution of correct anti-saccades (Roberts et al., 1994). For these reasons, protracted development of anti- as compared to pro-saccade task performance can be expected (Fischer et al., 1997; Klein, 2001a,b).

Slow negative potential shifts can be measured reliably (Klein and Berg, 2001), and are known to be larger preceding anti- as compared to pro-saccades at anterior-central sites (Everling et al., 1998; Klein et al., 2000a,b). This probably reflects the greater unit (Schlag-Rey et al.,

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