CORTICOMUSCULAR COHERENCE OF THE EXTENSOR CARPI RADIALIS MUSCLE IN A DYNAMIC RESPONSE TASK

by

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Corticomuscular Coherence of the Extensor Carpi Radialis Muscle in a Dynamic Response Task

Approved: ____

Dr. Nicole Swann and Dr. Ian Greenhouse

Corticomuscular coherence (CMC) is hypothesized to be a measure by which the robustness of connectivity between the brain and muscles can be measured. This study utilized EEG and EMG over both extensor carpi radialis muscles. Electrical activity between 13 and 30Hz was recorded while 11 healthy participants conducted a dynamic motor control task with 10 different task conditions. The three key questions I sought to answer were: how does contralateral vs. ipsilateral coherence vary within healthy participants? How does contralateral coherence of an arm change depending on whether the other arm is held in contraction or relaxed during a block? How does coherence change for an arm depending on response type: whether it is always the responding arm during the task, maybe responding during the task, or not responding to the task? Results showed that contralateral coherence and phase coherence were significantly greater between tasks for both the right and left arms. Both contralateral coherence and phase coherence were greater when the opposite arm was held in contraction, rather than relaxed. No difference in measurements were found depending

on the response type of either arm. Considering the variety of factors that affect CMC, I believe further research into a specific task is required to determine consistent patterns in heathy people. I hope that in the future a map of healthy coherence values will help to identify biomarkers for those living with motor system pathologies.

Acknowledgements

I have been incredibly privileged to have three fabulous advisors throughout this process. I thank Dr. Nicki Swann, who spent hours clarifying concepts in physiology, reviewing my papers, and aiding me in my task design and the coding process. She has been the best primary advisor I could have asked for. Equally important to the success and completion of this project is Dr. Ian Greenhouse, whose own curiosity helped spark the idea for this study. Dr. Greenhouse, too, was a guide in developing this experiment and a hero when coming to my rescue with his coding expertise. Dr. Swann and Dr. Greenhouse have been so patient with me along this process, and for that I am immeasurably grateful. In addition, I appreciate the Swann and Greenhouse labs as a whole for bringing me eager support, peer-advice, and unforgettable friendships.

At the most difficult points in this process, Dr. Melissa Graboyes offered me her sincere advice and motivational encouragement. Her consistent feedback and instruction on how to navigate research efficiently have helped me immensely. She serves as a model and inspiration for embarking on research which is important to oneself and maintains a focus on the human element.

Last, but not least, I would like to thank my family for having an undying belief in my abilities to complete a thesis, even though they had little idea of what it entailed. The emotional support of my mother has been paramount to my achievements. A sincere thank you to UO Women in Graduate Sciences for awarding me the Summer Undergraduate Research Award, which along with much appreciated support from the Swann lab, allowed me to further my research and coding skills for this project.

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Introduction

A crucial aspect in studying pathologies of the nervous system (i.e. Parkinson's Disease, stroke, dystonia) is determining the functional connectivity between the motor system and the muscular system. Electromyography (EMG), used in conjunction with electroencephalography (EEG) can help determine the degree of connectivity between these two systems. Electromyography (EMG) uses surface or intramuscular electrodes to record the electrical activity generated by muscles. EEG is a noninvasive way to measure electrical activity of the brain in which a series of electrodes placed over the scalp can be used to detect extracellular currents generated from the synaptic activity of neuron populations. EEG displays continuous brain activity as measured by the electrodes, but unfortunately, it offers poor spatial resolution, making it hard to assign observed activity to specific motor pathways of the brain. Although it was not used in this study, functional magnetic resonance imaging (fMRI) can be paired with EEG studies to complement the data with subject-specific spatial imaging of brain function. Magnetic resonance technology images parts of the brain that are activated in response to stimuli by detecting areas that experience an increase in oxygenated blood (Enders & Nigg, 2016).

One hypothesized way to measure the functional activity between the brain and muscles is with Corticomuscular Coherence (CMC). In 2005, neurophysiologist Pascal Fries suggested the Communication-through-coherence hypothesis: coherence between neuronal groups allows for effective communication because of phase-locking patterns between the oscillatory electrical potentials they send out. In other words, when neuronal groups' windows for receiving synaptic input or output have consistent relationships, communication is facilitated. Neuronal groups in the brain emit oscillatory electrical signals due to changes in synaptic potentials and some may be more likely to fire at certain phases in an oscillation. If neuronal Group A consistently fires at a time when neuronal Group B is at a crucial phase of its oscillation, it could have a heavier influence on Group B and therefore establish better communication with Group B. This could lead to a consistent phase relationship between the two separate neuronal groups. Dynamic and flexible neural communication enables healthy cognitive function. Coherence which is too high constricts neurons to inflexible patterns of signal transmission like that thought to be seen in Parkinson's Disease patients (Silberstein, 2005; Voytek and Knight, 2015). In contrast, low coherence disables adequate communication or is a sign of no communication between structures altogether (Fries, 2005).

Another manner by which coherence is paramount to flexible cognitive function is explained in Fries' Binding-By-Synchronization hypothesis (BBS). Coherence binds neurons together into assemblies which make them more flexible in channeling stimuli. It serves as a "binding tag" which leads to neuronal pathways having more "representational capacity" and the ability to create stronger signals by synchronizing beta (13-30Hz) or gamma (30-80Hz) frequency oscillations. In other terms, coherence helps to establish the "highway routes" through which motor neural signals travel in the brain. With the frequent use of certain pathways, communication within the motor cortex becomes structured and regulated. Different from structured pathway communication, is "global" communication through the brain. Global communication is characteristic of epileptic seizures and indicates intermittent failure of the brain's regulated communication system (Fries, 2005).

EEG-EMG coherence readings must be taken with a muscle held in tonic contraction in order to measure cortico-muscular connectivity. This is because EMG at rest is a flat signal with no activity to compare to the EEG (Enders & Nigg, 2016). Coherence is a quantitative measure of functional connectivity between the brain and a muscle. This study seeks to measure coherence value measures between electromyography and electroencephalography while a subject holds tonic contractions and performs a simple reaction time task. This particular task allows investigation of the functional connectivity between the sensorimotor cortex and muscles during preparation and execution of movement in a variety of contexts. This helps scientists better understand how movements are prepared and executed in the healthy brain. It also allows us to obtain a foundation for coherence patterns in healthy participants. It is hypothesized that motor control disorders are associated with abnormal coherence patterns when compared to those patterns in healthy people. If future research proves this hypothesis, it could be possible to compare these abnormal coherence patterns to a healthy baseline map and thereby identify biomarkers for motor pathologies (i.e. stroke or Parkinson's Disease).

In a task similar to the current experiment, Schoffelen, Oostenveld, and Fries sought patterns of corticomuscular coherence (CMC) between the motor cortex and distant corresponding motor units in the extensor carpi radialis muscle (ECR). Both included manual response tasks incorporating varying levels of muscle contraction and both looked at coherence between the nervous system and the extensor carpi radialis muscle. The study confirmed that beta-oscillations or “beta band” activity were seen before and during stimulus presentation and were strongest during weak and medium force muscle contractions. The prominence of the measured beta band activity suggested that communication in this frequency range was crucial to maintenance of contraction. Gamma band activity was noticed during anticipation of the stimulus and after presentation of the stimulus and are therefore thought to aid in readiness for response. Gamma oscillations are dominant during slow and maximal contractions. Overall findings included that gamma and beta oscillatory signals are detected in the same or overlapping neuronal groups and this overlap in coherence could contribute to the decreased reaction times noticed when subjects respond to anticipated stimuli (Schoffelen et al., 2005).

When changes in beta frequency activity in the brain are measured by EEG, it is expected to be most apparent on the side of the brain contralateral to limb movement. Some researchers believe this to indicate the brain’s processing of motor signals returning from the muscle (efference) as well as information returning from somatosensory systems (Novembre et al. 2018), (Ushiyama et al. 2012). Alternatively, beta signals could be traveling from the brain to muscles; a study conducted in 2010 by Miller et al. observed that subjects who thought about movement (motor imagery) (without any overt movement) elicited a change in beta values (Miller et al., 2010). It is highly possible that activity is in fact bilateral: beta travels from muscles to brain and from brain to muscles.

Consideration of coherence mechanisms and patterns can shed light on how motor systems change with time. The motor system develops in the early years after birth, into early adolescence, and deteriorates with aging (James et al., 2008). The lifetime trajectory of motor system flexibility mimics an inverted U-shape seen in several cognitive processes (McIntosh, 2013). With maturation of the brain into adulthood, variability of brain signals increases (in continuous EEG) (McIntosh, 2014). This is thought to be proof of more flexible cognition and greater neural complexity. However, with the elderly experiencing a decrease in variability of brain signals, it is suspected that their corticomuscular coupling will decrease as well. Contradictory to this hypothesis are the findings of Voytek and colleagues which showed that elderly patients displayed more signal variability across different frequencies (Voytek, 2015). Studies like the current will contribute towards a baseline map of what healthy motor system function looks like so it can be used to identify abnormalities and the effects of aging.

In the case of pathologies like stroke, CMC is shown to decrease in the areas of the brain most affected by the lack of blood flow. This is suspected to be due to decrease in the inhibitory neurotransmitter Gamma-Aminobutyric Acid (GABA) that results from stroke damage (von Carlowitz-Ghori et al., 2013). After the passage of time and patients' healing, however, CMC measurements begin to rise again and coincide with recovered control of the motor system and motor skills (von Carlowitz-Ghori et al., 2013). This is a prime example of where CMC mapping aided in the monitoring of a pathology's effects and subsequent recovery in patient populations. As the knowledge base of healthy coherence patterns grows, the biomarkers seen in pathologies will become more apparent and this clarity will enable earlier medical interventions.

This study sought to answers to how CMC between contralateral and ipsilateral sensorimotor cortices and the extensor carpi radialis muscle varies in different contexts of motor preparation and execution. These questions will be asked while considering bilateral and unilateral arm recruitment. The array of task conditions allows these measures to be taken in a variety of circumstances. The diversity of conditions might also better simulate motor functioning in response to real world tasks.

I hypothesized that beta activity and coherence will be greatest in conditions that involved both arms be contracted throughout the task, because of the extra attention and cross-hemispheric communication required to maintain the bilateral activation. Greater demands on the motor system should increase coherence. Seeing as participants were all right handed, I expected coherence to be greater in trials where the right arm was held in contraction (verses in trials where the left arm was held in contraction). If an arm was either not responding, definitely responding, or maybe responding to the task cue, I would expect coherence to be greatest when the arm was maybe responding. Tzagarakis et al., found that beta-band activity increased with greater motor preparation. This preparation as well as inhibitory activity would be most probable in trials where the arm is definitely responding (Tzagarakis et al., 2015).

METHODS

Participants

All participants were oriented to the task with a verbal introduction and written description. Engagement was entirely voluntary— the subjects were welcome to leave the study at any point in time. Subjects gave written consent before any experimentation began. The study was conducted within the Swann Lab at the University of Oregon. The IRB protocol for this study was covered under Dr. Nicole Swann's protocol titled "EEG signatures of the motor system". IRB approval was granted as of January 2018. The IRB protocol number is 01222018033.

Right-handed participants of either gender, between the ages of 18 and 40, and with healthy motor systems were sought for this study. No specified levels of fitness were required, however decent health was assumed considering the age range of subjects. Members of no specific socioeconomic status were sought. Participants were recruited through the UO Department of Psychology Human Subject Pool (SONA). Compensation was given in the form of research credit required for students in psychology courses at the U of O.

Datasets from eight student participants (4 female, mean age 19.125 ± 0.87 years) were utilized in this study. A total of 11 participants were recruited for EEG. For two people, data sets were incomplete, and for the third, response accuracy was below the acceptable level for all blocks. Six behavioral subjects were also recruited prior to EEG testing to pilot the behavioral task (3 female, mean age 19.33), although data from their experiments are not included here.

Task Design

For this experiment, the movement of joysticks was used to react to stimuli displayed on a monitor. A total of ten task conditions (blocks) were presented in random order. During three of the blocks, both hands were held in contracted positions (bimanual task). One of these blocks featured responses from either the right or left hand, another, responses from only the right, and another responses from only the left. Three similar blocks existed, but with the arms remaining in the relaxed position (unilateral task). Two additional trials required the right arm to be the sole responder—one in which it was held at rest, and one in which it was held contracted. The final two blocks had the same design for the left arm. In the case of this task a "contracted" arm was one that was held in tonic contraction during the block. A contracted arm was not necessarily the a "response arm". Only if the responding arm is held in tonic contraction between stimuli presentations was it considered to be held in contraction.

The participants performed 60 trials for each of the task conditions. Fixations appeared as centered white squares and stimuli appeared as white, left or right pointing triangles against a dark grey background. For each trial, there was a jittered delay (0.5-1.5 seconds) between the fixation and stimulus appearance, then another delay period of up to 1.5 seconds before the disappearance of the stimulus. If the subject did not respond within 1.5 seconds of the stimulus appearance, the arrow would disappear and the next fixation would arise. A one second interval separated trials. All in all, each trial lasted approximately 3.5 seconds. The entire experimental run-time was approximately 35 minutes. Responses were recorded regardless of which arm responded.

The first three subjects were run on a longer version of the experiment than the last five. This was due to errors in the code which caused each successive block to be longer than the one before. As a consequence, the task time for the first three participants was approximately 70 minutes. This error was not considered impactful to the study, as it did not alter the condition of the task block or require any additional response.

Between each block the participant was allowed a break of however long was needed to prepare for the next portion of the task. Specific instructions were displayed on the screen prior to the beginning of subsequent blocks. To proceed with the next condition, a numeric keypad was pressed.

If an arrow pointing to the right was shown, the subject would twist the right wrist to deflect the joystick outwards. The desired movement was akin to an outward flick of the hand. If a contraction were to be held, the wrist would be kept at an angle that induced a constant extension of the extensor carpi radialis muscle. All of these movements were explained and demonstrated to the participants prior to the start of the experiment.

Experimental Setup

Upon the desk in front of the monitor was a numeric keypad which the participant would use to proceed with the block between tasks. On either side of the keypad were the joysticks. Prior to experimental setup and the start of the trial, the subject was allowed to adjust how wide apart the joysticks would be from each other and move them forward or backward depending on comfort. Adjustment was allowed as long as the joysticks remained rotated at a slight inward angle. It was determined that this orientation would require a greater extension of the wrist and therefore more obvious contraction of the erector carpi radialis muscle while discouraging movement at the elbow or shoulder joint. Two crossed pieces of masking tape were used to anchor the lightweight base of the joystick to the table.

As part of EEG data collection, participants wore a BioSemi 64-channel electrode cap and eight additional BioSemi external flat active electrodes. Placement of the additional electrodes was as follows: one on each mastoid process as possible alternative references for EEG, one under the left eye and one lateral to the right eye for blink and eye movement recordings, and two on both the left and right extensor carpi radialis muscles. These last four EMG electrodes on the two arms were necessary for coherence calculations (Ho et al., 2014). Finally, on each wrist, an accelerometer was velcroed for a more accurate recording of movement times.

Upon completion of the experimental set-up, participants were oriented to the task and given demonstrations on the type of wrist-response desired. They were not explicitly asked to avoid unnecessary movement. Prior to the beginning of the computer task, three minutes of resting EEG data were collected.

Data Collection and Preprocessing

EEG data was collected with a 64-channel Biosemi ActiveTwo system with sampling at 1024 Hz. Electrode offset was limited to ±20 microvolts. Processing of all subjects was conducted in MATLAB using a combination of custom code and build in eeglab functions (Delorme & Makeig, 2004). For preprocessing, first the mean of each electrode was removed followed by application of average reference (including all 64 scalp channels). Additionally, high pass filtering at 0.5 Hz with FIR1 in eegfilt served to eliminate low frequency fluctuations/drift (Delorme & Makeig, 2004). Dataset 1 exhibited exceptional electrical artifact and was therefore low pass filtered at 30Hz to remove 60Hz noise. EMG electrodes were referenced with a bipolor referencing scheme (neighboring electrodes over the same muscle were subtracted). Next, datasets underwent manual artifact rejection. Artifacts representing clear muscle movements, eye blinks, errant electrical noise, etc. were marked and indices of these events were saved for removal following filtering (to avoid filtering over discontinuous signals which can cause artifacts). The two electrodes nearest to the sensorimotor cortex of the brain, C3 and C4, supplied the data used to calculate coherence for each block separately.

The algorithm used for coherence was:

$$\gamma_{ij}(f) = \frac{|G_{ij}(f)|}{\sqrt{G_{ii}(f)Gh_{jj}(f)}}$$

Where

$$G_{ij}(f) = \frac{1}{N}\Sigma_n X_{in}(f)X_{jn}(f)^*$$

(Chorlian et al. , 2003)

X_{in} represents the Hilbert transform, which picks out the phase angle and frequency from a signal at time point *n* (Wang et al., 2014). The asterisk indicates that complex conjugates of the values were applied for each 0.5Hz frequency bin (Chorlian et al. , 2003).

In addition to coherence, phase coherence was measured for each arm in each condition. This measure extracts phase using a Hilbert transform and measures the consistency of the phase difference between the two signals over time. Coherence analysis takes into account both the amplitude and phase of a signal when calculating values. It is the traditional and most common way of examining EEG-EMG data. Some believe this leaves data vulnerable to error caused by excess noise or artifacts that would inflate the amplitude of a signal (Galka, 2000; Mezeiová et al., 2012). To circumnavigate this issue, scientists may look at phase coherence as a more reliable coherence measure, because it only takes into account differences in signals' phases when assessing their synchronization. It is therefore thought to be less affected by artifact (Lachaux et al., 1999, Mezeiová et al., 2012). By taking these two measures, we were able to compare coherence and phase coherence values.

Data Analysis

Three core comparisons for both the right and left arm were looked at during data analysis. The first was to see how contralateral and ipsilateral coherence/phase coherence compared. The second was to examine how contralateral values changed depending on whether the opposite arm was contracted or relaxed. The third was to see how response type (definitely responding, maybe responding, or not responding) affected values.

Data analysis was completed using MATLAB and Microsoft Excel. Significance between groups of coherence values (whether looking at contralateral vs. ipsilateral, left arm or right arm, etc.) was found using paired t-test functions in excel ($p<0.05$). An ANOVA with repeated measures was completed using the Two-factor without replication ANOVA test offered in the MS Excel data analysis toolpack. To correct for multiple comparisons, since both right and left hands were examined separately, a Bonferroni correction was applied. Hence, significance was considered to be a p-value under 0.025 (0.05/2).

Any coherence or phase coherence value that originated from a block with less than 50% accuracy from any subject, was excluded in calculations. Accuracy was determined by the percentage of trials responded to by the correct arm. Reaction times were calculated per block. Reaction times less than 0.1 seconds were considered to be premature and excluded. The reaction time was recorded as the time when the joystick first started moving after stimulus presentation. Asterisks are applied adjacent to significant differences.

RESULTS

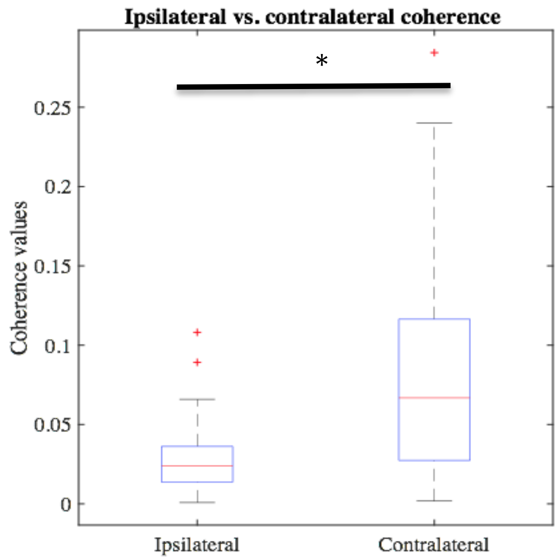

Figure 1. Ipsilateral versus contralateral coherence

Values are from both arms across 7 block types. Contralateral coherence was found to be significantly greater (p = 0.0034) (n=8).

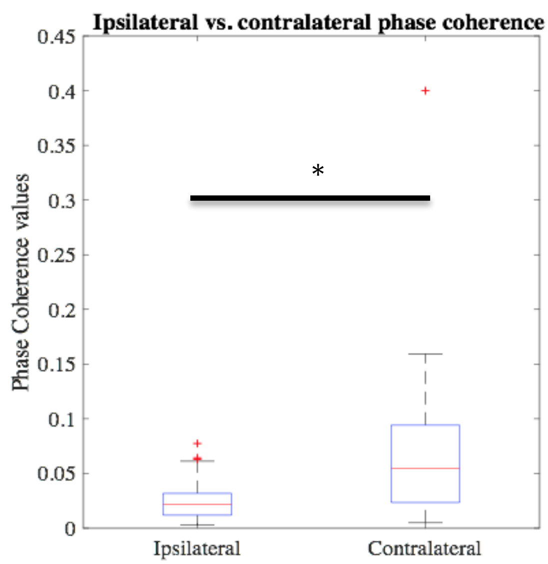

Figure 2. Ipsilateral versus contralateral phase coherence

Values are from both arms across 7 block types. Contralateral phase coherence was found to be significantly greater (p = 0.00040) (n=8).

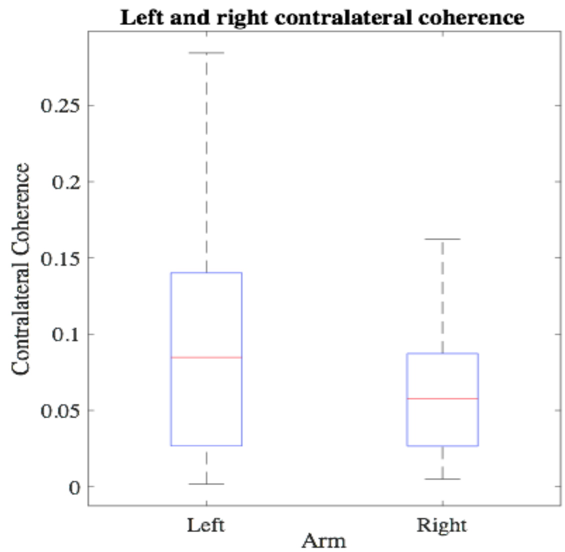

Figure 3. Contralateral coherence for the left and right arm

Values are from both the left and right arm across 7 blocks (n=8). No significant difference was noticed between the two data sets (p = 0.093).

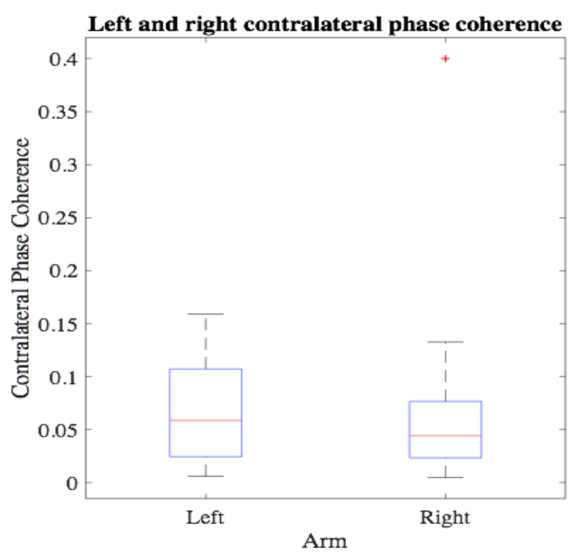

Figure 4. Contralateral phase coherence for the left and right arm

Values are from both the left and right arm across 7 blocks (n=8). No significant difference was noticed between the two data sets (p = 0.429).

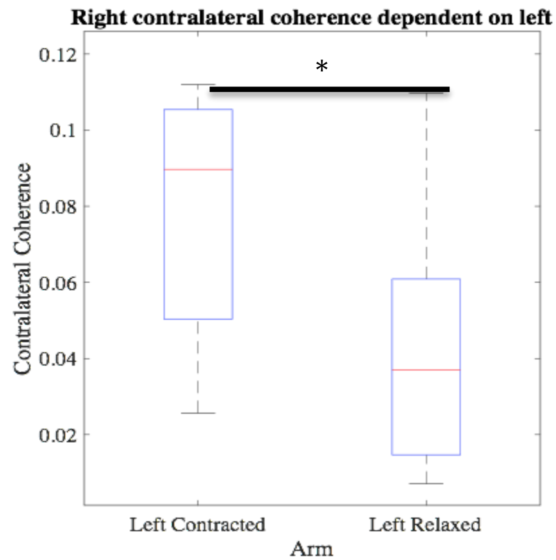

Figure 5. Right contralateral coherence dependent on whether the left arm was contracted or relaxed

Coherence measurements for the right arm were significantly greater when the left arm was held in contraction (blocks 1, 5, 6) versus when it was relaxed (block 9), ($p = 0.0049$) ($n=8$).

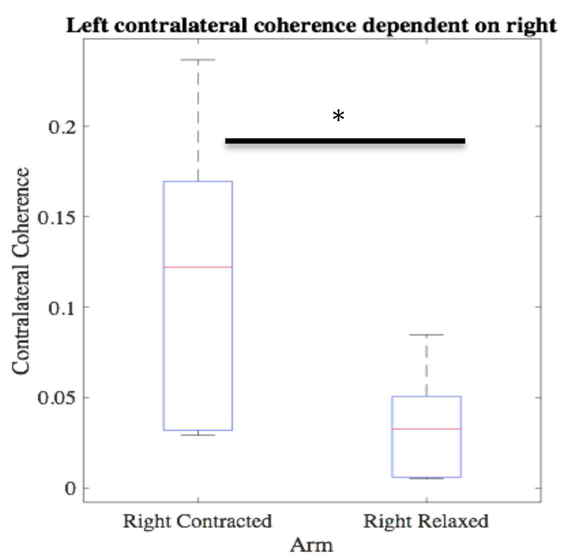

Figure 6. Left contralateral coherence dependent on whether the right arm was contracted or relaxed

Coherence measurements for the left arm were significantly greater when the right arm was held in contraction (blocks 1, 5, 6) versus when it was relaxed (block 10), ($p = 0.048$) ($n=8$).

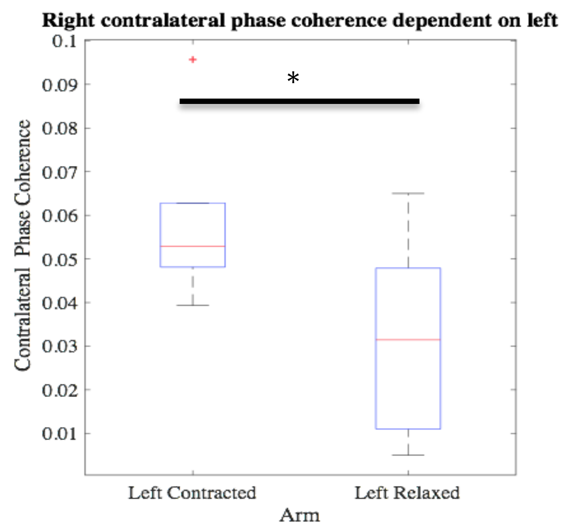

Figure 7. Right contralateral phase coherence dependent on whether the left arm was contracted or relaxed

Phase coherence measurements for the right arm were significantly greater when the left arm was held in contraction (blocks 1, 5, 6) versus when it was relaxed (block 9), ($p = 0.011$) ($n=8$).

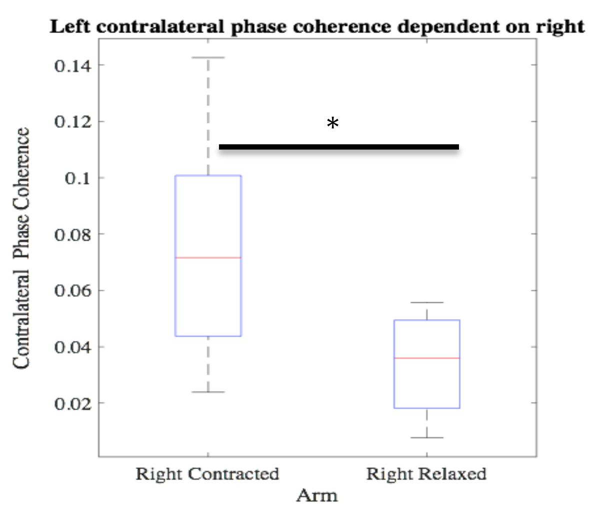

Figure 8. Left contralateral phase coherence dependent on whether the right arm was contracted or relaxed

Phase coherence measurements for the left arm were significantly greater when the right arm was held in contraction (blocks 1, 5, 6) versus when it was relaxed (block 10), (p = 0.011) (n=8).

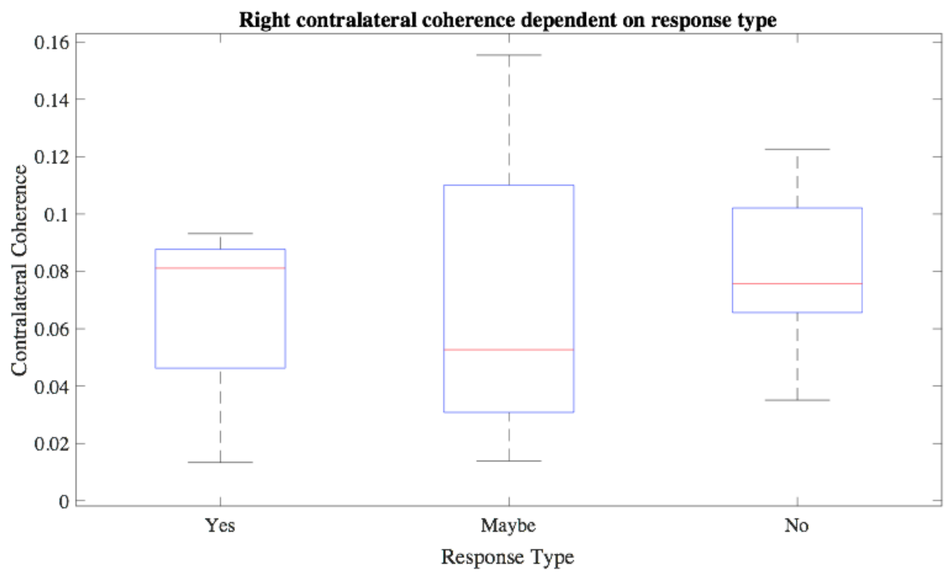

Figure 9. Right contralateral coherence dependent on response type

Right contralateral coherence values dependent on whether the right arm was definitely responding to a task (blocks 5,9), maybe responding (block 1) or definitely not responding (blocks 6,8). A multiple repeated measures ANOVA analysis detected no significant differences between response types.

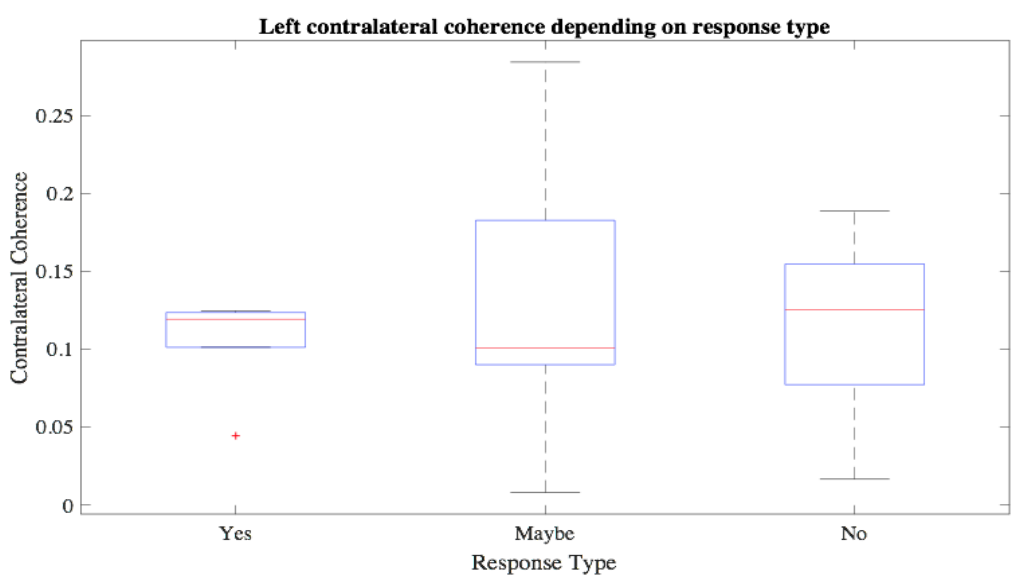

Figure 10. Left contralateral coherence dependent on response type

Left contralateral coherence values dependent on whether the left arm was definitely responding to a task (blocks 6,10), maybe responding (block 1) or definitely not responding (blocks 5,7). A multiple repeated measures ANOVA analysis detected no significant differences between response types.

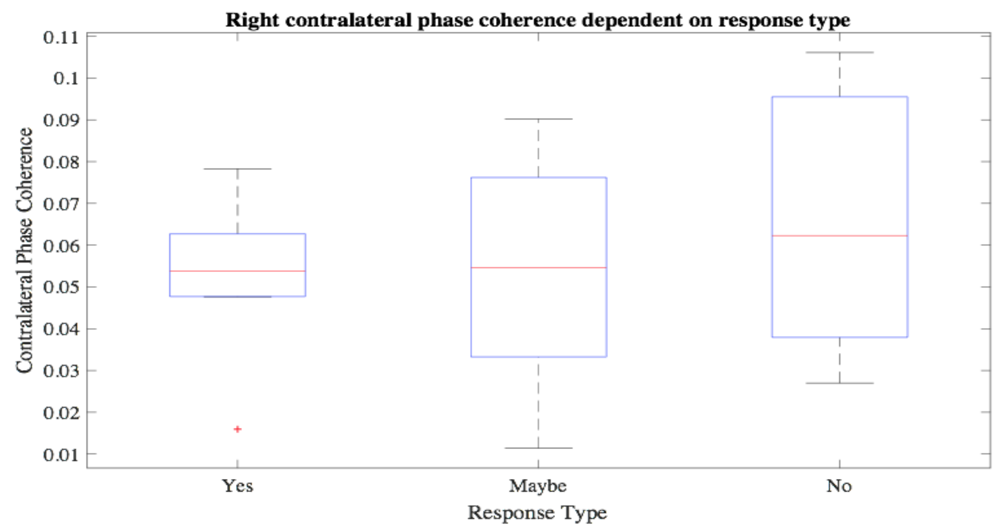

Figure 11. Right contralateral phase coherence dependent on response type

Right contralateral phase coherence values dependent on whether the right arm was definitely responding to a task (blocks 5,9), maybe responding (block 1) or definitely not responding (blocks 6,8). A multiple repeated measures ANOVA analysis detected no significant differences between response types.

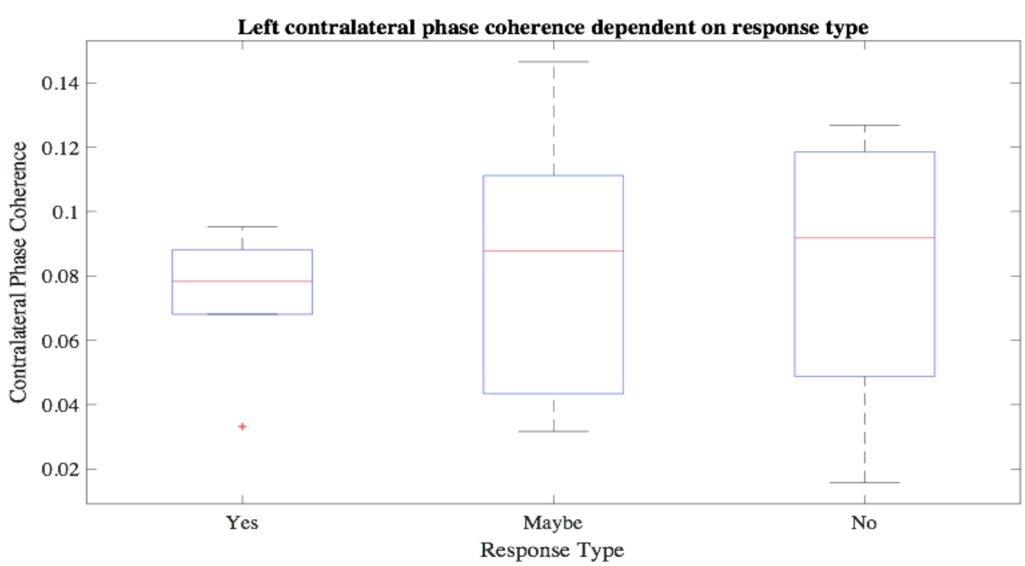

Figure 12. Left contralateral phase coherence dependent on response type

Left contralateral phase coherence values dependent on whether the left arm was definitely responding to a task (blocks 6,10), maybe responding (block 1) or definitely not responding (blocks 5,7). A multiple repeated measures ANOVA analysis detected no significant differences between response types.

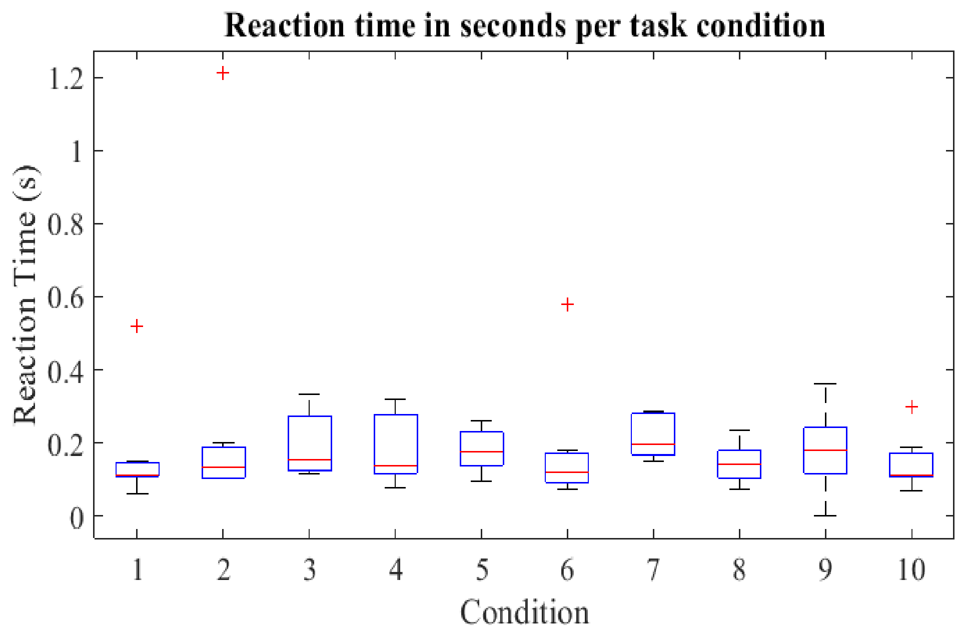

Figure 14. Average reaction times per task condition

Reaction times, averaged between all subjects over the 10 blocks, showed no significant differences.

Without regard for arm or block type, coherence and phase coherence values were significantly greater for contralateral responses (as opposed to ipsilateral responses) in the majority of blocks. Contralateral versus ipsilateral coherence and phase coherence showed p-values of 0.0034 and 0.00040 respectively (Fig. 1; Table 1, Fig. 2; Table 2).

Neither coherence nor phase coherence showed significant differences between left and right contralateral values (Fig. 3, Fig. 4) with p-values of 0.093 and 0.429 respectively.

Contralateral coherence values for the right arm when the left arm was held contraction were significantly greater than those when the left arm was relaxed, indicated by a p-value of 0.0049 (Fig 5; Table 5, Fig. 6; Table 6). This finding was not significant when considering left coherence values depending on the condition of the right arm (Fig. 6; Table 6, p=0.0487). Contralateral phase coherence values for the right arm when the left was held in contraction were significantly greater than when the left was relaxed (Fig. 7; Table 7, p = 0.011). The same finding existed for left phase coherence when the right arm was flexed versus relaxed (Fig. 8; Table 8, p =0.011). These findings suggest that bimanual tasks elicit greater coherence.

Neither coherence nor phase coherence values were significantly different for an arm depending on whether it was definitely responding, maybe responding, or not responding during a block. ANOVA testing for coherence values of the right and left arm depending on response type yielded p-values of 0.77 and 0.62 respectively (Fig. 9, Fig. 10). Phase coherence values for the right versus left arm depending on response type showed no significance either and elicited p-values of 0.60 and 0.68 respectively (Fig. 11, Fig. 12).

A repeated measures ANOVA test found no significant difference between task condition reaction times.

DISCUSSION

Limb movements are controlled by the contralateral hemispheres of the brain. Findings that contralateral coherence values exceeded those of ipsilateral values are therefore expected and have been confirmed by several previous studies (Novembre et al., 2018; Ushiyama et al., 2012; Conway et al., 1995; etc.). In contrast, ipsilateral coherence has been found to be insignificant. The discovery of increased contralateral coherence led to use of coherence to test corticomuscular connectivity (Conway et al., 1995; Liu et al., 2019), and those past findings have been upheld here. I hypothesized that right coherence values would be greater as the right arm was the dominant arm for all participants in this study, however no significant differences were found between dominant or nondominant values.

There are several factors to a task that affect coherence values: the amount of attention required, the amount of resistance applied to muscles, the amount of movement required, the amount of force exerted by a muscle, etc. These can all be legitimate factors that compete in influencing coherence calculations. It appears that further research is needed to determine how the dominant versus nondominant arm is affected by dynamic tasks in terms of corticomuscular coherence.

The findings of Perez et al., could shed light on how and why coherence and phase coherence values were greater for the left and right arm when the opposite arm was contracted versus relaxed in a bimanual task. Their 2012 paper outlines a study in which participants were made to perform a tonic contraction task with their non-dominant hand while keeping their dominant arm either stationary or active in a task. They found that contractions above 40% of subjects' maximal isometric voluntary contraction elicited an increase in contralateral coherence values for the non-dominant hand (Perez et al., 2012). This relationship between left and right coherence, depicted in Figure 3, does not take into consideration the activity of the opposite hand, so clear parallels cannot be drawn between these results and those of Perez and colleagues. However, Perez et al. hypothesized that their findings of increased coherence in non-dominant hands could be contributed to "mirroring". Mirroring is when a seemingly stationary muscle (in an arm, for example) experiences partial activation as a result of the opposite arm's full recruitment. As a consequence of this mirroring, extra inhibition must be present in the opposite arm as well. This suggests that many corticomuscular pathways must be working for each arm to be doing what is directed by a task. This is one reason why it is thought that increased coherence complements increased inhibitory ability. Perez adds that such mirroring and inhibition might be possible through the reticulospinal tract, a brainstem output pathway with bilaterally spanning neurons. This tract has also been found to be important in fine motor output and to have some effect over hand movement (Perez et al., 2012; Davidson and Buford, 2006; Baker, 2011; Peterson et al., 1975).

The findings of Perez could play a part in explaining why the response type of the active arm (responding, maybe responding, not responding) did not show a clear pattern in coherence values. The findings of Perez could suggest that conditions where the arm was definitely responding would require the greatest contraction and therefore, perhaps, the greatest coherence, because maximal contraction of one arm would be more likely to elicit mirroring in the other. Meanwhile, as cited above, previous studies would suggest that the element of uncertainty/ necessary preparation could show the highest values. No significant differences in coherence values depending on the response type were detected.

Contradictory to the findings of Perez are those of Johnson et al., who observed beta-band coherence decreased during bimanual tasks. Johnson attributed this to the greater division of attention that accompanies more complex tasks (Johnson et al., 2011). Johnson's findings complemented those of previous studies that had found divided attention lowers EEG-EMG synchronization in the beta range (Kristeva-Feige et al., 2002).

In yet another bimanual motor task, Zheng and colleagues found that coherence of the right arm increased as contraction of the left arm grew. However, once contraction of the left arm reached 50% of its maximal isometric voluntary coherence, no contralateral coherence of the right arm was observed. Following their study, Zheng et al., argued that Perez and Johnson hypotheses (mirroring increasing coherence and attention division decreasing coherence) might both be at play depending on the task.

Were Johnson's findings corroborated by the current study, uncertainty in response (a "maybe respond" condition) might show a lower coherence value. Zheng's considerations offer a fair idea of why no pattern was seen when looking at coherence depending on response types: when we are looking at one arm, we do not see what the opposite arm is doing to change expected coherence values. A reasonable future path would be to examine more carefully what the opposite arm is doing during the various response type tasks.

LIMITATIONS

Reaction times in this task were recorded when the participant had completed a response by moving a joystick to the end of its deflection zone/ had contracted the wrist fully. In reality, the beginning of a reaction would have been when the participant first began to move the wrist. Thus, reaction times were inflated by nature of the recording system. By looking closely at accelerometer data in relation to task events, a more accurate picture of reaction times could be found. Not all conditions for each subject were completed with 100% accuracy. If the activity of the arms were not consistent in regard to the task condition requirements, the calculated values are not from a "pure" block. By analyzing data from the entire blocks, I could not see how beta coherence values fluctuated between different parts of each trial. For example, I was unable to see if there were clear patterns in CMC changes between the preparation and execution phases of each trial. Additionally, this study looked at coherence from only two electrodes and only in the beta range. As mentioned earlier, it is known that gamma frequencies can also exhibit patterns with maximal muscle contraction.

CONCLUSION

In the hopes of contributing to a picture of healthy motor function and aiding in discovery of a biomarker of motor pathologies, this experiment sought patterns in coherence values during a bimanual task. In agreement with previous studies, it was found that contralateral coherence was significantly greater across all blocks and coherence was greater when the opposite arm was contracted versus relaxed. Whether an arm was definitely responding, maybe responding, or not responding during a block appeared to have no significant effect on coherence.

It is important to remember that coherence is a measure that is subject to dynamic and versatile neural and muscular systems. These findings, although they do not offer conclusive patterns, contribute to the realization that coherence measurement is highly dependent on task design. To create a reliable baseline map of coherence values that could be used clinically in the future, a standard and accessible task would have to be developed. Of course, before this can be achieved, further research and corroboration of findings is necessary to understand the underlying mechanisms that modulate coherence and phase synchrony.

A follow-up on this current study would be to consider beta-power in addition to coherence between the right and left arms. Beta-power would look closely at the power of the signal within the beta range of 13 to 30 Hertz. Spectral power is measured in various ways and has displayed promising patterns in different motor tasks over the years. Patterns in power changes could offer information on which factors of a task are more heavily affecting coherence.

SUPPLEMENARY DATA

Condition Number	Condition Name	Ipsilateral Mean	Contralateral Mean	P- Value	Significant? (uncorrected)
1	Both Contract-- Choice	0.029 ±0.020	0.0950 ± 0.074	0.0018	Yes
5	Both Contract -- Right	0.030 ±0.012	0.100±0.062	0.0007	Yes
6	Both Contract-- Left	0.036 ±0.030	0.104 ±0.079	0.0073	Yes
7	Left Contract-- Right	0.0218 ±0.0082	0.065 ±0.060	0.026	Yes
8	Right Contract-- Left	0.02 ±0.012	0.078 ±0.055	0.000837	Yes
9	Right Contract-- Right	0.026±0.019	0.062±0.044	0.028	Yes
10	Left Contract-- Left	0.020±0.015	0.048±0.034	0.0112	Yes
All Conditions (1, 5-10)	All Conditions (1, 5-10)	0.025±0.006	0.073 ±0.036	0.0034	Yes

Table 1. Ipsilateral and contralateral coherence values per condition

Values for both hands are combined in ipsilateral and contralateral readings per condition. The p-value was found by comparing a set of each subject's average ipsilateral values to a set of each subject's averaged contralateral values (n=8). Contralateral coherence was found to be significantly greater.

Condition Number	Condition Name	Ipsilateral Mean	Contralateral Mean	P-Value	Significant? (uncorrected)
1	Both Contract-- Choice	0.024±0.015	0.064 ±0.041	0.00220	Yes
5	Both Contract -- Right	0.024±0.011	0.072±0.038	0.000175	Yes

6	Both Contract--Left	0.031 ± 0.018	0.071± 0.046	0.005	Yes
7	Left Contract--Right	0.0202 ±0.009	0.053 ±0.047	0.0297	Yes
8	Right Contract--Left	0.028±0.017	0.059±0.042	0.0149	Yes
9	Right Contract--Right	0.024±0.022	0.058±0.045	0.098	No
10	Left Contract--Left	0.019±0.010	0.067±0.092	0.045	Yes
All Conditions (1, 5-10)	All Conditions (1, 5-10)	0.024 ± 0.007	0.056± 0.018	0.00040	Yes

Table 2. Ipsilateral and contralateral Phase-coherence values per condition

Values for both hands are combined in ipsilateral and contralateral readings per condition. The p-value was found by comparing a set of each subject's average ipsilateral values to a set of each subject's averaged contralateral values (n=8). Contralateral phase coherence was found to be significantly greater.

Condition Number	Condition Name	Arm Contracted	Ipsilateral Mean	Contralateral Mean	P-Value	Significant? (uncorrected)
1	Both Contract--Choice	Right	0.027 ±0.026	0.071 ± 0.052	0.016	Yes
1	Both Contract--Choice	Left	0.031 ± 0.015	0.112 ±0.096	0.049	Yes
5	Both Contract -- Right	Right	0.034 ±0.011	0.093 ±0.043	0.0064	Yes
5	Both Contract -- Right	Left	0.029 ±0.012	0.099 ±0.080	0.052	No
6	Both Contract--Left	Right	0.024 ±0.020	0.067 ±0.053	0.040	Yes

6	Both Contract--Left	Left	0.048 ±0.035	0.141 ±0.086	0.0043	Yes
7	Left Contract-- Right	Left	0.0236 ±0.0075	0.104 ±0.063	0.012	Yes
8	Right Contract--Left	Right	0.031 ±0.013	0.078 ±0.042	0.0073	Yes
9	Right Contract--Right	Right	0.0165 ±.0066	0.037 ±0.024	0.070	No
10	Left Contract--Left	Left	0.021 ± 0.014	0.030 ±0.028	0.46	No

Table 3. Contralateral vs. ipsilateral coherence for contracted arms in each block (n=8)

Condition Number	Condition Name	Arm Contracted	Ipsilateral Mean	Contralateral Mean	P-Value	Significant? (uncorrected)
1	Both Contract--Choice	Right	0.021 ±0.015	0.054 ± 0.028	0.0023	Yes
1	Both Contract--Choice	Left	0.026 ± 0.016	0.073 ±0.050	0.068	No
5	Both Contract -- Right	Right	0.026 ±0.010	0.073±0.031	0.0044	Yes
5	Both Contract -- Right	Left	0.021 ±0.013	0.064 ±0.047	0.034	Yes
6	Both Contract--Left	Right	0.029 ±0.018	0.052 ±0.040	0.11	No
6	Both Contract--Left	Left	0.034± 0.019	0.091 ±0.044	0.0046	Yes
7	Left Contract-- Right	Left	0.0250 ±0.0076	0.082 ± 0.051	0.018	Yes
8	Right Contract--Left	Right	0.036 ± 0.018	0.068± 0.044	0.021	Yes

9	Right Contract--Right	Right	0.012 ± 0.0047	0.025 ±0.016	0.17	No
10	Left Contract--Left	Left	0.023 ±0.010	0.034 ±0.019	0.65	No

Table 4. Contralateral vs. ipsilateral phase coherence for contracted arms in each block (n=8)

Condition Number	Condition Name	Relaxed or Contracted Left Arm	Right Arm Coherence
1	Both Contract--Choice	Contracted	0.071±0.052
5	Both Contract --Right	Contracted	0.102 ±0.047
6	Both Contract-- Left	Contracted	0.060±0.054
9	Right Contract--Right	Relaxed	0.037±0.024

Table 5. Contralateral coherence values for a contracted Right hand in conditions where the left arm was relaxed versus where the left arm was contracted

The p-value was found by averaging left contracted readings per subject and comparing that data set to left relaxed values per subject (n=8). Values where the left arm was contracted were found to be significantly greater (p=0.0049).

Condition Number	Condition Name	Relaxed or Contracted Right Arm	Left Arm Coherence
1	Both Contract--Choice	Contracted	0.11±0.096
5	Both Contract --Right	Contracted	0.089 ±0.080
6	Both Contract-- Left	Contracted	0.141±0.086
10	Left Contract--Left	Relaxed	0.030±0.028

Table 6. Contralateral coherence values for a contracted left arm in conditions where the right arm was relaxed versus when the right arm was contracted throughout a block

The p-value was found by averaging right contracted readings per subject and comparing that data set to right relaxed values per subject (n=8). A slim significance ($p = 0.048$) was found with values being higher when the right arm was contracted.

Condition Number	Condition Name	Relaxed or Contracted Left Arm	Right Arm Phase Coherence
1	Both Contract--Choice	Contracted	0.057 ±0.028
5	Both Contract --Right	Contracted	0.0700 ±0.032
6	Both Contract--Left	Contracted	0.052±0.040
9	Left Contract--Left	Relaxed	0.025±0.016

Table 7. Contralateral phase coherence values for a contracted Right hand in conditions where the left arm was relaxed versus when the left arm was contracted throughout a block

The p-value was found by averaging left contracted readings per subject and comparing that data set to left relaxed values per subject (n=8). Values where the left arm was contracted were found to be significantly greater ($p=0.011$).

Condition Number	Condition Name	Relaxed or Contracted Right Arm	Right Arm Phase Coherence
1	Both Contract--Choice	Contracted	0.073 ±0.050
5	Both Contract --Right	Contracted	0.070 ±0.048
6	Both Contract--Left	Contracted	0.091±0.046
10	Left Contract--Left	Relaxed	0.034±0.019

Table 8. Contralateral phase coherence values for a contracted left hand in conditions where the right arm was relaxed versus when the right arm was contracted throughout a block.

The p-value was found by averaging right contracted readings per subject and comparing that data set to right relaxed values per subject (n=8). Values where the right arm was contracted were found to be significantly greater (p=0.011).

BIBLIOGRAPHY

Baker S. N. (2011). The primate reticulospinal tract, hand function and functional recovery. *The Journal of physiology*, *589*(Pt 23), 5603–5612. doi:10.1113/jphysiol.2011.215160

Bowyer, S. M. (2016). Coherence a measure of the brain networks: past and present. *Neuropsychiatric Electrophysiology*, 2(1), 1. https://doi.org/10.1186/s40810-015-0015-7

Chorlian, D. B., Madhavi, A. E., Ae, R., & Porjesz, B. (2003). EEG coherence: topography and frequency structure. https://doi.org/10.1007/s00221-009-1936-9

Conway, B. A., Halliday, D. M., Farmer, S. F., Shahani, U., Maas, P., Weir, A. I., & Rosenberg, J. R. (1995). Synchronization between motor cortex and spinal motoneuronal pool during the performance of a maintained motor task in man. *The Journal of physiology*, *489 (Pt 3)*(Pt 3), 917–924.

Davidson, A. G., & Buford, J. A. (2006). Bilateral actions of the reticulospinal tract on arm and shoulder muscles in the monkey: stimulus triggered averaging. *Experimental Brain Research*, *173*(1), 25–39. https://doi.org/10.1007/s00221-006-0374-1

Delorme, A., & Makeig, S. (2004). *EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis*. *Journal of Neuroscience Methods* (Vol. 134). Retrieved from http://www.sccn.ucsd.edu/eeglab/

Enders, H., & Nigg, B. M. (2016). Measuring human locomotor control using EMG and EEG: Current knowledge, limitations and future considerations. *European Journal of Sport Science*, *16*(4),416–426. https://doi.org/10.1080/17461391.2015.1068869

Fries, P. (2005). A mechanism for cognitive dynamics: neuronal communication through neuronal coherence. *Trends in Cognitive Sciences*, *9*(10), 474–480. https://doi.org/10.1016/j.tics.2005.08.011

Galka, A., 2000. Topics in Nonlinear Time Series Analysis. World Scientific

Ho, M. C., Chen, T. C., Huang, C. F., Yu, C. H., Chen, J. M., Huang, R. Y., … Liu, C. J. (2014). Detect AD Patients by Using EEG Coherence Analysis. *Journal of medical engineering*, *2014*, 236734. doi:10.1155/2014/236734

James, L. M., Halliday, D. M., Stephens, J. A., & Farmer, S. F. (2008). On the development of human corticospinal oscillations: age-related changes in

EEGEMG coherence and cumulant. *European Journal of Neuroscience*, *27*(12), 3369–3379. https://doi.org/10.1111/j.14609568.2008.06277.x

Johnson, A. N., Wheaton, L. A., & Shinohara, M. (2011). Attenuation of corticomuscular coherence with additional motor or non-motor task. *Clinical Neurophysiology*, *122*(2), 356–363. https://doi.org/10.1016/J.CLINPH.2010.06.021

Kristeva-Feige, R., Fritsch, C., Timmer, J., & Lücking, C.-H. (2002). Effects of attention and precision of exerted force on beta range EEG-EMG synchronization during a maintained motor contraction task. *Clinical Neurophysiology*, *113*(1), 124–131. https://doi.org/10.1016/S1388-2457(01)00722-2

Lachaux, J.-P., Rodriguez, E., Martinerie, J., & Varela, F. J. (1999). Measuring phase synchrony in brain signals. *Human Brain Mapping*, *8*(4), 194–208. https://doi.org/10.1002/(SICI)1097-0193(1999)8:4<194::AID-HBM4>3.0.CO;2-C

Liu, J., Sheng, Y., & Liu, H. (2019). Corticomuscular Coherence and Its Applications: A Review. *Frontiers in human neuroscience*, *13*, 100. doi:10.3389/fnhum.2019.00100

McIntosh, A. R., Kovacevic, N., & Itier, R. J. (2008). Increased Brain Signal Variability Accompanies Lower Behavioral Variability in Development. *PLoS Computational Biology*, *4*(7),e1000106. https://doi.org/10.1371/journal.pcbi.1000106

McIntosh, A. R., Vakorin, V., Kovacevic, N., Wang, H., Diaconescu, A., & Protzner, A. B. (2014). Spatiotemporal Dependency of Age-Related Changes in Brain Signal Variability. *Cerebral Cortex*, *24*(7), 1806–1817. https://doi.org/10.1093/cercor/bht030

Mezeiová, K., & Paluš, M. (2012). Comparison of coherence and phase synchronization of the human sleep electroencephalogram. *Clinical Neurophysiology*, *123*(9), 1821–1830. https://doi.org/10.1016/j.clinph.2012.01.016

Novembre, G., Pawar, V. M., Bufacchi, R. J., Kilintari, M., Srinivasan, M., Rothwell, J. C., Iannetti, G. D. (2018). Saliency Detection as a Reactive Process: Unexpected Sensory Events Evoke Corticomuscular Coupling. *The Journal of Neuroscience*, *38*(9), 2385–2397. https://doi.org/10.1523/JNEUROSCI.2474-17.2017

Paul Silberstein, Alek Pogosyan, Andrea A. Kühn, Gary Hotton, Stephen Tisch, AndreasKupsch, Patricia Dowsey-Limousin, Marwan I. Hariz, Peter Brown; Cortico-cortical coupling in Parkinson's disease and its modulation by therapy, *Brain*, Volume 128, Issue 6, 1 June 2005, Pages 1277–1291, Perez, M. A., Soteropoulos, D. S., & Baker, S. N. (2012). Corticomuscular coherence during bilateral isometric arm voluntary activity in healthy humans. *Journal of Neurophysiology*, *107*(8), 2154–2162. https://doi.org/10.1152/jn.00722.2011

Peterson, B. W., Maunz, R. A., Pitts, N. G., & Mackel, R. G. (1975). Patterns of projection and branching of reticulospinal neurons. *Experimental Brain Research*, *23*(4), 333–351. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/1183508

Tzagarakis, C., West, S., & Pellizzer, G. (2015). Brain oscillatory activity during motor preparation: effect of directional uncertainty on beta, but not alpha, frequency band. *Frontiers in neuroscience*, *9*, 246. doi:10.3389/fnins.2015.00246

von Carlowitz-Ghori, K., Bayraktaroglu, Z., Hohlefeld, F. U., Losch, F., Curio, G., & Nikulin, V. V. (2014). Corticomuscular coherence in acute and chronic stroke. *Clinical Neurophysiology*, *125*(6), 1182–1191. https://doi.org/10.1016/j.clinph.2013.11.006

Voytek, B., Kramer, M. A., Case, J., Lepage, K. Q., Tempesta, Z. R., Knight, R. T., & Gazzaley, A. (2015). Age-Related Changes in 1/f Neural Electrophysiological Noise. *The Journal of neuroscience : the official journal of the Society for Neuroscience*, *35*(38), 13257–13265. doi:10.1523/JNEUROSCI.2332-14.2015

Voytek, B., & Knight, R. T. (2015). Dynamic network communication as a unifying neural basis for cognition, development, aging, and disease. *Biological psychiatry*, *77*(12), 1089–1097. doi:10.1016/j.biopsych.2015.04.016

Ushiyama, J., Masakado, Y., Fujiwara, T., Tsuji, T., Hase, K., Kimura, A., … Ushiba, J. (2012). Contraction level-related modulation of corticomuscular coherence differs between the tibialis anterior and soleus muscles in humans. *Journal of Applied Physiology*, *112*(8), 1258–1267. https://doi.org/10.1152/japplphysiol.01291.2011

Wang, K., Steyn-Ross, M. L., Steyn-Ross, D. A., Wilson, M. T., & Sleigh, J. W. (2014). EEG slow-wave coherence changes in propofol-induced general anesthesia: experiment and theory. *Frontiers in Systems Neuroscience*, *8*, 215. https://doi.org/10.3389/fnsys.2014.00215