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Cortical, muscular, and kinetic activity underpinning attentional focus strategies during visuomotor control

Johnny V. V. Parr[1] 🅾 | Germano Gallicchio[2] 🅾 | Andrés Canales-Johnson[3,4] | Liis Uiga[1] 🅾 | Greg Wood[1] 🅾

[1]Department of Sport and Exercise Sciences, Manchester Metropolitan University Institute of Sport, Manchester, UK

[2]School of Human and Behavioural Sciences, Bangor University, Bangor, UK

[3]Consciousness and Cognition Lab, Department of Psychology, University of Cambridge, Cambridge, UK

[4]Centro de Investigación en Neuropsicología y Neurociencias Cognitivas, Facultad de Ciencias de la Salud, Universidad Católica del Maule, Talca, Chile

Correspondence
Johnny V. V. Parr, Department of Sport and Exercise Sciences, Faculty of Science and Engineering, Manchester Metropolitan University, 99 Oxford Road, Manchester M1 7EL, UK.
Email: johnnyvvparr@gmail.com

Abstract

Focusing internally on movement control or bodily sensations is frequently shown to disrupt the effectiveness and efficiency of motor control when compared to focusing externally on the outcome of movement. Whilst the behavioral consequences of these attentional strategies are well-documented, it is unclear how they are explained at the corticomuscular level. The aim of the present study was to investigate how attentional focus strategies affect kinetic, cortical, muscular, and corticomuscular activity during an isometric force precision task. In a repeated measures design, we measured force, EEG and EMG activity from twenty-seven participants who performed isometric contractions of the right hand whilst encouraged to adopt either an internal or external focus through a combination of instructions, secondary tasks, and self-report evaluations. Results indicated that focusing internally led to poorer force accuracy and steadiness compared to an external focus. An internal focus also increased muscle activity of the forearm flexor, increased EEG alpha activity across the parieto-occipital cortex, lowered frontal midline EEG theta activity, and lowered beta corticomuscular coherence between the forearm flexor and contralateral motor cortex. The results of this study provide a holistic understanding of how attentional focus strategies alter corticomuscular control during an isometric force precision task, paving the way for exploring how the behavioral consequences of attentional strategies can be explained at the corticomuscular levels across a wide range of motor tasks and contexts.

KEYWORDS
corticomuscular coherence, EEG, EEG alpha activity, frontal midline theta, internal focus, isometric force precision

1 | INTRODUCTION

Extensive research suggests that adopting an internal focus of attention, compared to an external focus of attention, is less effective for motor performance and learning (for reviews, see Wulf, 2007, 2013). An internal focus of attention occurs when an individual directs attentional resources inward toward the control of movement or associated

bodily sensations, whereas an external focus occurs when an individual allocates attentional resources toward the outcomes of the movement or the effects the movement has on the environment. The behavioral consequences of these strategies are well documented. For example, studies have shown that instructions promoting an internal focus can disrupt the accuracy (Bell & Hardy, 2009; Lohse et al., 2014), stability (Kim et al., 2017), and fluency of motor control (Kal et al., 2013).

A common mechanism purported to explain the disruptive effects of an internal focus is that it promotes "constrained action" consisting of elevated conscious control of movements through self-regulation, triggering the tendency to constrain the motor system and "freeze" the degrees of freedom (McNevin et al., 2003). By contrast, an external focus is proposed to place greater emphasis on the motor system's self-organizing capabilities, allowing for reflexive and automatic control. Interestingly, the constraining effect of an internal focus is supported by evidence that focusing internally elevates electromyographic (EMG) activity across antagonistic muscle pairs during isometric force production tasks, reflecting a "stiffening" strategy supported by co-contractions (Lohse et al., 2011; Lohse & Sherwood, 2012). An internal focus therefore appears to promote a state of diffuse muscular activity in a manner that is not supportive of efficiency and optimal task performance.

Although little is known about how the effects of an internal focus are explained at the cortical level, there is evidence that elevated EMG activity might be caused by a disruption to intracortical inhibition within the primary motor cortex (i.e., M1). Specifically, Kuhn et al. (2017a, 2017b) measured motor evoked potentials (MEPs) across several hand muscles in response to single-pulse transcranial magnetic stimulation to M1 during isometric contractions of the index finger. Their results showed that MEPs of the primary and surrounding muscles were greater when adopting an internal focus compared to an external focus, suggesting an internal focus diminished the activity of the inhibitory intracortical circuits within M1. Thus, focusing internally may disrupt the capacity to exert inhibitory control, leading to an overflow of activation at the cortex that becomes reciprocated at the muscular level.

There is also evidence that adopting an internal focus can have a significant effect on visual processing. For example, solving word generation tasks without the availability of task-relevant information (i.e., "in the mind's eye"; internal focus) has been shown to elevate EEG alpha activity across posterior brain regions compared to when task-relevant visual information is available (i.e., the word; external focus; Ceh et al., 2020). Given that elevated EEG alpha activity is proposed to reflect regional inhibition in the cortex (Jensen & Mazaheri, 2010; Klimesch

et al., 2007), these findings suggest that focusing internally may prevent visual inflow to shield ongoing internal processing (Benedek, 2018). These findings have recently been supported in the context of a single-limb balance task. Specifically, Sherman et al. (2021) found that focusing on knee angle position (i.e., internal focus) led to poorer balance performance and relatively greater EEG alpha activity across the visual and sensorimotor regions compared to when focusing on the position of a laser pointed toward a target (i.e., external focus). Interestingly, Sherman et al. also found that the internal focus condition decreased frontal midline theta activity compared to an external focus. Frontal midline theta is proposed to reflect the activity of the anterior cingulate cortex and is commonly measured as an index of top-down volitional attentional control to adjust behavior in response to feedback error (Cavanagh et al., 2010; Cavanagh & Frank, 2014). Taken together, these findings suggest that focusing internally disrupts the detection and correction of somatosensory and visual information in a manner that impairs effective visuomotor control.

Whilst varying the attentional focus appears to drive changes in brain and muscle activity, it is unclear how these changes are related. Investigating functional interactions between the central and peripheral nervous systems may, therefore, provide new insights to the mechanisms underpinning the visuomotor response to attentional focus instructions. A promising technique to study cortical-muscular coupling during movement is corticomuscular coherence (CMC), a measure that evaluates the frequency-wise similarity between EEG and EMG signals (Mima & Hallett, 1999). CMC is typically observed during periods of isometric contraction (Kilner et al., 2003; Riddle & Baker, 2006) and reaches its peak in the beta frequency band (approx. 15–30 Hz) for EEG sites located over the primary sensorimotor cortex contralateral to the innervated limb (Witham et al., 2011). Evidence suggests that beta-range CMC increases after visuomotor skill learning (Perez et al., 2006), and is larger when isometric contractions are steadier and more precise (Kristeva et al., 2007; Kristeva-Feige et al., 2002; Witte et al., 2007). CMC is therefore proposed to reflect the effective cortical control of motor unit firing via the direct corticospinal pathway (Mima & Hallett, 1999), supporting the integration and upregulation of afferent and efferent signals to promote a stable sensorimotor state (Baker, 2007). CMC may also reflect the effective transmission of sensorimotor beta oscillations to the periphery (Bourguignon et al., 2019) which, at the cortical level, are thought to play an active role in signaling the "status quo" (Engel & Fries, 2010) and transmitting endogenous inhibitory motor signals for inhibitory motor control (Picazio et al., 2014). Importantly, CMC shows a clear task dependency, decreasing in dual-task scenarios when attention is divided between the motor

task and a simultaneously performed secondary task (e.g., mental arithmetic; Johnson et al., 2011; Kristeva-Feige et al., 2002), and increasing when individuals are required to exert increased cognitive engagement toward the maintenance of force precision (Safri et al., 2006). For this reason, CMC appears to be directly influenced by the extent to which attention is either coupled or decoupled from motor execution. Interestingly, an acknowledged disadvantage of focusing internally is that it can require learners to divide attentional resources between both external and internal information (Maxwell & Masters, 2002), a process that will likely increase demands on working memory and impose a task-switching cost to account for the decoupling and recalibration between attentional foci (Verschooren et al., 2019). Given that an internal focus is typically associated with less-precise force control *and* is proposed to decouple attention from motor-execution, it is possible that an internal focus might drive reductions in CMC.

The aim of the present study was to explore how varying the attentional focus alters force control, the activity of the cortex (via EEG), the muscles (via EMG), and their interaction (via CMC analyses) during a visually guided isometric handgrip task. Based on previous research, we hypothesized that internally focused instructions would encourage contractions that are less accurate, less stable, and supported by greater EMG activity of the forearm compared to external focused instructions. At the cortical level, we hypothesized that focusing internally compared to focusing externally would disengage visual processing (increased occipital alpha activity) and disrupt executive functions required for the detection and correction of visual feedback (decreased frontal midline theta activity). Finally, we hypothesized that an internal focus would decrease beta CMC between the forearm muscles and the contralateral sensorimotor cortex compared to an external focus.

2 | METHOD

2.1 | Participants

Twenty-seven participants were recruited (17 males, 10 females, all right-handed, age M = 23.76 ± 4.34 years) based upon an a-priori sample size estimation performed using G*POWER software (version 3.1; Heinrich Heine University Dusseldorf, Dusseldorf, Germany; Faul et al., 2009). Whilst it is unclear how attentional focus strategies affect beta CMC, large effects ($d = 0.80$) have been observed when increasing attentional demands during motor tasks through dual tasks (Johnson et al., 2011; Johnson & Shinohara, 2012). If assuming a large effect ($d = 0.80$) with 80% power and an alpha level of $p = .05$

a sample size of at least 15 participants would have been required to compute the difference between two dependent means. However, we decided to increase our sample size to enable the detection of more subtle effects given the novelty of our study, and match or exceed the samples achieved across relative research studies who have investigated the muscular (Lohse et al., 2011; Lohse & Sherwood, 2012) and cortical (Kuhn et al., 2017a, 2017b) underpinnings of attentional foci. Post-hoc sensitivity analyses therefore indicated that with 27 participants and an alpha level of $p = .05$, 80% power is achieved for medium effect sizes ($d \geq 0.56$, ~ $r = .3$). All participants were free from any known neurological/musculoskeletal disorders and were instructed to avoid stimulants (caffeine, alcohol, energy drink, etc.) 48 hr prior to testing. Ethical approval was granted by an institutional ethics committee and written informed consent was obtained from all participants.

2.2 | Study protocol

2.2.1 | Procedure

All participants attended the laboratory on one occasion for approximately two hours. Upon arrival, participants were debriefed about the study protocol before being sat comfortably at a desk facing a computer screen. Participants were then prepared for EEG and EMG data collection prior to performing two maximal voluntary contractions (MVC's) separated by one minute of rest. The maximal force produced across these two attempts was used to personalize the target force output in the subsequent experimental task.

2.2.2 | Experimental task

Participants were instructed to squeeze a dynamometer by contracting their right hand at $15 \pm 5\%$ of their MVC for five seconds. The force produced and target force boundaries (i.e., $\pm 5\%$) were displayed in real time on a monitor using Labchart 8.0 (Figure 1). Following a familiarization block, participants completed 160 contractions, divided into 16 blocks of ten contractions. Each 5-s contraction was followed by a 5-s rest, and each block was separated by 30-s of rest to minimize muscular fatigue. The onset and offset of each 5-s contraction were indicated by auditory tones (10 ms duration) controlled by PsychoPy software (v2021.1.1.3) (Peirce, 2007) and used as event triggers for the physiological and kinetic data. At the beginning of each block, participants were instructed to adopt either an external or internal attentional focus. The attentional
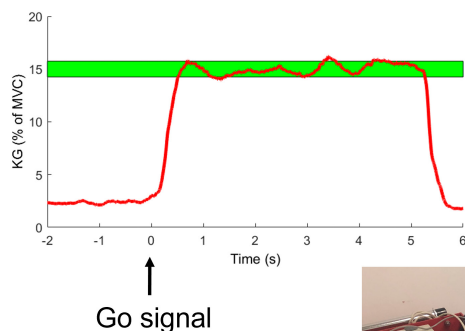
FIGURE 1 Visual representation of the experimental task set-up. The participant's right hand is strapped in a cushion rig whilst wearing EEG and EMG equipment. Participants received ongoing visual feedback of force output on the monitor, trying to maintain the red force trace within a green boundary zone (depicted top left).

conditions were presented in equal proportion (8 consecutive blocks per condition) and their order was permuted for each participant through PsychoPy (14 participants began with the internal focus). The attentional focus was manipulated through a combination of instructions, secondary tasks, and self-report evaluations.

2.2.3 | Attentional focus instructions

Our attentional focus instructions were developed in accordance with the recommendations set out by Wulf (2013), who stated instructions should differ only with regard to the attentional focus they induce. For this reason, it was crucial that both conditions (a) encouraged the same performance goal, (b) provided consistent visual feedback, and (c) imposed a comparable number of instructions to focus upon. To achieve this, both our EF and IF instructions encouraged participants to maintain highly accurate performance and to additionally focus on either an external or internal aspect of their movement that aligned with the goal of the secondary task.

For the external focus condition, the following instructions were provided: "*For the next set of trials, carefully maintain your focus on the screen and the line being produced as you squeeze the dynamometer. Try and keep this line within the green boundary zone as accurately as possible*". In addition, participants were asked to rate their accuracy on a scale from 1 (very inaccurate) to 5 (very accurate) at the end of each block. The secondary task required participants to verbally report whether the force line was "above" or "below" the mid-point of the green boundary zone upon the sound of a bell. This bell sounded 2.5 s into a randomly selected contraction during each block (controlled by Psychopy). Whilst performance in the secondary task was not subsequently assessed, participants were told that they would be assessed to further encourage their adherence to the task. Together, the EF instructions encouraged participants to focus on (a) task accuracy, and (b) the specific location of the force trace with respect to the boundary (i.e., the outcome of movement). Physiological and kinetic data recorded during trials containing a bell stimulus were removed from all analyses. Participants were informed the accuracy of their responses was being measured to assess their adherence to the task instructions.

For the internal focus condition, the following instructions were provided: "*For the next set of trials, carefully focus on the contraction of your forearm muscles as you squeeze the dynamometer. Try and keep the contracted force line within the green boundary zone as accurately as possible whilst applying an equal amount of force across your index and middle fingers*." In addition, participants were asked to rate how equally they maintained the force across their index and middle fingers upon the dynamometer from 1 (not equally at all) to 5 (completely equally) at the end of each block. The secondary task required participants to verbally report whether the index or middle finger was applying the most force at the instance of the bell sound. Participants were told their ability to maintain

equal force across the index and middle fingers would be assessed using the EMG electrodes, despite these analyses not being subsequently performed. Together, the IF instructions encouraged participants to focus on (a) task accuracy, and (b) the balance of force output between the index and middle fingers (i.e., control of movement).

2.2.4 | Physiological and kinetic data

The EEG signals were recorded from 63 active shielded AgCl electrodes embedded in a stretchable fabric cap (eego sports, Ant Neuro, Hengelo, Netherlands) and positioned according to the extended 10–20 international system (Jurcak et al., 2007). Electrodes in sites CPz and AFz were used as reference and ground, respectively. Nasion, Inion, and preauricular points were used as anatomical landmarks to position the EEG cap. Conductive gel for electrophysiological measurements was used (Signa gel, Parker), and impedance was kept below 20 kΩ. The EMG signals were recorded from two pairs of bipolar surface EMG electrodes (eego sports, Ant Neuro, Hengelo, Netherlands) placed on the skin to record activity from the flexor carpi radialis and extensor carpi radialis of the right forearm according to the guidelines set out by SENIAM (http://seniam.org/sensor_location.htm). The participant's right forearm was then strapped to a cushioned rig positioned on the desk, where participants held a dynamometer connected to a PowerLab 4/25T (AD Instruments, Bella Vista, Australia) to record hand contraction force (in kilograms) via Labchart 8 software (ADinstruments). The force, EEG, and EMG signals were recorded at a sample rate of 1000 Hz and were synchronized through a square-wave trigger (i.e., time point zero in subsequent analyses) sent by a LabJack U3 device (LabJack Corporation, Lakewood, United States) at each auditory contraction prompt generated through a bespoke Psychopy program.

2.3 | Data processing

For EMG-specific analyses, signals were down-sampled (500 Hz), band-pass filtered using the EEGLAB "basic FIR filter (new)" (10–200 Hz, default filter order, −6 dB cut-off frequency, 2.5 Hz transition bandwidth), and notch filtered (48–52 Hz, default filter order, −6 dB cut-off frequency, 2 Hz transition bandwidth) prior to being cut into epochs ranging from −2 to +6 s relative to the onset auditory stimulus. For EEG and EEG–EMG analyses, signals were down-sampled (250 Hz) and band-pass using the EEGLAB "basic FIR filter (new)" (1–45 Hz, default filter order, −6 dB cut-off frequency, 1 Hz transition bandwidth) prior to being

cut into epochs ranging from −2 to +6 s relative to the onset auditory stimulus. These epochs were visually inspected, and those showing large EEG contamination from muscular artifacts were discarded (from both EEG and EMG analyses). No bad EEG channels were identified. Independent component analysis (ICA) weights were obtained through the RunICA infomax algorithm (Jung et al., 1998) running on EEG signals. ICA weights that presented obvious non neural activity upon visual inspection (e.g., eyeblinks, line noise, muscular artifact) were manually rejected. These processing steps were performed using EEGLAB (v2020.0) functions (Delorme & Makeig, 2004) for MATLAB. Given that beta CMC is known to occur during steady-state (but not dynamic) phases of force contraction (e.g., Omlor et al., 2007), we focused our analysis of force, EEG and EMG data across the window occurring between 1.5 and 4.5 s following the onset stimulus. The initial 1500 ms and final 500 ms were not considered to minimize data containing initial dynamic contractions or anticipatory relaxations.

2.4 | Measures

2.4.1 | Attention allocation

Following the completion of each condition, participants were asked to report how they divided their attention among external factors (e.g., computer screen and force trace), internal factors (e.g., muscular contraction of each finger), and other factors (e.g., mind wandering). Specifically, participants were asked to indicate the percentage (%) of their attention dedicated to each factor (as a whole), ensuring that the three factors combined to make a total of 100%. These measures were included to elucidate the extent to which our manipulations shifted the balance between external and internal factors for our task as intended. The document used for this purpose can be found with the supplementary material (https://osf.io/gktu2/).

2.4.2 | Force control

Force was analyzed to determine the steadiness of each contraction and the extent to which participants accurately maintained their force within their target boundary. Steadiness was defined as the coefficient of variance (CoV), calculated as the ratio between standard deviation and mean during the steady phase (i.e., between 1.5 and 4.5 s following the onset stimulus). Task accuracy was defined as the percentage of time that participants were able to maintain their force within the target boundary (i.e., $15 \pm 5\%$ MVC).

2.4.3 | EMG activity

Muscular activity was calculated as the root-mean-square (RMS) of the EMG signal occurring across the steady phase (i.e., 1.5 to 4.5 s post stimulus) for each trial. Data were normalized across participants by dividing trial-level RMS by the largest RMS value recorded by each participant across all experimental trials (i.e., % of max RMS).

2.4.4 | EEG power

Time-frequency decomposition was performed through a short-time Fast Fourier Transform (FFT) conducted on 129 overlapping windows, each of 0.5 s length, with central points ranging from −1.75 to 5.75 s relative to the onset of the auditory go stimulus. Prior to FFT, data points in each window were Hanning tapered and zero padded to reach 1 s. This procedure generated complex-valued coefficients in the time-frequency plane with a precision of 58.6 ms and 1 Hz. EEG power (μV^2) was calculated for the theta (4–6 Hz), alpha (8–12 Hz) and beta (15–30 Hz) frequency bands as the squared amplitude of each FFT coefficient, which was then averaged across the 51 overlapping segments spanning the steady phase.

2.4.5 | Corticomuscular coherence

Coherence between the EEG and EMG signals were calculated by magnitude-squared coherence using the following equation:

$$\left| C_{xy}(f) = \frac{\left| P_{xy}(f) \right| 2}{P_{xx}(f) \cdot P_{yy}(f)} \right|$$

where P_{xx} and P_{yy} are the averaged power spectral densities, respectively, of the EEG and EMG signals throughout the 51 overlapping segments for a given frequency f, and $P_{xy}(f)$ is the averaged cross-spectral density between the two parameters throughout the segments. The coherence function provides a normative measure of linear correlation on a scale from 0 to 1, where 1 indicates a perfect linear correlation. For multiple corrections across the 16 frequency points within the beta band (i.e., between 15 and 30 Hz), we applied a Bonferroni correction to the following equation defining the significance level of coherence (SL; Rosenberg et al., 1989)

$$SL(a) = 1 - \left[\frac{1}{N} \cdot \left(1 - \frac{a}{100} \right) \right]^{1/(L-1)}$$

where a is the confidence limit (%), N is the number of frequency bins, and L is the number of overlapping segments. As an N of 16, L of 51, and a of 95 were chosen, the SL was determined to be 0.109 in the present study. This revision eliminates the potential risk that the coherence value is judged to be significant owing to statistical error. We measured the area under the coherence curve and above the significance level in the beta frequency range. In this type of area analysis, it is reasonable to take the area under the curve of the coherence because it is a measure of the mean coherence within the considered frequency band (Chakarov et al., 2009; Mendez-Balbuena et al., 2012; Omlor et al., 2007; Parr et al., 2022; Trenado et al., 2014). This procedure addresses the overall effect within frequency bands on interest and considers potential shifts in the location of peak coherence across trials, meaning that essential information on the correlated activity between EEG and EMG activity does not get overlooked. Power spectra density plots for all participants are available in supplementary material to highlight the presence of beta peaks in both EEG and EMG data.

2.5 | Statistical analysis

The Gaussian distribution of data were checked via Shapiro–Wilk. Consequently, all subsequent analyses were conducted using nonparametric Wilcoxon signed-ranks tests to compare our dependent variables across each experimental condition (i.e., external vs internal). Descriptive data are presented by the median and interquartile range. Regional effects of alpha power, beta power, and beta CMC were analyzed through nonparametric permutation testing. Beta power analyses were included to provide added context to any changes observed in beta CMC given their proposed, yet inconsistent, association (see Bourguignon et al., 2019). The multiple comparison problem (i.e., one test for each channel) was solved through the "maximum statistic" method (Cohen, 2014) applied to the channel dimension. Namely, we compared the observed Wilcoxon signed-ranks Z values of each channel between the external and internal conditions with an empirical distribution of Z values constructed in the following way. First, we permuted the data by randomly swapping the condition labels (external/internal) within each participant before running a Wilcoxon signed-ranks test separately for each channel. We then pooled the Z values across channels and stored the two most extreme values (i.e., minimum and maximum). We then repeated this procedure 2000 times to create a distribution of 4000 minimum and maximum Z values. Finally, we compared the observed (i.e., non-permuted) Z values of each channel-wise comparison with the empirical distribution of Z values described above, and computed p

values as the proportion of the permutation Z values that were more extreme than the Z values of each channel. For alpha and beta power, all 63 channels were included to investigate broad regional effects. For beta CMC, we included the 6 channels spanning the contralateral (left) sensorimotor cortex. Effect sizes for Wilcoxon signed-ranks tests were reported as r, with values of 0.1, 0.3, and 0.5 reflecting small, medium, and large effects, respectively (Cohen, 1992). Significant differences are presented across figures at the $p < .05$ (*), $p < .01$ (**), and $p < .001$ (***) levels.

3 | RESULTS

3.1 | Attention allocation

Participants self-reported a significantly greater allocation of attention toward external factors during the external focus condition (median = 70, iqr = 20%) compared to the internal focus condition (median = 36.11, iqr = 20%), $Z = 4.090$, $p < .001$, $r = .78$. Conversely, participants self-reported a significantly greater allocation of attention toward internal factors during the internal focus condition (median = 55, iqr = 20%) compared to the external focus condition (median = 17, iqr = 18.06%), $Z = 4.460$, $p < .001$, $r = .85$. Attention directed toward other factors was not different between conditions ($p = .703$; Figure 2).

3.1.1 | Force control

A Wilcoxon signed-rank test revealed that force variability (CoV %) was significantly greater during the internal
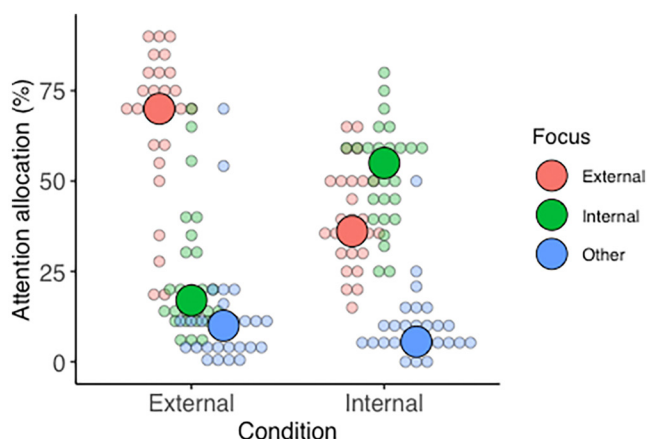

FIGURE 2 Dot plot displaying the self-reported allocation of attention toward external, internal, and other factors across the experimental conditions. Small points represent individual responses whilst larger points represent the group median.

focus condition (median = 3.93, iqr = 1.48%) compared to the external focus condition (median = 2.71, iqr = 0.73%), $Z = 4.361$, $p < .001$, $r = .84$. Additionally, participants were significantly less accurate at the task during the internal focus condition (median = 81.58, iqr = 6%) compared to the external focus condition (median = 91.30, iqr = 10%), $Z = 4.373$, $p < .001$, $r = .84$ (Figure 3).

3.1.2 | EMG activity

A Wilcoxon signed-ranks test revealed that EMG activity of the flexor carpi radialis was significantly greater during the internal focus condition (median = 59, iqr = 10%) condition compared to the external focus condition (median = 50, iqr = 30%) condition, $Z = 2.115$, $p = .034$, $r = .41$. However, EMG activity of the extensor carpi radialis was not different between conditions, $Z = 0.361$, $p = .718$, $r = .07$ (Figure 4).

3.1.3 | Regional alpha power

Permutation testing to control for the multiple comparisons in the channel x condition dimension identified the observed Z values to surpass the critical threshold if they fell below -2.794 or above 2.731. Consequently, results showed that alpha power was significantly greater across a cluster of parieto-occipital channels during the internal focus condition compared to the external focus condition, including O2 ($Z = 3.003$, $p = .009$, $r = .578$), PO4 ($Z = 2.931$, $p = .019$, $r = .564$), PO6 ($Z = 3.195$, $p = .003$, $r = .615$), PO8 ($Z = 3.003$, $p = .013$, $r = .578$), and Oz ($Z = 3.051$, $p = .005$, $r = .587$; Figure 5).

3.1.4 | Regional beta power

Permutation testing to control for the multiple comparisons in the channel x condition dimension identified the observed Z values to surpass the critical threshold if they fell below -2.811 or above 2.811. Consequently, no significant differences were observed between the internal and external focus conditions for any channels (see supplementary material for topoplots).

3.1.5 | Frontal theta power

A Wilcoxon signed-ranks test showed that frontal theta power was significantly greater during the external focus condition (median = 2.11, iqr = 1.65 μV^2) compared to the
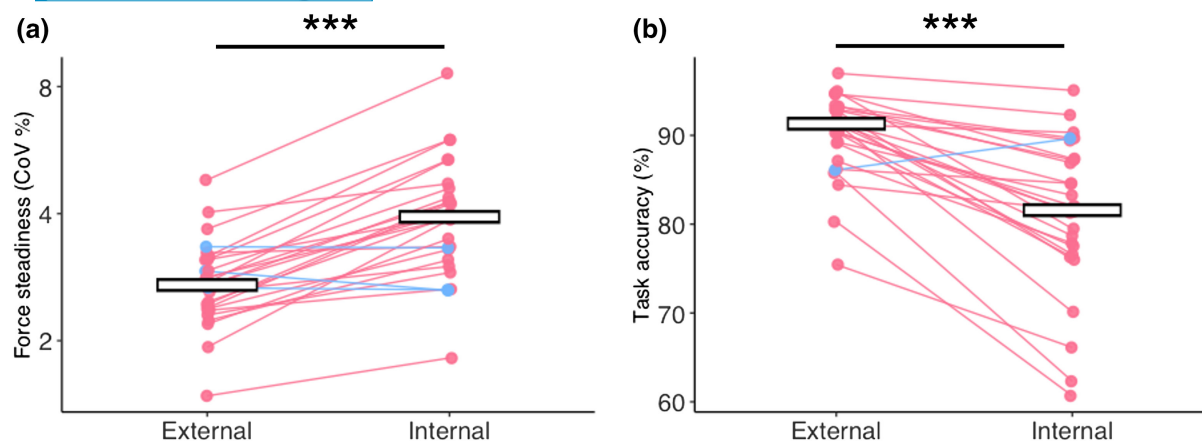
FIGURE 3 Jitter plots displaying force steadiness (a) and task accuracy (b) across the external and internal conditions. Y-axis values for force steadiness have been log transformed for visualization purposes. Jitter points represent individual participant means and the horizontal crossbar represents the overall group median. Lines connect jitter points from the same participant across each condition, with a red line representing poorer performance during the internal condition and a blue line representing better performance during the internal condition. Asterisks indicate a significant difference between conditions at the $p < .001$ (***) level.
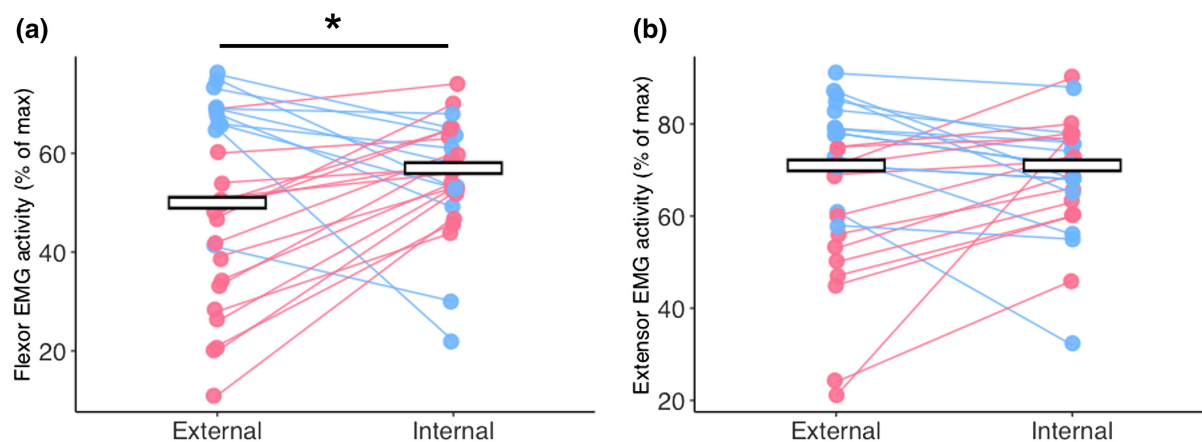

FIGURE 4 Jitter plots displaying EMG activity (% of max) for the flexor carpi radialis (a) and extensor carpi radialis (b) across the external and internal conditions. Jitter points represent individual participant means and the crossbars represent the overall group median. Lines connect jitter points from the same participant across each condition, with a red line representing increased EMG activity during the internal condition and a blue line representing decreased EMG activity during the internal condition. The asterisk (*) indicates a significant difference between conditions at the $p < .05$ level.

internal focus condition (median $= 2.00$, iqr $= 1.52\,\mu V^2$), $Z = 3.027$, $p = 002$, $r = .583$ (Figure 6).

3.2 | Corticomuscular coherence

3.2.1 | Flexor carpi radialis

Permutation testing to control for the multiple comparisons in the channel x condition dimension identified the observed Z values to surpass the critical threshold if they fell below -2.040 or above 2.040. Consequently,

results showed that beta CMC was significantly greater across electrodes CP1 ($Z = -2.090$, $p = .045$, $r = .402$) and C1 ($Z = -2.427$, $p = .015$, $r = .467$) during the external focus condition compared to the internal focus condition (Figure 7).

3.2.2 | Extensor carpi radialis

Permutation testing to control for the multiple comparisons in the channel x condition dimension identified the observed Z values to surpass the critical threshold if they
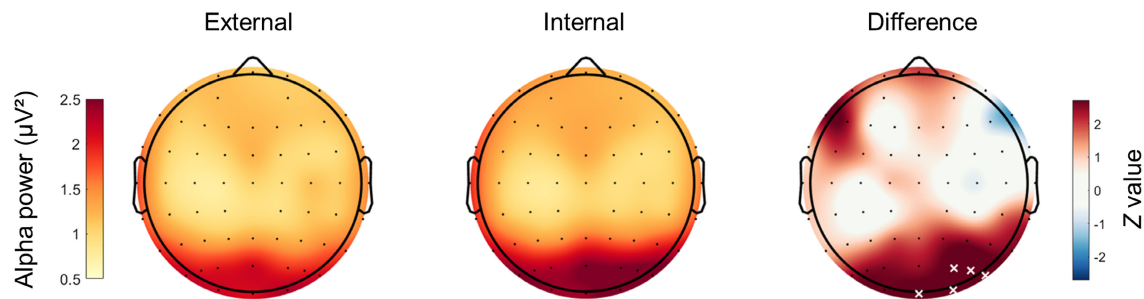
FIGURE 5 Topographical scalp maps depicting the mean alpha power (μV²) recorded during the external focus (left column) and internal focus (middle column) conditions. A scalp map of the paired samples *Z* values comparing alpha power across the external and internal conditions (right column). Areas that are red indicate greater alpha power (i.e., greater inhibition) in the internal condition, whereas areas that are blue indicate lower alpha power in the internal condition. Statistical thresholding was applied using the maximum-statistic permutation testing (Cohen, 2014; Nichols & Holmes, 2002) controlling for multiple comparisons in the channel dimension. Statistically significant channels are indicated by white X markers.
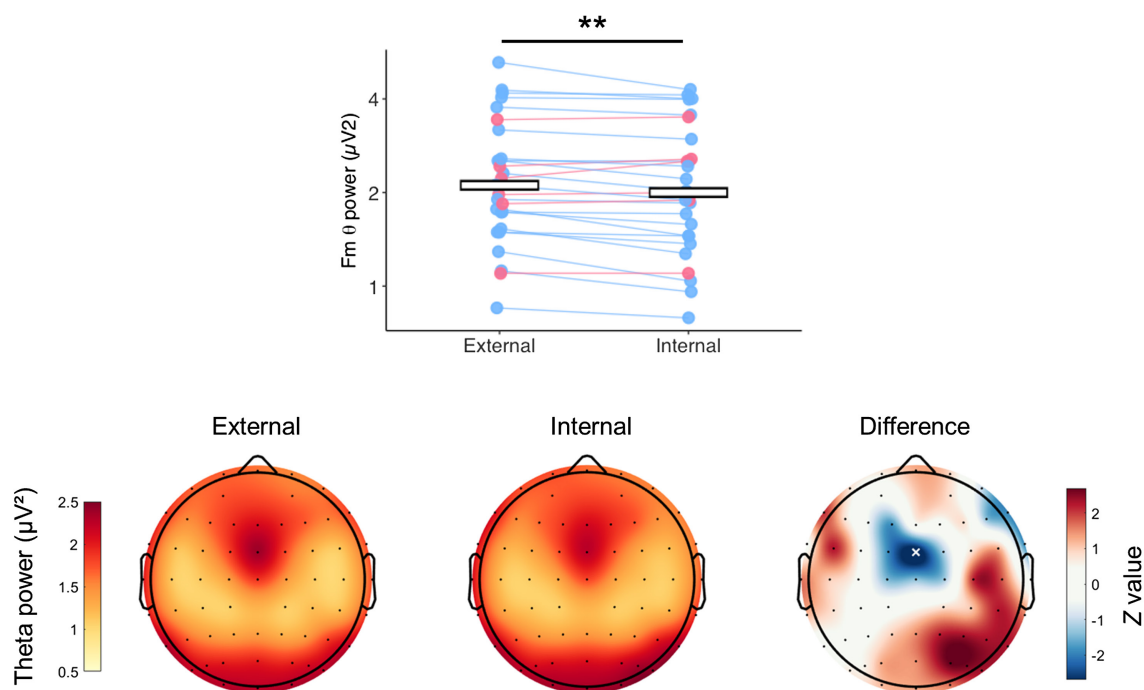

FIGURE 6 Jitter plots displaying frontal midline theta (Fmθ) power (μV²) across the external and internal focus conditions. Jitter points represent individual participant means and the crossbar represents the overall group median. Lines connect jitter points from the same participant across each condition, with red lines representing participants who displayed increased frontal midline theta power during the internal condition and the blue lines represent participants who displayed decreased frontal midline theta power during the internal condition. The y-axis values have been log transformed for visualization purposes, and asterisks reflect a significant difference between conditions at the $p < .01$ (**) level.

fell below -2.103 or above 2.040. Consequently, no significant differences were observed between the internal and external focus conditions.

4 | DISCUSSION

This study provided the first cross-modal investigation of how attentional focus alters the kinetic, cortical, muscular, and corticomuscular activity associated with force

production in a task requiring precise visuomotor control. As we hypothesized, shifting attentional focus to internal factors (e.g., force across index and middle fingers), as opposed to external factors (e.g., the position of the force trace) impaired force control (accuracy and steadiness) resulting in poorer task performance. The impaired force regulation induced by an internal focus emerged alongside a psychophysiological profile consisting of elevated activity of the forearm muscles, increased alpha activity across the parieto-occipital cortex, decreased frontal
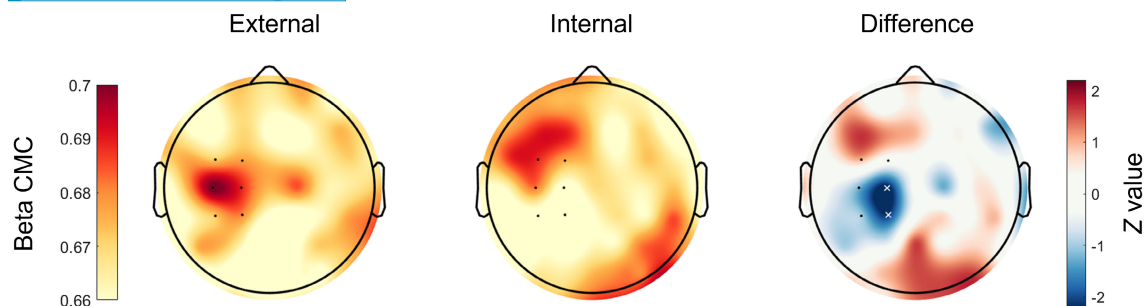
FIGURE 7 Scalp maps depicting the mean beta CMC recorded during the external (left column) and internal (middle column) focus conditions. Red areas indicate greatest levels of beta CMC whereas blue areas indicate lowest levels of beta CMC. Black dots indicate the channels of the left sensorimotor cortex included in analyses. A scalp map of the paired samples Z values comparing beta CMC across the external and internal conditions (right column). Red areas suggest greater beta CMC during the internal focus condition, whereas the blue areas suggest lower beta CMC during the internal focus condition. Statistical thresholding was applied using the maximum-statistic permutation testing (Cohen, 2014; Nichols & Holmes, 2002) controlling for multiple comparisons in the channel dimension. Statistically significant channels are indicated by white X markers.

midline theta activity, and decreased beta CMC between the forearm and contralateral sensorimotor cortex. The results of this study provide a holistic understanding of how attentional focus strategies alter corticomuscular control.

4.1 | An internal focus disrupts force regulation and elevates muscular activity

When focusing internally, participants displayed isometric contractions that were less steady (~1.22% more variable) and less accurate (~9.72% less accurate) compared to when focusing externally. These findings are synonymous with a large body of literature indicating that an internal focus of attention can broadly disrupt the effectiveness of visuomotor control (Wulf, 2007, 2013). Changes to these task performance metrics were also reflected by differences at the muscular level. When focusing internally participants displayed greater EMG activity of the forearm flexor muscle, suggesting elevated muscular activation that was not supportive of optimal task performance. Elevated EMG activity in response to an internal focus has been observed previously (Vance et al., 2004; Wulf et al., 2010; Zachry et al., 2005), and is typically interpreted as an attempt to constrain (or "freeze") the motor system through co-contraction of antagonistic muscles to decrease variability in the movement pattern (Lohse & Sherwood, 2012). However, given that decreased variability would support accuracy in our isometric task (lower CoV), it is unlikely that focusing internally encouraged a "freezing" of action in this instance. Rather, our findings suggest that focusing internally promoted a less efficient muscular output. Interestingly, the forearm flexors specifically contribute to the production of grip force rather than grip force maintenance and relaxation (Ambike et al., 2014). We could, therefore, speculate that the elevated EMG activity of the

forearm flexor may not reflect co-contraction per se, but elevated muscular activation in response to a greater frequency and magnitude of large grip force adjustments.

4.2 | An internal focus elevates parieto-occipital alpha activity

Adopting an internal focus led to greater alpha activity across the parieto-occipital cortex compared to an external focus, aligning with previous findings in word-solving (Ceh et al., 2020) and balance control tasks (Sherman et al., 2021). Our findings therefore extend previous research in the context of a visuomotor force precision task. Alpha activity is widely agreed to reflect regional inhibition, with greater alpha activity indicating increased inhibition and lower alpha activity indicating release from inhibition (Jensen & Mazaheri, 2010; Klimesch et al., 2007). Therefore, our data suggest that elevated posterior alpha activity during an internal focus reflects the functional inhibition of visual processing, likely reflecting the limit of attentional capacity and the consequent need to flexibly divide attentional resources between the different perceptual modalities (visual and proprioceptive) involved with task performance. This is aligned with evidence that attending to visual stimuli whilst ignoring auditory distractors elevates alpha in regions involved with auditory processing whilst simultaneously diminishing alpha in regions involved with visual processing (Mazaheri et al., 2014). Consequently, internally focused attention may induce a state of "*looking without seeing*", reducing the preparedness to detect and process task-relevant visual information required for the maintenance of task accuracy (Ceh et al., 2020), possibly explaining some of the behavioral differences typically observed between attentional focus strategies.

4.3 | An internal focus lowers frontal midline theta activity

We also found frontal midline theta activity to be significantly lower during the internal focus condition compared to the external focus condition, corroborating previous findings in balance control (Sherman et al., 2021). Frontal midline theta activity is often proposed to reflect the underlying activity of the anterior cingulate cortex and is commonly measured as an index of the monitoring and updating executive function utilized when exerting top-down volitional attentional control to adjust behavior in response to feedback error (Cavanagh et al., 2010; Cavanagh & Frank, 2014; Womelsdorf et al., 2010). Heightened frontal midline theta activity has been observed in expert golfers compared to novice golfers when putting (Baumeister et al., 2008) and during the "flow-state" of a mental arithmetic task (Katahira et al., 2018), implying a functional role in maintaining highly focused attention and immersion within a task. Focusing internally therefore appears to disrupt aspects of attentional control that are required for assembling task-relevant information to prime sensory and motor pathways for efficient communication and enhanced task performance.

4.4 | An internal focus disrupts corticomuscular coherence

Beta CMC between the forearm flexor muscle and EEG channels spanning the contralateral sensorimotor cortex decreased when focusing internally. As force control was also poorer when focusing internally, our findings support evidence that the magnitude of beta CMC is reduced under conditions that interfere with the stability and precision of force contractions (Kristeva et al., 2007; Kristeva-Feige et al., 2002; Witte et al., 2007). Beta CMC has been shown to reduce in dual-task scenarios, suggesting that CMC may be hindered when attention is functionally decoupled from the motor task. Indeed, there is evidence that external and internal information cannot be processed simultaneously as they rely on shared resources (Verschooren et al., 2019). Dividing attention equally between the visual (i.e., external) and proprioceptive (i.e., internal) aspects of our task (as our findings suggest; Figure 2) would have therefore depended on frequent switches of attention, possibly driving momentary unbinding of cortical and muscular activity to account for decoupling and recalibration between attentional foci. Based on evidence that cortical beta oscillations are implicated in the maintenance of inhibitory motor control (Picazio et al., 2014), beta CMC may also reflect the effective transmission of inhibitory sensorimotor beta oscillations from the cortex to the periphery (Bourguignon et al., 2019). Decreased CMC can therefore be interpreted as reflecting the departure from a steady-state control of a particular muscle and possibly the disruption of corticomotor inhibition. Our findings may therefore provide additional evidence that focusing internally can interfere with motor inhibitory activity across the motor cortex (Kuhn et al., 2017a, 2017b). Interestingly, CMC has been shown to be modulated when applying force to unstable objects that require individuated finger control (Reyes et al., 2017). Decreased beta CMC across the contralateral motor cortex could suggest that focusing internally encouraged individuated finger control and the unbinding of muscles from a synergistic control strategy. Given that our internal instructions specifically focused upon the control of the index and middle fingers, these findings may reflect the decoupling of these fingers from the overall grip force synergy.

4.5 | Interpretation, limitations and future directions

Taken together, our findings highlight several corticomuscular responses that co-occur with impaired force control when adopting an internal focus of attention. To contextualize how these responses may interact with one another to interfere with force precision, we propose the following cascade events. First, our internal focus instructions required participants to divide their attention between both visual (i.e., external) and proprioceptive (i.e., internal) information, a process that likely required the shifting of attention back and forth between foci. Directing attention away from the external environment in this manner appeared to reduce the processing of visual feedback that was vital for the maintenance force precision in this task. Correcting for more frequent drifts in force error may then have required more frequent corrective grip force adjustments, elevating the activity of the forearm flexors and disrupting brain-muscle synchronization.

However, it is important to recognize that our findings may not extend beyond the context of our visuomotor task. To elaborate, our task required high levels of force precision and the upregulation of visual feedback to actively detect and correct for ongoing performance error. Focusing internally therefore necessitated that attention was divided between external and internal information if performance levels were to be maintained. As such, it is perhaps unsurprising that inhibition of visual processing during an internal focus (as we have found) might have negatively influenced performance in our task. However, research on the preparation for closed loop aiming tasks has shown that diminished visual processing, as indexed by elevated

EEG posterior alpha activity, is associated with better task accuracy (Gallicchio & Ring, 2019). It is therefore possible that disengaging visual processing through internalized attention is a mechanism that disrupts performance only in tasks that contain a dynamic (open-loop) versus stable (closed-loop) visual environment. Indeed, external and internal focus strategies are often compared in motor tasks that do not involve online visual feedback of movement and are therefore less likely to induce a dual-task/task-switching cost when focusing internally. Future work should therefore elucidate how attentional focus strategies influence corticomuscular activity in tasks that are less demanding on the upregulation of visual information.

The possible interpretations of our data are also limited by the absence of a control condition, whereby no attentional focus instructions are given. We chose to exclude a control condition from the design given the large number of trials required for EEG analyses and the possible increase in physical and mental fatigue. Consequently, whilst we interpret these findings as reflecting the negative effects of focusing internally, it is also possible that they represent the beneficial effects of focusing externally. It would therefore be useful to establish how corticomuscular profiles might relate to behavioral (i.e., performance) and perceptual (i.e., attentional strategies) outcomes when no instructions are given during a visuomotor task requiring high levels of precision.

5 | CONCLUSION

This study provides evidence for a wide range of kinetic and psychophysiological alterations consequent to the adoption of attentional focus strategies in a visuomotor task. We showed that focusing internally impairs the ability to maintain accurate and steady isometric force contractions. These performance deficits were accompanied by elevated parieto-occipital alpha activity and decreased frontal midline theta activity, suggesting that focusing internally might promote the disengagement of visual processing and disrupt neuronal processes critical to the realization of cognitive control. An internal focus also increased EMG activity of the forearm flexor and reduced beta CMC between the forearm flexor and the contralateral motor cortex. It is hoped that these findings pave the way for exploring how the well-documented behavioral consequences of attentional strategies can be explained at the corticomuscular level across a wide range of motor tasks and contexts.

AUTHOR CONTRIBUTIONS
Johnny V. V. Parr: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; software; visualization; writing – original draft; writing – review and editing. **Germano Gallicchio:** Conceptualization; investigation; methodology; software; writing – review and editing. **Andrés Canales-Johnson:** Investigation; software; writing – review and editing. **Liis Uiga:** Methodology; writing – review and editing. **Greg Wood:** Conceptualization; investigation; methodology; writing – original draft; writing – review and editing.

CONFLICT OF INTEREST
The authors have no relevant financial or non-financial interests to declare.

DATA AVAILABILITY STATEMENT
Supporting data is freely available here: https://osf.io/gktu2/.

ORCID
Johnny V. V. Parr https://orcid.org/0000-0002-3096-2601
Germano Gallicchio https://orcid.org/0000-0002-2180-8848
Liis Uiga https://orcid.org/0000-0002-5371-9428
Greg Wood https://orcid.org/0000-0003-0851-7090

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