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Check size dependency of the sources of the hemifield-onset evoked potential

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Abstract. The checkerboard-onset evoked potential does not obtain its adult waveform until late puberty. The changing waveform results from the development of the underlying sources originating in distinct areas of the visual cortex. Since the waveform of checkerboard-onset evoked potential also varies with check size, we studied the dependency of the activity of these sources on check size.

A dipole source localization procedure yielded the position and orientation of the equivalent dipoles and the constituent components of the pattern-onset evoked potential, each corresponding to one of these dipoles. For every check size used, the checkerboard-onset evoked potential could be described by a summation of the relative amplitudes of these components. Since the relative amplitude versus check size curves showed a different behavior for each source, they provided evidence of functionally distinct cortical generators. The strength of the striate source was especially sensitive to the fine structure of a pattern, whereas the extrastriate sources contributed mainly for coarse pattern elements.

Introduction

It is well established that the scalp-recorded potentials elicited by the onset of a pattern stimulus contain contributions from different cortical areas and/or different cortical processes [1–5]. Maier *et al.* [6] described a method that determines the dimensionality of the response space and provides the constituent components of the responses. In this model it is assumed that the responses originate from a fixed number of dipoles, each with a fixed position and orientation, but varying in strength. The dipole analysis described by Maier *et al.* [6] over a time window covering the first positive (CI) and negative (CII) peaks of the pattern-onset evoked potential (EP) yielded two dipoles, situated in the extrastriate and striate visual areas, respectively. Using the same dipole localization approach, Ossenblok and Spekreijse [7] reported that three dipoles are responsible for the full pattern-onset EP, including CIII. It was also shown that striate area 17 activity dominates the checkerboard-onset EP of the youngest children [8], while extrastriate activity starts to contribute later in life [9]. These developmental processes and the changing activity profile of the striate sources [8] change the waveform of the pattern-onset EP from childhood to adulthood.

Since the waveform of the pattern onset EP varies with check size [10], we studied the dependency of its sources on check size. The variation in strength of these sources is reflected in the components of the checkerboard-onset EP. By means of a least-square analysis of each of these components and the pattern-onset EPs, the relative amplitudes of the components of the pattern-onset EP were obtained. These relative amplitudes versus check size are defined as the strength curves of the components. This study shows that the EP amplitude versus check size curve can be described as a summation of the strength curves of the components. Each of these components differs in check size dependency, thus providing evidence of functionally distinct cortical generators. It appears, furthermore, that the strength curves are age related.

Methods

Stimuli

Stimuli were generated on a digital display system (Genisco 3000) viewed binocularly [11]. All stimuli were presented in the left or right hemifield with a field size subtending to 4°. The stimuli were surrounded by a steady homogeneous field of the same mean luminance of 65 cd/m^2. To obtain a visual evoked potential to pattern onset, a checkerboard pattern was presented for 300 ms every 800 ms, without net variation in overall luminance level. In this way the responses evoked by the onset and offset of the checkerboard could be registered separately. The results presented are recorded as a function of check size, ranging from $4'$ to $56'$ or $64'$. Because of the scattering of light in the eye, the retinal contrast changes with the check size of the pattern. Therefore, the threshold contrast per check size was determined on the basis of a correction function for the light scattering in the eye [12]. By means of this function, the retinal contrast was kept approximately constant at 25.3%, irrespective of check size, for all the subjects studied.

Recording

The results presented in this report were obtained in eight healthy subjects ranging from 6 to 16 years of age and one adult subject. All of these subjects were tested with best corrected visual acuity, which was at least 20/20 for each eye as measured with the Landolt C acuity card. The visual evoked potentials were recorded at 24 electrodes according to an electrode grid with a vertical and horizontal spacing of the electrodes of 4 cm. The reference was placed frontally, at the midline of the head. For further information on the procedure followed during the recording sessions, see Ossenblok *et al.* [8].

Signals were amplified (Medelec 5000) and bandpass filtered between 1.5 and 70 Hz. The high cutoff frequency was set by a low-pass fourth-order Butterworth filter, which introduces a phase shift increasing the response latencies by 7 ms [11]. Peak latencies estimated from the recordings depicted in this article should be corrected for this latency increase. The electroencephalograms were sampled at a rate of 240 Hz and on-line averaged with an HP 2100 minicomputer. Since only 16 electroencephalogram amplifiers were available, all recordings were made in two sessions. The eight double recordings were used to estimate the signal-to-noise ratio and the reproducibility of the responses. For the analysis of the pattern-onset EP, a time window was chosen that included the prominent maxima and minima of the responses. The maximal length of the time window for the dipole analysis was 58.4 to 266.9 ms after stimulus onset, thus accounting for the CI-CII-CIII interval of the pattern-onset EP.

Equivalent dipole analysis

To localize the equivalent dipoles, the spatio–temporal dipole model of Maier *et al.* [6] was used. In this model it is assumed that the number of activated dipoles equals the minimal number of principal components of the onset EP that are necessary to account for the significant variance of the data. This whole procedure, described in detail in Maier *et al.* [6], yields the constituent components of the pattern-onset EP, each corresponding to a single dipole with a time profile reflecting the variation in strength of that dipole source. To determine the position and orientation of these equivalent dipoles, the head is described as a spherical three-shell model [13], while no further constraints are placed on the parameters of the dipoles or on the volume searched. Although the activity of three distinct equivalent dipoles may contribute to the adult-onset EP [6, 7], because of noise and the limited number of electrodes used, a reliable estimation of the parameters of only two dipoles is attainable. Thus, the most reliable solution of the source localization problem can be found in a check size range in which one of the components is weakened, whereas the other two are selectively stimulated [7]. Since stimulation with 6′ and 18′ checks satisfies this condition for adults, we used these results to estimate the strength curves of the components of the adult pattern-onset EP. For children a one- or two-dipole solution was obtained.

Strength curve description

To quantify the relative strength contribution of the equivalent dipoles to the checkerboard-onset EP, their components were least-square fitted with

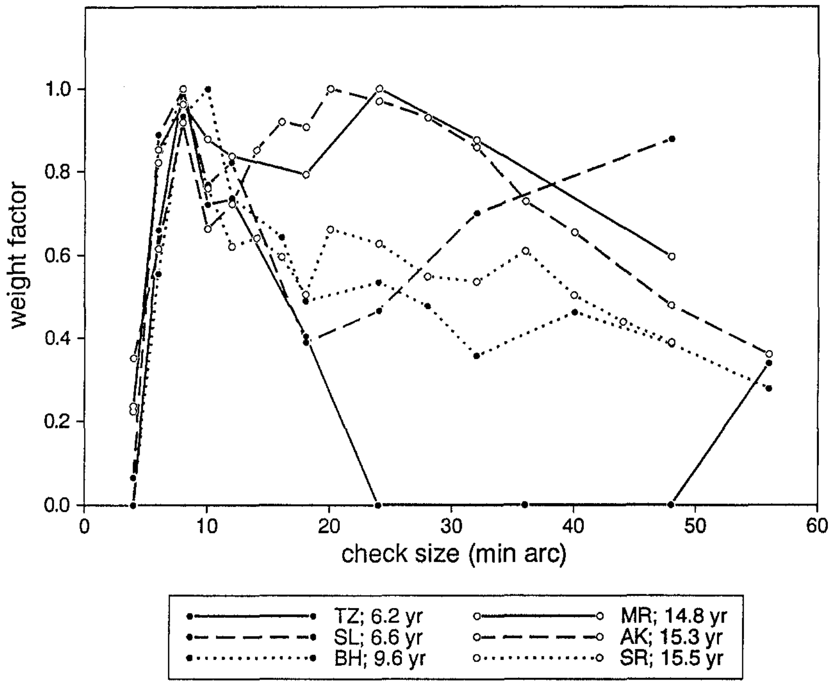

Fig. 1. Variation in strength of the striate components of six of the subjects studied versus the check size of the stimulus. The striate components used in the fitting procedure and their spatial distributions were published previously [8]. The responses were recorded to the onset of a checkerboard of 25.3% retinal contrast with check sizes ranging from 4′ to 56′ presented in the central 4° of the right half of the visual field.

the onset EP, and the weight factors were determined. For this procedure we chose the response recorded at the electrode located 2 cm above the inion at the midline of the head for two reasons; (1) for children this response is maximal [8] and (2) in adults all three sources contribute to the midline electrode [6, 7]. It is assumed that the shape of the components of the dipoles does not vary with check size [6] and that their relative contributions account for the change in waveform with check size. Thus, the weight factors, normalized with respect to their maximum, give the relative amplitude of the constituent components of the checkerboard-onset EP as a function of check size. Superimposed in the responses are plotted the linear combinations of the weighted components, calculated for each of the check sizes. The linear combinations of the weighted components of the checkerboard-onset EP are an indication that the strength curves are a good estimate for the variation of strength of the sources.

Results

Figure 1 depicts the strength curves of striate activity for six of the subjects studied. All curves show a sharp tuning for small checks and become maximal at 8′ or 10′. Note that for some of the subjects the strength starts to increase again until a second maximum is reached for coarser pattern elements. Although the maximal peak-to-peak amplitudes of the traces at the inion had a shape similar to that of the graph of the strength of the striate component, for the coarsest patterns extrastriate activity may also contribute to the checkerboard-onset EP.

For another subject studied, the results of stimulation with check sizes ranging from 4′ to 56′ are depicted in Fig. 2. On stimulation with the smallest checks, the responses consist mainly of a negative-positive complex that is specific for the striate component of children of this age [8]. A singular value decomposition of these responses showed that the power of the first principal component, amounting to 86% of the total power of the response set, accounts for the significant power of the response to 6′ checks. The corresponding dipole is located near the midline of the head, above the inion, and the potential field is nearly symmetric with respect to the midline of the head (Fig. 3b). Note that for coarser checks the early negativity disappears, probably because a positive peak becomes apparent in the responses. A singular value decomposition of the responses evoked by stimulation with checkerboard elements of 48′ showed that the accumulated power of the first two principal components, amounting respectively to 69% and 26% of the total power of the response set, account for the significant variance of the responses. Thus, two dipoles are needed to account for the significant variance of this response set [9]. The activity of one of these dipoles dominates the early positive peak and probably has its origin in the extrastriate cortex, since the equivalent dipole is located away from the midline of the head (Fig. 3a). In the lower right part of Fig. 2, the weight factors of the striate and extrastriate components are depicted as a function of check size. Note that the strength of the striate component is tuned for small checks, whereas the extrastriate component starts to contribute to the response from about 32′ on.

The contribution of extrastriate activity to the checkerboard-onset EP in children is especially pronounced on stimulation of the left half of the visual field [9]. Note that the shape of the responses shown on the left side of Fig. 4 changes from a negative-positive complex for the smallest checks into a positive-negative deflection for checks exceeding 20′. The least-square fit of the striate and extrastriate components (upper right) yields the weight factor curves versus check size shown in the lower right part of the figure. Note that the striate component is sharply tuned to small checks while the extrastriate component contributes from about 20′ on and then levels off.

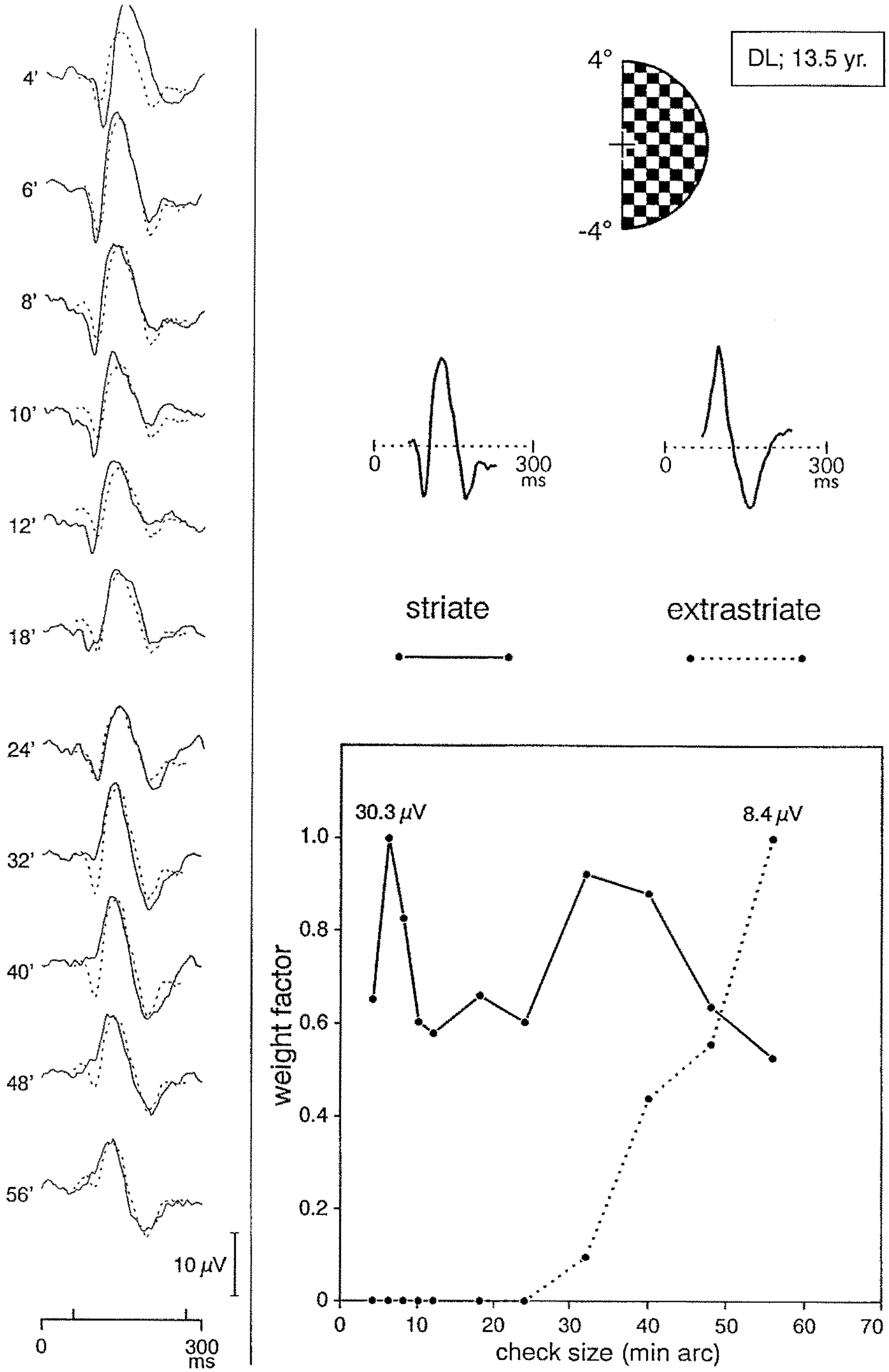

Fig. 2. Strength curves of the component for a 13 and a half year- old subject. Left pattern-onset EPs evoked by a checkerboard restricted to the central 4° of the right half of the visual field for the check sizes used. The dotted lines depict the linear combinations of the components. Top right, striate and extrastriate components. The components covered a time window that started 58.4 ms after pattern onset and ended at 266.9 ms. Bottom right, weight factors of the components as a function of the size of the checkerboard elements, normalized to their maximum. Maximal weights for the two sources are depicted in microvolts.

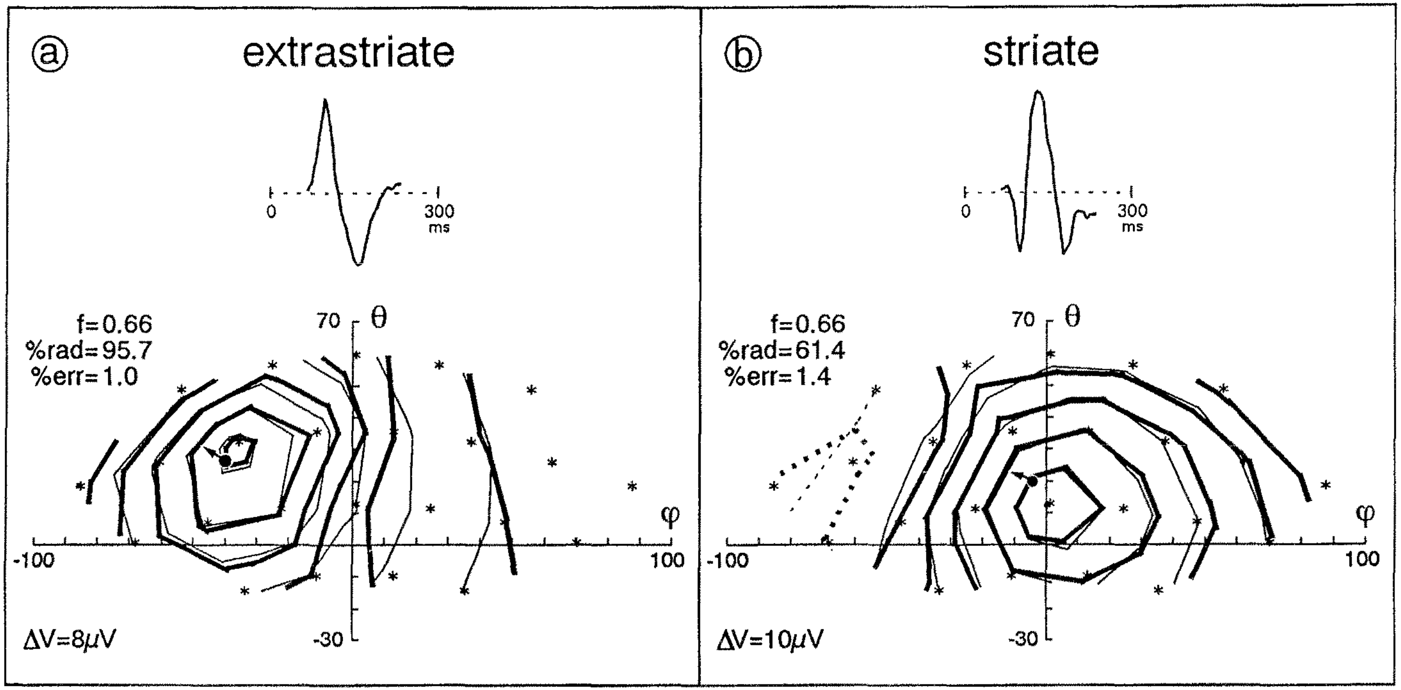

Fig. 3. Components used to obtain the weight factor curves in Fig. 2 and equipotential maps of the corresponding dipoles. The equipotential maps were derived from the responses evoked by the onset of a 24′ (a) or 6′ (b) checkerboard presented in the central 4° of the right half of the visual field. The map at left is for the extrastriate component and at right, for the striate component. The equipotential maps are plotted in the ϕ-θ coordinate frame, with the zero-point of the coordinate frame (i.e., ϕ=0 and θ=0) coinciding with the inion. Heavy solid lines represent the positive values of the recorded potentials, heavy dotted lines the zero values, and heavy dashed lines the negative values. Also shown are the best-fitting dipole distributions, represented by thin continuous, thin dotted and thin dashed lines for positive, zero and negative potentials, respectively. The asterisks indicate the electrode positions, and the difference between adjacent contours is given in microvolts. The quality of a dipole fit is indicated by the percentage error (%err) based on the sum of the squared potential differences. In each plot the location of the equivalent dipole source depicted by a dot, is given by the spherical coordinates f, ϕ and θ (see Maier et al. [6]). The radial part of the dipole (%rad) is expressed as a percentage of the strength of the equivalent dipole. The arrow gives the orientation of the dipole projection in the tangential plane.

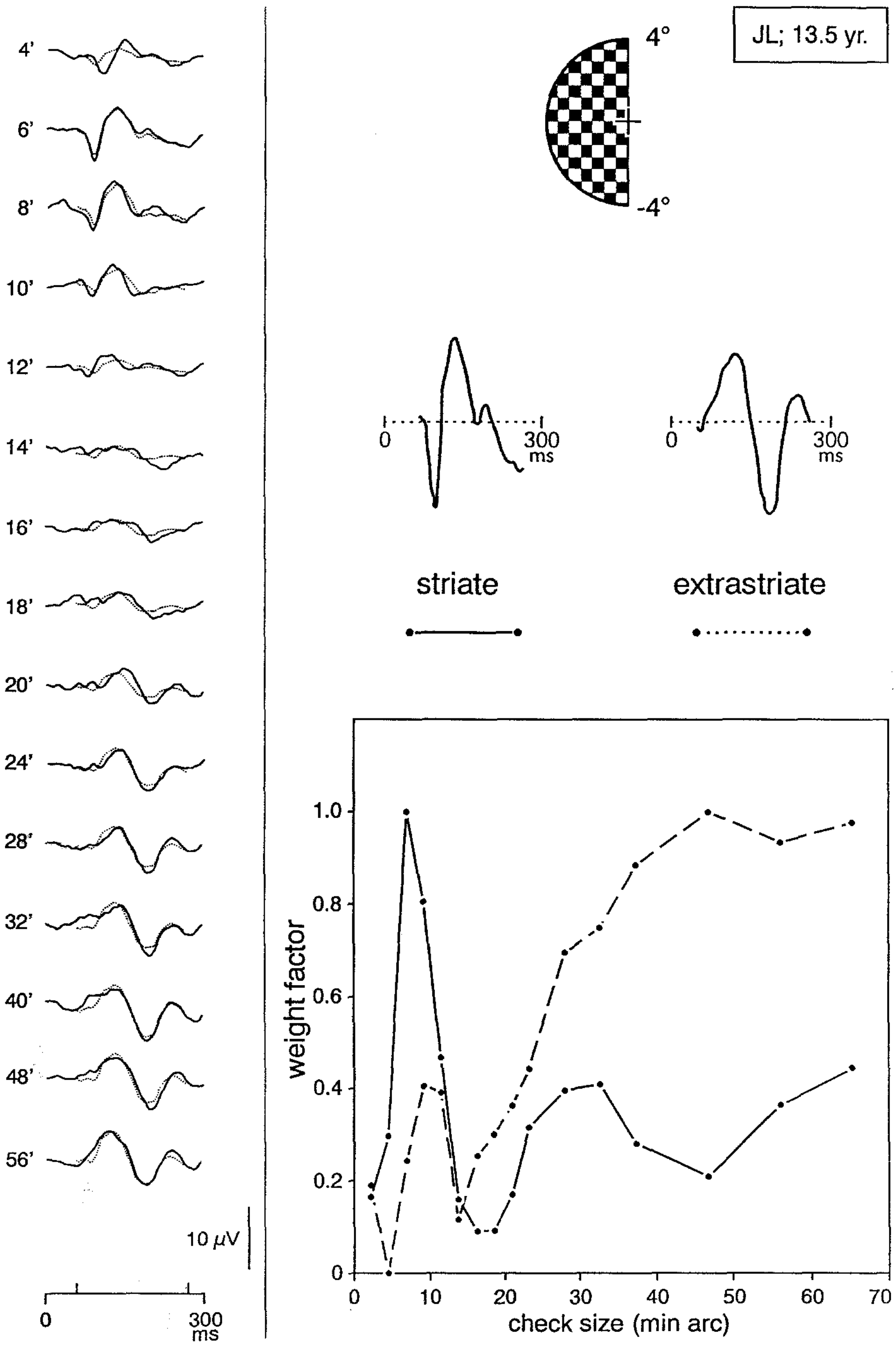

Fig. 4. Left, pattern-onset EPs evoked by a checkerboard restricted to the central 4° of the left half of the visual field for the check sizes used. Top right, striate and extrastriate component. The components were derived from the responses evoked by the onset of a 28′ (extrastriate) or 6′ (striate) checkerboard presented in the central 4° of the left half of the visual field. The components covered a time window that started 58.4 ms after pattern onset and ended at 266.9 ms. Bottom right, weight factors of the components as a function of the size of the checkerboard elements, normalized to their maximum.

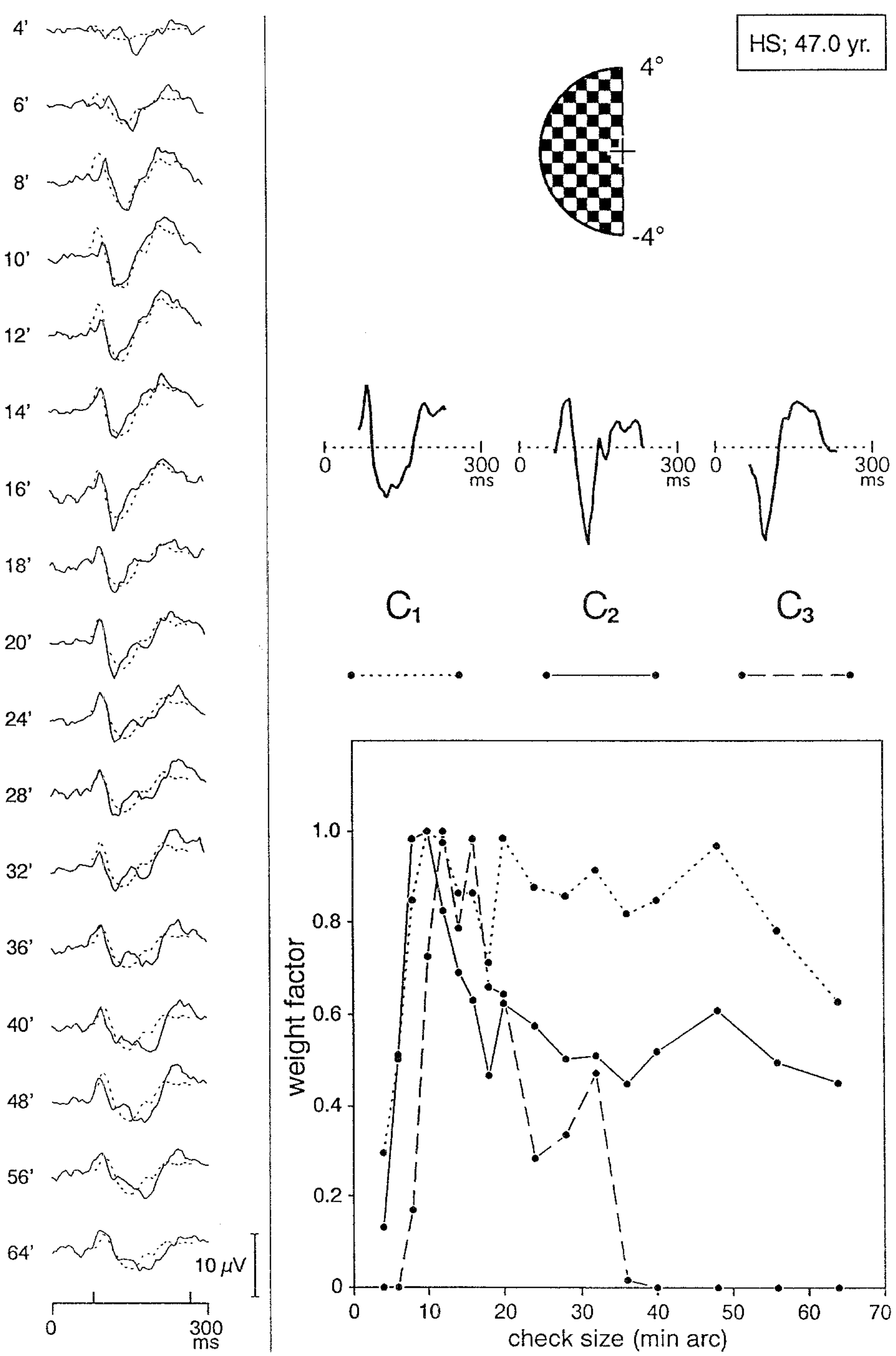

Fig. 5. Left, pattern-onset EPs evoked by a checkerboard restricted to the central 4° of the left half-field for the check sizes used. Top right, shape of the C1, C2 and C3 components. The components were derived from the responses evoked by the onset of an 18′ (extrastriate) or 6′ (striate) checkerboard presented in the central 4° of the left half of the visual field. The components were least-square fitted, with the responses shown at left yielding the weight factors as a function of check size (bottom right), normalized to their maximum.

The variations in strength of the equivalent dipoles underlying the adult checkerboard-onset EP are depicted in Fig. 5. Note that the striate activity, as in children, is sharply tuned around 8′ to 10′. However, whereas in children a second maximum may occur for larger checks, in adults striate activity does not increase for coarse patterns [6, 7]. A further comparison shows that the extrastriate component (C1) of the adult response increases up to a maximum at about 10′ and then remains constant, whereas the extrastriate component extracted from the checkerboard EPs in children only starts to contribute to the response for coarser patterns. The strength of the C3 component of the adult EP, which probably originates in area 19 [7], is more widely tuned than C2 and reaches its maximum at 12′ to 16′ (Fig. 5).

Discussion

The EP amplitude versus check size curve can be described by a summation of the strength curves of the underlying dipole sources. Note, however, the decreased correlation of the 4′ response (see Figs. 2, 4 and 5). This latency shift of the finest checks is likely due to an overestimation of the contrast sensitivity of the eye for high spatial frequencies, as was pointed out recently by Drasdo *et al.* [14]. The correction function we used also does not account for individual differences caused by refraction or age. Note, furthermore, that each of the strength curves has a different check size dependency, thus suggesting distinct mechanisms contributing to the pattern-onset EP.

Child versus adult strength curves

The dipole analysis shows that the left hemispheric responses of children are dominated by striate activity [8, 9]. Therefore, it is not surprising that the strength curves of striate origin and the peak-to-peak amplitude curves are similar. Because of close correspondence between the strength curves of the striate components of children and adults, it seems likely that they have a common origin in the striate cortex. Note that for coarser pattern elements, extrastriate activity may also contribute to the checkerboard-onset EP in children. The contribution of extrastriate activity becomes more pronounced on stimulation of the left half of the visual field, although a large inter-individual variability in both strength and peak-latency has been reported [9]. Of course, the weighting factors obtained at a single electrode site can be influenced by the location and orientation of these sources, which parameters may also depend on check size [8]. However, since the potential distribution and strength profile of the extrastriate source in children (see Fig. 3a) highly resemble those of the area 18 source of the adult checkerboard-onset EP [6, 7] the larger contribution of extrastriate activity to the contralateral electrodes

[9] will be the same for adults. For the children in the age group studied, sources resembling the area 19 source of adults could not be extracted from the responses for either check size used.

Acuity

Striate activity dominates the checkerboard-onset EP in children. Its sensitivity to small checks is in accordance with the results of De Vries-Khoe and Spekreijse [10], who showed that the high-spatial-frequency slope of the EP amplitude versus check size curve correlates well with the development of acuity. All studies on this topic show that acuity develops rapidly during the first year of life [10, 15, 16, 17, 18], which probably correlates with the morphologic maturation of the retina. De Vries-Khoe and Spekreijse [10] and Spekreijse [19] described a subsequent slow improvement phase that ends around puberty and is reflected in the development of the waveform of the checkerboard-onset EP. The acuity development during this phase correlated with the growth of the negative peak in the pattern-onset EP (CII). Ossenblok *et al.* [8] showed recently that the growth of this negative peak is due to the changing shape of the striate component between childhood and adulthood. Thus, since the growth of the negative peak in the checkerboard-onset EP during development (1) correlates with acuity development [10] and (2) may be due to changes in the activity pattern of the striate sources [8], it seems likely that acuity development from childhood to adulthood depends on the maturation of central visual processes, probably reflecting the synaptogenesis of the primary visual cortex, as suggested by Carey and De Courten [20]. Thus, visual evoked potential acuity assessment during the slow improvement phase may provide insight into striate cortical development.

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