An event-related potential study on visual perceptual learning under short-term and long-term training conditions

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The present study investigated learning-induced changes of event-related potentials in a visual discrimination task, focusing on making a comparison between short-term and long-term learning perceptual processes. Event-related potentials were recorded from two groups of human adults. One group (short-term training group) was given 1.5 h of training in a single day, and another group (long-term training group) was given the same training procedure (1.5 hour of training) on each of 3 consecutive days. The results demonstrated that for short-term training group, along with the reduction of reaction times, the amplitudes of N1 and N2 negativities over the central/parietal areas decreased during the training. For long-term training group, however, after long-term training, the N2 effect disappeared and the N1 effect occurred over the posterior areas. In addition, the amplitudes of N2 for long-term training group were less than those for short-term training group. Our results suggest that neural activity depends not only on perceptual mechanisms and on the parameters of the physical stimuli but also on the extent of the observer's previous learning. *NeuroReport* 13:2053–2057 © 2002 Lippincott Williams & Wilkins.

Key words: Event-related potentials (ERPs); Human adults; Long-term learning; Short-term learning; Visual perceptual learning

INTRODUCTION

The improvement of perceptual performance as a function of training (perceptual learning) has been found in a v ariety of visual tasks [1]. For example, the study of vernier acuity showed that response accuracy increased dramatically within < 1 h of training [2]. Such short-term learning effects were also found in pop-out detection [3] and waveform discrimination [4]. On the other hand, some studies showed long-term learning effects developed over days. For instance, when subjects were given training everyday in an orientation discrimination task, orientation sensitivity improved significantly after several days of training [5]. Interestingly, recent studies have reported that both short-term and long-term learning effects could be observed in a given task, i.e. performance was improved not only over a few of hundred trials in the first day of training, but also over subsequent several days of training [6].

In contrast to a great number of behavioral studies, there were only a few of cognitive neuroscience findings regarding the neural mechanisms of short-term and long-term learning effects. For example, by recording visual evoked potentials (VEPs) from humans, Skrandies *et al.* found that 25 min of training resulted in larger occipital potentials with shorter latencies [7]. In a PET study, however, Schiltz *et al.* reported that the activities over the human striate and extrastriate cortex decreased after several days of training [8].

These results give rise to an important question: What is the relationship between short-term (hours) learning and long-term (days) learning? In the present study, two groups of human adults were trained with a same visual perceptual task, but the length of training is different for each group. We directly compared the event-related potentials (ERPs) of short-term training group with those of long-term training group. By using the scalp distribution and the amplitude changes of ERPs, we intended to determine whether there were some differences in the underlying brain substrates between short-term and long-term learning processes.

MATERIALS AND METHODS

Subjects: Two groups of undergraduate and graduate students (aged 18–26 years) participated in this experiment as paid volunteers. One group (eight male, six female) was given short-term training while the other group (eight male, three female) was given long-term training. All had normal or corrected-to-normal vision. All except one were right-handed.

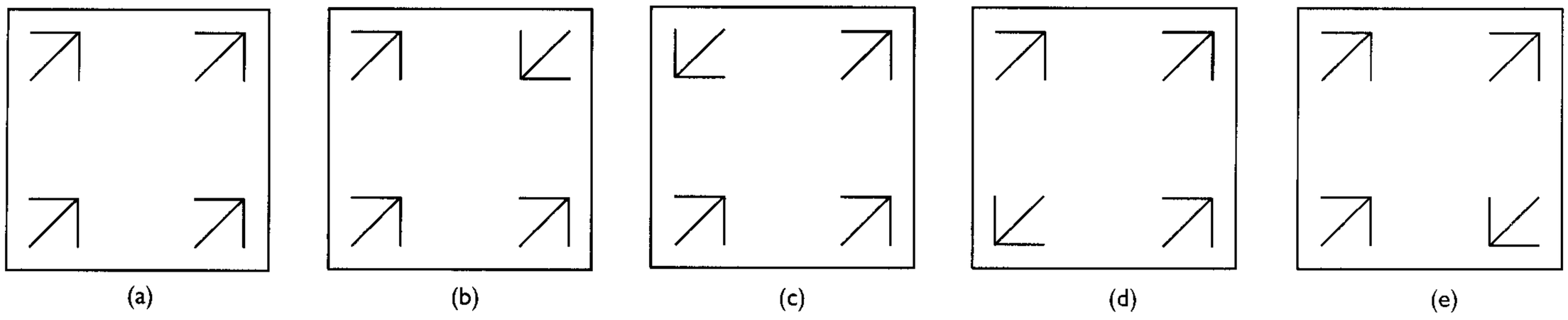

Fig. 1. Stimuli used in the present experiment. The target stimuli with a press response (**a**) and the four types of non-target stimuli without explicit response (**b**–**e**) used in equi-probability.

Stimuli, task and procedure: Five types of stimuli, illustrated in Fig. 1, were used in the present study. Each stimulus (10.9 × 10.9°) was composed of four arrows (each 2.5 × 2.5°) in a 2 × 2 array. The four arrows were either identical (Fig. 1a) or one of them differed from the rest in orientation (Fig. 1b–e). All the stimuli were white on a black background. A fixation cross (0.3 × 0.3°) was continuously visible at the center of display. Stimulus duration was 200 ms. Interstimulus intervals were randomized between 1600 and 2000 ms. The task was to discriminate whether the four arrows in a stimulus had identical orientation or not. The subjects were instructed to press a button with their dominant hands when the target (i.e. four arrows with identical orientation, Fig. 1a) was presented. Both accuracy and speed were emphasized. The target and four non-target stimuli were presented in a pseudo-random order and equal probability (each 20%). One group of subjects was given three consecutive training sessions in a single day while both reaction times and ERPs were recorded during the training. Each session contained nine blocks of 40 trials and lasted about 30 min. This group was designated as short-term training group. In another group, the same training procedure (three training sessions) was repeated on three consecutive days and data were recorded only during the third day of training. This group was designated as long-term training group.

ERP recording and data analysis: The EEG was recorded from 29 scalp electrodes (including 19 electrodes of the 10/20 system and 10 nonstandard electrodes, Fig. 4). Horizontal and vertical electro-oculograms (EOGs) were also recorded. EEG was physically referenced to the left mastoid and then was off-line re-referenced to the average of the left and right mastoid. Electrode impedance was kept below 5 kΩ. EEG was amplified with a band pass of 0.1–40 Hz, digitized online at a sampling rate of 250 Hz. Each epoch of EEG was 200 ms of pre-stimulus to 1000 ms of post-stimulus. To minimize movement-related artifacts of finger response, EEG for all non-target stimuli (without explicit response) within each session was averaged. Trials contaminated by eye blinks or muscle potentials at any electrode and incorrect behavioral responses were excluded from the ERP averages. The baseline for ERP measurements was the mean voltage of a 200 ms prestimulus interval.

Behavioral data were analyzed by repeated measures ANOVAs with two factors: group (short-term or long-term training group) and session (the first, second, or third training session). For ERP analysis, nine electrodes (C3, Cz, C4, P3, Pz, P4, O1, Oz, and O2) in the central/parietal/occipital areas were selected. The ANOVAs of mean ERP amplitudes were computed with factors being group, session, and electrode site (central, parietal, or occipital sites).

RESULTS

Behavioral measures: The results of reaction times are shown in Fig. 2. Reaction times for the long-term training group were faster than those for short-term training group ($F(1,23) = 8.046$, $p < 0.010$). The main effect of session was significant ($F(2,46) = 16.063$, $p < 0.001$). However, there was also a significant session × group interaction ($F(2,46) = 19.968$, $p < 0.001$). Separate ANOVAs showed that, for short-term training group, reaction times decreased significantly across training sessions ($F(2,26) = 25.154$, $p < 0.001$). For the long-term training group, however, reaction times did not differ among training sessions ($F(2,20) = 0.580$, $p > 0.548$). Further pairwise comparisons revealed that reaction times decreased gradually for the short-term training group (first *vs* second session: $p < 0.002$; second *vs* third session: $p < 0.001$). Response accuracy (averaged 99%) was high and stable, and it was not affected by group or different training sessions.

ERP measures: The ERPs were all characterized by P1, N1, and N2 with maximum over the posterior areas, P2 with maximum over the frontal-central area, and a broadly distributed P3. Peak latencies of each component were similar for all training sessions. There were, however, differences of ERP amplitude on three important components, i.e. N1, N2, and P3 (Fig. 3). Their amplitudes were measured as the mean voltages within the intervals 125–155, 290–340, and 360–480 ms, respectively.

N1 amplitudes did not differ between the two groups ($F(1,23) = 0.086$, $p > 0.771$). However, the N1 amplitudes decreased across training sessions ($F(2,46) = 10.963$, $p < 0.001$; Fig. 2, Fig. 3). The session × group × electrode site interaction was significant ($F(4,92) = 6.482$, $p < 0.004$), suggesting that the involved brain region for N1 decrement was different for each group. Separate ANOVAs showed that the N1 decreased at the central/parietal sites for short-term training group (central: $p < 0.005$; parietal: $p < 0.041$; occipital: $p > 0.886$; Fig. 4) but at the parietal/occipital sites for the long-term training group (central: $p > 0.601$; parietal: $p < 0.002$; occipital: $p > 0.002$; Fig. 4). Further pairwise

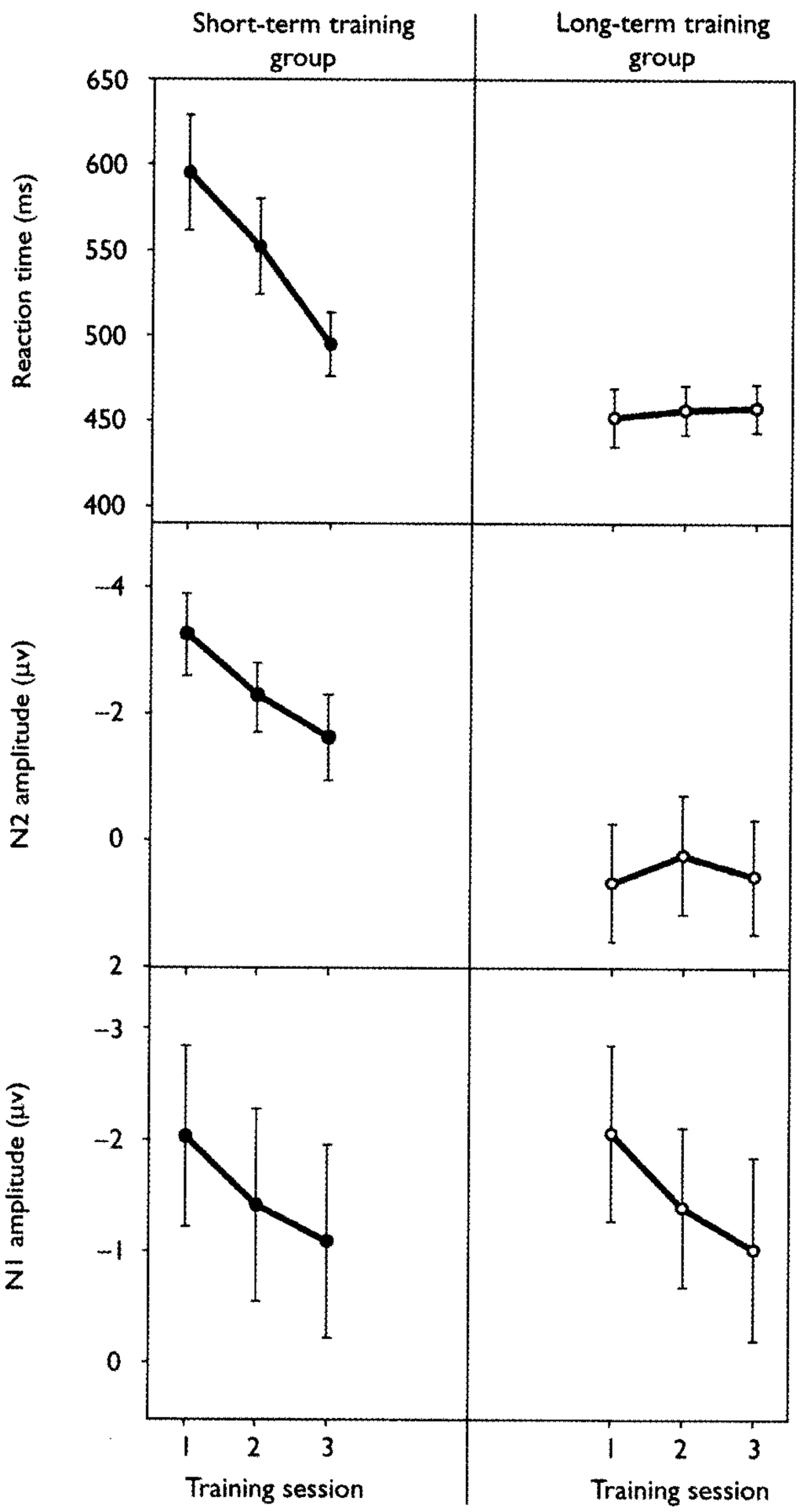

Fig. 2. Changes in reaction times (upper), N2 amplitudes at P4 site (middle) and N1 amplitudes at Pz site (lower) in the course of learning. Closed circles, short-term training group; open circles, long-term training group. Error bars indicate s.e.m.

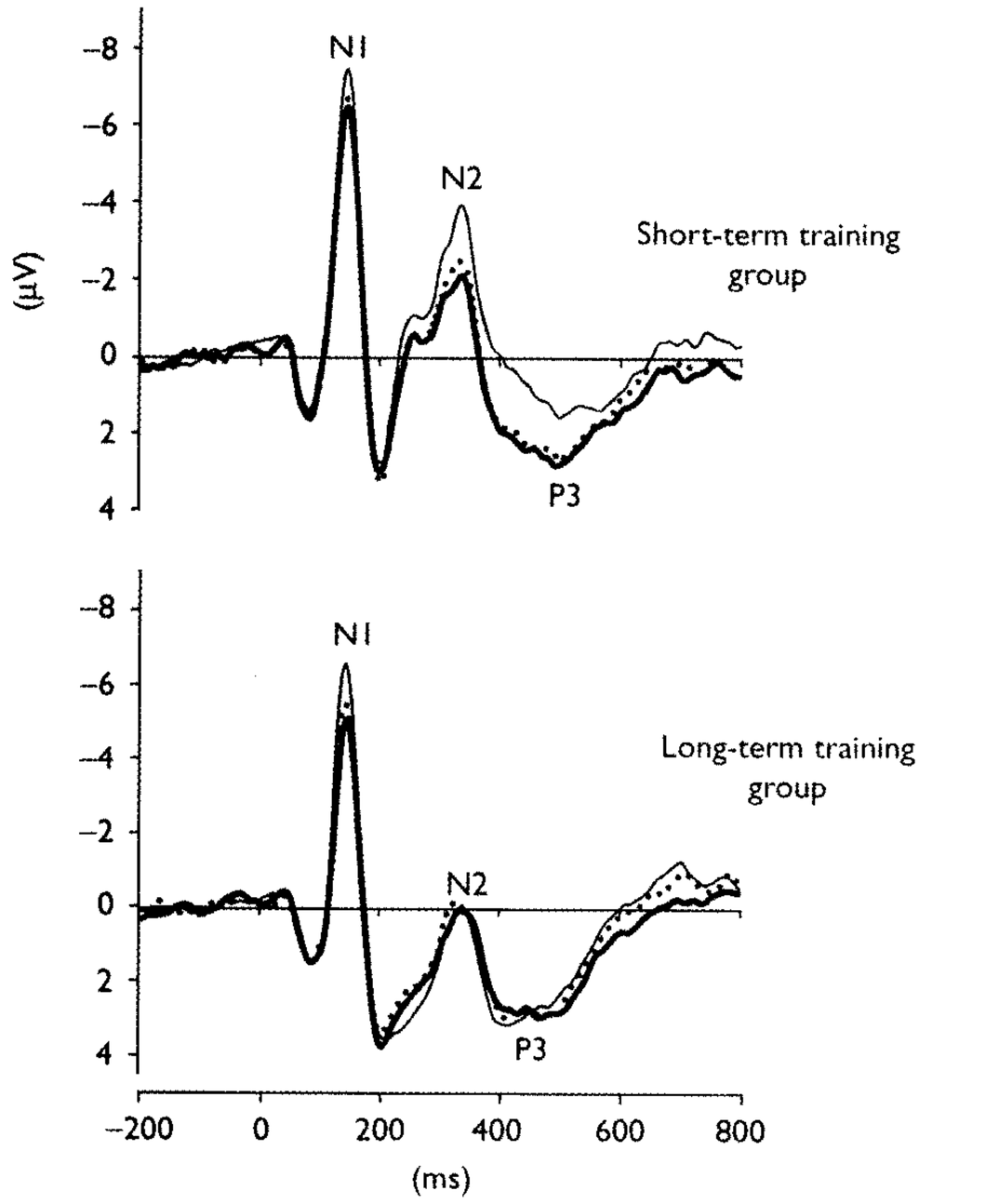

Fig. 3. The grand averaged ERPs (recorded at P4 site) to non-target stimuli during the three training sessions. The thin continuous, dotted, and thick continuous waveform referred to the first, second, and third training session, respectively. For short-term training group, the N1, N2 decreased and the P3 increased across training sessions. For long-term training group, however, only the N1 decreased across training sessions.

comparisons revealed that the N1 decrement occurred mainly during the first two sessions (first *vs* second session: $p < 0.032$, 0.003; second *vs* third session: $p > 0.437$, 0.134; for short-term and long-term training groups, respectively).

The N2 amplitudes were much smaller for the long-term than short-term training group ($F(1,23) = 5.558$, $p < 0.028$; Fig. 2, Fig. 3). There was a significant session × group interaction ($F(2,46) = 6.461$, $p < 0.006$). For the short-term training group, separate ANOVAs showed that the N2 decreased across training sessions ($F(2,26) = 7.586$, $p < 0.006$; Fig. 2, Fig. 3). For the long-term training group, however, the N2 amplitudes did not differ among sessions ($F(2,20) = 0.896$, $p > 0.416$; Fig. 2, Fig. 3). Further analyses revealed that the decrement of N2 for short-term training group was mainly over the central/parietal areas (central: $p < 0.031$; parietal: $p < 0.005$; occipital: $p > 0.113$; Fig. 4), and occurred gradually (first *vs* second session: $p < 0.047$; second *vs* third session: $p < 0.022$). These results suggested that the time course of N2 was similar to that of reaction times. Figure 2 clearly illustrates the high correspondence between the N2 amplitudes and the reaction times.

For the amplitude of P3, no significant difference was found between groups ($F(1,23) = 0.852$, $p > 0.365$), whereas there was a significant session × group interaction ($F(2,46) = 6.280$, $p < 0.006$). Separate ANOVAs showed that, the P3 for the short-term training group increased across training sessions ($F(2,26) = 9.796$, $p < 0.006$; Fig. 3) whereas the P3 for the long-term training group did not differ among sessions ($F(2,20) = 0.725$, $p > 0.448$; Fig. 3). For the short-term training group, the enhancement of P3 was mainly at the central/parietal sites (central: $p < 0.003$; parietal: $p < 0.002$; occipital: $p > 0.126$; Fig. 4), and occurred during the first two sessions (first *vs* second session: $p < 0.005$; second *vs* third session: $p > 0.104$).

DISCUSSION

In the present study, two groups of subjects who had different training experience did the same visual perceptual

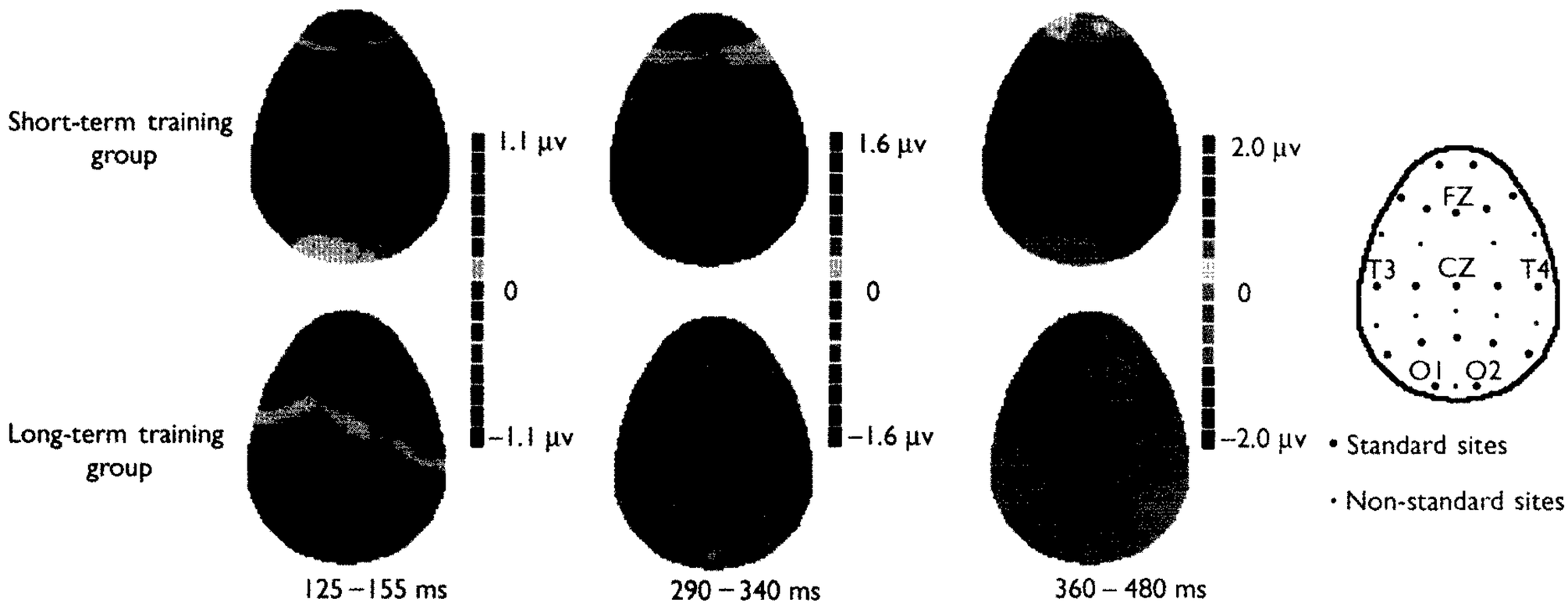

Fig. 4. The maps of difference wave (ERPs in the third session minus those in the first session). Note that, for short-term training group, the difference wave in the N1 (125–155 ms) time window focused over the central/parietal areas (pink color). For the long-term training group, however, the distribution of difference wave in the same N1 time window receded to the parietal/occipital areas. In addition, for the short-term training group, the difference wave in the N2 (290–340 ms) and P3 (360–480 ms) time windows also focused over the central/parietal areas (pink color). For the long-term training group, however, the difference wave in the same two time windows (290–340 ms, 360–480 ms) did not reach significance over the whole scalp. The distribution of 29 scalp electrodes used for EEG recording is shown on the right side.

task. We found that the learning-induced changes for the short-term training group were fundamentally different from those for the long-term training group, which was manifested in not only behavioral performance but also event-related potentials. For instance, for the short-term training group, the amplitudes of N2, like the reaction times, decreased gradually across training sessions. However, for the long-term training group, no such change in N2 or in reaction times was found, and the amplitudes of N2, like the reaction times, were smaller than those the of short-term training group. The reaction time data showed that, until a stable level of performance was attained, the participants responded faster along with more practice and their discriminabilities improved gradually. Previous studies proposed that N2 might reflect on-line perceptual processing, stimulus identification, and selection based on stimulus features, such as orientation [9–12]. The present results observed in N2 might be partially related to the electrophysiological substrates of perceptual mechanisms underlying the learning effect observed in reaction times.

In contrast to the N2, the N1 decreased for both short-term and long-term training groups, and its amplitudes did not differ between groups. It is, however, interesting to see the brain region involved in N1 decrement was different for each group. The training effect on N1 amplitudes shifted from central/parietal to parietal/occipital region as a consequence of long-term learning. Note that the discrimination task we used in this experiment might involve the processing of complex shapes in higher brain areas, and consequently, the related activities at the same areas were also modulated by training [13]. However, if subjects were repeatedly presented with the same stimulus in long-term training, the task might have become highly familiar and could be done rapidly and automatically. Then the involvement of higher brain areas may not be necessary and may be replaced by those of relatively lower brain areas. This shift could account for the enhancement of efficiency and rapidity in recognizing familiar objects [14]. Such pattern of changes was also found from the PET study of motor skill learning in humans [15]. Regarding the N1 component, our result provides one more piece of evidence to support the hypothesis that different areas of the brain are involved in performing a task during and after learning it [16] and that, as a consequence of learning, the representation of complex objects may be shifted from higher to lower areas [17].

The amplitude decrement of N1 and N2 caused by training is consistent with brain imaging studies in humans [8] and single unit recording in animals [18], which showed reductions of neural activity after learning. However, this result was different from the VEP study by Skrandies *et al.*, who found that learning simpler stimuli induced enhancement of evoked potentials [7]. The difference between the findings might be accounted for by the different stimuli and paradigms used in these experiments. Further experiments are needed to determine whether the modulation of ERP amplitudes induced by learning is related to complexity of stimuli and task difficulty. Compared to the N1 and N2, the P3 was a relatively later component and its amplitudes increased with training. Our P3 data might reflect a consequence of perceptual learning such as enhanced confidence [19]. It is also possible that the P3 effect was partly due to the decrement of its neighboring positive wave N2. Further experiments are also needed to determine whether the decrease of N2 and the increase of P3 are related.

CONCLUSION

Our results illustrate that short-term perceptual learning can influence the amplitudes of several ERP components, in which the earliest one was the N1 wave. While long-term perceptual learning does not simply influence the amplitudes of ERPs, but also influences the topography of brain electrical activity in a systematic way, which in turn, might

reflect a shift of processing pattern in the human cortex toward earlier stages in the visual pathway. Neural activity depends not only on physical stimulus parameters and on perceptual mechanisms but also on the observers' extent of previous learning.

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