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Parr, Johnny , Gallicchio, Germano and Wood, Greg  (2023) EEG correlates of verbal and conscious processing of motor control in sport and human movement: a systematic review. *International Review of Sport and Exercise Psychology*, 16 (1). pp. 396-427. ISSN 1750-984X

**DOI:** <https://doi.org/10.1080/1750984X.2021.1878548>

**Publisher:** Taylor & Francis (Routledge)

**Version:** Accepted Version

**Downloaded from:** <https://e-space.mmu.ac.uk/627097/>

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**EEG correlates of verbal and conscious processing of motor control in sport and human movement: A systematic review**

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**Cite as:-**

Parr, J.V.V., Gallicchio, G. & Wood, G. (2021). EEG correlates of verbal and conscious processing of motor control in sport and human movement: A systematic review. *International Review of Sport and Exercise Psychology*

## Abstract

Studies from the sport and human movement sciences have proposed that electroencephalographic (EEG) measures of left-temporal alpha power and left-temporal-frontal connectivity reflect verbal, conscious processing during the learning and control of motor skills. The aim of this systematic review was to synthesize these studies, bring awareness to key methodological considerations, and suggest future research agendas and practices to help generate new knowledge on this topic. An extensive search of electronic databases (PubMed, PsychInfo, GoogleScholar, and SportDiscus) was conducted to identify peer-reviewed literature relating to EEG, conscious movement control and verbal processing. Thirty-eight studies met the inclusion criteria and were retained for quality assessment and synthesis of results. Results suggested that only 36% of studies measuring left-temporal alpha power and only 47% of studies measuring left-temporal-frontal connectivity supported their putative association with verbally-guided, conscious motor processing. There were great methodological inconsistencies across studies and overall studies scored moderate for quality criteria. In conclusion, we question the use of these EEG indices as markers of verbally-guided conscious control until more substantive evidence of their efficacy is provided and stronger methodologies are adopted. We outline six recommendations that can be used to guide such work in the future.

**Keywords:** EEG alpha; reinvestment; left-temporal; power; connectivity; coherence

## **EEG correlates of verbal and conscious processing of motor control in sport and human movement:**

### **A systematic review**

Traditional models of motor skill acquisition propose that as learners become more proficient, they progress through a series of learning stages (Fitts & Posner, 1967). In the early stage, performance is typically erratic, and movement is described as consciously controlled, inconsistent, error strewn, and mentally effortful. As expertise develops, performance improves, and movements become more consistent, effortless, and autonomous. Crucial to this development are fundamental changes in the knowledge structures that are used when controlling movement. During the early stages of learning, novices are thought to test hypotheses about how best to accomplish the task, which builds an explicit understanding of the related movements that are encoded verbally. With increasing expertise, the reliance on these verbal processes (declarative knowledge) diminishes as movement gradually becomes integrated into a procedural, automatic, and non-verbal format. Expert performers can also regress back to an earlier stage of learning when anxious. In such situations, performers are thought to reinvest in declarative knowledge in an effort to safeguard performance by attempting to consciously control their movements using task-specific verbal processes (Masters & Maxwell, 2008). Given the proposed importance of verbal processing in these contexts, it is unsurprising that researchers in sport and human movement sciences have attempted to measure the latent verbal processes employed during movement in order to infer a performer's level of expertise, the development of learning, the efficacy of training interventions, and gain a mechanistic understanding of performance failure under pressure.

Over the last four decades, a number of studies have proposed that the extent to which movement is consciously guided by verbal processing can be quantified objectively by measuring alpha activity (~8 - 12 Hz) recorded across the left-temporal region of the cerebral cortex using electroencephalography (EEG). The reason for this is that the left-temporal region lies at the center of a cortical network that is spatially associated with the processing of verbal information, while EEG activity in the alpha frequency is hypothesized to reflect neuronal inhibition (Klimesch et al., 2007; Jensen & Mazaheri, 2010).

Consequently, researchers have proposed that greater left-temporal alpha indicates decreased verbal processing whereas decreased left-temporal alpha power indicates greater verbal processing in the planning and performance of motor skills.

Hatfield, Landers, and Ray (1984) provided much of the conceptual and empirical basis for the inference of movement-related verbal processing from left-temporal alpha activity in a seminal study. The authors compared the EEG activity of elite marksmen recorded during rifle shooting with the activity recorded during ‘comparative tasks’ performed from the shooting position and designed to elicit predominantly either verbal processing (paragraph reading and comprehension) or visuospatial processing (solving geometric puzzles). They found the ratio of alpha power between right (T4) and left (T3) temporal sites to be higher during the verbal task (shift towards left hemisphere activation) and lower during the visuospatial task (shift towards right hemisphere activation). Consequently, the progressive decrease in the T4-to-T3 alpha ratio observed in the final seconds preceding trigger pull was interpreted as a progressive reduction of left hemispheric verbal activity and a concomitant increase of right hemispheric visuospatial activity. Since then, the construct validity of EEG left-temporal alpha power as a marker of verbal processing during movement preparation and execution has been supported by studies reporting diminished left-temporal alpha power in experts compared to novices (e.g., Haufler et al., 2000; Janelle et al., 2000) and after a period of motor skill practice resulting in improved performance (e.g., Kerick et al., 2004). These findings have been purported to identify a convincing neurophysiological substrate to the notion that, compared to novice performance, expert performance is characterized by diminished verbally-guided motor control.

With the development of more complex EEG signal processing algorithms, researchers have included measures of functional connectivity between cortical regions to explore the influence of verbal processing during the conscious control of movement. While measures of EEG power are thought to reflect the activity of the underlying cortical structures, indices of EEG connectivity are intended to quantify the amount of information that is shared between two cortical regions. For instance, greater alpha

connectivity is interpreted to indicate a more similar and consistent inhibition pattern between two regions, whereas lower alpha connectivity would suggest more distinct inhibition profiles (Gallicchio et al., 2016). Accordingly, researchers in human movement science have focused their efforts in examining alpha connectivity between the left-temporal (T7)<sup>1</sup> and frontal (Fz) regions to infer the co-activation of language and motor processes and, therefore, the extent to which movements are guided by verbal processing. Interestingly, some researchers have exclusively examined left-temporal-frontal connectivity in the upper alpha sub-band (~10-12 Hz) due to evidence that it is more responsive to semantic or task specific information processing compared to the lower alpha sub-band (~8-10 Hz) that is more responsive to general attentional demands (Klimesch, 1999). Left-temporal-frontal alpha connectivity has been reported to reduce as a function of sporting expertise (Deeny et al., 2003) and motor learning (Ghasemian et al., 2017), supporting the proposition that verbal processing decreases with increased skill acquisition. Furthermore, it appears to be sensitive to personality traits, such as the self-reported propensity to consciously control movements (Zhu et al., 2011a), and has been shown to differentiate explicit and implicit motor learning methods that aim to increase or decrease the accrual of declarative knowledge, respectively (Parr et al., 2019, exp 2; Zhu et al., 2011a, 2011b). Finally, left-temporal-frontal connectivity has been reported to increase when encouraging an internal focus of attention during a postural threat task (Ellmers et al., 2016), and under heightened anxiety in a darts task (Lo et al., 2019), suggesting an association between self-focused attention and the propensity to reinvest in declarative knowledge when anxious (Masters & Maxwell, 2008).

Based on these seemingly consistent findings, it could be argued that measures of EEG alpha activity involving the left-temporal cortical region can be used to adequately infer verbal and conscious processes implicated in motor control. However, there are several factors that invite caution on this position. First, it is not deductively valid to infer a specific cognitive process (e.g., verbal processing)

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<sup>1</sup> By the current nomenclature system, site T7 corresponds to the older site T3. Similarly, site T8 corresponds to the older site T4 (American Clinical Neurophysiology Society, 2006).

solely from the activity of a specific brain region (e.g., left-temporal) when a one-to-one mapping cannot be demonstrated (this practice is known as reverse inference; Poldrack, 2006). For example, the left-temporal region is implicated in a diverse and complex range of functions beyond that of language, such as inhibitory motor control (Swick et al., 2008), working memory (Liakakis et al., 2011), and multisensory processing (Wong & Gallate, 2012). Though the comparative task approach pioneered by Hatfield et al. (1984) and developed in subsequent studies has represented an important first step to understand the functional meaning of EEG patterns observed during motor tasks, it cannot establish unambiguously that changes in left-temporal alpha during movement uniquely reflect verbal processing rather than another psychophysiological phenomenon. An extension of this is the experimental manipulation approach adopted in two recent studies by Parr et al. (2020) and Bellomo et al. (2020), whereby cortical activity was assessed via EEG while verbal processing was directly manipulated (via self-talk instructions) during the execution of a jar-manipulation and golf putting task, respectively. Contrary to expectations, changes in verbal processing during movement did not elicit changes that could be attributed to left-temporal alpha in either study, casting doubt on its validity as a marker of verbal processing during the conscious control of movements.

Second, the EEG has a low spatial resolution due to “volume conduction”, a phenomenon whereby the electric fields produced by local neuronal populations propagate across the nearby tissues. While this phenomenon enables the recording of an EEG from the scalp, it also poses challenges for the interpretation of regional effects due to the difficulty of identifying the cortical sources accounting for the sensor-level EEG pattern. Namely, an EEG channel is sensitive not just to local (underlying) cortical sources but also to more distal, or even global, sources (Cohen, 2015). For example, the left-temporal EEG sites could also detect the activation of the left precentral gyrus (Harmon-Jones, 2006), an area that is not involved in verbal processing, when performing movements of the right hand. Similarly, a spatially broad alpha power pattern that included the left-temporal region was reported in a shooting task

performed under exercise-induced arousal (Gallicchio, Finkenzeller, Sattlecker, Lindinger & Hoedlmoser, 2016).

Finally, it is important to acknowledge that, when recording and processing EEG signals, researchers adopt a series of choices that have cascade effects on the data and the resultant interpretation (Robbins et al., 2020). For example, spatial filtering techniques (such as the surface-Laplacian) influence the extent to which sensor-level data are maximally sensitive to local vs global activity, whereas signal denoising procedures influence the extent to which sensor-level data are influenced by non-neural components (i.e., artefacts), often of muscular or motoric origin due to the dynamic nature of motor tasks. In addition, spectral decomposition techniques vary for the level of precision they achieve in identifying the alpha frequency band accurately and in avoiding smearing with neighboring frequencies. As a further complication, while the exact frequency range defining the alpha band (and sub-bands) can vary across individuals (Grandy et al., 2013), many researchers opt for fixed frequency bands (e.g., 10 - 12 Hz for the upper alpha sub-band) rather than individualizing the alpha frequency for each participant (e.g., IAF - IAF+2 for the upper alpha sub-band). While these processing parameters are often chosen on the basis of the study design and objectives, the breadth and sophistication of signal processing procedures has grown remarkably over the last 40 years (Jiang, Bian & Tian, 2019). Therefore, a methodological synthesis of this variation is required to illustrate how certain results may be influenced by the signal processing choices.

The aim of this systematic review was, therefore, to synthesize and critically evaluate the published literature that has inferred a link between verbally-guided, conscious motor processing from measures of left-temporal alpha power or left-temporal-frontal alpha connectivity. By doing so, we intend to (1) determine the efficacy of these EEG indices of verbally-guided conscious motor control, (2) bring awareness to methodological details and how they may influence interpretation, and (3) put in place recommendations for future research agendas and practice.

## Method

The methodology employed for the systematic review was based on the five-step guidelines outlined by Khan et al. (2003). To this end, an electronic search of PubMed, PsycInfo, GoogleScholar, and SPORTDiscus databases was conducted, for research relating to EEG and conscious movement control, up to, and including, September 2020. The following five search terms were used to provide a comprehensive search of the literature: -

1. EEG AND (T7 OR T3) AND Verbal\* AND Motor
2. EEG AND Alpha AND (Coherence OR Connectivity) AND Verbal\* AND Motor
3. EEG AND Alpha Power AND Verbal\* AND Motor
4. EEG AND (ERS OR ERD) AND Verbal\* AND Motor
5. EEG AND Attention\* AND Verbal\* AND Motor

Further studies were identified by searching reference lists. All retrieved results were initially assessed for relevance based on their title and abstract. Studies that were ineligible, irrelevant, or duplicates were removed. The full-text articles of the remaining papers were then screened, and further ineligible or irrelevant results were removed. Included articles must have met the following criteria: (1) be in a peer-reviewed, English language journal, (2) describe an original experimental study, (3) must have used a movement task, (4) must have explicitly related EEG activity to verbal processes and conscious motor control, and (5) must have used an adult population. Full details of, the search results from each database and each search term and an overview of the reason why every paper was excluded is available on the Open Science Framework portal (see here:

[https://osf.io/g4qyb/?view\\_only=2ba2d9b55fc0435bbc1bf9c0c1e49942](https://osf.io/g4qyb/?view_only=2ba2d9b55fc0435bbc1bf9c0c1e49942)). The review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; (Moher et al., 2010) guidelines (see Figure 1).



## PRISMA 2009 Flow Diagram

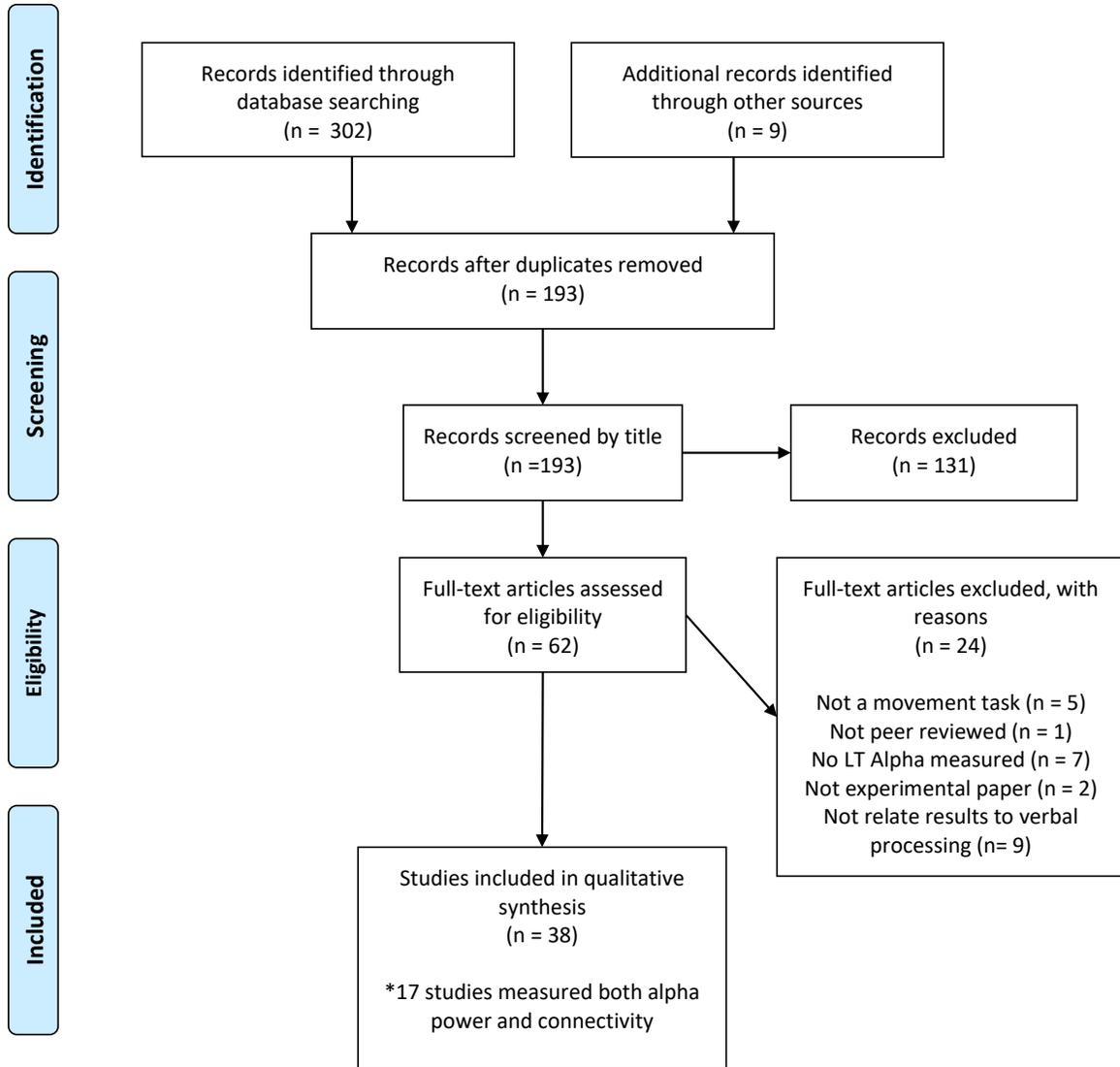


Figure 1.

Key data were extracted from the selected research articles. Data extraction summarized the following information from each paper: authors; year; design; task; definition of alpha frequency; number of electrodes used; connectivity metric computed and the main study findings. To ensure consistency, the authors discussed and cross checked the details of all included studies. Studies were then assessed for quality using the Quality Assessment Tool for Quantitative Studies (QATQS; National Collaborating Centre for Methods and Tools, 2008). QATQS assessed methodological rigor in six areas: (a) selection bias; (b) design; (c) confounders; (d) blinding; (e) data collection method; and (f) withdrawals and dropouts. Each area is assessed on a quality score of 1 to 3 (1 = strong; 2 = moderate; 3 = weak). In addition, we evaluated the rigor of the EEG data acquisition and analysis through six criteria, including artifact handling, alpha definition, regional specificity, temporal precision, controls to volume conduction and secondary measures of verbal and/or conscious processing. Full details are presented in Table 1.

Scores for each area were collated, and a global score was assigned to each included study (Table 2). If there were no weak ratings, the study was given a score of 1 (judged as strong); one weak rating led to a score of 2 (moderate); and two or more weak ratings generated a score of 3 (weak). When calculating the global scores for Table 2, those studies whose average score (for both power and connectivity) lies between two boundaries (i.e., 2 for Power (moderate) and 3 for connectivity (weak)), resulting in a mean of 2.5) will be rounded down (to a 2) in recognition of a more comprehensive EEG analyses procedure. The overall (global) quality rating of each study is presented in Table 2, but full details of this analysis are available in Supplementary Tables 1 and 2.

**Table 1.** A detailed breakdown of the Quality Assessment Tool for Quantitative Studies (QATQS) criteria and additional quality assessment criteria related to EEG

Quality Component	Strong (1)	Moderate (2)	Weak (3)
Selection bias	Very likely to be representative of the target population and greater than 80% participation rate	Somewhat likely to be representative of the target population and 60–79% participation rate	All other responses or not stated
Design	Randomised controlled trial and Controlled clinical trial	Cohort analytic, case-control, cohort, or an interrupted time series	All other designs or design not stated
Confounders	Controlled for at least 80% of confounders	Controlled for 60–79% of confounders	Confounders not controlled for, or not stated
Blinding	Blinding of outcome assessor and study participants to intervention status and/or research question	Blinding of either outcome assessor or study participants	Outcome assessor and study participants are aware of intervention status and/or research question
Data collection methods	Tools are valid and reliable	Tools are valid, but reliability not described	No evidence of validity or reliability
Attrition	Follow-up rate of >80% of participants	Follow-up rate of 60–79% of participants	Follow-up rate of <60% of participants or withdrawals and dropouts not described
Artefact handling	All three pre-processing steps	Two pre-processing steps	One pre-processing step
Evaluated the number of pre-processing steps that included band-pass filtering, waveform inspection to discard noisy channels/trials, and advanced denoising techniques (such as Independent Component Analysis) to identify and reject non-neural components			
Temporal Precision	Analyses time-locked to critical events of the motor task.	Analyses performed on task contingent data only (e.g., no inter-trial activity).	Analyses performed on a mixture of task contingent and task non-contingent data (e.g., inter-trial activity).

Alpha definition	Examined individualized alpha based on the individual reactivity to eye closure or movement execution  AND  Distinguished lower and upper alpha ranges, such as 8 to 10 Hz and 10 to 12 Hz or IAF-2 to IAF and IAF to IAF+2.	Examined individualized alpha based on the individual reactivity to eye closure or movement execution  OR  Distinguished lower and upper alpha ranges, such as 8 to 10 Hz and 10 to 12 Hz or IAF-2 to IAF and IAF to IAF+2.	Only examined a fixed broadband alpha frequency range (such as 8 – 12 Hz) without distinguishing its subbands
Regional specificity	Conducted an extensive analysis of channels and channel pairs related to a large area of the cerebral cortex	Examined the channel or channel pair from the opposite hemisphere	Examined only left-temporal power or left-temporal-frontal connectivity
Controls to volume conduction	Used spatial filtering, such as source reconstruction or surface Laplacian transformation, or used metrics that are insensitive to volume conduction, such as imaginary coherence and PLI	Performed control analyses to show non-zero true connectivity	No control
Secondary measures of verbal and conscious processing (excluding performance measures)  (e.g., self-report, kinematics, EMG, eye-movements)	Two or more secondary measures	One secondary measure	None

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**Note:** For objectivity, we based our evaluation strictly on what was reported in the publications. We concede that a 'weak' score for temporal precision might be due to a mere lack of reporting.

## **Results**

### *Search Results*

The initial literature searches returned 311 papers that, after screening for relevance and matching to inclusion criteria (Figure 1) resulted in 38 papers, three of these papers contained two separate experiments (41 experiments in total). Of these experiments, 17 reported both left-temporal alpha power and left-temporal-frontal alpha connectivity, 11 only reported left-temporal alpha power and 13 only reported left-temporal-frontal alpha connectivity to infer verbal processing during the planning or control of movement. To add clarity to the synthesis of results, studies were grouped under four categories. The category 'Expertise, Training and Performance' included studies that compared experts vs. novices, pre vs. post training, or good vs. poor performances. The category 'Implicit/Explicit Motor Learning and Performing under Pressure' included studies that manipulated implicit learning or competitive pressure. The category 'Personality and Situational Factors' included studies that screened participants for their propensity to consciously control their movements and other situational factors. Finally, the category 'Attentional Focus' included studies that manipulated the focus of attention. An overview of the findings of these studies is now given and an overall rating of the quality of studies in each of these areas is outlined.

### *Expertise, Training and Performance*

Based on the prediction that superior motor performance is generally underpinned by the attenuation of verbal processing, it would be expected that increased left-temporal alpha power and decreased left-temporal-frontal connectivity would be observed as a function of increased expertise, skill learning and performance accuracy.

**Table 2.** An overview of the studies included in the systematic review showing key aspects related to study design, EEG acquisition, analysis procedures and each study's main findings. The colour represents the study quality assessment score for weak (red), moderate (orange) and strong (green) ratings.

Authors	Year	Design	Task	Hand dominance	Alpha definition	Number of electrodes	Connectivity method	Main finding (power)	Main finding (connectivity)
Bellomo et al.	2018	n=56 Explicit vs. implicit learning	Sequence learning task	Right	10-12	4	ISPC	Linear increase in T7 high-alpha power for the explicit group only who also showed steeper learning.	T7-Fz high alpha similar across groups and increased rather than decreased across learning
Bellomo et al.	2020	n=40 Instructional vs motivational self-talk	Golf putting	Right	IAF to IAF+2	32	ISPC	Greater parietal alpha observed for instructional self-talk compared to motivational self-talk	Lower connectivity between Fz and all other channels for instructional group compared to motivational group.
Bertollo et al.	2016	n=10 elite shooters Comparison of performance type	Air-pistol shots	Right	Lower: 8 – 10  Upper: 10-12	32	N/A	Suboptimal-controlled performance associated with greater alpha ERD across frontal, central, and parietal regions. No effects found for the left temporal site (T7)	N/A
Buszard et al.	2015	n=18 Low vs. high anxiety	Tennis task	n/a	10–12	14	Coherence	N/A	Larger verbal working memory associated with increased T3-F3 coherence during pressure condition.
Chan et al.	2019	n=43 Wide vs. narrow Stance	Balancing	n/a	10-12	3	Coherence	N/A	Increased T3-Fz coherence during narrow stance predicted by increased MSRS
Cheng et al.	2017	n=24 Best vs. worst shots	Pistol shooting	Right	Lower: IAF-2 to IAF  Upper: IAF to IAF+2	32	Coherence	N/A	Best shots were associated with significantly lower T3-Fz high-alpha coherence.

Chow et al.	2018	n=39 (young) vs. n=40 (old)  Baseline vs internal focus	Balancing	n/a	10-12	2	Coherence	N/A	T3-Fz increased during internal focus for young adults but not older adults. No association between T3-Fz and MSRS.
Chu & Wong	2018	n=29  High vs low reinvestors	Postural control task	n/a	10-12	6	Coherence	N/A	Increased perceived standing difficulty increased T3-Fz coherence but not T4-Fz. No difference between high and low reinvestors (MSRS).
Daou et al.	2018	n=60  Practice with intention to teach vs. intention to be tested	Golf putting	Right	10-12	20	Coherence	N/A	T8-Fz higher than T7-Fz. Overall coherence reduced at post-test. No effect of group despite more declarative knowledge in teach group.
Deeny et al.	2003	n=19  Experts vs. novices	Rifle shooting	Right (n = 18), Left (n = 1)	Lower: 8-10  Upper: 10-13	13	Coherence	No difference between groups at any electrodes for any frequencies. Suggests similar activation.	Experts lower T3-Fz low alpha (8-10 Hz) and low beta (13 – 22 Hz) coherence. Experts also lower high alpha (10 – 13 Hz) coherence between Fz and all left hemisphere sites. No differences in power observed.

Deeny et al.	2009	n=36 Expert vs. novices	Rifle shooting	Right	Lower: 8–10 Upper: 10–13	10	Coherence	N/A	Experts lower F4-T4 coherence in low alpha. Experts exhibited lower high alpha coherence for all electrode pairs except for T3-F3. The same effect was found for low beta.
Dyke et al.	2014	n=13 Best vs. worst shots	Golf putting	n/a	Lower: 8–10 Upper: 10–12	11	Coherence	Low- and high-alpha frequency bandwidths revealed no significant results of interest.	None of the ANOVAs for EEG coherence revealed significant results.
Ellmers et al.	2016	n=24 Internal vs. external focus conditions	Postural sway task	n/a	Lower: 8–10 Upper: 10–12	3	Coherence	N/A	Internal focus instructions increased self-reported internal focus and T3-Fz coherence
Gallicchio et al.	2016	n=20 Expert vs. novice	Golf putting	Right	10–12	16	Coherence, ISPC	N/A	Lower T7-Fz connectivity for experts compared to novices and for successful compared to unsuccessful putts.
Gallicchio et al.	2017	n=12 Pre vs. post training	Golf putting	Right	10–12 (spectral features assessed)	32	ISPC, imISPC	Performance improvements mediated by increased left-temporal alpha power in the second before backswing initiation.	Performance improved from pre to post. T7-Fz did not change, but did mediate performance within the [-2 -1] epoch.

Ghasemian et al.	2017	n=17 Pre vs. post training	Pursuit tracking task	Right	8–12	8	Coherence	Increased Fz theta and Cz alpha power was observed on the second day of testing.	T3-Fz and Fz-Cz alpha coherence reduced from the first to the second day of testing. Beta Fz-Cz also reduced from pre to post-test within the same testing day.
Hatfield et al.	1984 (Exp. 1)	n=17 Exploratory analysis of experts	Rifle shooting	Right	8–12	5	N/A	Experts display progressive increase in T3 alpha power and decrease in T4 alpha power prior to trigger pull.	N/A
	1984 (Exp.2)	n=15 Shooting vs cognitive task	Rifle shooting	Right	8–12	3	N/A	Results from Exp1 replicated. Additionally, greater T4:T3 alpha power ratio observed for a verbal task compared to a visuospatial task.	N/A.
Hatfield et al.	2013	n=19 Novices Low vs. high anxiety	Pistol shooting	Right	Power: Upper: 10-13 Lower: 8-12  Connectivity: 8-13	30	Coherence	During competition, participants were more anxious/aroused and exhibited a global desynchronization in alpha power.	Increased alpha (8-13 Hz) coherence between Fz and all other sites (F3, F4, C3, C4, T3, T4, P3, P4, O1, O2) observed under pressure.
Haufler et al.	2000	n=15  Expert vs. novice	Rifle shooting	Right	Lower: 9  Upper: 10-11	10	N/A	Experts displayed greater upper-alpha power across left hemisphere compared to novices. Comparative task showed decreased T4:T3 alpha power ratio.	N/A
Hillman et al.	2000	n=7 Skilled marksmen	Rifle shooting	Right	8 – 13	10	N/A	Rejected shots associated with greater alpha power across both cerebral hemispheres compared to executed shots.	N/A

Rejected vs  
executed shots

Hoskens et al.	2020	n=28 Left vs right hand contractions	Hand contractions prior to golf putting	Right	10-12	32	ISPC	N/A	Pre-performance left hand contractions decreased T7-Fz connectivity compared to right hand and no contractions, but this had no effect on performance, kinematics, or muscle activity.
Hunt et al.	2013	n=19 Winners vs. losers	Pistol shooting	Right	Lower: 8-10 Upper: 10-13	30	Coherence	Winning group displayed lower high-alpha power and lower theta power across both hemispheres and time points relative to the losing group.	Cerebral coherence with Fz did not differ between conditions (F3, F4, C3, C4, T3, T4, P3, P4, O1, O2), despite differences in performance and reported confidence.
Kerick et al	2001	n=8 Shooting vs sham conditions	Rifle Shooting	Right	11-13	4	N/A	Marksmen exhibited higher power at T3 than at all other sites during shooting compared with the no-shoot conditions. No such difference between conditions was detected at C3 and C4.	N/A
Kerick et al	2004	n=11 Pre vs Post training	Pistol Shooting	Right	11-13	11	N/A	Event related T3 alpha power increased from the beginning to end of training. However, increased alpha power was also observed over F3, F4, C3, C4, Cz, P3, P4.	N/A

Law & Wong	2020	N = 61 Novices Internal focus vs no focus (repeated measures)	Darts throwing	Right	10-12	3	Coherence	Internal focus decreased throwing accuracy, increased throw time, increased stress (indicated via GSR) and increased T3-Fz coherence compared to the no focus condition	N/A
Lo et al.	2019	n=21 Low vs. high anxiety	Dart throwing	Right	Lower: 8-10 Upper: 10-12	28	Coherence	Increased alpha power during stress condition at O2 only.	Increased T3-Fz coherence [-1 -0.5s] in the stress condition compared to the non-stress condition. No effect for T4-Fz.
Loze et al.	2001	n=6 Best vs. worst shots	Pistol shooting	Right	8-13	3	N/A	Best shots were accompanied by increased occipital (Oz) alpha power prior to shooting. Power over temporal sites (T3 and T4) did not differentiate best and worst shots.	N/A
Parr et al.	2019 (Exp. 1)	n=20 Normal hand vs. prosthetic hand	Reach and grasp task	Right	IAF-2 to IAF+2	32	N/A	When using the prosthetic hand, participants performed worse and exhibited a global decrease in EEG alpha power.	N/A
	2019 (Exp. 2)	n=24 Explicit vs. implicit learning	Reach and grasp with a prosthetic hand	Right	Power: IAF-2 to IAF+2 Connectivity: IAF to IAF+2	32	ISPC	Both groups displayed decreased temporal alpha power at retention despite performance improvements.	Implicit learning lowered upper-alpha T7-Fz connectivity and visual attention.
Parr et al.	2020	n=20	Reach and grasping task	Right	Power: IAF-2 to IAF+2	32	ISPC	Left-temporal alpha power decreased during conscious control, but this	T7-Fz connectivity did not change in response to verbal processing or

		Self-talk vs. no self-talk			Connectivity: IAF to IAF+2			decrease was observed across the entire topography.	conscious motor processing demands.
Reitschel et al.	2011	n=13 Alone vs. social evaluation conditions	Drawing aiming task	Right	Power: Upper: 10-13 Lower: 8-12  Connectivity: 8-13	58	Coherence	No differences were observed in the alpha frequencies. There was a bilateral increase in gamma power in the social evaluation condition.	Higher arousal caused by social evaluation resulted in lower beta T4-Fz and higher Fz coherence with parietal and occipital regions.
Taliep & John	2014	n=18 Skilled vs. less skilled	Cricket batting video anticipation	Right	10-12	108	N/A	Skilled batsmen displayed greater T3 alpha power compared to less skilled batsmen prior to making anticipatory judgements	N/A.
Van Duijn et al.	2017	n=48 Within subject design	Hockey push pass	n/a	10-12	4	Coherence	N/A	WM capacity positively associated with T8-Fz coherence. T7-Fz not associated with performance or MSRS.
Van Duijn et al.	2019	n=48. Implicit vs. explicit learning	Hockey push pass	n/a	10-12	4	Coherence	Analogy displayed higher T7 fast alpha power compared to explicit and control.	No difference between groups for T7-Fz or T8-Fz
Van Duijn et al.	2020	n=28 Preference for verbal vs. visual instructions	Modified basketball free-throw shooting	n/a	10-12	6	Coherence	T7 alpha power increased following analogy instruction for those with high preference for verbal instructions.	T7-Fz and T8-Fz did not differ between participants with either a high or low preference for verbal instructions
Wang et al.	2020	n=38 Elite vs amateur golfers	Golf putting	Right	IAF to IAF+2	32	Coherence	Elite golfers displayed lower alpha power over parietal, right temporal, frontal, and central regions compared to amateurs.	Amateurs displayed higher T7-Fz and T8-Fz coherence compared to elites in the

									second prior to putt execution.
Zhu et al.	2010	n=14 Pre vs. post training	Finger-tapping task	Right	Lower: 8–10 Upper: 10–12	5	Coherence	Higher Fz theta power at post-test for the sequential finger tapping task. No changes in T3 power.	After learning only Fz-T4 slow beta coherence decreased
Zhu et al.	2011a (Exp. 1)	n=16 High vs low reinvestors	Golf putting	Right	Lower: 8–10 Upper: 10–12	7	Coherence	No difference in T3/T4 alpha power between conditions	High reinvestors exhibit increased T3-Fz coherence despite no performance difference. Coherence did not covary with power.
	2011a (Exp. 2)	n=18 Implicit vs. explicit learning	Golf putting	Right	Lower: 8–10 Upper: 10-12	7	Coherence	N/A	Errorless performed better at retention and transfer. They also showed lower T3-Fz and T4-Fz coherence in both the lower and upper alpha bands.
Zhu et al.	2011b	n=18 Implicit vs. explicit learning	Bimanual tracking task	Right	8-12	7	Coherence	N/A	Implicit learning group displayed lower alpha band (8 – 12 Hz) coherence compared to explicit group.

Notes: IAF = Individual Alpha Frequencies; ISPC = Inter-site Phase Clustering

*Left-temporal alpha power.* Three studies compared expert and novice performers, all of which reported increased left-temporal alpha power in experts compared to novices (Haufler et al., 2000; Taliep & John, 2014; Parr et al., 2019, exp 1). Of these, two studies found that experts displayed greater alpha power across multiple regions of the scalp (Haufler et al., 2000; Parr et al., 2019, exp 1), and one study only reported EEG data from temporal regions (Taliep & John, 2014). One study found experts to display lower alpha power over frontal, central, parietal and right temporal regions compared to amateurs (Wang et al., 2020). Another study found “winners” (best performers) to display globally lower alpha power compared to “losers” (Hunt et al., 2013). Four more studies examined the EEG activity before and after a period of training. Of these, only one study found evidence of increased left-temporal alpha power after training (12-14 weeks), though a similar increase was observed across other regions of the cortex (Kerick et al., 2004). The other studies found training to induce a global reduction in alpha power (3 sessions, Gallicchio, 2017), increased alpha power at Cz only (7 training sessions, Ghasemian et al., 2017) and no changes in alpha power (before and after 1 session, Zhu et al., 2010). Three studies reported left-temporal alpha power did not differ when comparing the best and worst shots of skilled shooters (Cheng et al., 2017; Loze et al., 2001) and novice golf-putters (Dyke et al., 2014). Finally, one study found performance that was suboptimal and more controlled to be associated with greater alpha desynchronization across frontal, central and parietal regions, but not across left-temporal regions (Bertollo et al., 2016).

*Left-temporal-frontal alpha connectivity.* Three studies compared sport performers of varying expertise, reporting that left-temporal-frontal connectivity was lower in expert compared to less-skilled shooters (Deeny et al., 2003), lower in expert compared to novice golfers (Gallicchio et al., 2016), and was on average higher, although not significantly, in expert compared to novice shooters, despite the experts displaying significantly lower frontal connectivity across all other channel pairings (Deeny et al., 2009). Three studies measured pre-post changes in T7-Fz connectivity after extended practice, reporting a steady increase in a golf putting task (Gallicchio, 2017), a significant decrease in a pursuit tracking motor skill (Ghasemian et al., 2017), and no change in a sequential finger tapping task (Zhu et al., 2010). Of the

five studies that examined performance accuracy, two found lower T7-Fz connectivity for more accurate performance (Cheng et al., 2017; Gallicchio et al., 2016), and three found no difference between accurate and inaccurate performances (Dyke et al., 2014; Hunt et al., 2013; van Duijn et al., 2017). One study experimentally decreased T7-Fz using pre-performance hand contractions, but this had no significant effect on performance or kinematics (Hoskens et al., 2020).

Overall, of the 13 studies that reported left-temporal alpha power, only 4 (31%) provided some evidence to suggest that increased left-temporal alpha power was associated with increase expertise, training or performance; however, all of these studies found similar effects across multiple regions of the cortex, when they were measured. Of the 11 studies that reported left-temporal alpha connectivity, only 5 studies (45%) provided evidence consistent with the hypothesis that decreased left-temporal-frontal connectivity was associated with increased expertise, training or performance. The overall quality of studies in this area was rated as moderate ( $M = 2.47$ ).

#### *Implicit/Explicit Motor Learning and Performing under Pressure*

Based on the prediction that implicit motor learning lowers the accrual of declarative knowledge compared to explicit motor learning, it would be expected that implicit methods would facilitate increased left-temporal alpha power and decreased left-temporal alpha connectivity, compared to explicit methods. As anxiety has been linked to a propensity to reinvest in declarative knowledge and conscious control, it would be expected that increased anxiety would decrease left-temporal alpha power and increase left-temporal alpha connectivity.

*Left-temporal alpha power.* Three studies compared explicit and implicit training programs, deemed to, respectively, increase and decrease the accrual of movement-related declarative knowledge and the propensity for verbal processing. While one study reported greater left-temporal alpha power following implicit learning (via analogy) compared to explicit learning (van Duijn et al., 2019), another study reported the opposite effect, whereby left-temporal alpha power was greater for explicit learning

compared to implicit learning (Bellomo et al., 2018). The other study found a bilateral reduction in temporal alpha power post-test following both implicit (gaze-training) and explicit training (adhering to movement specific cues; Parr et al., 2019, exp 2). Four studies employed a pressure manipulation to determine the influence of anxiety on cerebral cortical dynamics, two using social evaluation (Bellomo et al., 2018; Rietschel et al., 2011) and two using competition (Hatfield et al., 2013; Hunt et al., 2013). None of these studies found an effect specific to the left-temporal region. Two of these studies found elevated anxiety to induce a global decrease in alpha power (Hatfield et al., 2013; Hunt et al., 2013), and two found no effects for alpha power (Rietschel et al., 2011; Bellomo et al., 2018).

*Left-temporal-frontal alpha connectivity.* Five studies compared pre and post left-temporal-frontal connectivity between groups that received explicit or implicit motor skill training. Implicit training was reported to lower left-temporal-frontal connectivity compared to explicit training for golf putting (Zhu et al., 2011a, exp 2), laparoscopic skills (Zhu et al., 2011b) and prosthetic hand control (Parr et al., 2019, exp 2). However, no difference in T7-Fz connectivity between implicit (via analogy), explicit, or control training was found for hockey push-pass performance (van Duijn et al., 2019), and both implicit and explicit training groups exhibited increased T7-Fz connectivity in a motor sequence task (Bellomo et al., 2018). Seven studies compared T7-Fz connectivity under varying pressure manipulations. Of these, one study found pressure to heighten anxiety and T7-Fz connectivity in a dart throwing task (Lo et al., 2019), and one study found greater pressure to elevate T7-Fz connectivity following explicit but not implicit golf-putting training (Zhu et al., 2011a, exp 2). One study found T7-Fz connectivity to increase linearly across four training blocks followed by a pressurized transfer block for both explicit and implicit training groups, though it is unclear if increased T7-Fz at transfer was driven by heightened anxiety or extended practice (Bellomo et al., 2018). However, T7-Fz connectivity was unaltered under levels of heightened pressure in a golf-putting task (Gallicchio et al., 2016), an aiming task (Rietschel et al., 2011), and a tennis task (Buszard et al., 2016). A global increase in frontal (Fz) connectivity was observed under pressure in pistol shooting (Hatfield et al., 2013).

Overall, of the 6 studies that reported left-temporal alpha power, 3 (50%) provided some evidence to suggest left-temporal alpha power is responsive to manipulations that might influence the reliance on declarative knowledge. Of the 10 studies that reported left-temporal alpha connectivity, only 5 (50%) provided evidence consistent with the hypothesis that left-temporal-frontal connectivity would increase in response to conditions that increase the likelihood of declarative and/or conscious processing. The overall quality of studies in this area was rated as moderate ( $M = 2.09$ ).

### *Attentional Focus*

It would be predicted that those studies that manipulate an internal focus of attention to movement-specific verbal cues would elicit decreased left-temporal alpha power and increased left-temporal alpha connectivity reflective of conscious movement control.

*Left-temporal alpha power.* Only two studies attempted to directly manipulate the attentional focus of participants during motor performance via self-talk (Parr et al., 2020; Bellomo et al., 2020). One study reported a global decrease in alpha power when encouraging participants to engage in conscious, verbal, motor processing, but no changes when encouraging verbal rehearsal only (i.e., task unrelated verbal rehearsal; Parr et al., 2020). The other study found instructional self-talk (assumed to provoke increased conscious processing) to increase parietal alpha power relative to motivational self-talk during a golf-putting task (Bellomo et al., 2020). No differences were observed across the left-temporal region.

*Left-temporal-frontal alpha connectivity.* Five studies examined how changes in attentional focus during motor performance influence T7-Fz connectivity. Two of these studies showed an internal focus of attention to increase T7-Fz connectivity relative to baseline (Chow et al., 2019; Ellmers et al., 2016). One study found an internal focus of attention to increase T7-Fz connectivity compared to a no-focus condition (Law & Wong, 2020). One study reported T7-Fz connectivity to be unchanged, relative to baseline, when encouraging verbal or conscious processing (Parr et al., 2020). The other study found

motivational self-talk to elicit greater frontal (Fz) connectivity with all channels (including T7) compared to instructional self-talk (greater engagement of conscious processing; Bellomo et al., 2020).

Overall, the only one of the two studies that manipulated attentional focus via self-talk provided evidence that left-temporal alpha power would decrease under conditions that increase self-talk and direct an individual's attention to the mechanics of the movement. Of the 5 studies that reported left-temporal-frontal connectivity, 3 provided evidence consistent with the hypothesis that an internal focus of attention is associated with increased T7-Fz connectivity. The overall quality of studies in this area was rated as moderate ( $M = 2.20$ ).

### *Personality and Situational Factors*

There are certain situations and individual characteristics that have been shown to increase the propensity or preference for verbal processing and conscious control. Such individuals or circumstances would be expected to be related to decreased left-temporal alpha power and increased left-temporal alpha connectivity.

*Left-temporal alpha power.* One study found expert marksmen to display a progressive decrease in the ratio between right and left-temporal alpha power prior to trigger pull (Hatfield et al., 1984, exp 1). A follow up experiment using comparative verbal and visuospatial tasks suggested that the shift to greater left-temporal alpha power reflects the inhibition of verbal processes (Hatfield et al., 1984, exp 2). Only one study compared individuals with either a high or low propensity to consciously control their movements, reporting no differences in left-temporal alpha power between groups (Zhu et al., 2011a, exp 1). One study examined whether the preference for verbal instructions influence cortical activity following the provision of an analogy instruction, reporting those with high verbal preference exhibited an increase in left-temporal alpha power whereas those with a low verbal preference did not show any change (van Duijn et al., 2020). Another study compared cortical activity during a shooting task with a “sham” shooting task and a stance-only task (Kerick et al., 2001). They reported increased left-temporal

alpha power during the actual shooting task only, suggesting task specific cognitive processing rather than simply motor activity to position the gun. Finally, one study compared EEG activity between executed (optimal state) and rejected (suboptimal state) rifle shots and found rejected shots to be associated with greater alpha power across both cerebral hemispheres (Hillman et al., 2000).

*Left-temporal-frontal alpha connectivity.* Six studies examined whether the propensity to reinvest in conscious control processes could affect left-temporal-frontal connectivity. These studies reported no differences between high and low reinvestors (Chu & Wong, 2019; Ellmers et al., 2016), no correlation between MSRS scores and T7-Fz connectivity (Chow et al., 2019; van Duijn et al., 2017), higher MSRS scores to be associated with less change in T7-Fz connectivity during postural threat (Chan et al., 2019), and high reinvestors to exhibit greater T7-Fz connectivity compared to low reinvestors in golf putting (Zhu et al., 2011a, exp 1). One study found that larger verbal working memory scores were associated with increased T7-F3 connectivity (Buszard et al., 2016). One study found that learning with the intention to teach a golf putting did not affect T7-Fz connectivity despite encouraging greater declarative knowledge (Daou et al., 2018). One study found that the preference for verbal instructions when given a task-related analogy did not influence T7-Fz connectivity (van Duijn et al., 2020).

Overall, 2 of 5 studies (40%) provided evidence to suggest that decreased left-temporal alpha power was associated with personality and/or situational factors that were predicted to increase conscious and/or verbal processing. Of the 9 studies that reported left-temporal alpha connectivity, only 3 studies (33%) provided evidence to suggest that increased left-temporal-frontal connectivity was associated with personality and/or situational factors that were predicted to increase conscious and/or verbal processing. The overall quality of studies in this area was rated as weak ( $M = 2.61$ ).

## **Discussion**

The aims of this systematic review were threefold. First, to synthesize and critically evaluate the published literature that has inferred a link between verbally-guided, conscious motor processing from

measures of left-temporal alpha power and/or left-temporal-frontal alpha connectivity. Second, to increase knowledge on the influence of different EEG processing routines on the interpretation of these EEG measurements. Third, to inform future research agendas and practice.

### *Literature synthesis*

The evidence-base for the reliability of left-temporal alpha power and left-temporal-frontal connectivity as a measure of conscious, verbally-guided action is weak. Only 36% of the experiments reporting left-temporal alpha power (i.e., 10 of 28) and only 47% of the studies reporting left-temporal-frontal alpha connectivity (i.e., 14 of 30) provided evidence to support the predictions that would be expected if these EEG measures were truly reflective of verbal guided, conscious motor processing. These studies scored moderate for quality ( $M = 2.32$ ).

If left-temporal alpha were an adequate (inverse) index of verbally-guided motor control, we expected it to be reliably associated with superior motor performance across studies. Yet, only 38% of all studies examining the cortical dynamics underpinning superior motor performance and learning found greater expertise to be associated with decreased left-temporal activity or left-temporal-frontal connectivity. Furthermore, although some research suggests a link between the self-reported propensity for conscious control and poor motor execution, there is limited evidence that this link can be inferred through measures of left-temporal alpha activity and connectivity. Finally, it is widely accepted that verbally-guided, conscious processing can be directly increased or decreased by manipulating the content of practice (explicit vs implicit learning strategies), the magnitude of performance pressure, and the focus of an individual's attention. These manipulations also failed to reliably influence left-temporal alpha activity in the manner predicted.

When considering the incongruences between predictions and empirical findings, together with the null findings of studies that have directly manipulated verbal and conscious processing in motor tasks (i.e., Bellomo et al., 2020; Parr et al., 2020), it appears sensible to cast doubt on the thesis that left-

temporal alpha power and left-temporal-frontal alpha connectivity are reliably related to changes in verbal processing during conscious motor control.

### ***Methodological and interpretation caveats***

It is important to acknowledge that inconsistencies in the evidence associating left-temporal alpha power and left-temporal-frontal connectivity with verbal guided, conscious processing may also be driven by equally inconsistent methods used to collect and analyze EEG data. For example, when extracting features of interest from EEG signals, researchers are required to take a number of signal processing decisions – some more intentional than others – that can have an impact on the results and their interpretation (cf. Robbins et al., 2020). Consequently, there are a number of methodological issues that could be considered as caveats to the interpretation of left-temporal alpha and confounding variables that need greater consideration in this context.

### ***Skill Level***

The findings of this review failed to support a common assumption within the literature that suggests the reliance on verbal processing and conscious control shares a negative linear relationship with increased task expertise. It has been recently outlined that this view is over simplistic and potentially underplays the complex nature surrounding the cortical dynamics related to skill acquisition and expertise (Toner & Moran, 2020). For example, some degree of practice in novices may elevate verbal processing (i.e., diminished left-temporal alpha power and elevated left-temporal-frontal alpha connectivity) as the participants become familiar with the details of the task (e.g., Gallicchio et al., 2017). The phenomenological experience of decreased verbally-guided movement control (and the accompanying brain dynamics) may, therefore, only be achieved at the later stages of learning (Hatfield, 2018). However, it has been suggested that even expert performers can show an adaptability in their attentional focus (and their propensity to consciously control their movement) when faced with challenging situations or to increase the certainty of performance outcome (Toner & Moran, 2014; Bertollo., 2016).

For example, Wang et al. (2020) recently found expert golfers to display a more global reduction in alpha power compared to amateurs, concluding that experts display greater psychomotor refinement via resource allocation to motor programming and visuospatial attention. Evidently, although these measures can provide useful insights to the cortical dynamics underpinning motor performance, researchers should be cautious when attempting to use these measures to infer an individual's status or progression along the, arguably non-linear, skill acquisition continuum.

### *Secondary measures of verbal and conscious processing*

A key issue in the reviewed literature is the tendency to infer verbal processing solely from the activation of the left-temporal region (reverse inference). While such inference is appealing and often useful, confirmation of the inferred cognitive process can be supported by using supplementary measures confirming its presence. Despite this, 19 experiments (46%) assumed verbal processing during conscious movement control from the inferred relationship between EEG alpha activity and poorer learning and performance. Twenty-two experiments (54%) used either one ( $n = 14$ ) or two or more ( $n = 8$ ) secondary measures to triangulate evidence to support this assumption. The majority of these studies used self-report inventories that either suggested participants might have a propensity to reinvest in explicit, verbal processing (Bellomo et al., 2018; Chan et al., 2019; Chow et al., 2019; Chu & Wong, 2019; Ellmers et al., 2016; Gallicchio, 2017; Gallicchio et al., 2016; van Duijn et al., 2017; Zhu et al., 2011a) a preference for verbal processing (Buszard et al., 2016; van Duijn et al., 2020) or they were used as a measure of the magnitude and frequency of verbal processing, as well as the amount of mental effort required to perform the task (Parr et al., 2020). Other studies used verbal recall protocols that asked participants what they were thinking about during the task (Daou et al., 2018; van Duijn et al., 2019; Zhu et al., 2011a, exp. 2), eye tracking to correlate EEG activity and eye movement behaviors (Parr et al., 2019) and measures of cardiac activity as markers of conscious control (Bellomo et al., 2020). Despite conscious control being related to changes in movement kinematics (e.g., increased movement jerk and slower movements) only three studies used kinematics to show how verbal processing impacted upon movement control (i.e.,

Bellomo et al. 2020; Parr et al., 2020; Hoskens et al., 2020). While the adoption of such methods is encouraging, it is clear that a large proportion of work in this area simply infers verbal processing from left-temporal alpha activity coupled with poorer learning and performance.

*Regional specificity, temporal precision and artefact correction*

The regional specificity of data described is generally low, with 17 experiments using 7 or fewer electrodes (41%), and only 13 using electrode arrays of 28 or more (32%). Additionally, less than a third of experiments ( $n = 10$ , 24%) reported using advanced denoising techniques (such as ICA) to remove signal artefacts, none of which were those experiments using 6 or fewer electrode arrays ( $n = 13$ , 32%). This is potentially problematic if we are to recognize that activity recorded over channels Fz and T7 are likely to be strongly influenced by a complex mixture of volume-conducted local and distal sources rather than uniquely reflecting the activity of the underlying motor planning and left-temporal regions (Cooke, 2013). Additionally, EEG data is sensitive to the muscular contractions typically exhibited during the motor-skill tasks seen in the present review (18 experiments analyzed EEG data during movement, 44%), increasing the risk of frequent biological artefacts that produce electrical activity of a much higher amplitude than the ones generated by neural sources (Mognon et al., 2011). Consequently, those experiments that apply simplistic artefact rejection techniques to small electrode arrays are faced with a serious inferential hazard, as muscular activity can be detected across the entire scalp (Goncharova et al., 2003) and masquerade as true neural activity (McMenamin et al., 2010).

This issue is typically tackled by including an extensive number of trials of high temporal precision, allowing for the identification and rejection of contaminated data, the mitigation of task irrelevant processes, and thus the enhancement of the signal-to-noise ratio. However, such measures are often difficult to achieve during motor tasks, given the element of fatigue and the temporal “jitter” that may occur when recording EEG during movement - as each movement repetition may differ for the exact timing of each movement phase. For example, several postural threat studies included in this review opted

to record low-density EEG (maximum 6 electrodes) over a single epoch of continuous data (at least 15 seconds) for a maximum of two trials, relying solely on band-pass filtering to correct for biological artefact. In such instances, appropriate EEG artefact rejection becomes increasingly important as “bad-trials” (or epochs) cannot be rejected and the intra/inter-individual differences in bodily movements are harder to control. Furthermore, data analyzed from these longer and less precisely defined epochs are more likely to capture inter-trial task-irrelevant processing, inhibiting the extent to which psychological meaning can be applied to the recorded signal.

It is therefore important that future research strives to optimize artefact correction, spatial resolution, and temporal precision if we are to understand the neural underpinnings of conscious and verbally-guided movement. As mentioned, advanced denoising techniques were applied by 24% of reviewed studies and are a reliable approach to the separation of artefactual activity from neural activity (Jung et al., 1998). Similarly, the surface Laplacian, applied in only two reviewed studies, is a spatial filter that strongly attenuates volume conduction and therefore minimizes the influence of activity that is common to a wide range of channels, such as movement artefacts. From the present review, it is evident that more research applying such methods is needed to validate left-temporal-frontal activity as a measure of conscious, verbal, motor control.

### *Connectivity estimates*

The poor controls to volume conduction evident from the present review is particularly problematic for the interpretation of connectivity. This is because connectivity can ambiguously reflect the enhanced co-activation between two independent neural sources, or the activity of a single neural source that is projected to multiple EEG channels. Indeed, the preferred method for estimating connectivity was magnitude-squared coherence ( $n = 24$ , 59%), with several more recent experiments (2016 onwards) instead opting for inter-site phase clustering (ISPC,  $n = 7$ , 17%). Despite its popularity, magnitude-squared coherence (often referred to simply as “coherence”) is a measure that has been

criticized for its reliance on the relative amplitude (power) as well as the relative phase (i.e., the temporal information of oscillations) between two signals (Lachaux et al., 1999), making it susceptible to strong increases or decreases in power across electrode pairings. Consequently, coherence does not specifically quantify phasic relationships and may be influenced by fluctuations in EEG amplitude and signal artefact (Cohen, 2014). For example, even if the phases at two channels are independent, coherence will increase if their amplitudes fluctuate in a synchronous manner. Given that differences in EEG alpha power across various cortical regions have been observed in the comparison between experts and novices of many sports skills (Babiloni et al., 2010; Baumeister et al., 2008; Del Percio et al., 2009; Janelle et al., 2000), it is important to recognize that coherence measures may reflect large scale changes in cortical activation that are projected to many electrodes simultaneously, as opposed to inter-regional communication.

The recent trend to measure connectivity using ISPC suggests an attempt to overcome the limitations of magnitude squared coherence. Indeed, ISPC is a connectivity estimation that is purely dependent on the consistency of the phase angle differences between two signals over time, and therefore subverts the independent influence of absolute power fluctuations (Cohen, 2014). Though advantageous, ISPC is still susceptible to the effects of volume conduction, as spurious activity projecting from a single source to two channels will mask as synchronized activation. Future work may therefore benefit from connectivity estimates that are insensitive to volume conduction, such as the phase-lag index (Stam et al., 2007) and imaginary coherence (Nolte et al., 2004), or consider the application of a surface Laplacian filter in combination with the more popular magnitude squared coherence and ISPC. However, methods to minimize volume conduction do come at the cost of being ultimately more conservative in their approach and are thus more likely to underestimate true phasic relationships. Deciding upon a more conservative or more liberal approach to calculating connectivity should therefore be considered alongside the relative risk of committing a type-1 (false-positive) or type-2 (false-negative) error (Cohen, 2015). For example, a study that has a low number of trials, poor control over muscular artefact, and undertakes fewer pre-processing steps will be at particular risk of volume conduction inflating their

connectivity estimates. This underlines the importance of such controls in research that examines the conscious control of more gross motor movements typical of those used in the reviewed research from sport and rehabilitation.

### *Alpha frequency band definition*

If we are to assume that upper alpha activity is the most relevant for deciphering verbal processing, then we should acknowledge that the *true* upper alpha frequency band shows large inter-individual differences. In fact, evidence has shown that the IAF - the dominant alpha frequency (ca. 10 Hz) around which the alpha frequency band is defined - can vary anywhere between 7.5 and 12.5 Hz (Grandy et al., 2013) with lower values associated with older age (Chiang et al., 2011; Grandy et al., 2013) and decreasing perceptual-cognitive ability (Klimesch, 1999). Consequently, averaging across fixed frequency bands (i.e., 10-12 Hz) may include activity from neighboring frequencies and, therefore, generate spurious interpretations. Despite this, only 5 experiments from the present review defined upper alpha by attempting to identify the IAF of participants (upper alpha defined as IAF to IAF+2 Hz). From the experiments opting to calculate upper alpha using fixed alpha frequency bands, the definition of the upper alpha band also varied from 10-12 Hz ( $n = 21$ ), 10-13 Hz ( $n = 5$ ), 11-13 Hz ( $n = 2$ ) and 10-11 Hz ( $n = 1$ ). Seven experiments opted not to separate alpha between its upper and lower components. Evidently, these inconsistencies in the definition of upper alpha raise further concerns regarding the inclination to limit analyses within this somewhat arbitrary frequency band - particularly for those studies using older adults.

### *Task characteristics*

There was an overwhelming tendency to use tasks that primarily involved the upper limbs ( $n = 38$ , 93%), with the majority of these experiments reporting the use of right-handed tasks ( $n = 16$ , 39%) or tasks that were bimanual in nature but biased to the right-hand side (i.e., golf putting,  $n = 17$ , 41%). Only one study used a task that was completely bimanual in nature (i.e., bimanual tracking task, Zhu et al.,

2011b), whereas four studies did not report the laterality of their upper-limb task (Buszard et al., 2016; van Duijn et al., 2017, 2019, 2020). Of these upper-limb experiments, 32 (78%) also reported the recruitment of right-handed participants, whereas 5 did not report hand dominance. Only a single participant was reported as being left-handed (Deeny et al., 2003).

This clear bias towards right upper-limb tasks questions the interpretation of left-temporal alpha power and left-temporal-frontal connectivity when acknowledging evidence that task laterality, handedness, and the type of movement can independently influence cortical activity. For example, pre-movement alpha desynchronization displays a contralateral preponderance, such that right-handed motor actions will elicit a decrease in alpha power that is larger in the left hemisphere (Pfurtscheller & Aranibar, 1979; Pfurtscheller & Berghold, 1989). While this effect is primarily observed over the sensorimotor cortex, reflecting the activation of the left precentral gyrus (approximately electrode C3; Homan et al., 1987), it has also been observed over left-frontal and temporal regions during right hand contractions (Harmon-Jones, 2006), like those reported in the movement tasks described above. The lateralization of alpha desynchronization to the contralateral side is also larger when using the dominant hand, larger for right-handed participants, and larger for slower movements (Pfurtscheller et al., 1996; Stancák & Wackermann, 1998). These findings therefore have important implications for the present review, given the overwhelming tendency to use both right-handed tasks and right-handed participants to describe a phenomenon localized to the left-temporal region. Indeed, the development of skilled motor performance is often characterized by a refinement of energy expenditure that is not only observed as reduced cortical arousal, but also as reduced motor unit recruitment to produce a given force (Lay et al., 2002). It could, therefore, be argued that the reduced left-temporal activity (i.e., greater alpha power) observed during skilled (right-handed) motor performance could be driven by improved motor-related efficiency that might dampen the spatial spread of the alpha desynchronization of alpha power. Accordingly, it would be highly beneficial if future studies indicated the extent to which current findings relating to left-temporal alpha activity might be independently affected by handedness and/or task laterality (cf. Cooke, 2013).

## ***Moving forward***

The findings of this systematic review provided evidence that questions the use of left-temporal alpha power and left-temporal-frontal alpha connectivity as reliable indices of verbally-guided, conscious movement control. The utility of EEG measures in applied and mechanistic research and the role of verbal processing in skill acquisition are undisputed. However, the thesis that some EEG measures reliably reflect verbally-guided conscious motor processing, or that this activity is uniquely localized to the left-temporal region, now has to be questioned. For clarity, this does not mean that these measures have no value, but rather that the current literature is not well equipped to provide rigorous tests of the interpretation of left-temporal alpha power and left-temporal-frontal connectivity due to the myriad of methodological inconsistencies across studies. Moving forward, one challenge is to facilitate the comparison across studies reporting different alpha frequencies, different number of electrodes, different artefact rejection protocols, poor controls to volume conduction and limited methods to confirm the presence of verbal and conscious processing. It is clear that consensus needs to be drawn regarding which methods should be used in order to examine the relationship between verbal processing, conscious control and motor performance in future work. Below are six recommendations that can be used as a guide in this endeavor, ranked in order of importance.

### **1. Secondary measures of verbal and conscious processing**

Researchers should adopt a cross-disciplinary approach to measurement and triangulate physiological, psychological, and behavioral data to evaluate the contribution of verbal processing and conscious control to movement execution (Bertollo, Doppelmayr & Robazza, 2020). Indices complementary to EEG could include self-report, verbal recall, eye tracking, kinematics, EMG activity or better still, a combination of these approaches (e.g., Parr et al., 2020; Bellomo et al., 2020).

## **2. Temporal precision**

Researchers should aim to design their studies in a manner that allows them to analyze and report the EEG signals in precisely defined intervals that are time-locked to the most relevant movement of the task and that are not influenced by task-irrelevant activity recorded between movement repetitions. By doing so, researchers can have greater confidence when attributing psychological meaning to the recorded EEG signal.

## **3. Artefact handling**

To adequately correct for the muscular artefacts that are likely to occur during motor control tasks, spatial decomposition techniques (such as ICA) should be used in combination with filtering and visual inspection to optimally separate non-neural activity from data. In addition, as newer technology emerges, we advise researchers to employ active electrodes and mobile systems to reduce electrical artefacts due to wire swinging during movement.

## **4. Controls to volume conduction**

To limit the influence of volume conduction upon connectivity estimates, researchers should consider applying a spatial filter (such as the surface Laplacian) to their data or using estimates that are insensitive to the effects of volume conduction (i.e., phase-lag index or imaginary coherence). A comparison between connectivity estimates that either do or do not control for volume conduction may provide insights to its independent influence on data (e.g. Gallicchio, 2017). A surface Laplacian will also improve the topographical localization of data and the likelihood that data only reflects the activity of local sources.

## **5. Regional and frequency specificity**

Conscious motor control should be considered with respect to the entire scalp, rather than being limited to the left-temporal region. This is because conscious motor control is a multifaceted

process where actions are not only associated with greater verbal processing, but also greater muscular effort, greater demands on working memory, and an increased reliance on sensorimotor feedback to monitor and correct ongoing movements. Indeed, the experiments in the present review that undertook more extensive EEG analyses ( $n = 19$ , 46%) generally found changes in power ( $n = 13$ ) and connectivity ( $n = 5$ ) to occur across various scalp locations ( $n = 17$ ) and frequency bands ( $n = 12$ ). Though a spatially broad effect does not exclude the interpretation of reduced verbally-guided motor processing per se, it suggests that the multitude of cognitive-motor processes that combine to characterise conscious motor control are likely to emerge from a distributed cortical network that is too extensive to be reduced to a single EEG measure that can be applied to all contexts and tasks (Parr et al., 2020). Researchers should also avoid overlooking changes in connectivity occurring outside of the upper alpha band until a theoretical basis for doing so becomes apparent. Indeed, the overwhelming tendency to uniquely measure left-temporal-frontal connectivity in the upper alpha band is generally driven by evidence that upper-alpha *power* is sensitive to semantic or task specific information processing (Klimesch, 1999) and that lower frequencies (including alpha *and* theta) are primarily responsible for mediating long-range cortical integration, including those between frontal and temporal regions (von Stein & Sarnthein, 2000). Yet, the conceptual relevance of changes in connectivity pathways across varying frequency ranges is still poorly understood. Restricting analyses to a narrow 2 Hz range is therefore likely to overlook a multitude of complex interactions that occur as the brain reorganizes across the learning process.

## 6. Individual alpha frequencies

Due to individual differences in the dominant alpha frequency, it is useful to adjust the boundaries of the alpha band for each participant. A widely accepted procedure consists in using the IAF, determined as peak or center of gravity, as a cut-off point between its lower and upper sub-bands (Klimesch, 1999). This is particularly important for research recruiting older adults or

individuals with reduced perceptual-cognitive ability. Future research could even consider adjusting the IAF relative to each recording site, given that alpha waves are supposedly faster at posterior sites and slower at anterior sites (Niedermeyer & Silva, 2005). Furthermore, recent evidence suggests that the IAF can arbitrarily decrease across the course of a 1-hour recording session (Benwell et al., 2019). Monitoring changes in the alpha frequency boundaries across the course of an experiment may therefore be required to ensure optimal accuracy.

Although the application of the aforementioned steps would lead to more reproducible and consistent research, we are not attempting to advocate a strict ‘gold standard’ for which to follow, as this is likely to be counterproductive (cf. Robbins et al., 2020). We believe that individualizing alpha frequencies and using multiple, stringent pre-processing procedures in order to increase the reliability and validity of the data is critical but the specific analysis pathway researchers undertake (i.e., connectivity estimation, channel selection) will depend on their hypotheses and research design. The findings of this review suggest that such decisions are still in their infancy and therefore we believe that more exploratory analyses are needed in order to gain a better understanding of both the methods and the underlying neural phenomena behind conscious movement control.

### ***Conclusion***

A reliable neurophysiological marker of the verbal processes characteristic of conscious motor control could hold great value for understanding motor performance and learning in sport and rehabilitation. Based on the synthesis of the available evidence, we suggest that there is a need for stronger evidence before left-temporal alpha power or left-temporal-frontal alpha connectivity are accepted to uniquely represent such a marker. To strengthen or confute this conclusion, researchers need to employ a more rigorous methodological approach to the collection, pre-processing, analysis and interpretation of data and more research is needed which experimentally manipulates verbally-guided,

conscious motor control. It is hoped that the recommendations outlined in this systematic review will go at least some way in directing such work.

## **Acknowledgements**

We would like to acknowledge the anonymous peer reviewers. Their stimulating and insightful suggestions have significantly improved the quality of our review.

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## Appendix 1: Quality assessment

**Table S1.** An overview of the quality assessment details for the studies that reported left-temporal alpha power

Authors	Year	Selection bias	Design	Confounders	Blinding	Data Collection	Attrition	Artefact handling	Temporal precision	Alpha definition	Regional specificity	Verbal or conscious processing measures	Global score
Bellomo et al.	2018	1	2	1	2	1	1	2	3	2	2	1	2
Bellomo et al.	2020	1	2	1	2	1	1	1	1	1	1	1	1
Bertollo et al.	2016	1	2	1	2	1	1	2	1	2	1	3	2
Deeny et al.	2003	1	2	1	2	1	1	2	1	2	1	3	2
Dyke et al.	2014	1	2	1	2	1	1	1	1	2	1	3	2
Gallicchio et al.	2017	1	2	1	2	1	1	1	1	2	1	2	1
Ghasemian et al.	2017	1	2	1	2	1	1	2	3	3	2	3	3
Hatfield et al.	1984 (Exp.1)	1	3	1	2	1	1	3	1	3	2	3	3
	1984 (Exp. 2)	1	3	1	2	1	1	3	1	3	2	3	3
Hatfield et al.	2013	1	2	1	2	1	1	2	1	2	1	1	1

Haufler et al.	2000	1	2	2	2	1	1	2	1	2	1	3	2
Hillman et al.	2000	1	2	1	2	1	1	2	1	3	1	3	3
Hunt et al.	2013	1	2	1	2	1	1	2	1	2	1	3	2
Kerick et al.	2001	1	2	1	2	1	1	2	1	2	2	3	2
Kerick et al.	2004	1	2	1	2	1	1	2	1	2	2	3	2
Lo et al.	2019	1	2	1	2	1	1	2	1	2	1	3	2
Loze et al.	2001	1	2	1	2	1	1	2	1	3	2	3	3
Parr et al.	2019 (Exp. 1)	1	2	1	2	1	1	1	1	3	1	2	2
Parr et al.	2019 (Exp. 2)	1	2	1	2	1	1	1	1	3	1	2	2
Parr et al.	2020	1	2	1	2	1	1	1	1	3	1	1	2
Reitschel et al.	2011	1	2	1	2	1	1	2	1	2	1	3	2
Taliep & John	2014	1	2	1	2	1	1	2	1	2	2	3	2
Van Duijn et al.	2019	1	2	1	2	1	1	3	1	2	2	2	2

Van Duijn et al.	2020	1	2	1	2	1	1	3	1	2	2	2	2
Wang et al.	2020	1	2	1	2	1	1	3	1	1	1	3	3
Zhu et al.	2010	1	2	1	2	1	1	2	3	2	1	3	3

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**Table S2.** An overview of the quality assessment details for the studies that reported left-temporal frontal connectivity

Authors	Year	Selection bias	Design	Confounders	Blinding	Data Collection	Attrition	Artefact handling	Temporal precision	Alpha definition	Regional specificity	Volume conduction control	Verbal or conscious processing measures	Global score
Bellomo et al.	2018	1	2	1	2	1	1	2	3	2	2	3	1	3
Bellomo et al.	2020	1	2	1	2	1	1	1	1	1	1	2	1	1
Buszard et al.	2016	1	2	1	2	1	2	1	3	2	2	3	2	3
Chan et al.	2019	1	2	1	2	1	1	3	2	2	2	3	2	3
Cheng et al.	2017	1	2	1	2	1	1	2	1	1	1	3	3	3
Chow et al.	2019	1	2	1	2	1	1	3	2	2	3	3	2	3
Chu & Wong	2019	1	2	1	2	1	1	3	3	2	2	3	1	3
Daou et al.	2018	1	2	1	2	1	1	1	1	2	2	3	2	2
Deeny et al.	2003	1	2	1	2	1	1	2	1	2	1	3	3	3
Deeny et al.	2009	1	2	1	2	1	1	2	1	2	1	3	3	3
Dyke et al.	2014	1	2	1	2	1	1	1	1	2	1	3	3	3
Ellmers et al.	2016	1	2	1	2	1	1	3	2	2	2	3	2	3

Gallicchio et al.	2016	1	2	1	2	1	1	1	1	2	2	3	2	2
Gallicchio et al.	2017	1	2	1	2	1	1	1	1	2	1	1	2	1
Ghasemian et al.	2017	1	2	1	2	1	1	2	3	3	2	3	3	3
Hatfield et al.	2013	1	2	1	2	1	1	2	1	3	1	3	1	3
Hoskens et al.	2020	1	2	1	2	1	1	1	1	2	3	3	1	3
Hunt et al.	2013	1	2	1	2	1	1	2	1	3	1	3	3	3
Law & Wong	2020	1	2	1	2	1	1	3	2	2	2	3	2	3
Lo et al.	2019	1	2	1	2	1	1	2	1	3	2	3	3	3
Parr et al. (Exp. 2)	2019	1	2	1	2	1	1	1	1	1	2	1	2	1
Parr et al.	2020	1	2	1	2	1	1	1	1	2	2	1	1	1
Reitschel et al.	2011	1	2	1	2	1	1	2	1	3	1	3	3	3
Van Duijn et al.	2017	1	3	1	2	1	1	3	1	2	2	3	2	3
Van Duijn et al.	2019	1	2	1	2	1	1	2	1	2	2	3	2	2

Van Duijn et al.	2020	1	2	1	2	1	1	2	1	2	2	3	2	2
Wang et al.	2020	1	2	1	2	1	1	3	1	1	2	3	3	3
Zhu et al.	2010	1	2	1	2	1	1	2	3	2	1	3	3	3
Zhu et al.	2011a (Exp. 1)	1	2	1	2	1	1	2	1	2	2	3	2	2
	2011a (Exp. 2)	1	2	1	2	1	1	2	1	2	2	3	1	2
Zhu et al.	2011b	1	2	1	2	1	1	1	2	3	2	3	3	3