
Research Article: Negative Results | Cognition and Behavior

Long-range alpha-synchronisation as control signal for BCI: A feasibility study

<https://doi.org/10.1523/ENEURO.0203-22.2023>

Cite as: eNeuro 2023; 10.1523/ENEURO.0203-22.2023

Received: 25 May 2022

Revised: 15 December 2022

Accepted: 10 January 2023

This Early Release article has been peer-reviewed and accepted, but has not been through the composition and copyediting processes. The final version may differ slightly in style or formatting and will contain links to any extended data.

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1 **1. Manuscript Title (50 word maximum)**

2 Long-range alpha-synchronisation as control signal for BCI: A feasibility study.

3 **2. Abbreviated Title (50 character maximum)**

4 Alpha-synchronisation in BCI control

5 **3. List all Author Names and Affiliations in order as they would appear in**
6 **the published article**

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21 **6. Number of Figures:** 5

22 **7. Number of Tables:** 0

23 **8. Number of Multimedia:** 0

24 **9. Number of Extended Data Figures:** 6

25 **10. Number of words for Abstract:** 210

26 **11. Number of words for Significance Statement:** 112

27 **12. Number of words for Introduction:** 749

28 **13. Number of words for Discussion:** 2612

29 **14. Acknowledgements:** Authors report no acknowledgments

30 **15. Conflict of Interest:** Authors report no conflict of interest

31 **16. Funding sources:** This research was supported by AGAUR *Generalitat de*
32 *Catalunya* (2017 SGR 1545). This project has been co-funded with 50% by
33 the European Regional Development Fund under the framework of the

34
35

FEDER Operative Programme for Catalunya 2014-2020 Ministerio de Ciencia e Innovación (Ref: PID2019-108531GB-I00 AEI/FEDER).

1 **KEYWORDS**

2 Brain-Computer Interface; Alpha; EEG; Oscillations; Visuospatial Attention; Phase
3 Coupling.

4 **ABSTRACT**

5 Shifts in spatial attention are associated with variations in alpha-band (α , 8–14 Hz)
6 activity, specifically in inter-hemispheric imbalance. The underlying mechanism is
7 attributed to local α -synchronisation, which regulates local inhibition of neural
8 excitability, and fronto-parietal synchronisation reflecting long-range communication.
9 The direction-specific nature of this neural correlate brings forward its potential as a
10 control signal in brain-computer interfaces (BCI). In the present study, we explored
11 whether long-range α -synchronisation presents lateralised patterns dependent on
12 voluntary attention orienting and whether these neural patterns can be picked up at a
13 single-trial level to provide a control signal for active BCI. We collected
14 electroencephalography (EEG) data from a cohort of healthy adults ($n = 10$) while
15 performing a covert visuospatial attention (CVSA) task. The data shows a lateralised
16 pattern of α -band phase coupling between frontal and parieto-occipital regions after
17 target presentation, replicating previous findings. This pattern, however, was not
18 evident during the cue-to-target orienting interval, the ideal time window for BCI.
19 Furthermore, decoding the direction of attention trial-by-trial from cue-locked
20 synchronisation with support vector machines (SVM) was at chance-level. The present
21 findings suggest EEG may not be capable of detecting long-range α -synchronisation
22 in attentional orienting on a single-trial basis and, thus, highlight the limitations of this
23 metric as a reliable signal for BCI control.

24 **SIGNIFICANCE STATEMENT**

25 Cognitive neuroscience advances should ideally have a real-world impact, with an
26 obvious avenue for transference being BCI applications. The hope is to faithfully
27 translate user-generated brain endogenous states into control signals to actuate
28 devices. A paramount challenge for transfer is to move from group-level, multi-trial
29 average approaches to single-trial level. Here, we evaluated the feasibility of single-
30 trial estimation of phase synchrony across distant brain regions. Although many
31 studies link attention to long-range synchrony modulation, this metric has never been
32 used to control BCI. We present a first attempt of a synchrony-based BCI that, albeit
33 unsuccessful, should help break new ground to map endogenous attention shifts to
34 real-time control of brain-computer actuated systems.

35 **INTRODUCTION**

36 A few decades ago, imagining an interface between the human brain and a computer
37 was closer to science fiction than to scientific achievement. Nowadays, brain-computer
38 interfaces (BCIs) can read out brain activity, extract features from the signal in real-
39 time, and convert them into outputs for monitoring, controlling devices, or even
40 modifying cognitive states (Blankertz et al. 2016). One significant challenge of BCIs is
41 finding reliable control signals from brain activity with a sufficiently high signal-to-noise
42 ratio (SNR) at a trial-by-trial level to allow successful classification. Ideally, the
43 appearance of the target brain activity should depend on endogenous mental states
44 that a user can control at will. The use of non-invasive, cost-effective, and light-weight
45 neuroimaging devices can, in turn, facilitate transfer to real applications. For now, EEG
46 is the most viable candidate to achieve real-life BCI.

47 For example, some EEG-based BCIs have used motor imagery as a control signal
48 (e.g., imagined right/left-limb movement; Padfield et al. 2019), whereas others have
49 used neural correlates of covert visuospatial attention (CVSA) (van Gerven and
50 Jensen 2009; Treder et al. 2011; Tonin et al. 2013). Here, we will concentrate on the
51 latter. In human behaviour, CVSA is used to direct processing resources to relevant
52 locations in the environment whilst disengaging from irrelevant locations (Pashler
53 1999; Foster and Awh 2019). CVSA can be manipulated through a Posner cueing
54 protocol (Posner 1980), which shows a robust effect on behavioural performance:
55 higher accuracy and faster reaction times for targets appearing at the cued (attended)
56 location compared to targets appearing in un-cued, putatively unattended locations
57 (Posner 1980).

58 Shifts in CVSA are associated with changes in oscillatory activity in the alpha-band (α ,
59 8–14 Hz) at parieto-occipital regions (Klimesch 1999; Foster et al. 2017). Typically, α -
60 power shows an inter-hemispheric imbalance when attention is covertly oriented to
61 either the left or right visual field, revealing its potential as a control signal for BCI
62 implementations (Rihs et al. 2007; Thut et al. 2006, see Astrand et al. 2014b for a
63 review). Inter-hemispheric α -power imbalance corresponds to a late process in CSVA
64 shifts (van Diepen et al. 2019). First, cueing information is integrated through sensory
65 pathways in a bottom-up fashion, reaching higher visual areas in the parietal cortex
66 (e.g., intraparietal sulcus) and eventually frontal regions (e.g., frontal eye fields)
67 (Petersen and Posner 2012). From there on, top-down modulation shifts attention to
68 the corresponding hemifield, where it is maintained during target anticipation (Simpson
69 et al., 2012). The mechanism involved in this top-down modulation is thought to involve
70 long-range α -synchronisation between the frontal and posterior cortex, which
71 eventually leads to classical inter-hemispheric imbalances in α -power observed in the

72 visual cortex (Sauseng et al. 2005; Doesburg et al. 2009, Lobier et al. 2018). Long-
73 range synchronisation is a potential mechanism to increase the fidelity and
74 effectiveness of communication throughout the brain (Clayton et al. 2018) among
75 occipital, parietal, and frontal regions (Sadaghiani and Kleinschmidt 2016).
76 Synchronising excitability cycles between distant neural populations increases the
77 likelihood of spikes from one region discharging post-synaptic potentials during a
78 specific (excitable) phase of the other (Fries, 2015). Despite the evidence supporting
79 this model (Buschman and Miller., 2007; Cardin et al., 2009), there is still debate on
80 its temporal dynamics, lateralisation patterns and individual-level variability.

81 Despite the evidence of links between long-range α -synchronisation and behavioural
82 performance at group-level analyses (Sauseng et al. 2005; Doesburg et al. 2009;
83 Doesburg et al. 2016), BCI protocols based on endogenous attention orienting have
84 only used α -power as a control signal. In our study, we attempt to replicate a previously
85 demonstrated effect in attention orienting involving long-range α -synchronisation to
86 assess its feasibility in BCI paradigms. The original publication (Sauseng et al., 2005)
87 found significant increases in contralateral over ipsilateral connectivity around the time
88 of target appearance. We hypothesized that, if attention-driven connectivity emerged
89 in target-centered time windows, it may also be present in the cue-to-target interval,
90 where participants are putatively shifting attention towards the cued side. Further, this
91 cue-to-target time window would enable the use of long-range α -synchronisation in
92 BCIs based on purely endogenous brain signals. Therefore, we will test whether such
93 contra- and ipsilateral patterns in α -synchronisation emerge in single-trial dynamics
94 with sufficient signal strength to make them a reliable control signal. To do so, we used
95 an EEG dataset from a lateralised endogenous spatial attention task to replicate
96 group-level effects found by Sauseng et al. (2005), to explore the cue-to-target

97 interval, and to classify the direction of attention at the single-trial level using long-
98 range α -phase synchronisation as proof of concept for transference to BCI.

99 **MATERIALS AND METHODS**

100 **Participants**

101 We used data from a previous, unrelated study (Torralba et al 2016). The dataset
102 consisted of 15 participants (mean age = 22, SD = 3; 7 female). All participants
103 provided informed consent and had a normal or corrected-to-normal vision. The study
104 was ran in accordance with the Declaration of Helsinki and the experimental protocol
105 approved by the local ethics committee CEIC Parc de Salut Mar (Barcelona, Spain).

106 **Task**

107 Before the experimental session, the participant's EEG activity was recorded during a
108 five-minute recording at rest with eyes closed to extract the individual α frequency
109 (IAF) used in the analyses. In the experimental session, participants performed a
110 modified version of the Posner cueing task (see **Figure 1A**). The trial started with the
111 onset of a central fixation cross, placed between two placeholders located 20° of visual
112 angle left and right off-centre, vertically shifted 20° of visual angle below the fixation
113 cross (see **Figure 1A**). After 200 ms fixation period, a central auditory cue (100 ms
114 duration) indicated the likely target location through either high pitch (2000 Hz) or low
115 pitch (500 Hz) tones, the mapping was randomised across subjects. Participants
116 should covertly attend to the indicated side, without moving their eyes, during a jittered
117 inter-stimulus interval (ISI; 2000 ± 500 ms). The use of a jittered ISI was employed in
118 order to avoid participants using automatic temporal attention to solve the task. Next,

119 the target (a Gabor grating tilted 45° left or right, 50 ms duration) appeared briefly
120 inside one of the placeholders, with 75% validity regarding the cued location. The
121 grating contrast was adjusted individually, as described below. A noise pattern with an
122 equal overall luminance as the target was presented at the alternative placeholder,
123 with the exact timings as the target. Participants were asked first to indicate if they had
124 detected the target (yes/no detection) and, subsequently, the target's tilt (left/right
125 discrimination). Both answers were made by keypress, in an un-speeded fashion, and
126 with response mapping (top-bottom) orthogonal to the attention manipulation and
127 varied from trial to trial. A trial was considered correctly answered only when
128 participants both detected the stimulus and discriminated the hemifield in which it was
129 presented. An inter-trial interval of 1000 ms followed the response, and a new trial
130 began. Unless otherwise noted, the EEG analyses were done on validly cued trials
131 that responded correctly. On average, 289.9 ± 11.3 trials from each participant were
132 employed for the EEG analysis.

133 The Gabor gratings used as stimuli were 0.002 cycles per degree, with a size of 3.35° ,
134 embedded in white noise. The contrast was adjusted individually using a preliminary
135 threshold titration procedure in which thresholds for both sides (left and right) were
136 independently adjusted to a 70% detection rate when cued (in the attended location).
137 Stimuli were presented on a 21" CRT screen with a refresh rate of 100 Hz and a
138 resolution of 1024 x 768 pixels. The experiment was implemented in MATLAB R2015b
139 (MATLAB, RRID: SCR_001622) using the Psychophysics Toolbox (Psychophysics
140 Toolbox, RRID: SCR_002881).

141 **EEG recording and pre-processing**

142 EEG recordings were obtained from 64 Ag/AgCl electrodes positioned according to
143 the 10-10 system with AFz as ground and nose tip as reference. Impedance was kept
144 below 10 k Ω . The employed system was an active actiCHamp EEG amplifier from
145 Brain Products (Munich, Germany). The signal was sampled at 500 Hz and processed
146 in MATLAB 2020 and 2015 (MATLAB, RRID: SCR_001622) using custom functions
147 and the FieldTrip toolbox (FieldTrip, RRID: SCR_004849).

148 Manual artefact rejection was applied to discard trials where any EOG components
149 had an amplitude higher than 50 μ V. Defective channels were repaired using
150 neighbours calculated by triangulation and splines for interpolating channel data.
151 Then, the data was demeaned and notch filtered at 50 Hz to exclude line noise. Next,
152 fifth-order high-pass and sixteenth-order low-pass IIR Butterworth filters were
153 employed to limit the signal between 0.16 and 45 Hz (Sauseng et al. 2005). The
154 filtering was done forward and backwards (two-pass), which resulted in zero phase
155 lag.

156 **Time-frequency analysis**

157 We performed long-range synchronisation analyses in two time windows. The first was
158 time-locked to the target onset (target-locked) to replicate Sauseng et al. (2005)
159 methods and validate our analysis pipeline. The second was time-locked to the cue
160 onset (cue-locked) to estimate long-range α -phase synchronisation during covert
161 visuospatial attention shifts.

162 Following Sauseng et al. (2005), for the target-locked analysis, we used two windows
163 of 200 ms: a pre-target (-200 to 0 ms) and a post-target window (200 ms to 400 ms).
164 The latter excludes the interval 0 to 200 ms, most affected by the phase resetting effect
165 of target presentation. For the cue-locked analysis, we used the cue-to-target time
166 window between 500 ms and 1500 ms post-cue and divided it into five consecutive
167 and non-overlapping 200 ms windows. By analysing from 500 ms onwards we avoid
168 the event related potential (ERP) caused by cue presentation and allow endogenous
169 attention shift to build up, a process which takes a few hundreds of milliseconds (Foxye
170 and Snyder 2011). The cue-locked analysis period ends at 1500 ms, which was the
171 minimum possible duration of the cue-to-target interval (duration of 2000 ± 500 ms,
172 see methods). All epoched data was mirror-reflected to avoid edge artefacts (Cohen
173 2014) when performing the time-frequency analysis. Afterwards, data were trimmed,
174 and reflected edges were removed.

175 We computed the Fourier coefficients using 5-cycle Morlet wavelets (Grossmann and
176 Morlet 1984) with 16 logarithmically spaced frequencies ranging from 2.6 Hz to 42 Hz.
177 For the analysis aimed at replicating Sauseng's results, we only used wavelets within
178 the upper α -band (9.54 – 14.31 Hz) (Sauseng et al. 2005), whereas, for the exploratory
179 analysis, we used the whole frequency range (i.e., 2.6 – 42 Hz) to explore further long-
180 range α -phase synchronisation in other frequency bands beyond the IAF.

181 **Connectivity measures**

182 Three clusters of electrodes of interest (EOI) were defined for the connectivity
183 analyses, mimicking Sauseng et al., 2005: A fronto-medial (FM) EOI cluster (Fz, FC1,
184 FC2) and two symmetric posterior clusters located either at the parietal left (PL) region

185 (P3, PO3, PO1) or the parietal right (PR) region (P4, PO4, PO2). To infer connectivity
186 between each parietal EOI cluster and the FM location, we used Phase Locking Value
187 (PLV) (Lachaux et al. 1999). This metric reports the consistency of phase differences
188 between two locations across multiple trials and is not affected by power differences.
189 Mathematically, the PLV is expressed as the absolute value of the average complex
190 unit-length phase differences:

$$191 \quad PLV(x, y) = \left| \frac{1}{n} \sum_{k=1}^n e^{i(\varphi_x(k) - \varphi_y(k))} \right| \quad (1)$$

192 where n corresponds to the total number of trials indexed by k and φ_x, φ_y correspond
193 to the phases at electrodes x and y , respectively. PLV was calculated according to
194 equation (1) using the phases for every combination of individual electrode pairs of the
195 FM-PR and FM-PL networks. Then, these values were averaged, resulting in a time
196 series of PLV FM-PR and FM-PL networks for each of the frequencies of interest and
197 condition (*attended left* and *attended right*) trials. Subsequently, the PLV time series
198 were collapsed as either ipsilateral (FM-PL network and attend left; FM-PR and attend
199 right) or contralateral (FM-PR network and attend left; FM-PL and attend right).
200 Therefore, for each participant and frequency of interest, two time series of PLV were
201 obtained (contra- and ipsilateral PLV).

202 **Classification**

203 The trial classification was performed using support vector machines (SVM). We
204 selected FM-PR and FM-PL connectivity as input to the SVM. *Attended right* and
205 *attended left* labels for each trial were provided as ground truth for the algorithm. The
206 main goal of the classifier was to infer, on each trial, whether a participant was

207 attending on the left or right hemifield, based on the long-range α -phase
208 synchronisation in the left and right fronto-parietal networks. Note that PLV is
209 computed across trials, and SVM aims to classify on a single-trial basis, so PLV was
210 also calculated across time points (Cohen 2015). As a validation step, we repeated
211 the target-locked analysis employing this metric (i.e., cross-time PLV) before
212 proceeding with the cue-locked classification attempt.

213 We divided the cue-locked interval ranging from 500 to 1500 ms in bins of 200 ms,
214 yielding five values for FM-PR connectivity and five for FM-PL connectivity. The
215 resulting ten values were used as input to the SVM to perform the optimisation and
216 classification of the trials. Note that for the classification, we used the data from the
217 participant that achieved a significant difference in PLV values between parietal left
218 and right EOI clusters in all cue-to-target windows (P10). Trials were split into a training
219 (80%) and testing (20%) set of trials to avoid overfitting. Then, the training set was
220 subdivided into sub-training (80%) and validation sets (20%).

221 Our initial approach was to use a linear kernel for the classification. However, after
222 evaluating the option through cross-validation of the validation set and obtaining a
223 negative result (i.e., classification was not better than chance level), we decided to use
224 a Gaussian kernel (i.e., Radial Basis Function). In order to select the most suitable
225 and efficient values for classifying *attended left* and *attended right* trials from the
226 validation set, we optimised the parametric space of the SVM. This comprised margin
227 and gamma (γ) parameters, which were explored in logarithmic steps from 10^{-6} to 10^3
228 for both constants and every fold.

229 **Inter-hemispheric power imbalance analysis**

230 Besides calculating the long-range α -phase coupling, we also computed the inter-
231 hemispheric α -power imbalance at parietal regions, both at the individual and at group-
232 level, as a reality check. For this reality check, we used Thut et al., (2006) for guidance
233 to choose the electrodes of interest. First, we performed an independent component
234 analysis (ICA), during which 3 ± 1 components were discarded on average per
235 participant, based on a visual inspection, the components' topography, and time
236 course. The rejected components comprised both ocular and motor artifacts. Please
237 note that ICA was only performed for the power analysis, not for the connectivity
238 pipeline, in order to replicate the exact pre-processing as seen in Sauseng et al.,
239 (2005) and, importantly, because phase of electrophysiological recordings is affected
240 when ICA are rejected (Thatcher et al., 2020).

241 The frequency of interest used in lateralisation analyses was adjusted for each
242 participant depending on the individual α frequency (IAF) extracted from the five-
243 minute recording (eyes closed) previous to the experiment (see above). The IAF was
244 determined based on the presence of a single peak (i.e., a local maximum) within the
245 considered frequency band of interest (5-15 Hz) on the power spectrum density (PSD).
246 A spectrogram was extracted for each parieto-occipital electrode (P7, P5, P3, P1, Pz,
247 P2, P4, P6, P8, PO3, PO4, POz, PO9, PO10, O1, Oz, O2) using the Welch method
248 (segments of 1000 ms with a 10% overlap, a Hanning taper to avoid spectral leakage
249 and 0.25 Hz frequency resolution). The power spectrum was averaged across
250 electrodes for each participant and normalised by the mean power from 1 to 40 Hz
251 (Vigué-Guix et al., 2022).

252 To extract the α -power during the task, we selected the epoch from -1.5 to 3 s in cue-
253 locked trials by convolving the EEG signal with a set of complex Morlet wavelets
254 (Grossmann and Morlet 1984) of 5 cycles (n_c). The frequencies of the wavelets ranged
255 from $IAF \pm 1$ Hz, in 1 Hz steps. For instance, an IAF peak of 10 Hz would have a
256 bandwidth ranging from 8.33 Hz to 11.67 Hz. Power was extracted from two symmetric
257 regions of interest precisely in PR (P6, P8, PO4, O2) and PL locations (P5, P7, PO3,
258 O1) in order to replicate as closely as possible the original EOI electrodes used in Thut
259 et al., (2006). Power imbalance was computed according to the formula:

$$260 \quad \textit{Lateralization Index} = \frac{\alpha(\textit{PR EOI}) - \alpha(\textit{PL EOI})}{\textit{mean of } \alpha(\textit{PL+PR EOI})} \quad (2)$$

261 where α (PL EOI) and α (PR EOI) are the average of α -power over left and right
262 electrodes of interest, respectively. Equation (2) leads to smaller (negative) values
263 where α -activity is more prominent over the left hemisphere than the right (α (PL EOI)
264 $>$ α (PR EOI)) and to larger (positive) values for the opposite pattern (α (PL EOI) $<$
265 α (PR EOI)). According to theory and previous findings, values of LI reflecting attention
266 directed to the right hemifield should be larger than LI values reflecting leftward
267 directed attention.

268 Finally, we also checked whether there was any relationship between the α -power
269 imbalance and the contra-ipsi difference of PLV for each attended location. We
270 explored the correlations between α -lateralisation indexes and the effect in PLV
271 contra-ipsi differences at the pre-target (-200 to 0 ms) and post-target (200 to 400 ms)
272 windows using Pearson correlations.

273 **Statistical analyses**

274 A one-tailed nonparametric Monte Carlo permutation test was computed to determine
275 significant differences in PLV between networks for each attended location (Mostame
276 et al. 2019). For each participant, the *attended right* or *left* labels were randomly
277 assigned to trials, and surrogate PLVs were calculated from the resulting dataset. This
278 process was repeated 10,000 times (iterations) to create a null distribution of PLV
279 values. The obtained p-value corresponded to the proportion of surrogate iterations
280 with a contra-ipsi difference larger than the actual measured value (one-tailed test).
281 This process was performed on every time window defined in the previous section.
282 For the group analysis, the procedure was equivalent, but surrogate PLV distributions
283 were averaged across participants before the statistical test.

284 For the statistical assessment of the α -power imbalance over time between *attended*
285 *left* and *attended right* trials, we performed a cluster-based permutation test procedure
286 (100,000 randomisations) for each participant and at the group-level (one-tailed
287 permutation test) (Maris and Oostenveld 2007; Meyer et al. 2021). We assessed that
288 lateralisation indexes for *attended right* and *attended left* trials were two significantly
289 different distributions by applying a one-tailed t-test (independent samples) with α -
290 level = 0.05 for each participant. At group-level, we performed a one-tailed paired t-
291 test with the mean lateralisation indexes for *attended right* and *attended left* trials for
292 each participant with α -level = 0.05. Correlations between α -power imbalance and the
293 contra-ipsi difference of PLV were corrected for multiple comparisons by applying the
294 False Discovery Rate (FDR) of Benjamini and Hochberg (Benjamini and Hochberg
295 1995).

296 RESULTS

297 Behavioural results

298 Five participants who presented equivalent detection and discrimination rates for
299 stimuli appearing at cued and un-cued locations were discarded from the analysis,
300 leaving a total of 10 participants. As expected, behavioural results showed that the
301 detection rate calculated based on both the detection response (Yes/No) and the
302 discrimination response (Left/Right; chance level at 0.25) was superior for cued
303 (attended) trials $0.68 \pm \text{SEM}=0.02$ compared to un-cued (unattended) ones 0.46 ± 0.04
304 (see, **Figure 1B**). The pattern on each hemifield was equivalent: on the left hemifield
305 attended = 0.68 ± 0.03 and unattended = 0.47 ± 0.03 ; for the right hemifield attended
306 = 0.67 ± 0.03 , and unattended = 0.44 ± 0.06 . We used one tailed t-tests to assess that
307 performance was above chance level (25%) for each of the conditions (attended and
308 unattended) and hemifields separately: Attended Left trials (0.68 ± 0.11 , $p\text{-value}=2 \cdot 10^{-7}$,
309 $t(9)=12.593$), Attended Right trials (0.67 ± 0.11 , $p\text{-value}=3 \cdot 10^{-7}$, $t(9)=12.226$),
310 Unattended Left trials (0.47 ± 0.08 , $p\text{-value}=5 \cdot 10^{-6}$, $t(9)=8.876$) and Unattended Right
311 trials (0.44 ± 0.20 , $p\text{-value}=0.06$, $t(9)=3.117$).

312 Target-locked long-range α synchrony

313 Here, we describe the results from the target-locked analysis, carried out to reproduce
314 Sauseng et al.'s (2005) findings. Long-range synchrony was estimated using PLV
315 between frontal EOI and each of two lateralised parietal EOI. **Figure 2** shows the
316 group-level connectivity analysis of the upper α -band (9.54 - 14.31 Hz). Phase
317 coupling is depicted as the mean across the pre-target window (-200 to 0 s) and the

318 post-target window (200 to 400 ms), as well the temporal course (from to -500 to 500
319 ms). Regarding the left fronto-parietal network (**Figure 2A left**), PLV was consistently
320 higher when attention was directed rightward (contralateral) than leftward (ipsilateral)
321 in both pre-target and post-target windows, although the PLV difference only reached
322 significance in the post-target window ($p < 0.05$). Regarding the right network (**Figure**
323 **2A right**), PLV was stronger when attention was directed leftward (contralateral) than
324 rightward (ipsilateral) in the post-target window, whereas the pre-target window does
325 not show this difference. Neither window, however, emerged as significant. This
326 pattern generally replicates Sauseng et al. (2005) results, as indicated by the dashed
327 lines in **Figure 2A** representing the mean phase-coupling from their study. Lower
328 panels in **Figure 2A** display the temporal course of phase coupling to provide a time-
329 resolved illustration of the phase-coupling effect. For the *attended right* condition, PLV
330 values in the left network should be higher than PLV values for the *attended left*. The
331 inverse pattern should hold in the right network. Moreover, **Figure 2B** presents the
332 PLV with side of attention collapsed as contra- and ipsilateral with respect to the
333 corresponding network. Individual PLV values, marked as black dotted lines, exhibit
334 a consistent contra- to ipsilateral increase in the post-target window. Group-level
335 statistical analysis further showcased a significant difference limited to this time
336 window (200 to 400 ms, $p < 0.05$). This result was controlled by avoiding the pre-
337 processing band-pass filter which may affect phase estimation, and by computing a
338 Hjorth filter to avoid the effects of volume conduction (Hjorth 1975). Both analyses
339 maintained the significant differences between contralateral and ipsilateral PLV ($p <$
340 0.05).

341 At individual level, only 3 out of 10 participants showed significant contralateral PLV
342 increase (P02, $p < 0.01$; P05, $p < 0.01$; P07, $p < 0.01$; see **Figure 2-1**). The lack of a

343 significant group-level effects in the pre-target window is consistent with individual
344 phase coupling, as a multiple subject present a trend in the opposite direction as
345 expected (i.e., ipsilateral over contralateral PLV; see **Figure 2-1**). We further assessed
346 single-subject synchronization through the phase linearity measurement (PLM) as it
347 has been recently reported to be a robust metric for trial-level connectivity (Baselice
348 et al., 2018). We did not find any significant effects in any participant ($p > 0.05$; see
349 **Figure 2-2**).

350 **Cue-locked long-range α synchrony**

351 In the previous section, we replicated the results as in Sauseng et al., (2005). The
352 findings from here onwards correspond to original results to ascertain whether
353 attention-based long-range connectivity during the attention-orienting period could be
354 a reliable signal for BCI control. We explored the cue-to-target interval before target
355 presentation (500 ms to 1500 ms after cue onset). Considering that the cue indicates
356 the hemifield to which participants should voluntarily lateralise attention, differences in
357 contralateral and ipsilateral connectivity may potentially emerge in this time window.
358 So far, we have seen that attention shifts had significant consequences on behaviour
359 and target processing (post-target connectivity). At the group level, however, no
360 significant difference between contralateral and ipsilateral connectivity in the upper α -
361 band was found in any of the five 200 ms time windows considered in the cue-to-target
362 period (see **Figure 3A**). At the individual level, 7 participants had a significant
363 contralateral PLV increase in at least in one window (see **Figure 3-1**). However, only
364 one participant (P10) showed this effect in all time windows and, furthermore, did not
365 present a significantly higher contralateral connectivity in pre-target and post-target
366 time windows of the target-locked analysis.

367 We chose the upper α -band a priori given Sauseng et al. (2005)' findings, as well as
368 the effects in the target-locked analyses from the present dataset. However, we
369 conducted additional analyses to explore other frequencies (between 2.4 and 42 Hz)
370 in search of differences between contralateral and ipsilateral PLV (see, **Figure 3B**).
371 Values were collapsed as the difference between both measures (contra-ipsi) and z-
372 scored. Over time, neither clear trends across frequencies nor apparent increases
373 were observed in contralateral or ipsilateral connectivity. Individual results showed the
374 same trend and did not present relevant PLV patterns in any participant beyond those
375 from upper α -band findings in P10 (see **Figure 3-2**).

376 **Classification**

377 The results are hardly promising in generalising the use of long-range connectivity for
378 BCI control. However, BCI protocols are often very sensitive to individual patterns.
379 Here, we intended to seek a proof-of-concept, from at least a single participant. With
380 this goal in mind, we attempted single-trial classification, as either *attended right* or
381 *attended left*, according to cue-locked connectivity patterns. We selected the
382 participant (P10) for whom we found significant connectivity differences in the cue-to-
383 target time window of the cue-locked analysis. The total number of trials was 338.

384 We carried out a validation of cross-time PLV in the target-locked window to
385 understand whether this metric could replicate group-level differences between contra-
386 and ipsilateral networks found through cross-trial PLV. These results can be seen in
387 **Figure 4A**. Statistical analysis showed no significant differences between contra- and
388 ipsilateral scenarios in either time window. Individual values were also non-significant
389 (see **Figure 4-1**). Considering the large parametric landscape of SVM

390 implementations, we optimised the gamma and margin parameters of a Gaussian
391 kernel (see **Figure 4B**). From a qualitative perspective, no clear maximum validation
392 accuracy values emerge from the landscape, although quantitative analysis identified
393 minimum values of margin and γ to be used on the test set in every fold. The lack of a
394 clear minimum suggests that the model may be unable to classify individual trials
395 regardless of the parametric values.

396 Ten-fold cross-validation was carried out to maximise the available data and improve
397 the classification accuracy. Single trials predicted as either *attended right* or *attended*
398 *left* were contrasted with the actual cue direction in each trial. Classification outcomes
399 are shown in **Figure 4C**, which resulted in virtually chance-level sorting (0.541). The
400 confusion matrix displays the distribution of each class, revealing the skewed
401 distribution of values towards *attended right* labels, which is far from the ideal
402 clustering along the diagonal of the matrix. Finally, we employed two additional
403 algorithms to classify both *attended right* and *attended left* trials. These consisted of
404 shrinkage linear discriminant analysis (sLDA) and Riemannian minimum distance to
405 the mean (RMDM), as they are shown to work well in small training sets (Lotte et al.,
406 2018). Both decoding techniques yielded chance-level results (see **Figure 4-2**)

407 **Inter-hemispheric power imbalance**

408 As a reality check on the dataset, we addressed whether there was a difference in the
409 α -power inter-hemispheric imbalance between *attended left* and *attended right* trials.
410 We performed the cue-locked analysis at the group level, using the Lateralization
411 Index (LI) described by Thut et al. (2006) (see **Figure 5A**). On average, the
412 lateralisation index was significantly different between *attended right* and *attended left*

413 in the expected direction ($p < 0.01$, Cohen's $d = -0.8356$). At the individual level, 7 out
414 of the 10 participants showed a significant difference in lateralisation index between
415 the two attention conditions ($p < 0.05$; see **Figure 5-1**). We also performed a time-
416 resolved version of this analysis within the cue-to-target window. A cluster-based
417 permutation test (**Figure 5B**) showed significance within two time periods, from 0.66
418 to 0.82 s and 1.34 to 1.5 s. At the individual level, only for one participant (P01), the
419 cluster-based permutation test revealed a significant cluster over time from 0.6 to 1 s
420 (see **Figure 5-1**). These results are consistent with the results of previous studies (e.g.,
421 Tonin et al. 2012; Thut et al. 2006), at least at the group level. It is more challenging
422 to compare single-subject data with other studies, as it usually is not reported or
423 statistically analysed.

424 Finally, we explored the potential correlation between α -power inter-hemispheric
425 imbalance measured with the lateralization index and α -phase coupling for each
426 attended location (see **Figure 5 C-D**). In the pre-target window (**Figure 5C**), the
427 correlations for *attended right* ($r = -0.25$, $p > 0.05$) and *attended left* ($r = -0.13$, $p >$
428 0.05) did not reach significance. Neither did the correlations for *attended right* ($r = -$
429 0.44 , $p > 0.05$) and *attended left* ($r = -0.42$, $p > 0.05$) at the post-target (**Figure 5D**)
430 window. A visual inspection indicated that participants showing an effect in PLV
431 contra-ipsi differences are below the correlation fit in pre-target and post-target
432 windows, suggesting that those participants have a more negative effect in PLV
433 contra-ipsi differences.

434 **DISCUSSION**

435 The present study addressed the relationship between shifts in visuospatial attention
436 and the lateralisation of α -band coherence between frontal and parietal electrodes, to

437 assess their feasibility as a control signal in BCI. Previous studies, using group-
438 averaged multi-trial analyses, found increased long-range α -synchronisation in the
439 hemisphere contralateral to the attended hemifield, and suggested that it reflects top-
440 down mechanisms of visual spatial attention (Sauseng et al., 2005; Doesburg et al.,
441 2009). We reasoned that if contra- to ipsilateral differences in synchronisation would
442 emerge as a result of endogenous top-down mechanisms, they should be present
443 following cue presentation as participants shift their attention. This hypothesis stems
444 from how instructing participants to shift their attention laterally before target
445 appearance engages frontoparietal visual processing pathways (Corbetta and
446 Shulman 2002; Hopfinger et al. 2000; Asplund et al. 2010). Here, we sought proof that
447 long-range neural synchronisation engaged in this network could be used for BCI
448 control on a trial-by-trial basis.

449 In attention-orienting protocols, the cue-to-target period offers the possibility of
450 implementing a BCI control in anticipation of the target appearance. This would open
451 the possibility of designing active BCI systems controlled by the user's voluntary
452 decision to attend left/ rightward covertly. Therefore, our study employed long-range
453 α -synchronisation in the frontoparietal network (FPN) as means to investigate whether
454 this brain measure could potentially discriminate attended locations of the left/right
455 visual field.

456 We found significant group-level differences in contra- to ipsilateral long-range α -
457 synchronisation around target onset, replicating Sauseng et al. (2005). These results
458 demonstrate the involvement of lateralised long-range α -synchrony along the FPN
459 during the post-target period and especially reveal the potential of EEG to grasp these
460 effects, at the group level. However, similar differences in fronto-parietal synchrony

461 were not observed during the cue-to-target time window, which was the time of interest
462 for BCI purposes. We also extended the cue-locked analysis to other frequencies
463 outside the α -band, with equally negative results. Finally, given the high individual
464 variability of single-trial analysis outcomes, we attempted to classify the individual trials
465 of one selected participant for whom significant synchronisation differences following
466 cue presentation were found, as a benchmarking process. The results nevertheless
467 rendered chance-level classification. Below, we discuss how these results may be
468 influenced by various methodological aspects (e.g., different time windows, classifier's
469 input metric) and how they fit into state-of-the-art literature. Please note that because
470 the focus of our study was on single-trial analysis, the sample size was relatively small
471 for the group analyses ($n = 10$). Although this sample size was sufficient to confirm
472 previous findings on long-range α -synchronisation and lateralization index (Sauseng
473 et al., 2005; Thut et al., 2006), the negative results of the group analyses should be
474 interpreted with caution.

475 **Fronto-parietal network synchronisation characterises**

476 **visuospatial attention**

477 A result from our study is that long-range α -synchronisation within the FPN was
478 associated with the consequences of visuospatial attention orienting, in line with its
479 putative role in this cognitive process (Jensen et al. 2015; Sacchet et al. 2015;
480 Doesburg et al. 2009; Siegel et al. 2008). We observed significant increase in
481 contralateral vs. ipsilateral upper α coherence for targets appearing at the attended
482 location. According to the current attention theories, the mechanism underlying this
483 finding may be inherently related to top-down processing. More specifically, frontal

484 regions such as the frontal eye fields (FEF) and the intraparietal sulcus (IPS) may
485 modulate attention by causing a state of α -band desynchronisation in the visual cortex
486 contralateral to attended hemifield (Corbetta and Shulman 2002; Kastner and
487 Ungerleider 2000; Helfrich et al. 2018; Capotosto et al. 2009; Marshall et al. 2015).
488 This explanation further aligns with the well-established evidence that contralateral α -
489 power suppression (also reproduced in our results) enables visual stimuli processing
490 in the attended location (Doesburg et al. 2009; Thut et al. 2006; Yamagishi et al. 2003;
491 Babiloni et al. 2006; Foxe and Snyder 2011; Klimesch et al. 2007; Lange et al. 2013),
492 and that cyclic phase-dependent inhibition in low-level visual cortex dictates
493 behavioural performance (i.e., reaction times) (Haegens et al. 2011; Klimesch 2012;
494 Jensen et al. 2014; Samaha et al. 2015; VanRullen 2016). Both accounts fit with the
495 idea that local α -power and long-range α -synchronisation may have separate roles in
496 attention and perception (Bonfond et al. 2017; Palva and Palva 2007, 2011;
497 Sadaghiani and Kleinschmidt 2016).

498 Our results of the increased contralateral synchronisation within the FPN replicate the
499 work of Sauseng et al. (2005) and validate our methodology and analysis pipeline
500 (e.g., time-frequency analysis, synchronisation metric), setting the ground for the
501 intended proof of concept test regarding transference to BCI. However, lateralised
502 fronto-parietal connectivity patterns in attentional and perceptual disposition remain
503 challenged in the literature together with the role of α power/phase (Ruzzoli, Torralba
504 et al. 2019; van Diepen et al. 2019; Antonov et al. 2020; Keitel et al., 2022). Lobier et
505 al. (2018) found that α -synchronisation was associated with visuospatial attention but
506 revealed distinct lateralisation patterns regarding the visual system and top-down
507 attentional networks. They showed stronger ipsilateral synchronisation within the
508 visual system (in line with Siegel et al. 2008; Doesburg et al. 2009) but no consistent

509 lateralisation in long-range networks, suggesting their different involvement in
510 visuospatial attention. A study by D'Andrea et al. (2019) found a modulation of
511 frontoparietal α - β cross-frequency synchronisation during attention orienting, but not
512 in α -synchronisation alone. Further, this cross-frequency connectivity pattern was
513 strongly associated with right hemisphere frontal dominance, in line with Heilman and
514 van den Abell (1980) and Zago et al. (2017). This finding agrees with previous
515 evidence of the crucial role of the right FEF in top-down attentional modulation
516 (Esterman et al. 2015; Hung et al. 2011; Silvanto et al. 2006; Veniero et al., 2021),
517 supported by evidence using TMS (e.g., Capotosto et al. 2009). In light of this evidence
518 and our results, the exact relationship between contralateral frontoparietal α -
519 synchronisation and shifts in attention orienting is still unclear. Positive findings,
520 however, such as the ones in the present study using a target-locked analysis,
521 represent a basis for exploring earlier time windows capable of shedding light on the
522 mechanism underlying FPN α -synchronisation.

523 Correlations between long-range α -synchronisation and individual reaction times in
524 visuospatial tasks suggest this neural correlate may be observable at a single-subject
525 level (Lobier et al., 2018). However, significant group-level target-locked dynamics of
526 increased synchrony did not transfer to all individuals in our study. The observed
527 variability may be partially explained by individual anatomical differences in the neural
528 substrate of attention (e.g., superior longitudinal fasciculus) (Marshall et al., 2015).
529 Findings employing magnetic resonance imaging (MRI) suggest that volumetric
530 differences in these structures impact local visual cortex oscillations, leading to
531 variability in EEG traces (Marshall et al. 2015; D'Andrea et al. 2019). However, this
532 variability of individual results is challenging to set in the perspective of previous
533 research simply because published studies do not report single-subject statistics.

534 Ultimately, the outcomes of this study leave an incomplete understanding of whether
535 there is a reliable group effect that does not extend to all individuals or, contrarily,
536 whether individual effects of specific participants are large enough to induce a group-
537 level finding in previous research.

538 **Lateralized patterns of α -synchronisation appear in target-** 539 **locked but not cue-locked analysis**

540 In our study, long-range α -synchronisation presented contralateral increases at the
541 post-target (200 to 400 ms, with $t = 0$ as target appearance) and the pre-target window
542 (-200 to 0 ms), but only the former time window resulted significantly. This result is
543 slightly different from Sauseng et al. (2005), who observed significant increases in
544 contralateral synchronisation within the FPN network at both time windows. However,
545 the numerical differences were in the same direction in both studies, leaving the
546 possibility that statistical significance be just due to a lack of statistical power. Another
547 potential explanation for the absence of significant findings at the pre-target window
548 may be the difference in experimental paradigms. The task employed here had a
549 longer post-cue interval ranging from 2000 to 2500 ms (jittered between trials),
550 compared to Sauseng et al. (2005) (i.e., 600-800 ms). If participants shifted attention
551 at varying times from cue onset up to target appearance, this might explain why we
552 could not capture the effect in anticipatory visuospatial attention.

553 In cueing paradigms, bottom-up integration of cue information through sensory
554 pathways precedes top-down modulation of visuospatial attention (Simpson et al.,
555 2011). The temporal course of voluntary directed attention is thought to begin only
556 after 150 ms from cue onset and involves frontal regions approximately after 350 ms.

557 Furthermore, from 400-500 ms onwards, frontal and parietal regions are thought to be
558 involved in attentional shifting and target discrimination (Simpson et al. 2011). Thus, if
559 the FPN does present direction-specific synchronisation, we anticipated this would
560 appear from about 500 ms after cue onset onwards. Contrary to what we expected,
561 we did not observe any significant contra- to ipsilateral differences in the cue-to-target
562 time windows (500 to 1500 ms after cue onset). Previous studies employing a similar
563 time window showed lateralisation patterns in parietal regions in α and β bands (Siegel
564 et al. 2008; Pantazis et al. 2009) and frontoparietal lateralisation in low and high-
565 frequency bands (Green and McDonald 2008; Gregoriou et al. 2009). Therefore, we
566 extended our cue-locked analysis to other frequencies but again obtained no
567 significant contra- to ipsilateral differences. Note that PLV values were averaged
568 across 200 ms windows, and this excludes, to a certain extent, the confound of frontal
569 and parietal regions having different activation over time. Altogether, despite the
570 evidence across multiple frequencies of synchronisation in the cue-to-target time
571 window, we did not find patterns of lateralised cue-locked connectivity within or outside
572 the α -band.

573 Our negative results in the cue-locked analysis may align with the notion that late
574 periods after cue onset are associated with direction-specific activity in parieto-
575 occipital regions but not in frontal regions (e.g., FEF) (Doesburg et al. 2009; Simpson
576 et al. 2011). Long-range α -synchronisation may, therefore, be associated to an initial
577 shift of attention (shortly after cue presentation) and later (close to target presentation)
578 to attention maintenance at the directed hemifield (Lobier et al. 2018; Kastner and
579 Ungerleider 2000; Hopfinger et al. 2000; Grent-'t-Jong and Woldorff 2007). This idea
580 resonates with the essential question formerly posed by Sauseng et al. (2005),
581 debating whether frontal involvement in long-range α -synchronisation is a causative

582 or consequential correlate of posterior activation. Furthermore, it motivated the
583 exploration of cue-locked intervals where bottom-up and top-down processing may
584 have elicited stronger effects on α -band synchronisation.

585 Finally, to ensure participants correctly lateralised their attention during the cue-to-
586 target interval, we carried out a reality check by calculating the α -power imbalance
587 using the lateralisation index during this period (Thut et al. 2006). There was a clear
588 difference in the averaged lateralisation index during the time course between 500 and
589 1500 ms at group-level. We further employed the lateralisation index to perform an
590 exploratory analysis of its relationship with the difference in α -synchronisation between
591 contra- and ipsilateral networks. Considering lateralised local α activity and lateralised
592 long-range α -synchronisation are both relevant in successful attention orienting, we
593 explored whether these two mechanisms would have had a significant positive
594 correlation. Therefore, individuals with high lateralisation index values should also
595 present lateralised synchronisation within the FPN. In contrast to our expectations,
596 there was no significant correlation between these two metrics, neither at the pre-
597 target nor the post-target time windows.

598 Ultimately, we did not observe a significant increase in contralateral long-range α -
599 synchronisation in the five 200 ms bins following cue onset. This time frame offered
600 potential as it occurs much before target appearance and could be robustly employed
601 in a covert visuospatial BCI decoder. By expanding our analysis to several frequencies
602 and carrying out the aforementioned reality checks, we conclude that PLV measured
603 from EEG may not serve as a reliable metric in capturing direction-specific
604 synchronisation from frontal to posterior regions, despite this evidence being present
605 in parietal to occipital synchrony (Doesburg et al. 2009).

606 **EEG estimates of long-range α -synchronisation may not**
607 **serve as a reliable control signal for BCI**

608 The use of long-range α -synchronisation to decode attentional direction yielded
609 chance-level results. We employed 200 ms time bins of contralateral and ipsilateral
610 FPN connectivity as input in an SVM classifier. Non-linear SVMs are widely employed
611 in decoding cognitive neural correlates of behavioural states (Lotte et al., 2007).
612 Furthermore, SVMs outperform other classifiers, such as artificial neural networks,
613 non-linear Bayesian estimators, and recurrent reservoir networks (Astrand et al.
614 2014a). We also employed sLDA and RMDM classifiers, as they have low
615 computational cost, require small training sets, and perform well in real-time
616 applications (Lotte et al., 2018), with no success.

617 Prior work using SVMs, mainly centred around primate models and invasive
618 recordings, successfully decoded the attentional spotlight from frontal sites (Gaillard
619 et al. 2020; Tremblay et al. 2015; Esghaei and Daliri 2014). Clearly, these methods
620 (i.e., LFP, intracranial-EEG) have a higher signal-to-noise ratio (SNR) compared to
621 non-invasive imaging. However, the objective of the present study was to offer a BCI
622 proof of concept using α -synchronisation as a control signal. Therefore, a non-invasive
623 and portable technique must be employed. Other non-invasive modalities such as
624 functional magnetic resonance imaging (fMRI), where the temporal resolution is too
625 low for real-time implementations, or magnetoencephalography (MEG), where the
626 equipment is expensive and requires a magnetically shielded room (as fMRI), have
627 limited potential transfer in out-of-lab applications. Contrarily, EEG is an affordable
628 imaging modality with a straightforward setup which provides high temporal resolution
629 and portability. However, the inconvenience of using EEG is a low spatial resolution

630 and a low SNR. Despite this, decoders have been commonly employed in EEG-BCI
631 design employing parieto-occipital power changes in α -band activity to predict covert
632 visuospatial attention tasks (Tonin et al. 2013; Treder et al. 2011; van Gerven et al.,
633 2009). The integrated approach between frontal and parieto-occipital attentional
634 decoding based on α -synchronisation, however, has not been attempted. Here, we
635 found that cue-locked synchronisation enclosed in the FPN α -band is insufficient to
636 determine the attentional location at EEG single trial level. This may be due to an
637 inherent lack of connectivity in the cue-to-target interval, or else more likely, the poor
638 sensitivity of the EEG to register synchronisation patterns.

639 Another potential reason to explain the failed classification of cue-locked FPN
640 connectivity at single-trial level may be the change in PLV calculation from trial-
641 average to single-trial. Standard cognitive research employs multiple trials to estimate
642 consistent findings on electrophysiological markers (M/EEG). Instead, BCIs need
643 robust and accurate estimates in a single-trial fashion and thus require a trade-off
644 between spatial (i.e., single-channel decoding is preferred) and temporal resolution.
645 PLV is a measure of consistency across multiple trials and cannot serve as a single-
646 trial control signal. Therefore, we computed PLV across time points within the same
647 trial. This new measure is also referred to in the literature as the inter-site phase
648 clustering (ISPC) and may represent a different underlying process than that captured
649 by classic PLV (Cohen 2015). This prompts the question of whether long-range α -
650 synchronisation is incapable of decoding the attended location, or rather the single-
651 trial nature of IPSC over time is responsible for this.

652 In sum, long-range α -synchronisation within the FPN estimated with EEG may not
653 serve as a control signal for BCI. This limitation may be due to incomplete information

654 on neural correlates due to the lack of cross-frequency analysis or the computational
655 techniques surrounding ISPC over time.

656 **CONCLUSION**

657 We found direction-specific contralateral patterns of upper α -synchronisation (i.e.,
658 PLV) within the FPN following target appearance in a covert visuospatial task. This
659 finding, however, did not extend to pre-target or cue-to-target time windows. The
660 modulatory role of α -synchronisation in anticipatory attention through frontal, parietal
661 and occipital regions suggests that PLV may not constitute a reliable metric for this
662 top-down visual processing. Furthermore, chance-level classification resulting from
663 using this metric in an SVM indicates that long-range α -synchronisation computed with
664 EEG may not be a suitable control signal for BCI.

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- 947

948 **LEGENDS**

949 **Figure 1. Experimental design and response rates. (A) Schematic trial**
950 **representation.** A black fixation cross in the middle of the screen and two squares
951 (to-be-attended locations) at the bottom left, and bottom right positions were displayed
952 continuously. At the beginning of each trial, participants were instructed to gaze at the
953 fixation cross. After 200 ms (fixation period), an auditory cue appeared for 100 ms (cue
954 period) indicating which hemifields participants must attend (75% validity). After a
955 jittered interstimulus interval of 2000 ± 500 ms, a target appeared at the targeted
956 location during 50 ms (target period). Participants had to report first if they had seen
957 the target (detection task), and after 1000 ms, the location of the target (left/right
958 discrimination task) during 1500 ms. An intertrial interval (ITI) of 1000 ms followed,
959 and a new trial began (Adapted from Torralba et al. 2016). **(B) Response rates for**
960 **detected and discriminated trials (HITS) related to attended and unattended**
961 **trials.** Black lines over violin plots represent the mean value. Both overall performance
962 (top) and right/left hemifields (bottom) are shown. White dots indicate individual values
963 (adapted from Torralba et al. 2016).

964 **Figure 2. Target-locked results. (A) Target-locked results of the phase-coupling**
965 **for *attended left* (light blue) and *attended right* (dark blue) in FM-PL and FM-PR**
966 **networks.** The lower panels depict the cross-trial average time course (\pm shaded
967 SEM) of PLV in both conditions (*attended left* and *attended right*). Upper panels
968 present the binned violin plots (mean and median) of the pre-target window (-200 to 0
969 ms) and the post-target window (200 to 400 ms); * $p < 0.05$. **(B) Target-locked results**
970 **collapsed as either ipsilateral (FM-PL network and *attended left*; FM-PR and**
971 ***attended right*) or contralateral (FM-PR network and *attended left*; FM-PL and**

972 **attended right**). The lower panel shows the cross-trial average time course (\pm shaded
973 SEM) of PLV in ipsilateral (light grey) and contralateral (dark grey) conditions. The
974 upper panel exhibits the distribution of individual PLV with a violin plot, superimposed
975 by the mean and the contra- to ipsilateral differences between individual PLV; $*p <$
976 0.05. Individual results with PLV are found in Figure 2-1, and those with PLM are found
977 in Figure 2-2.

978 **Figure 3. Cue-locked results. (A) Group-level results of upper-alpha PLV.** Upper
979 panel shows phase coupling for ipsilateral (light grey) and contralateral (dark grey)
980 sides in time-windows of 200 ms from the cue-locked interval (500 ms to 1500 ms after
981 cue presentation). Lower panel shows mean and standard error of the mean (SEM) of
982 the PLV values. Individual results are shown in Figure 3-1. **(B) Exploratory analysis**
983 **of PLV differences.** Group-level temporal evolution of the z-scored difference
984 between contralateral and ipsilateral PLV for each frequency band (2.4 - 42 Hz with
985 16 logarithmic steps). Z-score values range from -0.03 to 0.03. Individual results are
986 shown in Figure 3-2.

987 **Figure 4. Classification outcomes. (A) Cross-time PLV reality check.** Replication
988 of results from Fig. 2 calculating PLV across time points rather than across trials.
989 Individual results are shown in Figure 4-1. **(B) Optimisation results of gamma and**
990 **margin parameters of the Gaussian kernel SVM.** Ten-fold validation accuracies with
991 varying margin values (x-axis) and gamma values (y-axis). Inset shows a detailed view
992 of the z-axis. **(C) Confusion matrix of the classification outcomes for one**
993 **participant.** Y-axis represents ground truth labels (*attended right* or *attended left*) and
994 x-axis represents the classifier's outcomes. Percentages represent the fraction of
995 correctly classified trials of each condition (i.e., each row sums to 100%). Under the

996 percentage is the gross number of classified trials. Results with additional classifiers
997 such as sLDA and RDMD are shown in Figure 4-2.

998 **Figure 5. Lateralisation index reality check. (A) Averaged lateralization index for**
999 ***attended left* (light blue) and *attended right* (dark blue; * $p < 0.05$; ** $p < 0.01$).**
1000 White dots denote individual scores, and horizontal line indicates the group mean. **(B)**
1001 **Lateralisation index (mean \pm SEM) over time.** Solid lines and shaded areas
1002 represent mean and standard error of the mean (SEM) interval, respectively. Dots on
1003 in the x-axis denote the significant difference over time between *attended left* (light
1004 blue) and *attended right* (dark blue) via cluster-based permutation test. Individual
1005 results are shown in Figure 5-1. **(C-D) Lateralisation indexes and the difference of**
1006 **contra- to ipsilateral PLV for *attended left* (light blue) and *attended right* (dark**
1007 **blue) at the pre-target window (C) and the post-target window (D).** At the pre-
1008 target the correlations for *attended right* ($r = -0.33$, $p > 0.05$) and *attended left* ($r = -$
1009 0.19 , $p > 0.05$) did not reach significance and neither did the correlations for *attended*
1010 *right* ($r = -0.38$, $p > 0.05$) and *attended left* ($r = -0.46$, $p > 0.05$) at the post-target window.
1011 Crosses denote participants with a significant effect in PLV contra-ipsi differences at
1012 the pre-target window (-200 to 0 ms; P05) and the post-target window (200 to 400 ms;
1013 P02 and P07). Dots represent the rest of the participants.

1014 EXTENDED FIGURE LEGENDS

1015 **Figure 2-1. Individual results of target-locked PLV index.** Violin plots represent the
1016 phase locking values (PLV) averaged over the pre-target (-200 to 0 ms, $t = 0$ as target
1017 appearance) and post-target time window (200 to 400 ms). Ipsilateral (FM-PL network
1018 and *attended left*; FM-PR and *attended right*) or contralateral (FM-PR network and
1019 *attended left*; FM-PL and *attended right*) scenarios are exhibited as either light grey or
1020 dark grey, respectively. $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

1021 **Figure 2-2. Individual results of target-locked PLM index.** Violin plots represent the
1022 phase linearity measurement (PLM) over the pre-target (-200 to 0 ms, $t = 0$ as target
1023 appearance) and post-target time window (200 to 400 ms). Ipsilateral (FM-PL network
1024 and *attended left*; FM-PR and *attended right*) or contralateral (FM-PR network and
1025 *attended left*; FM-PL and *attended right*) scenarios are exhibited as either light grey or
1026 dark grey, respectively. $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

1027 **Figure 3-1. Individual results of upper-alpha cue-locked PLV analysis.** Violin plots
1028 represent the phase locking values (PLV) averaged over the five time windows (500
1029 to 700, 700 to 900, 1100 to 1300, and 1300 to 1500 ms; $t = 0$ as cue appearance).
1030 Ipsilateral or contralateral scenarios are exhibited as either light grey or dark grey,
1031 respectively. $*p < 0.05$, $**p < 0.01$.

1032 **Figure 3-2. Individual results of cue-locked exploratory PLV analysis.** Differences
1033 of contra- to ipsilateral PLV are represented over frequencies (2.4 – 42 Hz in 16
1034 logarithmic steps) as a percentage of change regarding the cross-frequency mean of
1035 each individual.

1036 **Figure 4-1. Individual results of target-locked cross-time PLV.** Violin plots
1037 represent the phase locking values (PLV) obtained by calculating PLV as consistency
1038 throughout the pre-target (-200 to 0 ms) and post-target (200 to 400 ms) time windows.
1039 Ipsilateral or contralateral scenarios are exhibited as either light grey or dark grey,
1040 respectively.

1041 **Fig 4-2. Additional classifier analysis. (A) Shrinkage linear discriminant analysis.**

1042 The leftmost panel reveals how classification error is not modulated by gamma
1043 parameter of number of predictors. The rightmost panel presents the confusion matrix.

1044 **(B) Riemannian minimum distance to the mean classification results.**

1045 **Figure 5-1. Individual results of lateralisation index.** Violin plots represent the
1046 averaged lateralised index for *attended left* (light blue) and *attended right* trials (dark
1047 blue) over the cue-locked time window. Shaded plots represent lateralisation over time
1048 (mean \pm SEM). Dots on in the x-axis denote the significant differences over time
1049 between *attended left* and *attended right* via cluster-based permutation test. * $p < 0.05$,
1050 ** $p < 0.01$, *** $p < 0.001$.









