

α -modulation induced by covert attention shifts as a new input modality for EEG-based BCIs

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Abstract—Covert attention shifts to the visual periphery induce modulations of α -bandpower over occipital cortex. By demonstrating robust classification of covert attention shifts to four different target locations, a recent magnetoencephalography (MEG) study set the first step for its use as a new input modality to brain-computer interfaces (BCIs) [1]. Here, we set the next step by investigating its feasibility using electroencephalography (EEG). Eight healthy participants had to shift covert visual attention to one of six different target locations while strictly fixating the center of the screen. To enhance the spatial resolution, we used a current source density (CSD) estimate instead of raw voltage maps. Covert attention shifts to the different target locations yielded distinctive topographical distributions of posterior alpha activity.

Index Terms—BCI, EEG, visual speller, α -rhythm, covert attention

I. INTRODUCTION

Driven by the need for new communication and control technology for people with motor disorders such as amyotrophic lateral sclerosis (ALS), a lot of research in the last decade has focused on noninvasive brain computer interfaces (BCIs). A BCI typically works by distinguishing different mental states that are under conscious control of the user. The signal features used in BCIs based on electroencephalography (EEG) or magnetoencephalography (MEG) reach from slow cortical potentials over event-related potentials (ERPs) to event-related (de)synchronization (ERD/ERS) of sensorimotor rhythms [2] [3].

One application of BCIs are spellers that can be conceived of as BCI-pendants of computer keyboards. The first successful implementation was the visual ERP speller¹ by Farwell and Donchin [5] (Figure 1a), which uses a visual oddball paradigm. The speller consists of a matrix of letters whose rows and columns flash in a random order while the subject has to attend to the target letter. Typically, ERP components are enhanced when the row or column that is flashed contains the target letter. The oddball paradigm has also been applied to other modalities, using auditory [6], [7] or tactile stimulation [8].

As recently pointed out, the matrix speller relies on eye movements, which casts doubt on its application value in clinical practice [4]. Consequently, novel visual layouts and

different paradigms should be explored to make visual spellers more versatile and independent of eye movements. This paper pursues both issues. With respect to visual layout, we made use of the symbol arrangement of the Hex-o-Spell [9], which was recently applied to the oddball paradigm [4]. In the Hex-o-Spell, symbols are selected on two successive stages, as depicted in Figure 1b–d.

With respect to the experimental paradigm, we started off from a recent MEG study that introduced a new kind of control signal to the field of BCI, namely α -modulations associated with covert spatial attention shifts [1]. It is well-known that by shifting covert attention, the processing of visual stimuli appearing at the attended position is facilitated, while the processing of competing stimuli is actively suppressed [10]. At the behavioral level, this results in lower reaction times and higher detection rates. At the neural level, facilitation is associated with enhanced visual responses when stimuli appear at the attended location, which has been found in single cell recordings [11], functional magnetic resonance imaging [12] and EEG [12], [13]. In EEG, these enhanced visual responses include changes in the oscillatory α -band (8-14 Hz) activity over posterior sites in accordance with the direction of attention [13], [14]. An early (600-800ms) α -desynchronization was observed during shifting attention over cortical areas tuned to the attended locations in the visual field, which has been suggested to reflect enhanced excitability of these areas. With prolonged covert attention (>1500ms) an α -synchronization was observed in areas tuned to the unattended locations, which might serve to actively suppress visual input from irrelevant areas in the visual field [14]. In their MEG study, [1] showed robust classification results in a 2D covert attention shifting-task with four different target locations whereby α activity at posterior sites was used as input feature.

The study left open, however, whether an α -activity driven visual speller can be of significant practical use in BCI. Due to its size and immobility, MEG is not a viable device for many clinical applications. Moreover, due to its superior spatial resolution, it is unclear whether the paradigm can be successfully transferred to an EEG-based BCI. The present study addressed this question by measuring posterior α -modulation associated with covert attention shifts to one of six different target locations.

¹This speller is commonly referred to as P300 speller. However, this term is unfortunate because it obscures the fact that the speller often relies not only on the P300 component but also on other ERP components [4]. Therefore, we use the more general term ERP speller.

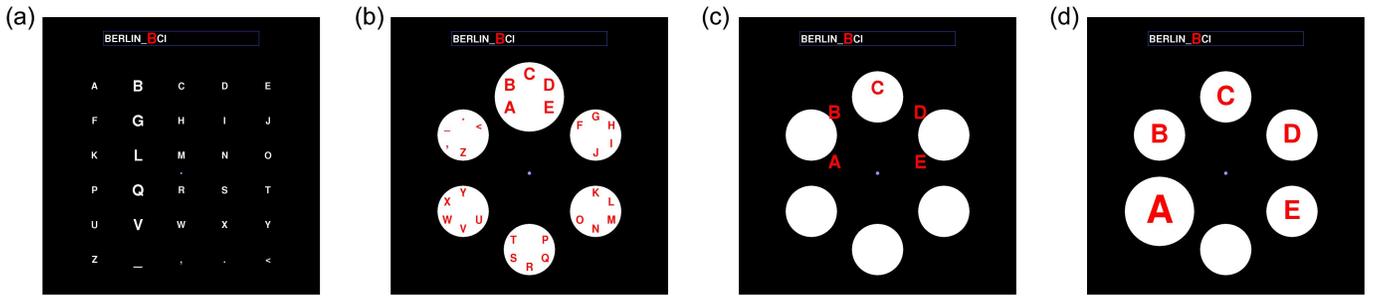


Fig. 1. ERP spellers. (a) Matrix speller. The rows and columns flash one after the other in a random order while the user fixates the desired letter. (b) ERP Hex-o-Spell. Here, the user fixates the center point and shifts his attention to the circle which contains the desired letter, while the circles flash in a random order. When a letter group is selected, the containing letters are distributed over all circles (c) and the procedure repeats for selection of the desired letter (d).

II. METHODS

Participants

Eight healthy volunteers (seven male, one female), aged 18–27 years, participated in this study. All were naive with respect to BCIs and all had normal or corrected-to-normal vision.

Task and Stimuli

The participants performed a cued visual attention task. The course of a trial is depicted in Figure 2. A white central fixation dot surrounded by six white target circles was presented. The target circles had a size of 3.27° of visual angle and they were presented at an eccentricity of 9° from the fixation dot. A cue appearing in the center of the screen for 200ms indicated the target location. Participants had to shift their covert attention to one of the target circles without moving their eyes away from the fixation dot. Since arrow-like stimuli can evoke different ERPs because of their different shapes, the cue was designed to be omnidirectional. It had the shape of a hexagon with each side pointing to one of the target circles. It was divided into six faces, three of them being grey and the other three being colored blue, red and green. One of these colors was used as target indicator, implying that the participant had to direct his attention to the circle to which this color was pointing. The use of one of the three colors as target color was counterbalanced across participants. After a variable duration (500–2000ms) the target appeared for 200ms in the circle as either a '+' or an 'x'. The participants had to press one of two buttons to indicate which of the symbols they had perceived. Two different targets had been chosen to reduce readiness potentials for pressing a button, as suggested by Rihs *et al.* [14]. After 200ms, a masker ('*') was presented on the target location for 200ms in order to control task difficulty.

Each participant performed 600 trials in six blocks of 100 trials with two minutes break between blocks. The target directions were chosen with equal frequency in a random order with 80% validity. In the other 20% of the trials the target appeared at a different location than the cue was indicating. The target symbols appeared randomly with a 1:1 occurrence. The duration for directing the attention to the target location was 2000ms in 50% of the trials to obtain enough trials with measurable α -modulation. To ensure that the participants shift

their attention immediately after the appearance of the cue and do not wait for the 2000ms to be over, 30% of the trials had an appearance of the target 500ms after the cue. In the other trials the duration was randomized between 500ms and 2000ms.

Apparatus

EEG was recorded from a Brain Products (Munich, Germany) 64 channel actiCAP, digitized at a sample rate of 1000Hz, with impedances kept below $20k\Omega$. We used electrodes FP2, AF3,4, Fz, F1–10, FCz, FC1–6, T7,8, Cz, C1–6, TP7,8, CPz, CP1–6, Pz, P1–10, POz, PO3,4,7–10, Oz,1,2 and Iz,1,2, placed according to the international 10-20 system and referenced against a nose reference. Eye movements were monitored using an EOG electrode placed below the right eye. The experiment was programmed in Python using the open-source BCI framework Pyff [15] with pygame. Data acquisition and analysis was performed using MATLAB® (MathWorks). Stimuli were presented on a 24" TFT screen with a refresh rate of 60 Hz and a resolution of 1920×1200 px².

Data Analysis

For EEG analysis, we used only the trials with 2000ms cue-target interval. The EEG channels were bandpass filtered for the 8–12Hz band using a Butterworth filter. The envelope was then calculated as a bandpower estimate and epoched into intervals ranging from -200ms to 2200ms relative to the onset of the directional cue. The 200ms pre-cue period was used for baseline correction. The EEG was automatically reviewed for artifacts and eye movements. Epochs containing artifacts were rejected based on a variance criterion. Epochs containing eye movements were detected and rejected using a min-max criterion ($75\mu V$) on the EOG channels. The spatial resolution of the EEG data was enhanced using a current density estimation (CSD) [16], [17]. For the grand average, the ERD/ERS curves were averaged across all trials and subjects.

To compare the ERD/ERS curves of two conditions or classes, $sgn r^2$ -values based on the point-biserial correlation coefficient were calculated as a measure of how much information one feature x carries about the class labels y . The point-biserial correlation coefficient is defined as

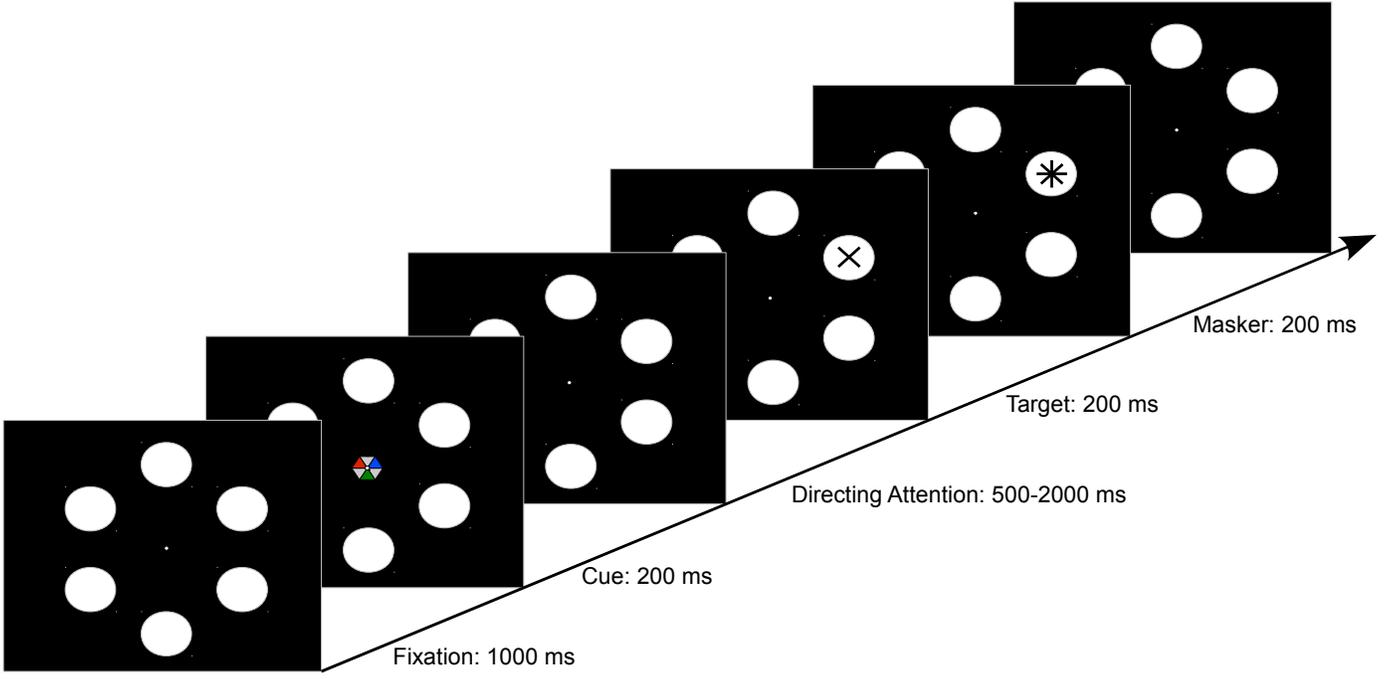


Fig. 2. Covert attention task. The cue tells the subject where to shift the attention. After a variable directing time an target appears (either '+' or 'x'), quickly followed by a masker (*). The subject then has to press a left or right button to indicate which symbol it was.

$$r = \sqrt{\frac{(N1 \cdot N2)}{(N1 + N2)}} \cdot \frac{(\text{mean}(x_i|y_i = 1) - \text{mean}(x_i|y_i = 2))}{\text{std}(x_i)}$$

where N1 and N2 are the numbers of elements (in our case, the number of epochs) in class 1 and 2. The r^2 -value is then multiplied by its sign. $\text{sgn } r^2$ -values were also averaged across all trials and subjects.

III. RESULTS & DISCUSSION

Behavioral Data

Overall response accuracy was $93.6\% \pm 4.6\%$. The accuracies in the valid and invalid condition were compared and found to be not significantly different ($t = 1.42, p > 0.05$). In contrast, the medians of the reaction times were significantly smaller in the valid condition than in the invalid one ($t = 4.49, p < 0.01$), indicating that the participants attended correctly the cued positions (valid: $719\text{ms} \pm 145\text{ms}$; invalid: $881\text{ms} \pm 216\text{ms}$).

Event-Related (De)Synchronization

Figure 3 illustrates the spatial distribution of relative changes in α -activity for each cued (attended) location in the interval (a) 600–900ms and (b) 1500–1700ms after cue onset. In both intervals the ERD/ERS-topography varies systematically with the locus of attention. There is an α -decrease (desynchronization) over the visual cortex with peaks contralateral to the attended locations in the earlier interval and an α -increase (synchronization) with peaks ipsilateral to the attended locations in the later interval. In the literature, α -desynchronization during directing of attention has been interpreted to reflect

enhanced excitability of cortical areas processing the attended part of the visual field [13], whereas α -synchronization was suggested to subserve active suppression of visual input from task-irrelevant locations [18], [19]. Our results are consistent with the findings of Rhis *et al.* [14], [20], who suggested that during a shift of visual spatial attention, which is estimated to take 600–800ms, facilitative mechanisms dominate, whereas after that period the focus of attention has to be maintained so that information from unattended locations is inhibited.

Class-Separability

The ERD/ERS data was investigated for separability of the different classes. In other words, we determined whether attention shifts to the different target locations yielded distinctive spatio-temporal maps of α -activity. First, the two target locations on the left and on the right, respectively, were pooled and then the left side was compared to the right side. The second condition regarded only the top location versus the bottom location. Finally, each location was separately regarded versus all remaining target locations combined and averaged to one class.

Figure 4 depicts the resulting ERD/ERS curves for the conditions 'Left vs. Right' and 'Top vs. Bottom'. Example channels are plotted and scalp topographies are given for each of the two classes and for the resulting inter-class contrast, expressed in terms of $\text{sgn } r^2$. The scalp plots are time-averages of selected intervals in which the classes were best separable (indicated in cyan and magenta in the channel plots).

Left vs. Right: For 'Left vs. Right' attention shifts, the ERD/ERS curves (upper left plot of figure 4) are well separable in the period 500–2000ms after cue onset. Regarding electrode

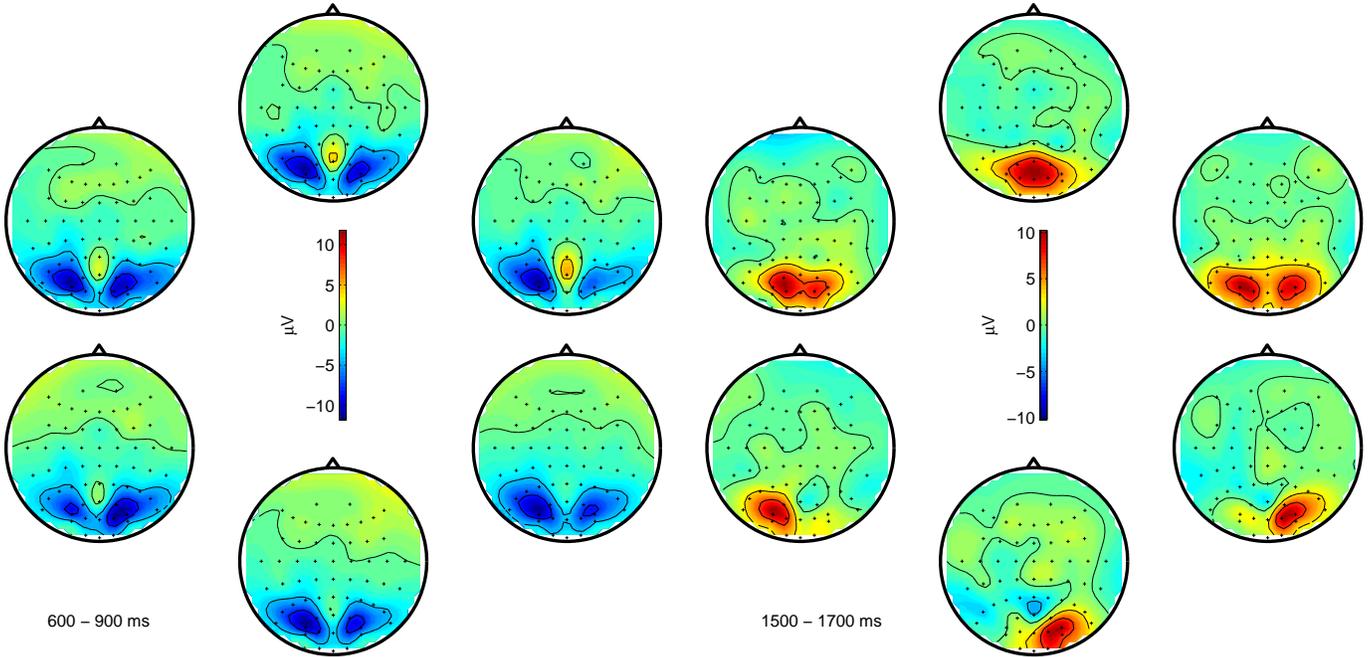


Fig. 3. Spatial distribution of the α -activity for each cued (attended) location. Left: 600–900ms after cue onset there is α -desynchronisation over occipital areas, which is stronger contralateral to attended location. Right: 1700–1900ms after cue onset there is α -synchronization over occipital areas, which is stronger ipsilateral to attended locations.

PO4 (solid lines), which is located over the right side of the visual cortex, the relative bandpower for right target locations (blue) is higher than the relative bandpower for the left target locations (green) during this period. Electrode POz on the other hand (dashed lines) allows almost no discrimination of these two classes, which is not surprising since it is located at a central position of the visual cortex and thus is invariant to horizontal changes of the visual field. The scalp plots show that in all four intervals, the ERD/ERS curves of the 'Right' class are higher on the right side than on the left side of the occipital areas, whereas these of the 'Left' class are higher on the left side. The corresponding $sgn r^2$ -values have a negative peak up to -0.02 on the left side and a positive peak up to 0.02 at the right side of these areas and thus indicate a separability of these classes.

Top vs. Bottom: For the condition 'Top vs. Bottom' (right side of Figure 4), α -modulation is again restricted to electrodes above occipital cortex. Channel POz displays a strong separability from 500ms on, but the ERD/ERS curves of channel PO4 are close to each other and thus less separable. For the 'Top' class, the central electrodes show higher ERD/ERS values than for the 'Bottom' class in all four intervals. The $sgn r^2$ -values in the central occipital region reach 0.03 , which indicates good separability in the 'Top vs. Bottom' condition.

Each vs. Rest: After showing that discrimination of two locations in horizontal and vertical direction is possible, we address the actual problem whether six locations in the 2D plane can be distinguished on basis of posterior α -activity. Figure 5 shows the ERD/ERS curves of the 'Each vs. Rest'

condition. Each of the six possible target locations is compared to the remaining locations which are pooled into a single non-target class. For the six locations, the maximum r^2 -values reach from ± 0.005 up to ± 0.015 which is less than in the two-locations cases, but still promising. Interestingly, the intervals for which the targets are best separable vary across the target locations. For instance, the ERD/ERS curves of channel PO4 in the 'Top-Right' condition are well apart during a large interval (600–2000ms), whereas in the 'Bottom-Right' condition these curves are only apart in an earlier (500–800ms) and a later (1500–2000ms) interval but run very close in between. Also the channels which are well separable vary across the locations. The POz channel is a good candidate for discrimination for the 'Top' and the 'Bottom' location (lines well separated), but channel PO4 would fail in discriminating target from non-target in these two locations (lines close to each other). In other words, different channels could be used with different intervals to test for the location the participant is attending to. These two quantities span a large feature space in which the six locations are well separated, so that a properly trained classifier could be able to discriminate the target locations in a reliable way.

IV. CONCLUSION

In the present study, it was demonstrated that modulations in the α -band related to shifts of covert spatial attention constitute a promising new input modality for EEG-based BCIs. In accordance with the results in other studies [1], [13], [14] it was found that α -modulations vary systematically

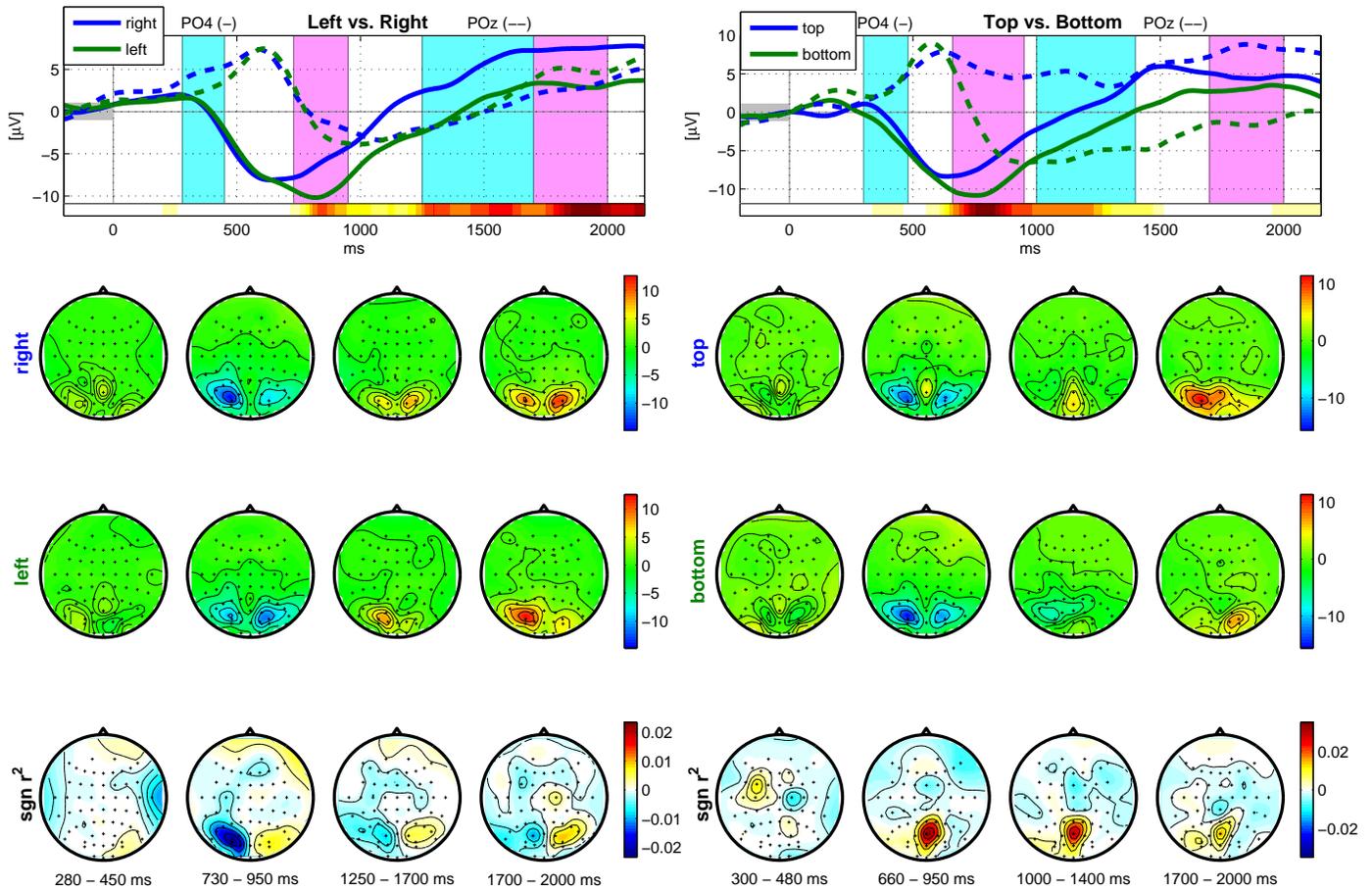


Fig. 4. ERD/ERS curves for the conditions 'Left vs. Right' and 'Top vs. Bottom'. The upper plots show grand average ERD/ERS curves for channels PO4 and POz. Four good separable intervals were manually chosen and their averages illustrated as scalp topographies for each class. The bottom row shows the topography of the resulting class differences, depicted in terms of $sgn r^2$ -values. While in the 'Left vs. Right' condition separability is best at left and right occipital areas, in the 'Top vs. Bottom' case the central occipital electrodes provide more distinctive information.

with the locus of covert attention. Using the $sgn r^2$ -value as an indicator of class separability, attended locations can be discriminated in certain time intervals and electrode channels. Offline classification accuracy is currently under investigation, whereby we use separate classifiers for each target tuned to its particular temporal and spatial features.

In our opinion, the α -paradigm is an intriguing new landmark in the field of visual BCIs. So far, visual spellers operated exogenously. To be clear, BCIs based on steady-state visually evoked potentials (SSVEPs) or on ERPs elicited in an oddball paradigm rely on the modulation of externally triggered ERP components by means of selective attention. A BCI based on the α -paradigm, in contrast, is endogenous because it picks up an internally generated signal. In other words, the neural process of selective attention itself is being tapped. The difference between exogenous and endogenous generation of the components also has practical implications. Particularly during very long BCI sessions, continuous external stimulation can be unpleasant if not irritating for the user. Additionally, the endogenous generation of the control signal potentially allows for the development of an asynchronous

BCI, that is, a BCI wherein the pace of symbol selection is set by the user and not by the machine. An example of an asynchronous BCI application would be spatial navigation. In a shared control setting, high-level navigation commands (e.g., for a wheelchair) could be issued via attention shifts in the corresponding spatial direction. The actual execution of these commands would then be delegated to the machine which would break down the command into an actual movement sequence, taking into account hindering factors such as the presence of obstacles.

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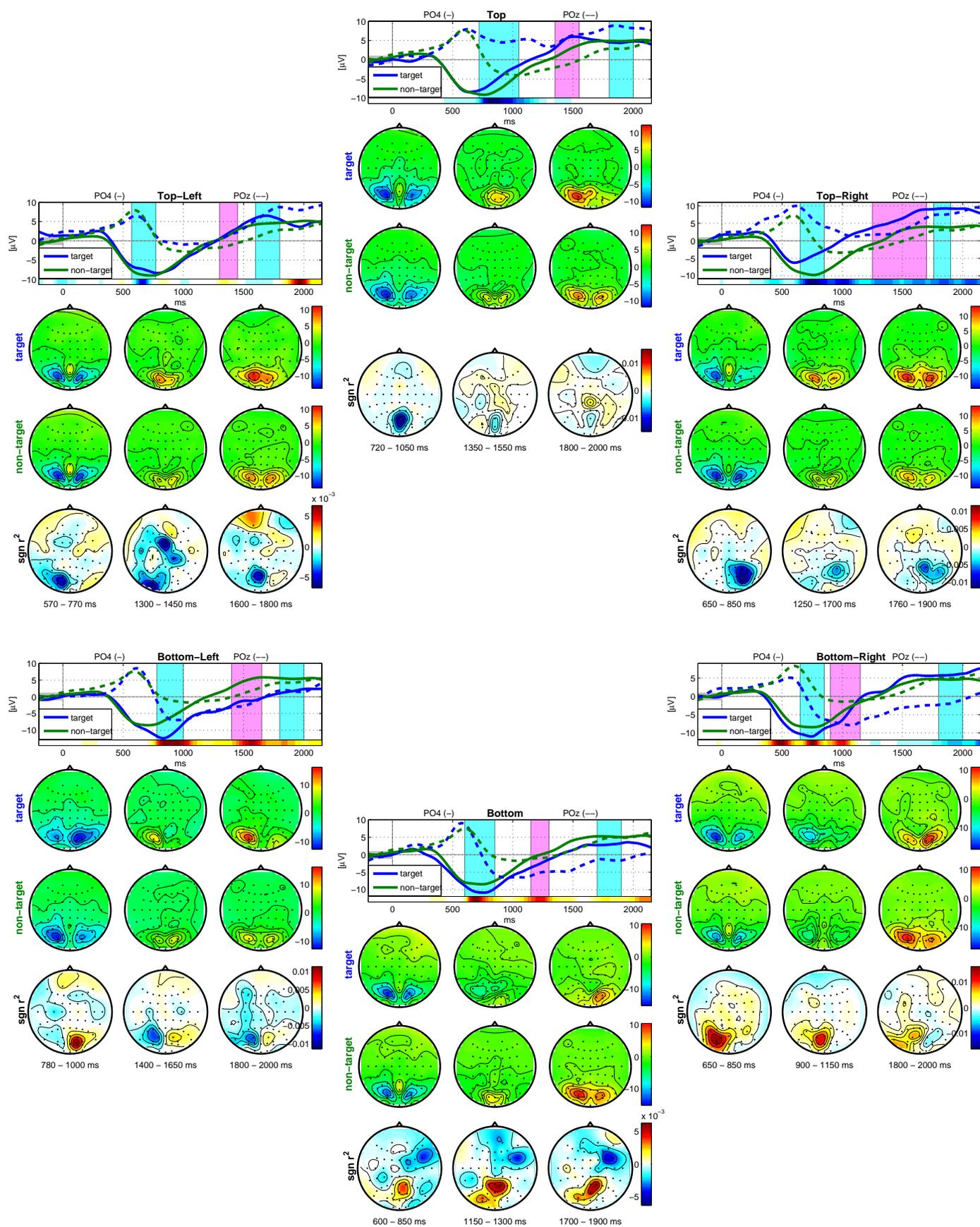


Fig. 5. ERD/ERS curves and scalp topographies for each single target location compared to all other classes. Early α -desynchronization and later synchronization vary with the locus of attention. For each target location, different intervals and different sets of channels are discriminative.