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Widespread cortical α -ERD accompanying visual oddball target stimuli is frequency but non-modality specific

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Abstract

Objective: Previous findings have shown that alpha event-related desynchronization (α -ERD) is associated with reaction to visual stimuli in oddball paradigm, as a reflection of attention allocation and memory updating. This study tested the hypotheses that it reflects a modality and/or frequency specific mechanism.

Methods: Electroencephalography (EEG) recordings (64 channels) were performed on 18 healthy subjects during visual, auditory, somatosensory, and pain oddball paradigms. Low- and high-frequency α rhythms were analyzed on individual basis, and their sources were estimated by low resolution brain electromagnetic tomography (LORETA). α -ERD, served as an index of cortical activation, was computed on the cortical voxel level and compared across the conditions (target vs. non-target), alpha sub-bands (lower vs. higher frequency), and modalities (visual, auditory, somatosensory, and pain).

Results: In the visual modality, α -ERD was mainly generated from occipital cortex for both target and non-target conditions. Its magnitude was enhanced across widespread cortical regions (e.g., bilateral occipital, parietal, and frontal areas) in the target condition and was greater in high-frequency α band. Finally, α -ERD difference between target and non-target conditions was not higher in visual than that in other control modalities.

Conclusions: Human high-frequency α -ERD reflects cognitive attention processes underlying reaction to oddball target stimuli regardless stimulus modality.

Introduction

The alpha oscillation suppression/enhancement, termed as alpha event-related desynchronization/synchronization (ERD/ERS), was observed during the presentation of controlled stimuli and specific cognitive tasks, and closely associated with cortical activation/inhibition related to stimulus processing or cognitive processing [1-13]. More recent evidence indicates that different frequency bands within the extended α frequency range reflect quite different cognitive functions [14-20]. Low-frequency α -ERD (8-10 Hz) appears to be associated with non-specific general attentional demands, such as alertness, arousal, and expectancy, whereas high-frequency α -ERD (10-12 Hz) is found to be related to task-specific attention processing.

In oddball paradigms involving both sensory stimulus and attentional cognitive task requirements, α -ERD was frequently reported [4, 20-24]. It has been shown that both auditory and visual target stimulus could induce greater α -ERD than non-target stimulus, suggesting that α -ERD reflects mental efforts related to intentional and voluntary attention process [23]. Our previous study also reported the close association between target stimulus induced α -ERD and P300 in auditory, visual, somatosensory, and pain modalities [4], further providing direct evidence for existence of α -ERD component underlying attention cognitive process to detect rare target stimuli from series of frequent non-target stimuli. However, it's still unclear whether such attention related α -ERD is different within the extended alpha frequency band or sensory modalities.

Thus, we hypothesized that the oddball related α -ERD relating to detect the rare target stimuli reflects frequency and modality specific attention processing. To test this hypothesis, by re-analyzing the Electroencephalography (EEG) data recorded in oddball paradigms, low- and high-frequency α rhythms were analyzed on individual basis, and their sources were estimated by low resolution brain electromagnetic tomography (LORETA). α -ERD, was computed on the cortical voxel level and compared across the conditions (target vs. non-target), α sub-bands (low- vs. high-frequency α band), and modalities (visual, auditory, somatosensory, and pain).

Methods

Eighteen right-handed healthy volunteers (nine males), aged from 19 to 29 years (21.8 ± 2.5 , mean \pm SD), took part in the experiment. Visual (center-filed presentation of ' \blacktriangle ' and ' \bullet '), auditory (auditory tones at 75 dB SPL at frequency of 500 Hz or 1000 Hz), somatosensory (square electric pulses through Electrocardiography [ECG] electrodes to the medial and lateral side of the left hand dorsum), and pain (noxious stimuli delivered through a stainless steel concentric bipolar needle electrode to the medial and lateral side of the left hand dorsum) modalities of stimuli were delivered in oddball paradigm with probabilities of non-target stimuli : target stimuli = 4 : 1. For each stimulus modality, EEG data were collected from two separated blocks, and types of non-target and target stimuli were reversed in the two blocks. Each block consisted of 200 stimuli with inter-stimulus interval (ISI) randomly between 2500 and 3000 ms. The subjects were required to respond as fast and accurate as possible to the predefined target stimuli by pressing the response button upon their appearance, using the right index finger. The order of the blocks was counterbalanced across subjects.

Continuous EEG was recorded from 64 Ag/AgCl electrodes using an electrode cap (Easy Cap Q40, FMS Falk Minow Services, Herrsching, Germany) according to the 10%-system (an extended montage of the standard 10–20% system). All electrodes were referenced to an electrode positioned at the left mastoid. Extracranial activity was continuously recorded using a Quick Amp EEG system (Brain Products GmbH, Munich, Germany) within a 0.01 and 100 Hz band-pass filter, and was digitized at a sampling rate of 500 Hz.

Continuous EEG data were low-pass filtered at 30 Hz. EEG epochs were segmented in 2000 ms time-windows (pre-stimulus 1000 ms and post-stimulus 1000 ms), and baseline corrected using the pre-stimulus time interval (pre-stimulus -800 to -200 ms). To rule out any statistical bias due to different size of trials in the two conditions, the same number of trials obtained in the target condition were randomly selected from the non-target condition for each subject and modality. Trials contaminated by eye-blinks and movements were corrected using independent component analysis (ICA).

The artifact-free EEG epochs of each subject were used as an input for EEG power spectrum analysis, which was performed by a standard FFT algorithm using Welch technique and Hanning windowing function. Individual alpha frequency (IAF) peak was defined as the frequency within the 6-13 Hz range of the EEG spectrum mean showing the maximum power. Then, the α sub-bands of interest were as follows: low-frequency α band as IAF-2 Hz to IAF and high-frequency α band as IAF to IAF+2 Hz.

Cortical sources of EEG rhythms were estimated using LORETA, which computes 3-D linear solutions (LORETA solutions) for the EEG inverse problem within a 3-shell spherical head model including scalp, skull, and brain compartments. The reference-free LORETA solutions of α rhythms were computed for both pre- and post- stimulus intervals separately. Then, cortical voxel level α -ERD was calculated according to the formula of $ER\% = (E - R)/R * 100$, where, E and R are the LORETA current density within the post- and pre- stimulus interval respectively. The

1 procedure was repeated for both low- and high-frequency α sub-bands. Percent negative values
2 represented the α -ERD, whereas percent positive values represented the α -ERS.
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4 Several cortical macro regions of interest (ROIs) were identified based on their close association
5 with visual attention, including occipital cortex (Brodmann area [BA] 17, 18, 19), left and right
6 parietal cortex (BA 5, 7, 39, 40), frontal eye fields (BA 8), and prefrontal cortex (BA 9). The
7 LORETA solutions of α -ERD were averaged across voxels of those identified cortical ROIs for
8 each condition (non-target and target) and sub-band (low- and high-frequency α band). Low- and
9 high-frequency visual α -ERD were compared between non-target and target conditions using two
10 paired t-test. To specifically extract attention related α -ERD relating to detect rare target stimuli,
11 the LORETA α -ERD specially accompanying rare target stimuli (i.e., α -ERD magnitude for target
12 stimuli minus α -ERD magnitude for non-target stimuli) was computed and obtained. Then, the
13 magnitudes of α -ERD accompanying visual target stimuli were compared between low- and
14 high-frequency α sub-bands with two paired t-tests to assess the frequency effect. As a control, to
15 assess the modality effect, the magnitudes of high-frequency α -ERD accompanying rare target
16 stimuli were compared across the modalities (visual, auditory, somatosensory, and pain) with
17 4-level (4 modalities) one-way repeated measure of Analysis of variance (ANOVA).
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25 **Results**

26 **Behavioral data**

27 The average values (\pm SEM) of reaction time to the target stimuli of different modalities were as
28 follows: Visual, 439 ± 9 ms; Auditory, 519 ± 18 ms; Somatosensory, 539 ± 21 ms; Pain, 586 ± 23
29 ms. Two paired t-tests revealed that the reaction time to the visual target stimuli was significantly
30 shorter than those to auditory, somatosensory, and pain target stimuli ($p < 0.05$, $p < 0.005$, $p < 0.001$,
31 respectively).
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37 **α -ERD**

38 Fig.1 shows the grand average of α -ERD at scalp level (upper panel) and cortical sources (lower
39 panel) for visual target and non-target stimuli. α -ERD is maximum in magnitude over posterior
40 scalp regions and underlying occipital-parietal cortical areas. Furthermore, it is noted that the
41 magnitude of α -ERD is greater at high- than low-frequency alpha as well as for target than
42 non-target stimuli.
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47 Fig.2 plots diagrams illustrating the comparison of the magnitude for cortical voxel level α -ERD
48 between visual non-target and target conditions. Compared to non-target condition, target
49 condition showed greater low-frequency α -ERD in bilateral occipital cortex, left and right parietal
50 cortex, frontal eye fields, and prefrontal cortex ($p < 0.05$ to 0.001). In the same line, target
51 condition showed greater high-frequency alpha ERD within those cortical ROIs ($p < 0.05$ to 0.001 ,
52 two paired t-test).
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56 Fig.3 shows diagrams illustrating the comparison of the magnitude for cortical voxel level low-
57 and high-frequency α -ERD accompanying visual target stimuli (i.e. α -ERD magnitude for target
58 stimuli minus α -ERD magnitude for non-target stimuli). Compared to low-frequency α -ERD,
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1 high-frequency α -ERD showed greater magnitude in bilateral occipital cortex, left and right
2 parietal cortex, frontal eye fields, and prefrontal cortex ($p < 0.05$ to 0.005 , two paired t-test).
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4 Fig.4 displays diagrams illustrating the comparison of the magnitude of cortical voxel level
5 high-frequency α -ERD accompanying rare target stimuli in visual, auditory, somatosensory, and
6 pain modalities. Compared to α -ERD in control modalities (auditory, somatosensory, and pain),
7 visual α -ERD did not show greater magnitude in bilateral occipital cortex, left and right parietal
8 cortex, frontal eye fields, and prefrontal cortex ($p > 0.1$, one way repeated measures of ANOVA).
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10 11 12 13 **Discussion**

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15 α -ERD, an index of cortical activation, could be induced by auditory, visual, and somatosensory
16 stimulus [8, 9, 13, 25], and also occurs in cognitive processing such as mental arithmetic, reading,
17 and task conditions engaging specific attention and memory processes [1, 2, 6, 11, 15, 17, 26-29].
18 Exactly, the oddball paradigm involves both sensory stimulus and task requirements, in which
19 low-probability target items are mixed with high-probability non-target items and the subjects
20 were required to respond to the infrequent target stimuli with button press and ignore the
21 non-target frequent stimuli. Here, both non-target and target oddball visual stimuli could induce
22 α -ERD maximally expressed at posterior-occipital regions (Fig. 1), despite differences in
23 probability and response requirements, suggesting the component of α -ERD reflecting transient
24 sensory stimulus processing.
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30 However, the attention load of task for target stimulus was different and greater than that for
31 non-target stimuli, because the subject must detect the infrequent target stimuli and make response
32 to it as soon as possible. The magnitude of α -ERD (both low- and high-frequency) for target
33 stimuli was obviously larger than that for non-target stimuli (Fig. 2) over widespread cortical areas,
34 including visual cortex (responsible for processing visual information [30]), left and right
35 posterior parietal (crucial region for visuo-spatial attention [31]), frontal eye fields (playing an
36 important role in visual attention and eye movements [32]), and prefrontal (store of short-term
37 memory [33]) cortical areas. It suggested that the enhanced α -ERD magnitude in the target
38 condition reflects more cortical fields to a greater degree than that expected for automatic
39 sensory-perception processing in the non-target condition.
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45 Since our previous study has shown the association between oddball related α -ERD in response to
46 target stimuli and P300 that only occurs if the subject is actively engaged in the task of detecting
47 the rare targets [34]. The target stimulus induced α -ERD component that is associated with P300,
48 should be an endogenous component and its occurrence does not link to the physical attributes of a
49 stimulus, but to a person's reaction to it. Thus, non-target stimuli induced α -ERD was mainly
50 about the automatic sensory stimulus processing, and target stimuli induced α -ERD reflects the
51 summary effects of stimulus and task-related processing of detecting infrequent target stimulus
52 among a series of frequent non-target stimulus. Thus, the difference of α -ERD between target and
53 non-target conditions, reflects attention cognitive processing for the task requirements.
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59 Even significant enhanced α -ERD accompanying target stimuli could be observed in both low- and
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1 high-frequency band, such difference was greater in high-frequency α band (Fig. 3), suggesting
2 the frequency effect on task-specific attention related α -ERD. Actually, previous studies have
3 shown that high-frequency α -ERD is selectively associated with specific task demands such as the
4 semantic processing of the imperative stimulus, whereas desynchronization in the low-frequency
5 band should be related to general alertness, attention or expectancy processes [3, 12, 14-16, 19,
6 20, 28]. In this sense, our current result hints that attention modulation of detecting infrequent
7 target stimulus among frequent non-target stimulus might support both global attentional
8 (low-frequency α rhythms) and task-specific (high-frequency α rhythms) processes, but such
9 modulation displayed frequency-specific effect, with greater effect in high-frequency α band.
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13 However, we did not observe significant difference across the modalities when comparing
14 high-frequency α -ERD accompanying target stimuli across the widespread cortical regions (Fig. 4).
15 It is quite possible that the amount of attention effort required in different modality oddball task in
16 the present study were not different, and it further suggests that high-frequency α -ERD relating to
17 detect infrequent target stimulus among frequent non-target stimulus, is non-modality specific
18 cognitive processing. Taken together, all these findings indicated that high-frequency α -ERD
19 reflects cognitive attention processes underlying reaction to target stimuli regardless stimulus
20 modality.
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Figure Legend

Fig. 1. Grand average scalp topographies and estimated cortical sources of α -ERD for visual target and non-target stimuli

Top panel: Group-level low- and high-frequency α -ERD scalp topography patterns for visual target and non-target stimuli. The color scale (ER%) stands for synchronization/desynchronization value of spectral power referenced to pre-stimulus interval within low- and high-frequency α sub-bands.

Bottom panel: Group-level low- and high-frequency α -ERD cortical sources estimated by LORETA. The color scale (ER%) stands for synchronization/desynchronization value of LORETA solutions referenced to pre-stimulus interval within low- and high-frequency α sub-bands. The left side of the maps (top view) corresponds to the left hemisphere. Legend: LORETA, low resolution brain electromagnetic tomography.

1 Fig. 2. Comparison of α -ERD magnitude between target and non-target conditions

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3 Mean regional LORETA solutions of low- and high-frequency α -ERD were compared between
4 non-target and target conditions, within cortical regions of bilateral occipital cortex, left and right
5 parietal cortex, frontal eye fields, and prefrontal cortex. Values are displayed in blue and red for
6 α -ERD magnitudes visual non-target and target stimuli respectively. Error bars represent, for each
7 condition, \pm SEM across subjects. Asterisk * indicates a significant difference of α -ERD
8 magnitude between non-target and target conditions ($p < 0.05$).
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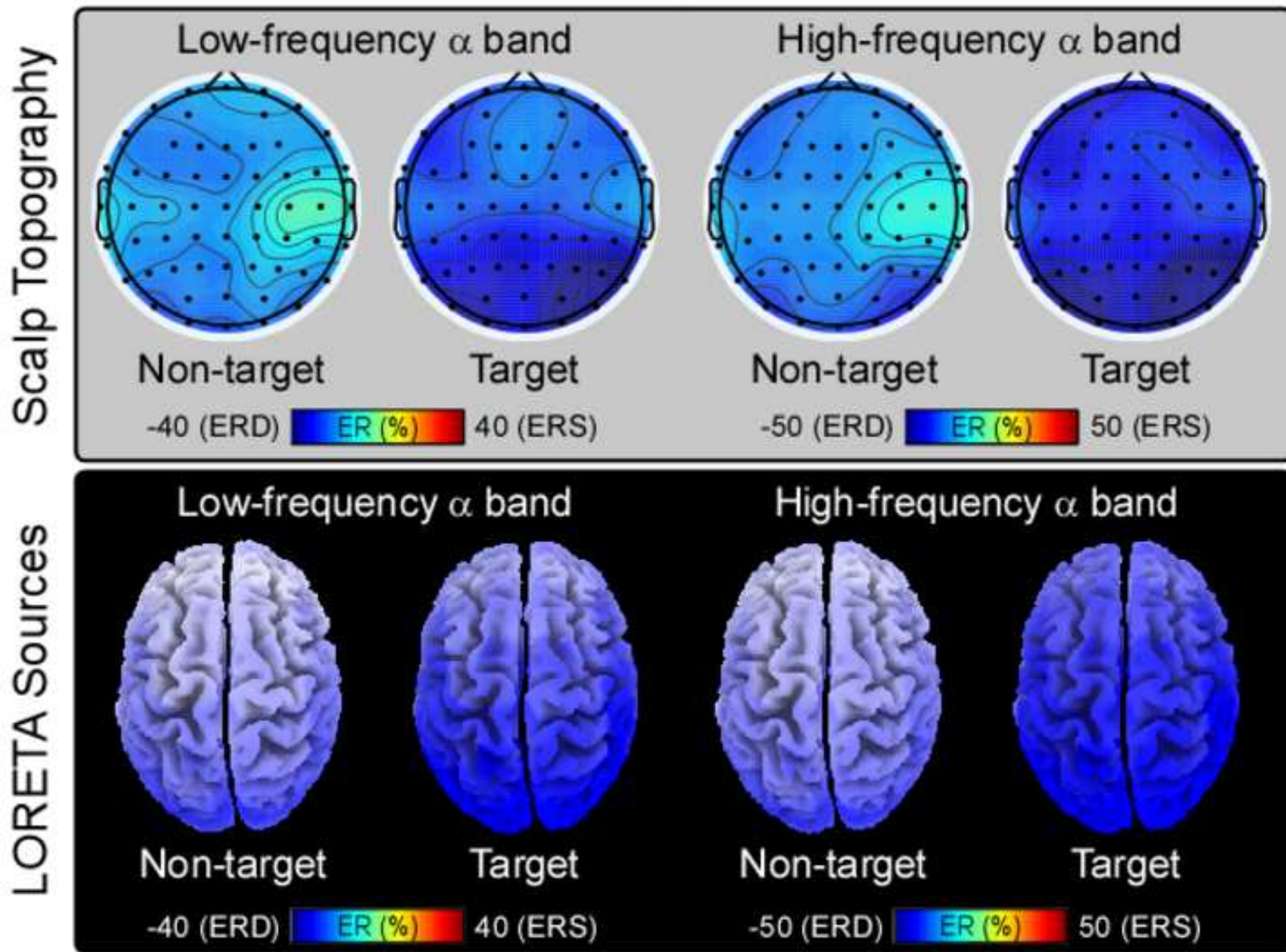
1 Fig. 3. Comparison of α -ERD magnitude between low- and high-frequency α band
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3 Mean regional LORETA solutions of α -ERD accompanying visual target stimuli (i.e., α -ERD
4 magnitude for target stimuli minus α -ERD magnitude for non-target stimuli) were compared
5 between low- and high-frequency α band, within those identified cortical ROIs. Values are
6 displayed in blue and red for low- and high-frequency α -ERD respectively. Error bars represent,
7 for each condition, \pm SEM across subjects. Asterisk * indicates a significant difference of α -ERD
8 magnitude between non-target and target conditions ($p < 0.05$).
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1 Fig. 4. Comparison of high-frequency α -ERD magnitude in visual, auditory, somatosensory, and
2 pain modalities
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4 Mean regional LORETA solutions of high-frequency α -ERD accompanying target stimuli were
5 compared across visual, auditory, somatosensory, and pain modalities, within those identified
6 cortical ROIs. Values are displayed in red, blue, yellow, and green for high-frequency α -ERD
7 from visual, auditory, somatosensory, and pain modalities.
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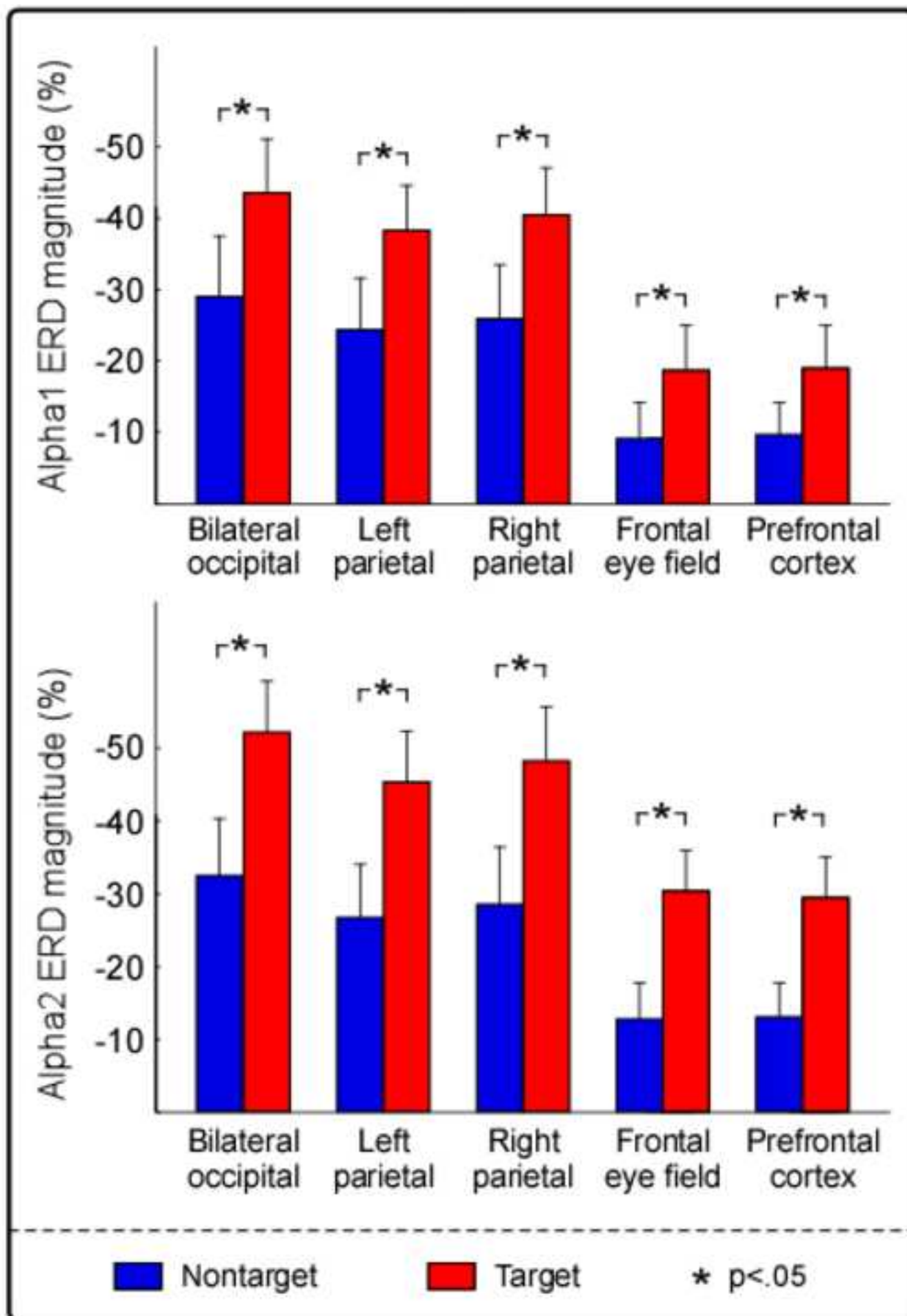
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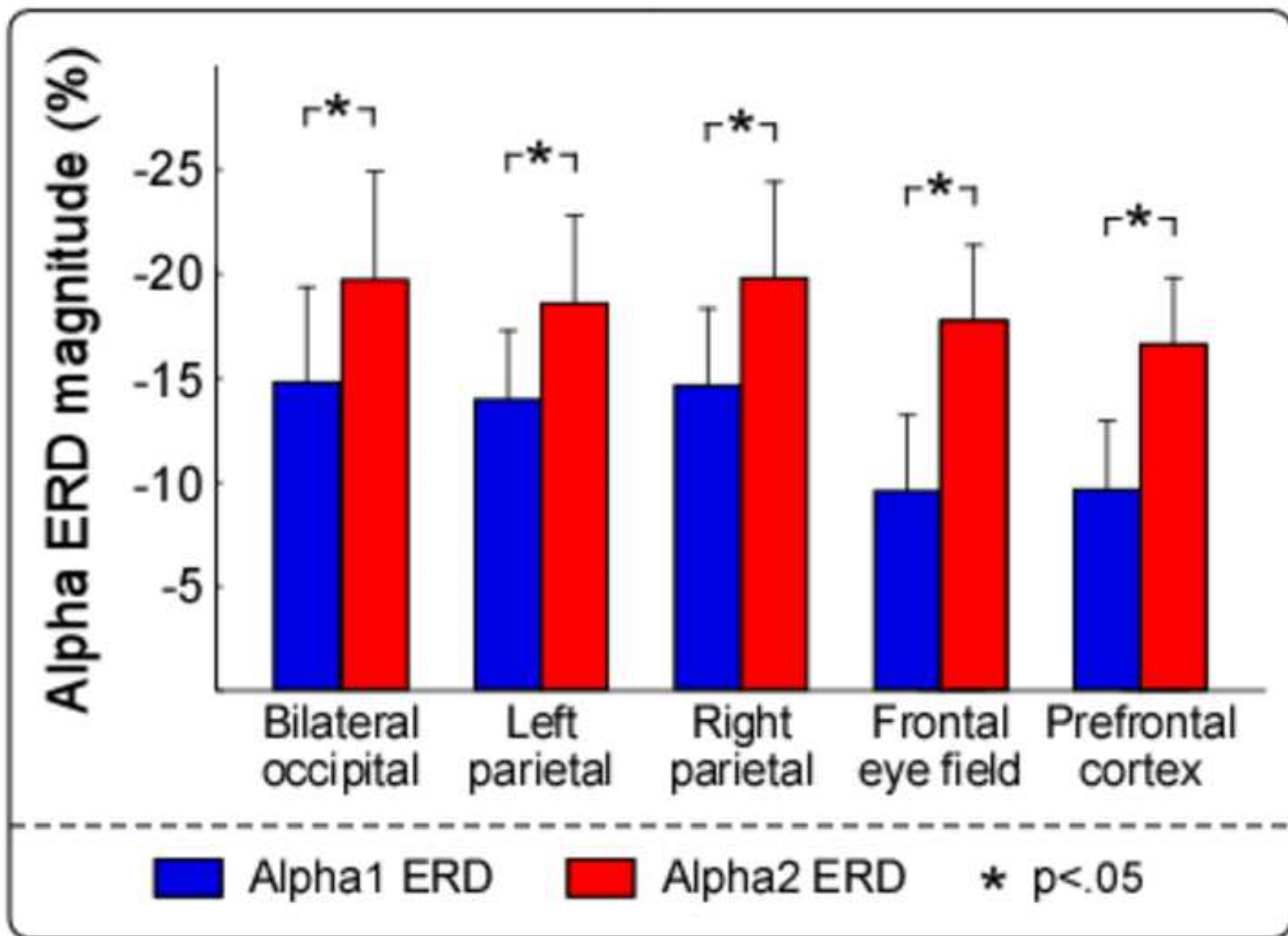
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