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1 **All talk? Left temporal alpha oscillations are not specific to verbal-analytical processing during**
2 **conscious motor control**

3

4 Johnny V. V. Parr¹, Germano Gallicchio², Neil R. Harrison³, Ann-Kathrin Johnen³, & Greg Wood⁴.

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6 1. School of Sport and Exercise Sciences, Liverpool John Moore's University, Liverpool, UK.

7 2. School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough,
8 UK.

9 3. Department of Psychology, Liverpool Hope University, Liverpool, UK.

10 4. Research Centre for Musculoskeletal Science and Sports Medicine, Department of Sport and
11 Exercise Sciences, Manchester Metropolitan University, Manchester, UK.

12

13

14 **Address correspondence to:**

15 Johnny V. V. Parr, PhD.

16 School of Sport and Exercise Sciences

17 Liverpool John Moore's University

18 Liverpool, L3 5AF, UK

19 Email: j.v.parr@ljmu.ac.uk

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28 **Abstract**

29 The present study tested the validity of inferring verbal-analytic motor processing from EEG
30 left-temporal alpha activity. Participants ($n = 20$) reached for and transport a jar under three
31 conditions: one control condition and two self-talk conditions aimed at eliciting either task-unrelated
32 verbal processing or task-related conscious control, while 32-channel EEG and kinematics were
33 recorded. Compared to the control condition, both self-talk conditions elicited greater self-reported
34 levels of verbal processing, but only the task-related self-talk condition was accompanied by greater
35 left temporal activity (i.e., EEG alpha power decreased) during movement production. However, this
36 increase was not localised to the left temporal region but was rather evident over all scalp regions
37 examined, suggesting an interpretation more consistent with diminished neural efficiency. No effects
38 for left temporal-frontal (T7-Fz) connectivity were detected across conditions. Our results failed to
39 endorse left-temporal EEG alpha activity as valid index of verbal-analytic processing during motor
40 tasks.

41 **Keywords:** *conscious motor processing, self-talk, verbal-processing, T7-Fz, neural efficiency.*

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52 **1. Introduction**

53 The progression from beginner to skilled motor performance is characterised by an
54 attenuation of energy expenditure as the expression of greater metabolic efficiency (Hatfield, 2018;
55 Hatfield & Hillman, 2001). Such adaptations are not only observed as decreased somatic activity (e.g.,
56 reduced muscular activation), but also as decreased mental activity (e.g., reduced regional activation
57 in the brain). By using neuroimaging techniques, such as electroencephalography (EEG), researchers
58 have provided evidence that practice of a motor skill induces changes in the cerebral cortex consistent
59 with the concept of “neural efficiency”.

60 A cortical region that is often deemed to be implicated in the attainment of greater neural
61 efficiency is the left temporal region. By recording the magnitude of EEG oscillatory activity within
62 the 8-12 Hz frequency range, an inverse marker of neuronal activity termed “alpha power” (Klimesch,
63 2012), researchers have observed diminished activity in the left temporal region as a function of
64 expertise (Haufler, Spalding, Santa Maria, & Hatfield, 2000; Janelle et al., 2000), training (Kerick,
65 Douglass, & Hatfield, 2004), and performance (Gallicchio, Cooke, & Ring, 2017). As the left
66 temporal region includes structures implicated in language processing (e.g., Broca’s area and
67 Wernicke’s area), the abovementioned findings have been interpreted as evidence that expert
68 performance is less reliant on declarative verbal-analytic processes that characterise the conscious
69 motor control of novices (e.g., Fitts & Posner, 1967).

70 In addition to regional activation, cortico-cortical networking has been examined to reveal the
71 interaction across various cortical regions. For example, phase-based measures of alpha connectivity
72 between the left temporal (T7) and the frontal premotor region (Fz) have been examined to assess the
73 influence of declarative verbal processing on the production of movement. Alpha connectivity reflects
74 the synchronicity in the inhibition profiles of two regions, with greater alpha connectivity suggesting
75 consistently similar inhibition (functional communication) and lower alpha connectivity suggesting
76 distinct inhibition profiles (regional independence). In line with the acquisition of greater automaticity
77 with training, researchers have shown that T7-Fz upper-alpha (~10-12 Hz) connectivity decreases
78 with increasing skill (Deeny, Hillman, Janelle, & Hatfield, 2003; Gallicchio, Cooke, & Ring, 2016;

79 Gallicchio et al., 2017; Kerick et al., 2004). This is suggestive of a gradual disconnect between the
80 verbal-analytical and premotor regions as individuals consolidate movement patterns and efficiently
81 organise task-related neural networks free from conscious control. Further work has shown that T7-Fz
82 upper-alpha connectivity increases when directing participants to exert conscious movement control
83 (Ellmers et al., 2016) and is greater for novices who undertake explicit motor learning (high exposure
84 to declarative knowledge) compared to those who undertake implicit motor learning (low exposure to
85 verbal-analytic rules) (Parr, Vine, Wilson, Harrison, & Wood, 2019; Zhu, Poolton, Wilson, Hu, et al.,
86 2011). Finally, participants who report a strong propensity to consciously monitor and control their
87 movements also display increased T7-Fz connectivity compared with those with a lower propensity
88 (Zhu, Poolton, Wilson, Maxwell, & Masters, 2011).

89 Taken together, these findings suggest that skilled, autonomous, expert-like motor
90 performance is associated with decreased left temporal involvement in the production of movement.
91 Conversely, less skilled, conscious, and novice-like motor performance is associated with increased
92 left temporal involvement in the production of movement. As the left temporal region is associated
93 with language, these findings fit well with classic models of motor learning that describe an early
94 reliance on declarative verbal knowledge to guide performance that becomes subsequently
95 “proceduralised” into a non-verbal memory units as skill progresses (Fitts & Posner, 1967). Left
96 temporal alpha oscillations would therefore appear a useful yardstick for verbal-analytical processes
97 during motor control.

98 Crucially, implicit within this proposition is the assumption that EEG activity recorded over
99 left temporal sites (i.e., T7) during motor execution is uniquely representative of the underlying
100 cortical structures associated with language (Cooke, 2013). However, this may not be the case for two
101 reasons: first, unless a one-to-one mapping can be demonstrated, it is not deductively valid to infer a
102 particular cognitive process from the activation of a particular brain region. This practice, termed
103 “reverse inference”, reasons backwards from the presence of brain activation to the engagement of a
104 particular cognitive function, and is limited by non-selectivity of activation in the region of interest
105 (Poldrack, 2006). For example, structures across the left temporal region are implicated not only in

106 language processing but also in auditory processing (Tiihonen et al., 1991) and the integration of
107 visual and auditory information (Beauchamp, Lee, Argall, & Martin, 2004). Second, the EEG has a
108 relatively low spatial resolution due to the propagation of electrical fields across tissues – a
109 phenomenon referred to as “volume conduction” – meaning that the activity recorded from a certain
110 channel can be significantly influenced not just by a local source but also by large distal sources
111 (Cohen, 2015).

112 Consequently, it is unclear the extent to which EEG alpha activity recorded over left temporal
113 sites may reflect a broader range of processes associated with unskilled and conscious motor control
114 beyond that of language, such as general demands on attention and motor effort. This issue is
115 corroborated by research showing that, compared to experts, novices display a global decrease in
116 alpha power that is not specific to the left temporal region (Babiloni et al., 2010; Baumeister,
117 Reinecke, Liesen, & Weiss, 2008; Del Percio et al., 2009; Janelle et al., 2000; Parr et al., 2019). It is
118 therefore plausible that differences in left temporal alpha during motor control are more reflective of
119 general reductions in neural efficiency rather than uniquely reflective of verbal processing.

120 The aim of this study was to manipulate the content of verbal-analytical processing to explore
121 how language processing affects measures of regional alpha power and connectivity during the
122 planning and production of reaching and grasping movements. Specifically, we compared task-related
123 and task-unrelated self-talk with uninstructed, natural performance. Whilst both types of self-talk
124 were administered to increase verbal processing during motor performance, only task-related
125 (declarative) self-talk was designed with the intention of interfering with movement automaticity and
126 increasing conscious motor processing (Masters, 1992). If left temporal alpha activity recorded during
127 motor execution uniquely reflects verbal-analytical processing, then we would expect *both* conditions
128 that encourage self-talk (task-related and task-unrelated) to increase activity in the left temporal
129 region (decreased lower alpha power). However, if self-talk induces changes in regions other than left
130 temporal, this would support the thesis that the association between left temporal activity and
131 language processing during motor performance can be attributed to a spatially broader phenomenon,
132 possibly consistent with decreased neural efficiency. Finally, if left temporal alpha activity were

133 related to the functional connectivity between the left temporal and premotor regions (T7-Fz) during
134 movement production, then we would only expect increased connectivity in the task-related self-talk
135 condition.

136 **2. Methods**

137 **2.1 Participants**

138 Twenty self-reported right-handed participants took part in the study (11 females, 9 males,
139 age: $M = 26.38$, $SD = 6.19$ years). All participants gave written consent and the procedures were
140 approved by our institutional ethics committee.

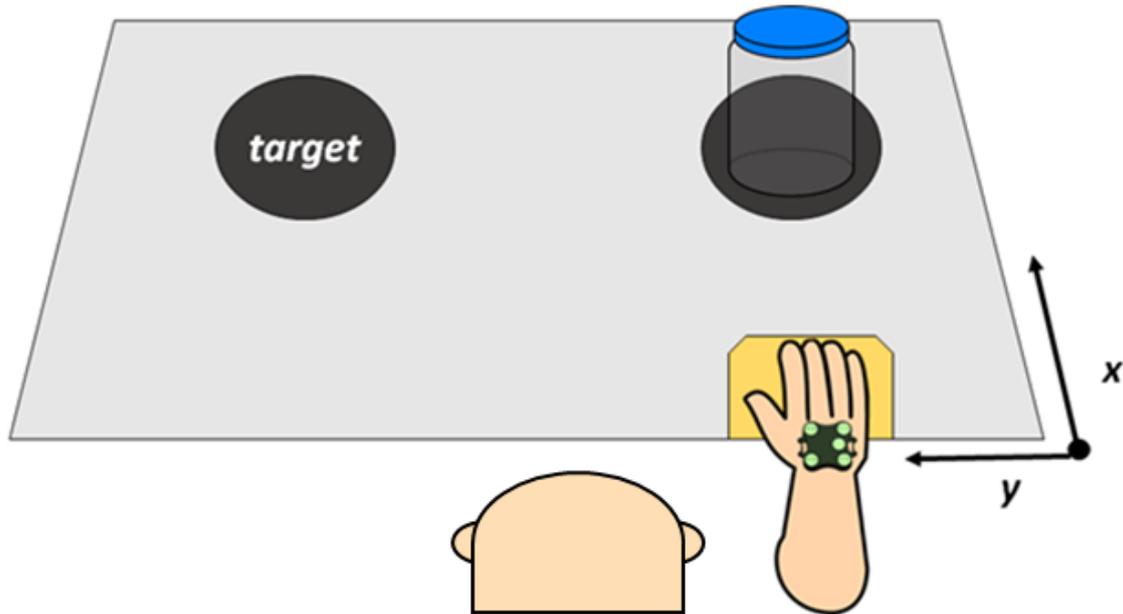
141 **2.2 Experimental task**

142 The task required participants to sequentially reach for and then transport a glass jar from a
143 home position to a target position on a desk (Figure 1). Prior to each trial, participants placed their
144 right hand on the start location positioned at the desk edge approximately 30cm away from the jar
145 home position. The trial started with the onset of an auditory tone (S1) indicating the start of a 2-
146 second preparation period. During this period, participants were instructed to stay still, maintain their
147 hand on the start location, focus their gaze on the jar, and avoid eye blinks and body movement to
148 minimise EEG data artefacts. At the end of this 2-second period, a second auditory tone (S2) acted as
149 a “go” signal to initiate the task. After placing the jar on the target position, participants returned their
150 hand to the start location and the researcher prepared the workspace for the following trial.
151 Participants were instructed to perform at a steady speed that felt comfortable and natural. In order to
152 decrease the repetitive nature of the task and increase task engagement, the weight of the jar was
153 randomly varied at each trial among five options (250, 350, 450, 550, 650 g). Auditory tones (each
154 0.67 seconds long) were controlled through E-Prime 2.0 (Psychology Software Tools, Inc., Pittsburgh,
155 PA, USA).

156 **2.3 Procedure**

157 Participants attended one 2-hour session. After briefing, participants were seated at a distance
158 that enabled them to reach the jar home and target positions at arms-length. Once instrumented for
159 EEG and kinematic recording, participants completed a 1-minute eyes-closed resting baseline and
160 then completed 10 practice trials to enable familiarise the task. Participants then performed 40 trials in
161 the *control condition*, which consisted of reaching and transporting the jar with no self-talk
162 instructions. Participants then completed manipulation checks at the end of the 40 trials assessing task
163 difficulty, mental load, conscious control, and self-talk (see below for details).

164 Then, the experiment was performed under two *self-talk conditions* – one task-related and one
165 task-unrelated – each composed of 40 trials. These trials were performed in eight blocks of ten in an
166 interleaved manner (e.g., 10 x task-related, 10 x task-unrelated, 10 x task-related etc.), with the
167 starting condition counterbalanced across participants. For the task-related condition, self-talk
168 instructions regarded the control of movements to encourage movement conscious processing: “*Keep*
169 *elbow below the wrist*”, “*Keep palm 5(cm) from table*”, “*Keep thumb below the index*”, “*Keep wrist*
170 *flexed at 90 degrees*”. For the task-unrelated condition, self-talk instructions included a collection of
171 well-known nursery rhymes that were not related to movement: “*Jack and Jill went up the hill*”,
172 “*Twinkle twinkle little star*”, “*Mary had a little lamb*”, “*Humpty dumpty sat on a wall*”. The to-be-
173 rehearsed self-talk instruction varied in a random manner for each block of 10 trials. Participants were
174 required to silently rehearse these instructions throughout the entirety of each trial (i.e., during both
175 movement preparation and execution phases) to the best of their ability. For both self-talk conditions,
176 participants were asked which word of the given phrase they finished on when placing each jar. This
177 word was written down in view of each participant to act as a manipulation check and to encourage
178 adherence to self-talk instructions. Adherence to the task-related self-talk condition was further
179 encouraged by positioning electrodes on the right upper-limb and workspace prior to each block of 10
180 trials to convince participants that their adherence to the task-related instructions would be
181 quantitatively evaluated (Appendix S1). After each of the ten blocks of trials, participants again rated
182 task difficulty, mental load, conscious control, and self-talk (see below for details).



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184 **Figure 1.** Visual representation of the experimental set-up. Participants began each trial with their
185 right hand on the start position (in yellow). A first auditory tone (S1) indicated the start of the 2-
186 second preparation period, during which participants maintained their hand on the start position and
187 their gaze on the jar. Following a second auditory tone (S2) participants reached for the jar and placed
188 it on the target location.

189 2.4 EEG

190 Thirty-two active EEG electrodes were positioned on the scalp at locations Fp1, Fp2, AF3,
191 AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7 (T3), C3, Cz, C4, T8 (T4), CP5, CP1, CP2, CP6,
192 P7, P3, Pz, P4, P8, PO3, PO4, O1, Oz and O2 of the 10-20 system (Jasper, 1958)¹. Common mode
193 sense (CMS) and driven right leg (DRL) electrodes were used to enhance the common mode rejection
194 ratio of the signal. The signal was amplified and digitized at 512 Hz using the ActiveTwo recording
195 system (Biosemi, The Netherlands). A digital trigger was automatically sent from E-Prime to the
196 Biosemi system via parallel communication at the onset of each S2 (“go” signal). All EEG signals
197 were re-referenced to the average of all channels and 1-35 Hz band-pass filtered (FIR [finite infinite
198 response]). Epochs were cut from -2.25 to +2.25 s relative to the onset of S2. Epochs were then

¹ Sites T7 and T8 are sometimes referred to as T3 and T4, respectively, in other EEG systems.

199 visually inspected so those showing movement artefact could be rejected (percentage of trials
200 rejected: $M = 13.33$, $SD = 5.89$ %). No bad channels were identified. Data were then subjected to
201 Independent Component Analysis (Runica Infomax algorithm; Makeig, Bell, Jung & Sejnowski,
202 1996) to identify and remove components accounting for blinks, eye movements and other non-neural
203 activity (components removed: $M = 5.70$, $SD = 3.05$). These processing steps were performed using
204 EEGLAB functions (Delorme & Makeig, 2004) and bespoke MATLAB scripts.

205 **2.5 Kinematic data**

206 Noraxon MyoMotion (Scottsdale, AZ, USA) motion analysis system was employed to
207 analyse kinematic characteristics of the task performance. A single MyoMotion inertial measurement
208 unit (IMU) was placed on the dorsal side of the right hand according to the rigid-body model defined
209 in the Noraxon MR3 software. Calibration was performed using the upright standing position, though
210 the use of a single IMU wavered the need for a zero/neutral angle in the measured joints. The
211 sampling frequency for the inertial sensor was set at 100Hz. To identify movement onset (S2) for each
212 trial, a tripod-mounted webcam (30Hz) was synchronised using a light-emitting diode (LED) and
213 Noraxon software to enable digital triggers to be applied to the data offline following visual
214 inspection of the recorded video. Data were then smoothed using a 10-point (corresponding to 100ms)
215 moving average before being epoched from -2.25 to + 2.25 s relative to S2 (“go” signal) for each trial.

216 **2.6 Measures**

217 **2.6.1 Manipulation check**

218 Manipulation checks were administered throughout testing to confirm that our experimental
219 conditions were having their desired effect. Using 7-point Likert scales, participants were asked to
220 self-report levels of task difficulty, mental effort, movement awareness, movement control, self-talk
221 frequency, and self-talk intensity.

222 **2.6.2 Movement time**

223 Movement time was measured as the time (in seconds) elapsed between S2 (i.e., “go” signal)
224 and jar placement on the target location. To obtain this, the researcher provided a keyboard response
225 upon jar placement, enabling movement time to be extracted from E-Prime.

226 **2.6.3 Peak acceleration**

227 The early characteristics of reaching and grasping movements can provide useful insights into
228 the extent to which movements are performed under predictive or online control. For example,
229 increased limb acceleration indicates more ballistic and pre-planned movement, whereas decreased
230 limb acceleration would suggest a more conservative approach with greater reliance on feedback to
231 supervise ongoing action (Desmurget & Grafton, 2000). Peak acceleration along the *x*- and *y*-axes of
232 movement was therefore measured for the reach and transport phases of our task to provide kinematic
233 evidence of how our self-talk instructions interfered with movement automaticity. Specifically, peak
234 reach acceleration was taken as the peak value recorded between 0 and +500 ms relative to S2 along
235 the *x*-axis of movement. Peak transport acceleration was taken as the peak value recorded between
236 500 and 1500 ms relative to S2 along the *y*-axis of movement. Separate axes were chosen for each
237 phase as they each capture the primary direction of movement. Time windows were selected upon
238 visual inspection of data from which clear peaks for each phase could be easily detected (see Figure
239 4).

240 **2.6.4 Alpha power**

241 Time-frequency decomposition of the epoched EEG signals was performed for each trial
242 through short-time Fast Fourier Transform (FFT) conducted on 37 overlapping windows, each of 0.5 s
243 (87.5% overlap), with central points ranging from -2 to +2 s. Prior to FFT, data points in each window
244 were Hanning-tapered and zero-padded to reach 4 s. This procedure generated complex-valued
245 coefficients in the time-frequency plane with a precision of 111ms and 0.25 Hz, separately for each
246 channel and trial. Alpha power was then computed as the squared amplitude within each participant’s
247 individual alpha frequency (IAF) band, identified using both the ‘peak frequency’ and ‘centre of
248 gravity’ (CoG) methods (Corcoran, Alday, Schlesewsky, & Bornkessel-Schlesewsky, 2018). To do

249 this, we first attempted to identify a visible peak (between approximately 7 – 15Hz) from the mean
250 EEG spectrum over occipito-parietal channels, recorded from the 1-minute eyes-closed baseline.
251 When a single peak was not present (40% of participants), IAF was instead taken as the power spectra
252 weighted mean (CoG) between 7 and 15 Hz (Appendix S2). Subsequently, the alpha frequency band
253 was denoted as IAF-2 to IAF+2. For one participant, baseline data was corrupted, resulting in alpha
254 being denoted as the typical 8 – 12 Hz range. As no neutral baseline could be identified, non-normal
255 distributions and inter-individual differences were dealt with by employing a median-scaled log
256 transformation. This transformation was implemented by scaling all alpha power values for each
257 participant (across all channels, trials, time-windows, and conditions) by the median alpha power
258 value within that participant, before then employing a 10·log10 transformation. Power was then
259 averaged across overlapping time windows and across trials to provide mean values for each channel,
260 separately from -2s to -1s (t^{-2}), -1s to 0s (t^{-1}), 0s to 1s (t^{+1}), and 1s to 2s (t^{+2}). To examine regional
261 effects, seven regions of interest (ROI) were identified based on inspection of topographical maps:
262 frontal (F3, Fz, F4), left temporal (F7, FC5, T7), left central (FC1, C3, CP1), right central (FC2, C3,
263 CP2), right temporal (F8, FC6, T8), parietal (P3, Pz, P4) and occipital (O1, Oz, O2). Values within
264 each ROI were averaged. Signal processing was performed in MATLAB.

265 **2.6.5 Alpha connectivity**

266 Functional connectivity was computed as the inter-site phase clustering (ISPC) over time
267 (Cohen, 2014; Lachaux, Rodriguez, Martinerie, & Varela, 1999). ISPC measures the phase lag
268 consistency across time between two channels independently from their power and reflects functional
269 connectivity between the oscillatory activity of two underlying cortical regions, with values ranging
270 from 0 (no connectivity) to 1 (perfect connectivity). ISPC was calculated for each trial using bespoke
271 Matlab scripts as, $ISPC(f) = |n^{-1} \sum_{w=1}^n e^{i(\theta_x(w,f) - \theta_y(w,f))}|$, where i is the imaginary operator; θ_x
272 and θ_y are the phase angles of the recorded signal at two different scalp locations at FFT time
273 window w and frequency f ; $e^{i(\theta_x(w,f) - \theta_y(w,f))}$ denotes a complex vector with magnitude 1 and angle
274 $\theta_x - \theta_y$; $n^{-1} \sum_{w=1}^n (\cdot)$ denotes averaging across the overlapping FFT time windows within each

275 predefined epoch (t^2 , t^l , t^{+l} , t^{+2}); and $|\cdot|$ is the module of the average vector. Following previous
276 research and our a priori hypotheses, we focused on left temporal (T7) – frontal (Fz) ISPC in the
277 upper-alpha (IAF to IAF+2) frequency band for our statistical analyses. Right temporal (T8) – frontal
278 (Fz) upper-alpha connectivity was also analysed to verify the extent to which connectivity effects
279 were localised to a given hemisphere. No baselines were used. Instead, to normalise their density
280 distributions, ISPC were Fisher Z transformed (inverse hyperbolic tangent); values could then range
281 from 0 to ∞ . Values were then averaged over trials and frequencies within the upper-alpha range (IAF
282 to IAF+2 Hz) to yield estimates of alpha connectivity separately for each condition.

283 **2.7 Statistical analyses**

284 For self-report data, a one-way repeated measures ANOVA was performed to assess the
285 effect of Condition (control, task-related, task-unrelated) on each of the six items (difficulty, mental
286 effort, movement awareness, movement control, self-talk frequency, self-talk intensity). One-way
287 repeated measures ANOVAs were also performed to assess the effect of Condition on movement
288 time, peak reach acceleration and peak transport acceleration.

289 A 3 Condition x 4 Epoch (t^2 , t^l , t^{+l} , t^{+2}) repeated measures ANOVA on the averaged alpha
290 power over channels T7, F7 and FC5 was performed to specifically test the prediction that left
291 temporal alpha power can be used to infer verbal processing. Following this, a 3 Condition x 4 Epoch
292 x 7 ROI (left temporal, frontal, left central, right central, parietal, right temporal, occipital) repeated
293 measures ANOVA was conducted to evaluate the presence of wider regional effects of alpha power.
294 Finally, a 3 Condition x 4 Epoch x 2 Hemisphere (T7-Fz, T8-Fz) repeated measures ANOVA was
295 conducted to assess time-varying changes in left and right temporal-frontal alpha connectivity across
296 Conditions. By comparing the 2 s preceding movement with the 2 s following movement, we can
297 determine whether effects are specific to the preparation or execution of motor performance.

298 For all ANOVAs, Greenhouse-Geisser corrections were applied when sphericity was violated
299 and effect sizes were calculated using partial eta squared (η^2). All post hoc pairwise comparisons
300 were adjusted using Bonferroni corrections to counteract the problem of multiple comparisons.

301 **Results**

302 **3.1 Manipulation checks**

303 Results from each one-way repeated measures ANOVA showed a significant main effect of
304 Condition for task difficulty, $F(2, 36) = 66.04, p < .001, \eta^2 = .786$, mental effort, $F(2, 36) = 49.37, p$
305 $< .001, \eta^2 = .733$, movement awareness, $F(2, 36) = 57.56, p < .001, \eta^2 = .762$, conscious control,
306 $F(2, 36) = 77.08, p < .001, \eta^2 = .811$, self-talk frequency, $F(2, 36) = 27.37, p < .001, \eta^2 = .603$, and
307 self-talk intensity, $F(2, 36) = 14.739, p < .001, \eta^2 = .450$. Post-hoc pairwise comparisons showed
308 significantly higher levels of self-talk frequency ($p < .001$) and self-talk intensity ($p < .001$) during the
309 task-related and task-unrelated self-talk conditions compared to the control condition, confirming the
310 intended manipulation of verbal processing. Task difficulty, mental effort, movement awareness, and
311 conscious control were rated significantly higher in the task-related condition compared to the task-
312 unrelated and control conditions ($p < .001$), but the task-unrelated condition as significantly more
313 difficult than the control condition ($p = .013$).

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325 **Table 1.** Means and standard deviations of self-report and kinematic data, together with the results

326 from each one-way repeated measures ANOVA.

	Control M (SD)	Task- related M (SD)	Task- unrelated M (SD)	F	np²
Difficulty	1.05 (0.23)	3.33 (1.09)	1.50 (0.62)	66.04*	.79
Mental effort	1.47 (0.96)	4.14 (1.00)	2.07 (1.00)	49.37*	.73
Movement awareness	3.16 (1.30)	5.74 (1.09)	2.88 (0.81)	57.56*	.76
Movement control	2.47 (1.07)	5.71 (0.85)	2.39 (1.08)	77.08*	.81
Self-talk frequency	4.16 (1.53)	6.54 (0.56)	6.43 (0.69)	27.37*	.60
Self-talk intensity	3.89 (1.79)	5.92 (0.88)	5.81 (0.86)	14.74*	.45
Reach (peak m/s ²)	2.20 (0.52)	1.49 (0.40)	2.04 (0.47)	34.38*	.86
Transport (peak m/s ²)	1.70 (0.37)	1.01 (0.19)	1.55 (0.37)	31.21*	.68
Movement time (sec)	1.64 (0.21)	2.66 (0.51)	1.86 (0.34)	74.56*	.80

327 *Note.*

328 * indicates a significant main effect of Condition ($p < .001$).

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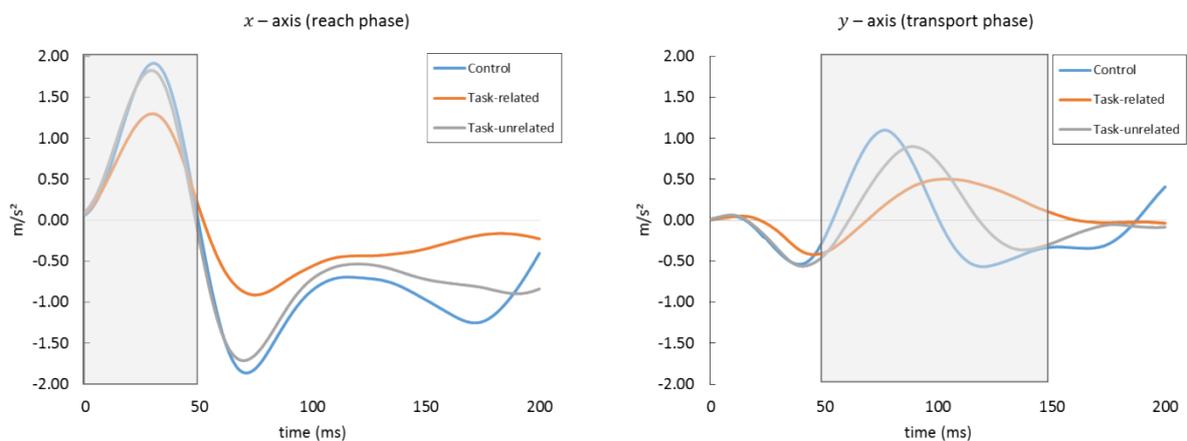
330

331 2.8 Movement time

332 The one-way repeated measures ANOVA showed a significant main effect of Condition, $F(2,$
333 $38) = 74.56, p < .001, \eta^2 = .797$. Post-hoc pairwise comparisons revealed participants performed
334 slowest during the task-related condition ($p < .001$), and fastest during the control condition ($ps =$
335 $.005$).

336 2.9 Peak acceleration

337 A one-way repeated measures ANOVA showed a significant main effect of Condition for
338 both the reach, $F(2, 32) = 34.38, p < .001, \eta^2 = .862$, and transport, $F(2, 30) = 31.21, p < .001, \eta^2 =$
339 $.675$, phases of the task. Pairwise comparisons showed peak acceleration to be lower for the task-
340 related condition, compared to control and task-unrelated conditions for both reach ($p < .001$) and
341 transport ($p < .001$) task phases (Figure 2).



342

343 **Figure 2.** Mean acceleration profiles over time for each condition. Shaded grey areas depict the time
344 window in which peak reach acceleration (left) and peak transport acceleration (right) were identified.

345 2.10 Alpha power

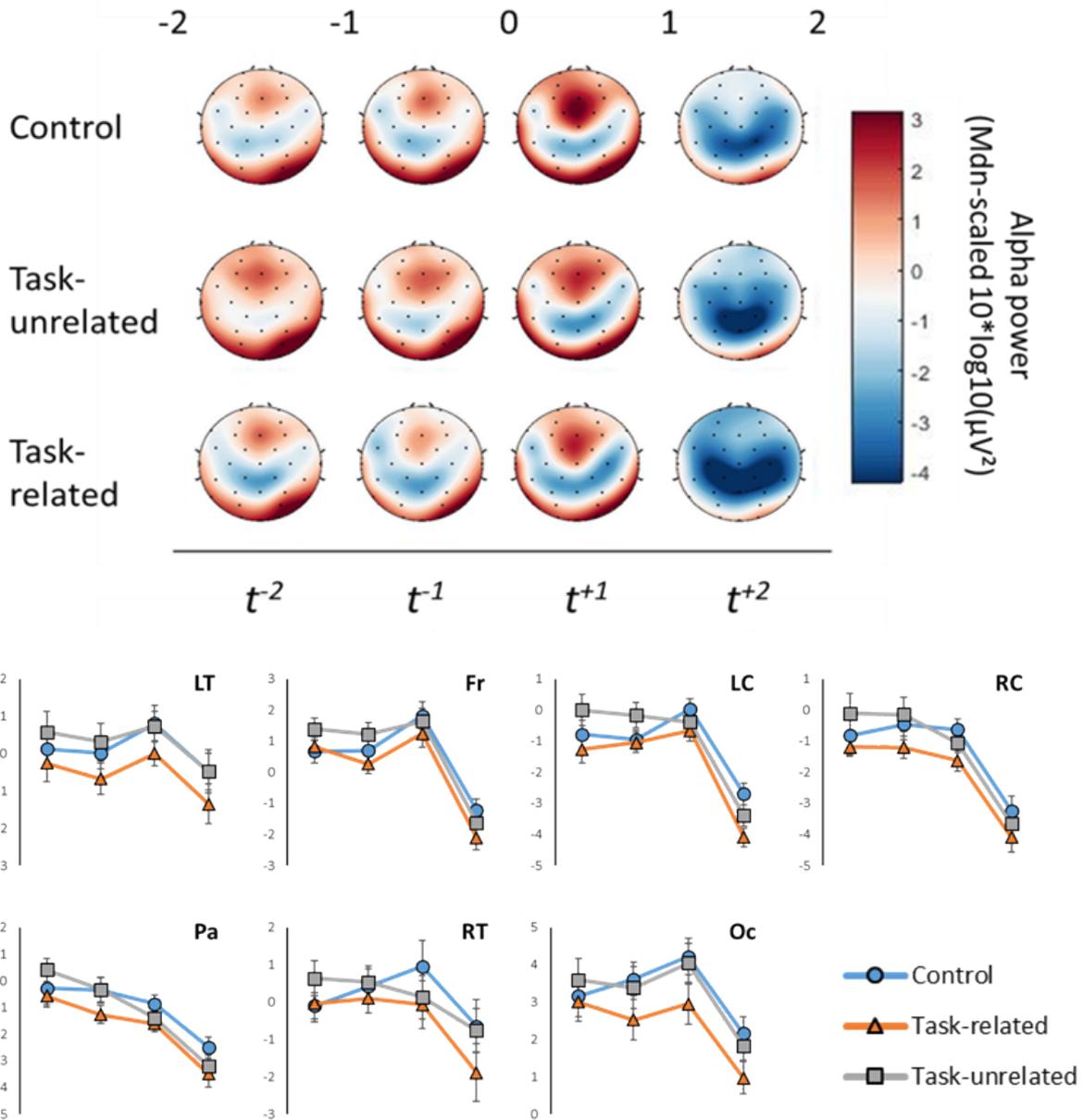
346 2.10.1 Left temporal alpha

347 The 3 (Condition) x 4 (Epoch) repeated measures ANOVA conducted on the averaged
348 activity recorded from channels T7, F7 and FC5 yielded a marginally significant main effect of

349 Epoch, $F(1.54, 29.26) = 3.273$, $p = .064$, $\eta^2 = .147$, and a significant main effect of Condition, $F(2,$
350 $38) = 7.031$, $p = .003$, $\eta^2 = .270$. The Condition x Epoch interaction was non-significant, $F(6, 114) =$
351 0.294 , $p = .938$, $\eta^2 = .015$. Post-hoc pairwise comparisons to interrogate the main effects revealed
352 that left-temporal alpha power decreased from t^{+1} to t^{+2} ($p = .001$). They also revealed lower left-
353 temporal alpha power in the task-related self-talk condition, compared to the control ($p = .042$) and
354 task-unrelated self-talk ($p = .002$) conditions.

355 **2.10.2 Regional alpha**

356 These analyses were conducted to examine topographical effects involving multiple regions
357 of interest covering the major areas of the cerebral cortex, including, but not limited to, the left
358 temporal region. Results from a 3 (Condition) x 4 (Epoch) x 7 (ROI) repeated measures ANOVA
359 yielded a main effect of ROI, $F(3.50, 66.57) = 22.99$, $p < .001$, $\eta^2 = .548$, indicating that alpha
360 power was highest over the occipital region, lower over the temporal and frontal regions, and lowest
361 over the central and parietal regions. There were also significant main effects of Epoch, $F(1.37,$
362 $26.13) = 17.18$, $p < .001$, $\eta^2 = .475$, and Condition, $F(2, 38) = 14.78$, $p < .001$, $\eta^2 = .438$. These
363 effects were superseded by a Condition x Epoch interaction, $F(6, 114) = 2.28$, $p = .041$, $\eta^2 = .107$,
364 and a ROI x Epoch interaction, $F(7.41, 140.93) = 7.95$, $p < .001$, $\eta^2 = .295$. For the Condition x
365 Epoch interaction, pairwise comparisons revealed alpha power across all regions to be lower for the
366 task-related condition compared to the task-unrelated condition at t^2 ($p = .017$) and t^1 ($p = .031$), and
367 lower for the task-related condition compared to both the control and task-unrelated conditions at t^{+1}
368 ($ps = .016$) and t^{+2} ($ps = .043$). For the ROI x Epoch interaction, pairwise comparisons revealed all
369 regions to significantly decrease in alpha power from t^{+1} to t^{+2} (rate of change (μV^2): LT = -1.22, Fr =
370 -3.21, LC = -3.06, RC = -2.56, Pa = -1.77, RT = -1.44, Oc = -2.08). However, for the frontal ($p <$
371 $.001$), central ($ps = .001$), parietal ($ps = .004$), and occipital regions ($ps = .073$), this significant
372 decrease was also evident from t^2 , t^1 and t^{+1} relative to t^{+2} . A marginally significant decrease in
373 parietal alpha power was also observed from t^2 to t^{+1} ($p = .08$). All other interactions were non-
374 significant (Figure 3).



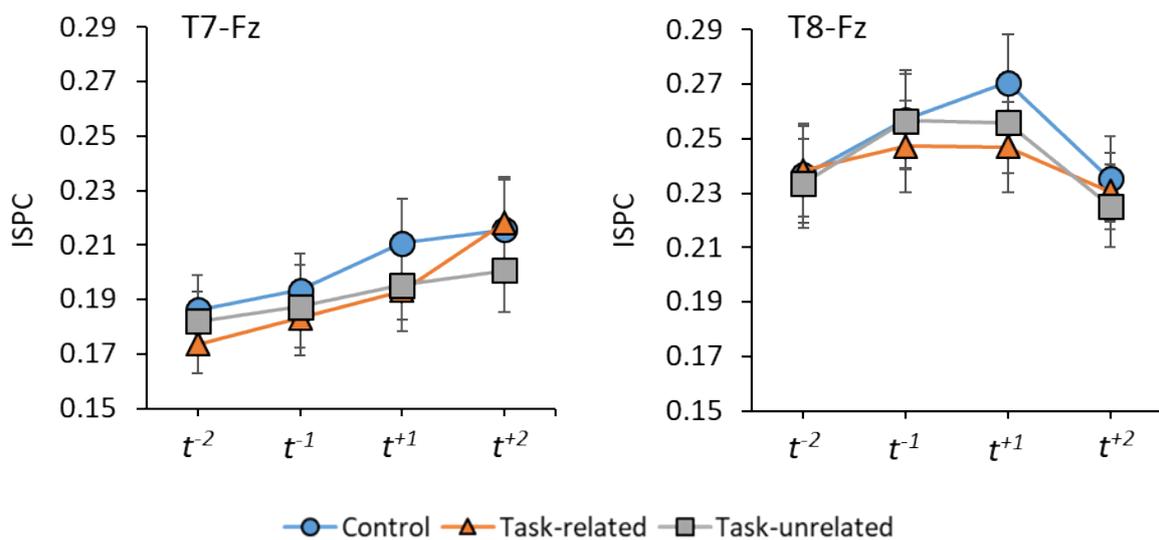
375

376 **Figure 3.** Scalp topographies (top) displaying alpha power across Epoch (t^{-2} , t^{-1} , t^{+1} , t^{+2} ; 0 = “go”
 377 signal) for each experimental condition. Line plots (bottom) display the mean (\pm s.e.m) alpha power
 378 for each region of interest (left temporal = LT, frontal = Fr, left central = LC, right central = RC,
 379 Parietal = Pa, right temporal = RT, occipital = Oc) as a function of Epoch.

380 2.11 Alpha connectivity

381 A 2 (Hemisphere) x 3 (Condition) x 4 (Epoch) repeated measures ANOVA yielded a
 382 significant main effect of Hemisphere, $F(1, 19) = 9.581$, $p = .006$, $np2 = .335$, a marginally significant
 383 main effect of Epoch, $F(1.58, 30.08) = 2.933$, $p = .079$, $np2 = .134$, but no effect of Condition, $F(1.39,$

384 26.56) = 1.938, $p = .173$, $np2 = .093$. These effects were superseded by a significant Hemisphere x
385 Epoch interaction, $F(1.89, 35.81) = 4.764$, $p = .016$, $np2 = .200$. Post-hoc pairwise comparisons
386 revealed that, for all conditions, T8-Fz connectivity was significantly higher than T7-Fz connectivity
387 at t^{-2} ($p = .007$), t^{-1} ($p = .003$), and t^{+1} ($p = .005$), but not t^{+2} ($p = .248$). They also revealed that T7-Fz
388 connectivity increased from t^{-2} to t^{+2} ($p = .072$), and that T8-Fz connectivity increased from t^{-2} to t^{-1} (p
389 = .077), and then decreased from t^{-1} to t^{+2} ($p = .010$).



390

391 **Figure 4.** Line plots displaying the mean (\pm s.e.m) inter site phase clustering (ISPC) as a function of
392 condition and epoch for both T7-Fz (left) and T8-Fz (right).

393 3. Discussion

394 The present study attempted to manipulate self-talk to evaluate the fidelity of associating EEG
395 alpha oscillations recorded from left temporal sites during motor preparation and execution with
396 verbal-analytic processes. Our results show that both self-talk conditions (task-related and task-
397 unrelated) were rated higher for self-talk frequency and intensity compared to the control condition,
398 confirming that our manipulations increased verbal processing as intended. Importantly, the task-
399 related condition was rated as being the most difficult, mentally demanding, and consciously
400 controlled condition. Participants also performed 60% slower and decreased the speed at which they
401 accelerated the hand when reaching for (30% slower) and transporting (40% slower) the jar. The task-

402 related condition therefore increased verbal processing and encouraged a more effortful and conscious
403 mode of motor control. The task-unrelated condition was rated as being more difficult than the control
404 condition, reflected by the slower movement times (~13%). However, as there was no difference in
405 reported levels of conscious control and mental effort, and no difference in hand acceleration profiles
406 between the task-unrelated and control conditions, it can be argued that task-unrelated self-talk
407 increased verbal processing without inducing increased levels of conscious movement control.

408 Despite both self-talk conditions increasing verbal processing compared to the control
409 condition, our EEG data showed activity in the left-temporal region of the cerebral cortex to only
410 increase (i.e., alpha power decreased) for the task-related condition during movement execution (t^{+1}
411 and t^{+2}). As no differences were observed between the control and self-talk conditions during
412 movement preparation (t^{-2} and t^{-1}), when participants were motionless, this questions the fidelity of
413 inferring verbal-analytic processing demands from left temporal EEG alpha power during movement
414 preparation. Rather, our findings suggest that left temporal alpha power is likely to reflect a broader
415 range of processes associated with conscious motor processing during movement, beyond that of
416 language (Poldrack, 2006).

417 An alternative interpretation for the increased left temporal activity during task-related self-
418 talk can be considered when acknowledging that this increase was evident across the entire scalp
419 topography (Figure 3). Such a finding mirrors previous research that has shown less-skilled
420 performers exhibit globally lower EEG alpha power (increased activity) compared to their higher-
421 skilled counterparts (Del Percio et al., 2009; Parr et al., 2019). This is thought to reflect reductions in
422 neural efficiency as individuals exert increased cognitive effort to meet the demands of the task.
423 Indeed, alpha rhythms are proposed to reflect thalamo-cortical and cortico-cortico loops that
424 facilitate/inhibit the transmission and retrieval of both sensorimotor and cognitive information into the
425 brain (Deeny et al., 2003; Pfurtscheller & Lopes da Silva, 1999). Accordingly, the global decrease in
426 alpha power during the more consciously performed task-related self-talk condition may therefore
427 reflect the greater demands on attentional resources to process sensory-motor information as the
428 mechanics of movements are monitored and updated online. It is important to acknowledge that the

429 task-related self-talk condition significantly altered movement kinematics. As such, it is difficult to
430 untangle the extent to which the present effect is driven by changes in neural efficiency, movement
431 efficiency, or an interaction of these factors. However, such a distinction is perhaps not necessary or
432 possible during dynamic motor tasks, given their shared association with the effortful and conscious
433 motor control that characterise the early stages of learning (Fitts & Posner, 1967).

434 Our results showed no difference in T7-Fz or T8-Fz connectivity between the two self-talk
435 conditions, despite the reported differences in verbal processing and conscious control. In fact, even
436 with a reanalysis of these data with a spatial filter (surface Laplacian), we found the lowest T7-Fz
437 connectivity for the more consciously performed task-related condition during jar-transportation
438 (Appendix S3). Whilst evidence exists to suggest that increased T7-Fz connectivity is characteristic of
439 less-skilled and more explicit motor performance (Gallicchio, Cooke, et al., 2016; Parr et al., 2019;
440 Zhu, Poolton, Wilson, Hu, et al., 2011), the results from the present study challenge the interpretation
441 of this measure as representing the functional communication between verbal-analytic and motor
442 planning processes.

443 The absence of change in T7-Fz connectivity for the task-unrelated self-talk condition
444 inadvertently addresses concerns that previous research utilising this measure may be confounded by
445 between and within participant variability in the use of motivational self-talk (Bellomo, Cooke, &
446 Hardy, 2018). Our findings suggest that changes in T7-Fz connectivity reflect processes that are not
447 directly related to verbal processes, be it task-related or task-unrelated. However, we cannot rule out a
448 floor effect due to participants being considered highly experienced in this rather rudimentary
449 reaching task. In other words, it is possible that our task was not novel or difficult enough to induce
450 the non-essential cortico-cortical communication between task-relevant and task-irrelevant cortical
451 regions. Some support for this thesis can be taken from Parr et al. (2019), who found group-level
452 (implicit vs explicit training) connectivity differences in a reaching and grasping task that was similar
453 to the one employed here but which required the use of a prosthetic hand.

454 T7-Fz connectivity may be more influenced by aspects related to the nature of movement
455 rather than simply verbal processing and/or conscious control. For example, we found a significant

456 increase in T7-Fz connectivity from t^{-2} to t^{+2} for all conditions, suggesting a greater response to the
457 changing demands of our task across time (i.e., movement preparation versus movement execution)
458 than to the between-condition alterations in self-talk and conscious control. It should therefore be
459 reiterated that phase-based connectivity merely measures the phase lag consistency between signals
460 recorded from two sites, with relations drawn to communication pathways being inferred rather than
461 directly assessed (Bellomo et al., 2018; Cohen, 2014). As such, it also becomes difficult to interpret
462 our finding that T8-Fz connectivity was significantly higher than T7-Fz connectivity for all conditions
463 across the majority of our task phases. Previously, researchers have inferred the involvement of
464 visuospatial processes in motor performance from T8-Fz connectivity (Bellomo et al., 2018; Cooke,
465 2013; van Duijn, Buszard, Hoskens, & Masters, 2017). It could therefore be argued that this observed
466 hemispheric asymmetry reflects the obvious visuospatial component of our reaching and grasping
467 task. However, attempts to directly assess the relationship between T8-Fz upper-alpha connectivity
468 and visuospatial processing during motor performance are required to investigate these claims, similar
469 to how we examined the involvement of T7-Fz connectivity with verbal processing in this study
470 (Poldrack, 2006). It could also be argued that these hemispheric differences may be driven by the
471 right-handed nature of our task, given activation of the motor cortex usually shows contralateral bias
472 during upper-limb control (Halsband & Lange, 2006; Kim et al., 1993). Whilst this is possible, future
473 work is needed to explore the independent contribution of task laterality to measures of EEG cortico-
474 cortical connectivity.

475 In light of our findings, several limitations should be considered. First, it could be argued that
476 our results are limited by administering our control condition in a fixed (always first) order. However,
477 we argue this was necessary to optimise the natural characteristics of initial performance and avoid
478 unintentionally inducing more conscious performance and the accrual of declarative task knowledge.
479 Second, the degree of temporal “jitter” evident in our EEG analyses should be noted. To elaborate,
480 our data were segmented into pre-defined epoch lengths relative to the onset of movement (-2 to +2
481 seconds) to enable meaningful comparisons to be made between conditions. However, this method
482 fails to guarantee the segmented data represent the same phase of movement (from 0 to +2 seconds)

483 on a trial-to-trial basis, especially given the differences in movement time. Although less than ideal,
484 our measures of alpha power and connectivity were highly consistent across time for all conditions,
485 suggesting a minimal effect of such temporal lag. Finally, our analyses are potentially limited by
486 solely examining alpha-based connectivity to infer cortico-cortical networking. Indeed, it is still
487 unclear how the interpretation of alpha connectivity differs from the interpretation of non-alpha
488 connectivity (e.g. theta, ~4 – 8 Hz). Future research could pay greater attention to this issue and
489 include measures of functional connectivity that either include several frequency bands or do not rely
490 on a specific frequency band (e.g., Granger causality, Phase Slope Index).

491 In conclusion, our results failed to endorse EEG alpha activity recorded from the left temporal
492 region as a valid index of verbal analytic processing demands during a motor task. Instead, our results
493 suggest that increased left temporal alpha activity exhibited during more consciously controlled motor
494 performance should be attributed to a spatially broader phenomenon consistent with decreased neural
495 efficiency. Furthermore, the approach presented in this study invites motor control scientists to be
496 cautious when inferring a certain cognitive process based solely on local activity. We encourage
497 researchers to explore how cognition maps onto regional brain activity considering the whole
498 topography, specifically during the performance of motor tasks to improve our understanding of how
499 the brain controls movements.

500

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610

611 **ORCID**

612 Johnny V. V. Parr - <https://orcid.org/0000-0002-3096-2601>

613 **Conflict of interest**

614 No conflicting interests are declared.

615 **Footnotes**

616 1. Sites T7 and T8 are sometimes referred to as T3 and T4, respectively, in other EEG
617 systems.

618

619

620

621 **Appendix 1: Manipulations to ensure adherence to task-related self-talk instructions**

622

623 Photos depicting the placement of electrodes both on the workspace and arm to
624 encourage full adherence to the task-related self-talk instructions. Manipulations were
625 designed to encourage a more conscious mode of movement control.

626

627 ***“Keep hand 5cm above table”***



Two additional electrodes were placed halfway between the hand start location and the jar, and halfway between the jar and target locations. Participants were informed that the distance between the electrode on hand and the electrodes on the workspace would be recorded during performance. As such, participants were instructed to ensure this distance was as close to 5cm as possible.

628

629

630 ***“Keep elbow below the wrist”***

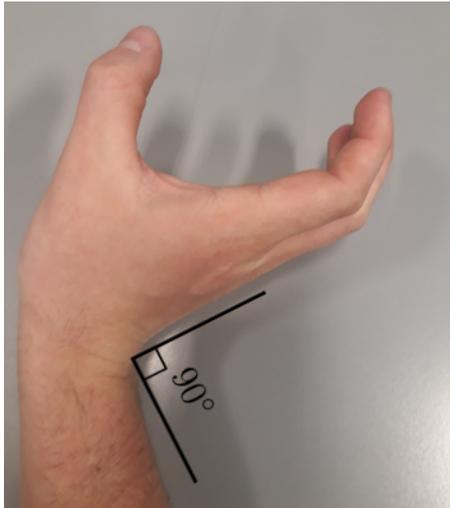


An additional electrode was placed towards the elbow using a Velcro strap. Participants were informed that the electrode on the elbow must remain below the electrode on the hand throughout task performance. Participants were told this would be objectively assessed.

631

632

633 ***“Keep wrist flexed at 90 degrees”***



Participants were required to perform the task with their hand hyperextended to create a 90 degree angle with the forearm (pictured). Participants were told that their adherence could be objectively monitored using the electrode placed on the hand (not pictured).

634

635

636

637 ***“Keep thumb below the index”***



Participants were required to rotate their hand in a manner that ensure the thumb was always positioned lower than the index finger (as opposed to being in-line. Again, participants were told that adherence would be objectively assessed by calculating the angle of the hand electrode during performance (not pictured).

638

639

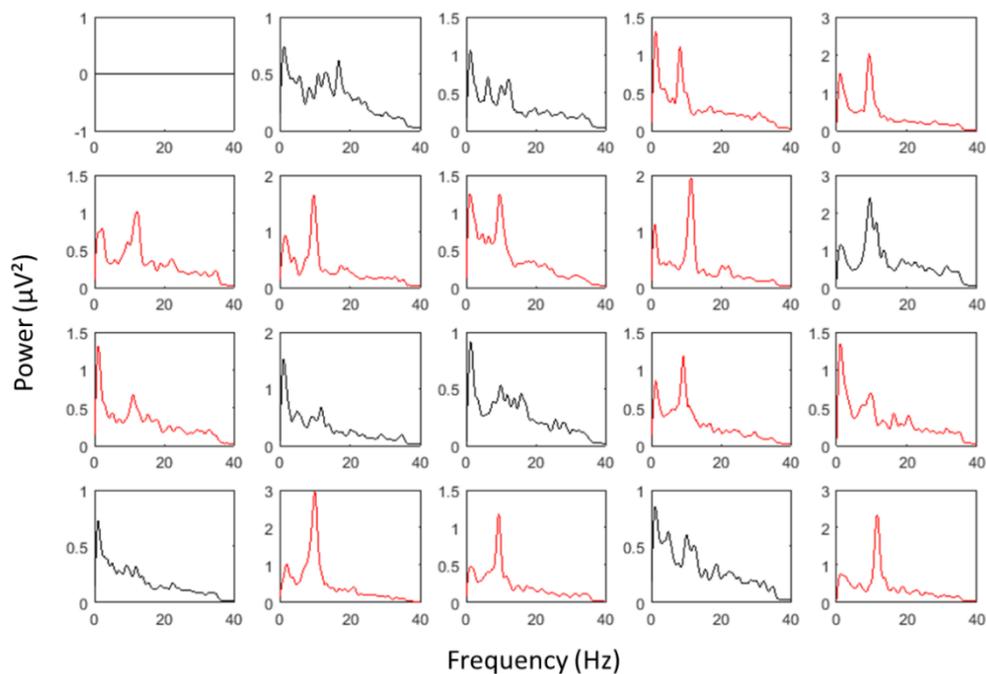
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641

Appendix 2: Individual alpha frequency identification

642

643 As the actual alpha frequency band can show inter-subject variability, we attempted to
644 specify each participant's individual alpha frequency band (IAF). The below figure displays
645 the mean spectra recorded over occipital-parietal electrodes during a 1-minute eyes closed
646 resting baseline. For the line plots that are in red, IAF was taken as the peak frequency
647 occurring between 7 and 15 Hz, as a clear single peak could be observed upon inspection
648 within this band. For the line plots that are in black, a clear single peak was not visible,
649 resulting in the IAF being taken as the power spectra weighted mean (centre of gravity)
650 within the 7 – 15 Hz band. For one participant, baseline data was corrupt resulting in IAF
651 being set at the typical 10 Hz.



652

653 **Fig 1.** Line plots displaying mean spectral power recorded over occipital-parietal electrodes
654 during a 1-minute eyes closed resting baseline. Each line plot represents a single participant.
655 Red lines indicate the identification of a single peak alpha frequency, whilst black lines
656 indicate the calculation of the centre of gravity.

657

658

659 **Appendix 3: Spatially enhanced analyses of alpha power and connectivity using surface**
660 **Laplacian and channel levels analyses.**

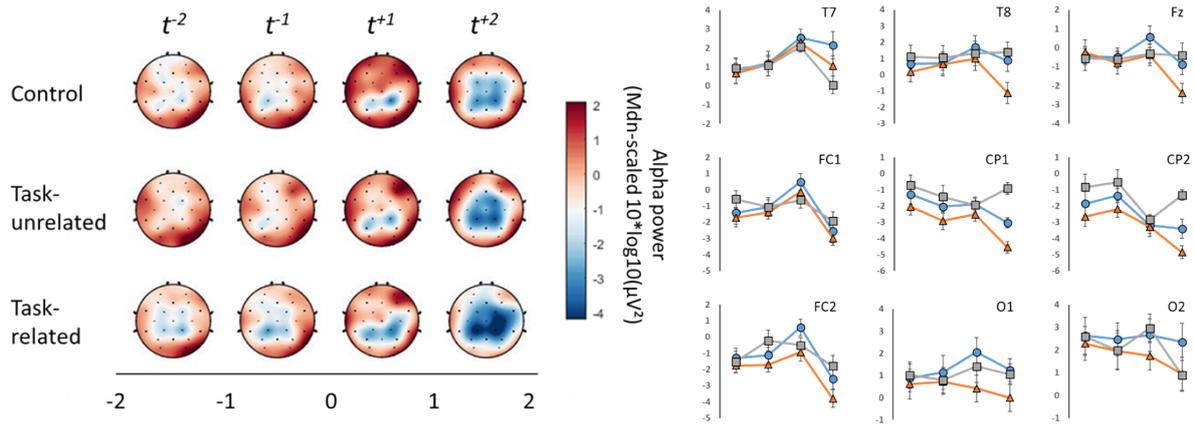
661

662 To enhance the local features of our data, we applied a scalp-level surface Laplacian
663 transformation (Cohen, 2014; function available at <http://mikexcohen.com/lectures.html>),
664 which acts as a spatial band-pass filter to attenuate the effects of volume conduction. In line
665 with our aim to highlight local features, we conducted analyses for alpha power on a channel
666 level over sites T7, T8, Fz, CP1, CP2, FC1, FC2, O1, O2. These channels were chosen based
667 upon previous literature and topographical inspection of our data (Figure 1).

668 **Results**

669 **Alpha power**

670 Results from a 3 (Condition) x 4 (Epoch) x 9 (Channel) repeated measures ANOVA
671 showed a significant main effect of Condition, $F(2, 38) = 11.168, p < .001, \eta^2 = .370$, a
672 main effect of Epoch, $F(1.36, 25.85) = 6.44, p = .011, \eta^2 = .253$, and a main effect of
673 channel, $F(3.74, 71.13) = 16.103, p < .001, \eta^2 = .459$. These effects were superseded by
674 significant Condition x Epoch, $F(6, 114) = 3.606, p = .003, \eta^2 = .160$, and Epoch x Channel,
675 $F(24, 456) = 7.126, p < .001, \eta^2 = .273$, interactions. Due to the aim of this analysis, we
676 only further examined effects involving the factor Channel. For the Epoch x Channel
677 interaction, Bonferroni pairwise comparisons revealed that whilst no channels differed in
678 activity from t^{-2} to t^{-1} , the onset of movement from t^{-1} to t^{-1} saw a significant increase in alpha
679 power at T7 ($p = .041$) and a significant decrease in alpha power at CP2 ($p = .024$) and FC1
680 ($p = .018$). The transition from t^{-1} to t^{+2} then saw significant reductions in alpha power at T8
681 ($p = .013$), Fz ($p = .003$), CP1 ($p = .001$), CP2 ($p = .009$), FC1 ($p < .001$) and FC2 ($p < .001$).
682 Channels O1 and O2 did not change across the entirety of the task.

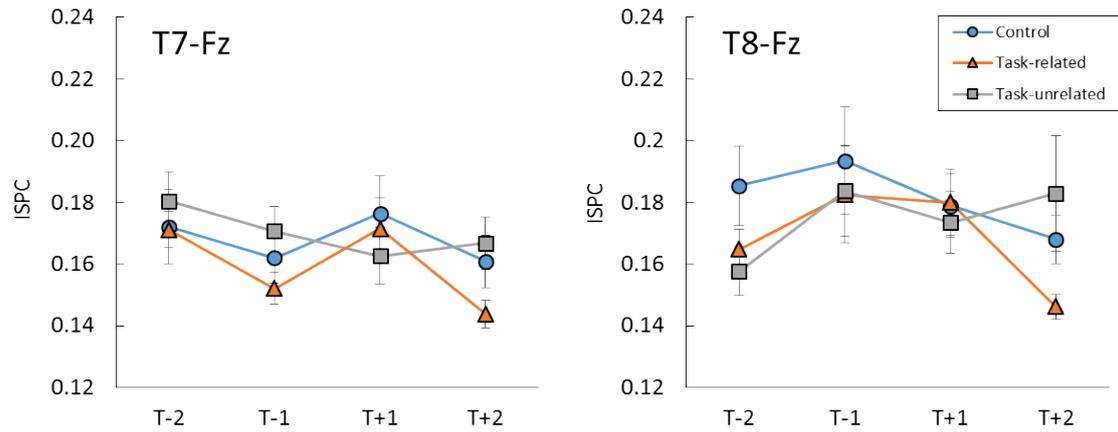


683

684 **Figure 1.** Scalp topographies (left) and line graphs (right) depicting surface Laplacian
685 spatially enhanced regional alpha power across time, relative to movement onset, for each
686 experimental condition.

687 Alpha connectivity

688 A 3 (Condition) x 2 (Hemisphere) x 4 (Epoch) repeated measures ANOVA showed
689 no main effect of Hemisphere, $F(1, 19) = 2.339$, $p = 1.43$, $\eta^2 = .110$, or Epoch, $F(3, 57) =$
690 0.831 , $p = .482$, $\eta^2 = .042$. There was however a significant main effect of Condition, $F(2,$
691 $38) = 4.048$, $p = .025$, $\eta^2 = .176$, that was superseded by a significant Epoch x Condition
692 interaction, $F(6, 114) = 2.489$, $p = .027$, $\eta^2 = .116$. Pairwise comparisons revealed that the
693 task-related condition produced a significant decrease in temporal-frontal connectivity at $t+2$
694 relative to all previous time-points ($ps = .031$), and relative to the control ($p = .017$) and task-
695 unrelated ($p = .02$) conditions (Figure 2). All other interactions were non-significant.



696

697 **Fig 2.** Line plots displaying the mean (\pm s.e.m) intersite phase clustering (ISPC) as a function
698 of condition and epoch for both T7-Fz (left) and T8-Fz (right).

699 **References**

700 Cohen, M. X. (2014). Analyzing neural time series data: theory and practice. MIT press.

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