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Alpha Band Signatures of Social Synchrony

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Alpha band signatures of social synchrony

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Abstract

Previous research has reported changes in mu rhythm, the central rhythm of the alpha frequency band, in both intentional and spontaneous interpersonal coordination. The current study was designed to extend existing findings on social synchrony to the pendulum swinging task and simultaneously measured time unfolding behavioral synchrony and EEG estimation of mu activity during spontaneous, intentional in-phase and intentional anti-phase interpersonal coordination. As expected, the behavioral measures of synchrony demonstrated the expected pattern of weak synchronization for spontaneous coordination, moderate synchronization for intentional anti-phase coordination, and strong synchronization for in-phase coordination. With respect to the EEG measures, we found evidence for mu enhancement for spontaneous coordination in contrast to mu suppression for intentional coordination (both in phase and anti-phase), with higher levels of synchronization associated with higher levels of mu suppression in the right hemisphere. The implications of the research findings and methodology for understanding the underlying mechanisms contributing to social problems in psychological disorders, leader-follower relationships, and inter-brain dynamics are discussed.

Keywords: Motor movements, interpersonal synchronization, mu suppression, EEG recording

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Highlights

- Weak behavioral synchronization was found for spontaneous coordination.
- Intentional coordination showed moderate or strong synchronization.
- Mu enhancement of alpha frequency band was found for spontaneous synchronization.
- Mu suppression was found during intentional social synchronization.
- Synchronization and mu suppression were associated in the right hemisphere.

Alpha band signatures of social synchrony

When two individuals interact socially, they tend to spontaneously coordinate their body movements. For example, if one person crosses his or her legs, the other tends to mirror this body posture. Moreover, this interpersonal coordination of body movements has been found to be psychologically significant in that it is positively correlated with multiple measures of relationship satisfaction and well-being [1, 2, 3, 4]. Conversely, disruptions in interpersonal synchrony affect behavioral and physiological measures of emotions [5, 6] and individuals with psychiatric diagnoses including schizophrenia and autism spectrum disorder synchronize atypically when interacting with partners [8, 9].

A coordination dynamics approach to behavior has been used as a framework for understanding interpersonal synchronization. This perspective was originally developed to evaluate rhythmic interlimb coordination [11, 12, 13, 14] and has been extended to model interpersonal social coordination of movements between two people [18, 19]. . This approach assumes that the limbs are assembled into oscillators that are governed by self-organizing entrainment processes [14, 15, 23], with each oscillator prefering to complete one cycle of its behavior at a certain rate (the preferred frequency or eigenfrequency). The entrainment processes of the oscillators have been captured by the Haken, Kelso, and Bunz (HKB) coupled oscillator model [16], which predicts changes in stability as a result of changes in frequency of oscillation of the oscillators and phase lag (deviation from perfect synchrony) due to differences in the inherent frequencies of the two oscillators (frequency detuning). This model predicts that in-phase coordination is more stable than anti-phase coordination and the stability of anti-phase coordination decreases as the frequency of oscillation is increased, eventually breaking down and leading to a transition to in-phase coordination. This research has found that dynamical coupled oscillator processes organize behavior not only within a single central nervous system (CNS) [25, 17] but also across the CNSs of two people connected by perceptual information [20, 21].

Moreover, this dynamical model has been used to appreciate social synchrony that arises spontaneously within a social interaction as well as intentional coordination (as in the studies above). Schmidt and O'Brien [22, 23] found that *spontaneous* entrainment of rhythmic movements did occur but rather than being phase-locked, the entrainment pattern observed was meta-stable and intermittent [24] and demonstrated frequency detuning. Both the meta-stable and intermittent phase locking in spontaneous coordination as well as the effect of frequency detuning are predicted by a weakly parameterized synchronization dynamic model such as the HKB and have been replicated many times[e.g., 20, 25].

To examine the brain dynamics underlying interpersonal synchrony, researchers have begun to evaluate the oscillations within specific power bands of the electroencephalogram (EEG). The mu rhythm, the central rhythm of the alpha frequency band (between 8 and 12 Hz), tends to de-synchronize when individuals execute movements but more importantly when they observe others' movements, or imagine performing movements but not when they observe objects moving [26, 27, 28]. Further, the degree of mu suppression correlates with the degree to which the observer identifies with the movement being observed [29], the level of motor experience the observer has with the action [30, 31, 32], and with the degree of social engagement [33]. This suppression of the mu rhythm is believed to reflect activity of the mirror neuron system in sensorimotor and parietal cortex [34, 35].

While the action observation studies have been important, they do not necessarily allow us to fully understand what happens during fluid social interactions in which each person emits information as well as receives information. Researchers have therefore begun using EEG to directly record the neural changes taking place during interpersonal coordination tasks. Evidence for mu suppression in intentional interpersonal finger tapping tasks has been found in several studies [36, 37, 38], with the strongest effects observed in the right centro-parietal regions. Naeem et al. [37, 38] also compared the pattern of mu activity during intrinsic coordination (similar to spontaneous coordination) with that observed during periods of intentionally synchronizing with a partner and observed mu enhancement during spontaneous synchronization in contrast to the typical mu suppression during intentional synchronization. Further, mu suppression was weaker when participants intentionally synchronized finger movements in-phase as compared to anti-phase. Novembre et al. [39] similarly observed suppression in the mu band in right centro-parietal scalp sites when synchronization was higher compared to enhancement when synchronization was lower. Taken together, these results, suggest a hemisphere-specific contribution of alpha activity to producing interpersonal coordination that modulates with the degree of synchrony between partners.

The current study extends existing findings on social synchrony to a pendulum swinging task. Following Naeem et al. [37, 38] we examined two sub-bands of mu, a lower band (8-10 Hz) and an upper band (10-12 Hz), to investigate modulations of power in the mu band of alpha in EEG recorded during spontaneous interpersonal pendulum swinging and intentional in-phase and anti-phase pendulum swinging. We predicted that mu suppression would be observed under conditions of intentional behavioral synchronization of pendulum swinging with a partner while mu activation would be observed in spontaneous pendulum swinging, and that these modulations would be most pronounced at right centro-parietal electrode sites, as found in Naeem et al. [37, 38].

Method

Participants

Twenty undergraduate students from the College of the Holy Cross and Assumption College ranging in age from 18 to 22 participated in the study. Through self-report, all participants reported normal or corrected-to-normal vision and hearing, no motor disabilities and no history of neurological disease. Participants were paired with a partner, creating ten dyads. They were compensated with a $10 gift card for their participation. The experiment was approved by the College of the Holy Cross Institutional Review Board (IRB) and by the University of Massachusett Medical School IRB. All participants provided informed consent.

Materials and Procedure

Upon arrival, participants were informed that the research study was examining behavioral and brain patterns while people participate in social movement tasks. One participant in each dyad was chosen to have his or her EEG patterns recorded and was fitted with an EEG net; we will hereafter refer to this participant as the EEG participant and the other member of the dyad as the partner.

Participants sat in chairs 1m apart from one another and oscillated a weighted pendulum using wrist ulnar and radial deviation in the sagittal plane (Figure 1). This behavior produced minimal muscle movement that was localized to the wrist. The pendulums were each composed of a wooden dowel that was 54 cm in length and had a 100 g weight attached to their bottoms. Each participant's swinging arm rested on the arm of the chair. The EEG participant swung his/her pendulum with the right hand and the partner swung with the left hand. Both participants were told to swing their pendulums at a comfortable tempo and to maintain that tempo for the duration of the trial. Participants' movement kinematics were recorded at a sample rate of 100

Hz using an electrogoniometer (Biometrics, Ladysmith, VA) attached to their wrist and their forearm.

Each dyad performed 27 trials (duration, 45 s each) corresponding to 9 experimental conditions (3 trials per condition). In every condition (except bi-manual conditions), the participants were instructed to look at each other's pendulums. The first three conditions served as control conditions: no-movement, EEG participant only swings, and partner only swings. The next three conditions were the social coordination conditions: spontaneous, intentional in-phase, and intentional anti-phase. To evaluate spontaneous synchrony, participants were instructed to swing their pendulum at a comfortable tempo and to maintain their own tempo while looking at the other's swinging pendulum. Participants were not instructed to ignore their partner but rather were simply told to maintain their own movement tempo. To evaluate intentional synchrony, dyads were instructed to coordinate their pendulum swinging with each other in either an in-phase pattern so their pendulums were in the same portion of their cycles at the same time, or anti-phase pattern so that their pendulums were in opposite portions of their cycles at the same time. Anti-phase and in-phase conditions were counterbalanced. The final three conditions were additional control conditions and were executed alone by the EEG participant: swinging one pendulum, bimanual in-phase, bimanual anti-phase.

Data reduction

Behavioral data. To evaluate the tempo of the pendulum swinging, we calculated the period of oscillation of the pendulum movements as the average of the time between the points of maximum extension (peaks) of the electrogoniometer wrist-movement time series. To assess the strength of coordination of the swinging of the two pendulums, a cross-spectral analysis was performed on the wrist-movement time series to compute the bidirectional weighted coherence

[40], a frequency domain method.. The weighted coherence is a weighted average measure of the correlation (an r^2 value) of the two time series across the frequency band from .11Hz to 2Hz and ranges on a scale from 0 to 1. A coherence of 1 reflects perfect correlation of the movements (absolute synchrony) and 0 reflects no correlation (no synchrony).

EEG data. EEG was recorded using a high-input impedance system (Electrical Geodesics, Inc., Eugene, OR) with 64 electrodes across the scalp. Data were acquired using NetStation software at a high sampling rate (1000 Hz), referenced to the vertex electrode, high pass filtered at .1 Hz, and with impedances maintained below 50 kOhms. Data were segmented with a 500 ms baseline and a 45000 ms post-stimulus epoch, high pass filtered at .3 Hz, and re-referenced offline to the average across all electrodes, to provide an unbiased reference.

In order to compare our findings with Naeem et al. [37, 38], analysis was focused on fourteen electrode sites from the EGI 64 channel HydroCel, seven per hemisphere that corresponded with the electrodes Naeem et al. [37, 38] used: Anterior sites 11 and 2, corresponding to AF3 and AF4 in international 10-10 configuration: Frontal sites 12 and 60, corresponding to F3 and F4: Fronto-central sites 15 and 53, corresponding to FC3 and FC4; Central sites 20 and 50, corresponding to C3 and C4; Centro-parietal sites 21 and 41, corresponding to CP3 and CP4; Parietal sites 31 and 40 corresponding to P3 and P4; and Parieto-occipital sites 33 and 38, corresponding to PO3 and PO4.

Data were processed using EEGLAB (RRID:SCR_007292), version 13.5.4b (running in Matlab 2016b on a MacBook Pro running the OSX 10.12.6 operating system). For each condition, data were visually inspected for artifacts (eye blinks, etc.). Time periods surrounding such artifacts were manually removed using the EEGLAB 'Reject continuous data by eye' function. The frequency spectrum for each channel for the epoch, and the power in the various bands, were calculated as the mean spectral intensity within two frequency ranges: low band (8-10 Hz) and high band (10-12 Hz). The EEGLAB function '*pop_spectopo*'[1] was used to generate the power spectrum. The default settings for 'window length' (512), 'fft length' (1024) and 'overlap' (0) were used. Sample code snippet representing the key elements of the calculation (data load, power spectrum calculation, and band averaging) follows; complete analysis script is provided in GitHub at https://github.com/dnkennedy/SocialSync_Power.

```
EEG = pop_loadset('filename',ifilnam,'filepath',subdir); # Load EEG data
[spectrum freqs] = pop_spectopo(EEG, 1, [0 45000], 'EEG' , 'percent', 100); # Power spectrum
alphaLPower = mean(spectrum(:, indexof8hz:indexof10hz),2); # Average power in band
```

These summary frequency band power results were then exported as a function of epoch and channel as text files for each epoch, and then used for the subsequent statistical analyses.

Results

Behavioral Analyses: Period of Oscillation and Weighted Coherence

The task instructions required the participants to swing their pendulum at the same comfortable tempo for all conditions of the experiment. Past research has found that most participants do not have trouble doing this [41]. An initial analysis of period of oscillation of the pendulum movements was conducted. A single factor ANOVA with pendulum condition as the independent variable (EEG cap pendulum alone, spontaneous, intentional in-phase, intentional anti-phase) and period as the dependent variable revealed a significant main effect of pendulum condition (F (3, 27) = 6.2, p = .002, η_p^2 = .41). The average tempo of the pendulum swinging was significantly slower in the EEG cap participant swinging alone control condition (M = 1.2 s, SD = .13) than the three social conditions of interest (M = 1.10 s, SD = .09) which did not themselves differ significantly (p > .05). The slowness of swinging in this swinging alone

[1] https://sccn.ucsd.edu/~arno/eeglab/auto/pop_spectopo.html

condition, however, seems to have been the consequence of three subjects who had extreme values greater than 2 SDs above the mean of the other three conditions. After eliminating these participants from the data set, a reanalysis of period of oscillation revealed no effect of condition (F (3, 18) = 2.3, $p > .05$, $\eta_p^2 = .28$) with mean periods of 1.13 s, 1.08 s, 1.05 s, 1.08 s for the alone, spontaneous, intentional in-phase, and intentional anti-phase conditions, respectively. All other analyses that follow were conducted without the three outliers (i.e., seven participant pairs). Although this elimination of outliers increases the probability that the observed suppression/enhancement we will analyze below is due to socialness of conditions and not their tempo, it does not eliminate it completely. Post-hoc correlational analyses will revisit this issue.

Whereas there were no significant differences in the tempo of the pendulum across conditions with outliers removed, an analysis of the cross-spectral weighted coherence found differences in the strength of the coordination of the pendulums across the three social conditions, spontaneous, intentional in-phase, and intentional anti-phase (F (2, 12) = 26.7, $p < .001$, $\eta_p^2 = .82$). Verifying past research [7, 10, 21], the spontaneous condition had the weakest coordination (M = .24, SD = .22), intentional in-phase was the strongest (M = .88, SD = .10), and intentional anti-phase was quite strong but weaker than in-phase (M = .66, SD = .29).

Evaluation of Alpha Band EEG activity

Following Naeem et al. [37, 38], we calculated the ratio of mu power recorded at the different electrodes for each of the three social conditions, spontaneous, intentional in-phase, and intentional anti-phase, by dividing the total power recorded during these conditions by the total of the control condition—swinging alone while observing the partner. This value was then log transformed (natural log) such that positive values indicated mu enhancement and negative values indicated mu suppression. This transformed ratio was calculated for the low (8-10) and high (10-12) ranges of the alpha band. It was then submitted to a four-way repeated measures ANOVA with factors of condition (spontaneous, intentional in-phase, and intentional anti-phase), hemisphere (LH, RH), channel (AF, F, FC, C, CP, P, OP) and alpha band (low, high). Least significant difference post-hoc pairwise comparisons were conducted on significant effects. Statistics reported here were adjusted using Greenhouse-Geisser corrections for nonsphericity as necessary.

We observed a main effect of condition (F (1.98, 11.85) = 6.16, p = .02, η_p^2 = .51). Post-hoc pairwise comparisons indicated that mu ratio recorded during the spontaneous coordination condition of swinging while just observing the partner (M= .24) was greater than that recorded for both the in-phase condition (M = -.11, p = .03) and anti-phase condition (M = -.12, p = .02); the in-phase and anti-phase conditions did not differ from each other. The in-phase and anti-phase conditions both elicited a negative mu ratio, indicating mu suppression, while the spontaneous condition elicited a positive mu ratio, indicating mu enhancement.

A significant main effect of channel (F (1.7, 10.2) = 6.21, p = .02, η_p^2 = .51) was observed. Post-hoc pairwise comparisons indicated that across all three social conditions the parietal electrode and parieto-occipital electrode locations recorded significantly smaller mu ratio than all other more anterior electrode sites (p's ranging from .004 to .048), but did not differ from one another. Thus, we observed a gradual increase in mu ratio from anterior to centro-parietal electrode sites, followed by a large decrease in the parietal and parieto-occipital sites.

As seen in Figure 2, a condition by channel interaction (F (2.22, 13.33) = 4.93, p = .02, η_p^2 = .45) indicated that the differences between conditions was largest at the parietal and parieto-occipital electrode locations. Post-hoc pairwise comparisons showed that the spontaneous coordination condition elicited a significantly greater mu ratio than both the in-phase and anti-phase conditions at the central electrode sites (*p*'s = .03 and .02, respectively), at the centro-parietal sites (*p*'s = .03 and .01, respectively), at the parietal sites (*p*'s = .01 and .003, respectively), and at parieto-occipital sites (*p*'s = .04 and .03, respectively). Thus, there were significantly lower values of mu ratio for the intentional social coordination conditions (in-phase and anti-phase) than the spontaneous coordination condition at the four most posterior electrode sites. One sample *t*-tests were performed to determine whether the positive values of the mu ratio were positive for the spontaneous coordination condition and negative for the intentional coordination conditions. Significant positive values were found for the frontal, fronto-central, central, centro-parietal, and parietal sites (*p*'s = .04, .001, .0004, .006, and .02, respectively), indicating significant enhancement. Significant negative values were found for intentional in-phase at the parietal and parieto-occipital sites (*p*'s = .008 and .03, respectively) and anti-phase at the parietal and parieto-occipital sites (*p*'s = .002 and .003, respectively), indicating significant suppression for both intentional coordination conditions.

There were no significant main effects or interactions associated with the independent variables of band or hemisphere.

Relationship between Brain Activity and Behavior

In order to determine the relationship between the alpha band EEG activity in the social conditions and the strength of the interpersonal coordination, bivariate correlations were performed between coordination strength (weighted coherence) and the average mu ratio. Table 1 (left columns) demonstrates negative correlations between coherence and mu ratio. A regression between coherence and mu ratio (a measure of mu suppression or enhancement) reveal that as the coordination became stronger, the mu ratio decreased, indicative of more suppression (see Figure 3). This negative correlation, although significant for both high and low alpha bands, was only significant for the right hemisphere electrodes.

As mentioned earlier, there was a potential concern that the tempo differences might influence the magnitude of observed mu suppression or enhancement. To evaluate this, correlations were performed between the difference in periods of oscillation between the alone and social conditions and the average mu ratio values. Table 1 (right columns) indicates no significant relationship between the difference in periods of oscillation and the average mu ratio values. Additional analyses using the mean period (rather than the differences between the alone and social conditions) also did not find any significant correlations. These results seem to suggest that the average mu enhancement/suppression observed across the social conditions was not affected by the tempo of the pendulum swinging. The period difference was included in the analysis below as an additional test of the influence of tempo.

To further probe the relationship between the coordination strength and alpha band activity, a factor analysis was performed that included weighted coherence, period difference between the alone and social conditions and the mu ratio of the 14 different electrodes (7 in each hemisphere) across all conditions. The low band and high band mu ratios were evaluated in separate analyses.

These factor analyses were conducted in SPSS and satisfied several adequacy criteria. First, all items correlated at least .5 with at least one other item, suggesting reasonable factorability. Second, the Kaiser-Meyer-Olkin measure of sampling adequacy was above the recommended value of .5 (.65 and .67 for low and high bands, respectively), and Bartlett's test of sphericity was significant (χ^2 (120) = 457.1, $p < .001$ and (χ^2 (120) = 495.0, $p < .001$ for low and high bands, respectively). Additionally, the communalities for both analyses were all at least .5 confirming that each item shared some common variance with other items.

The results of these analyses were similar for the two bands and will be reported together. For both bands, a principal components extraction with varimax (orthogonal) rotation found the three factors explaining 82.5% and 85.5% of the variance (see Tables 2 and 3). Loadings less than 0.40 were excluded. The first factor explained 39% and 35% of the variance for the low and high bands and is comprised of all the left hemisphere and the front right hemisphere electrodes but is unrelated to either of the behavioral variables. One might speculate that the correlated alpha band enhancement/suppression indicated by this factor relates to the cognitive activity associated with the general differences between these social conditions and swinging the pendulum alone (e.g., attending to another person). The second factor explained 27% and 30% of the variance for the low and high bands and more specifically identifies the relationship between the strength of the interpersonal coordination (weighted coherence) and frontal and parietal electrodes in both hemispheres. These areas have been identified in past research as comprising the social brain and the mirror system associated with social interactions. The final factor, which explains 17% and 21% of the variance of the low and high bands, identifies the relationship between the period difference between the alone control condition and the social conditions and alpha band enhancement/suppression. As stated above, as much as the tempo of pendulum swinging was to be identical across conditions, there was a nonsignificant tendency for participants to swing the pendulum more slowly in the alone condition. The activity of the central areas of the right hemisphere and as well as the central-parietal electrode on the left hemisphere seem to be associated with these tempos differences across the conditions.

Discussion

As expected, the behavioral measures of synchrony demonstrated the expected pattern of weak synchronization for spontaneous coordination, moderate synchronization for anti-phase coordination, and strong synchronization for in-phase coordination. With respect to the EEG measures, we found evidence for mu enhancement for spontaneous coordination in contrast to mu suppression for both in phase and anti-phase intentional coordination, with the level of mu suppression not significantly different for in phase and anti phase coordination. Follow-up correlations provide some additional insight into understanding this finding in that, for the right hemisphere, higher levels of synchronization were associated with higher levels of mu suppression. We also found more mu suppression in the posterior regions of the brain. In particular, the parietal and parieto-occipital regions had smaller mu ratios than other brain regions, with the differences between synchronization conditions most pronounced at these two regions. Our factor analysis points to the importance of activity in the frontal and parietal regions of both hemispheres in contributing to degree of synchronization.

The finding of mu enhancement for spontaneous coordination and mu suppression for in-phase and anti-phase coordination is consistent with the overall pattern of results reported by Naeem et al. [37,38]. These authors, however, found that mu suppression was highest for anti-phase coordination while we found no differences between the level of suppression for in-phase and anti-phase. In contrast, we found that the level of mu suppression was related to the strength of behavioral synchronization. These differences could be due to the fact that the finger movements in their study were much faster than the pendulum swinging employed in our experiment. As a result, it is possible that their anti-phase coordination was more unstable than the anti-phase behavior measured in our study and thus may have demonstrated a non-stationary pattern of coordination rather than stable phase-locking. In addition, our finding that the level of mu suppression was related to the strength of behavioral synchronization is consistent with Novembre et al. [42] findings of alpha suppression for trials with higher synchronization and alpha enhancement for trials in which synchrony was lacking. In addition, neurophysiological research on alpha oscillations has interpreted alpha enhancement as a way for the nervous system to prevent the integration of self and other actions [47, 48]. That is, in the spontaneous coordination condition, participants must suppress the tendency to entrain with the partner, which could be achieved by suppressing the input of the partner's movements, which would be result in alpha enhancement.

The finding that the underlying neural activity is different for spontaneous coordination and intentional coordination is also consistent with other behavioral research that suggests there is a dissociation between deficits in spontaneous and intentional interpersonal coordination. Whereas adult participants with schizophrenia have been found to have a social synchrony deficit during intentional synchronization but not spontaneous synchronization [10] in a pendulum swinging task, adolescent participants with autism spectrum disorder (ASD) demonstrated a less stable entrainment for *both* intentional as well as spontaneous social synchrony [7]. In addition, in the adolescent pendulum swinging experiment, a behavioral measure of intentional coordination was related to measures of social skill (social actions) while spontaneous coordination was related to social knowledge (theory of mind) [43]. Future research should examine the patterns of alpha activation and suppression in individuals with schizophrenia and ASD to isolate the exact neural mechanisms responsible for the behavioral disruptions in synchrony.

Our finding that there was more mu suppression for central and posterior brain regions is similar, although not identical to, the findings of past research [36, 37, 38]. These past studies isolated the centro-pariental region in the right hemisphere as having the highest degree of mu suppression and being the region that best differentiates between coordination conditions. For us, differences between conditions were most pronounced at the parieto and parieto-occipital regions. It is unclear to what extent these differences are due to features of the experimental tasks and directions. For example, our task was done with participants seated next to each other while other tasks were conducted face to face [37, 38] or while participants sat in separate booths and were provided with auditory feedback about the partner's movements [36, 42]. Future research should explore how task characteristics are related to patterns of activity in specific brain regions. While we did not find hemispheric differences in our ANOVAS, our significant correlations between synchronization and mu suppression for only the right hemisphere is consistent with the findings that there is a right lateralized mechanism implicated in interpersonal coordination. Right-lateralized brain mechanisms have also been shown to be important in focused attention [45] and perception of event timing [46]. Additional research is needed to explore the robustness of right lateralization and the role of attentional and timing neural mechanisms in interpersonal coordination.

Future research should also explore leader and follower relationships in interpersonal coordination. Konvalinka et al. [36] found evidence for the spontaneous emergence of leader-follower relationships using a finger tapping task and reported stronger asymmetric alpha suppression in the motor and frontal areas such that leaders had stronger alpha suppression. The wrist pendulum paradigm is particularly well-suited for being able to systematically manipulate leader and follower behavior. Differential manipulations of lengths of the pendulums allow the experimenter to manipulate the frequency detuning of the coupled oscillator system. The HKB model predicts that, although the pendulums are being swung isochronously, the inherently slower oscillator (i.e., the wrist swinging the larger pendulum) will lag in its cycle and that the increased frequency difference between the oscillators will increase this lag as well as the variability in the coordination. A number of studies have substantiated this increase in the relative phase lag and standard deviation of relative phase with increases of frequency detuning for intrapersonal bimanual coordination [17, 44] as well as interpersonal bimanual coordination [21, 19]. Using this methodology coupled with dual, two-person EEG recording, future researchers should explore whether the phase lag behavior is associated with asymmetric alpha suppression. The wrist pendulum paradigm is also a rich one to use in order to evaluate inter-brain activity during social synchrony. As Novembre et al. [39] found, the intra-brain dynamics are not likely identical to the inter-brain dynamics. The systematic manipulation of tempo and frequency detuning that is possible using the wrist pendulum paradigm makes it a viable methodology for advancing understanding of inter-brain dynamics.

In conclusion, our findings extend previous research findings regarding modulation of mu alpha brain activity as a result of interpersonal coordination. Namely, we confirmed that there is evidence for mu suppression during intentional synchronization during a wrist pendulum task in contrast to mu activation during spontaneous synchronization. In addition, the data confirmed that this is likely due to a right hemisphere mechanism. We also extended previous findings by demonstrating that the strength of the synchronization was related to the degree of mu suppression. The use of this paradigm in conjunction with dual-EEG recording holds much promise for understanding the mechanisms underlying social problems evidenced in neurodevelopmental disorders such as schizophrenia and ASD as well as understanding leader-follower relationships.

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Table 1

Correlations between Behavioral Measures and Alpha Band EEG Activity

	Weighted Coherence		*Period Difference*	
	r	*p*	*r*	*p*
Total Mu	-0.508	0.019^{*}	-0.031	0.90^{ns}
LH Mu	-0.396	0.075^{ns}	0.08	0.73^{ns}
RH Mu	-0.592	0.005^{**}	-0.14	0.55^{ns}
Low Band Mu	-0.501	0.021^{*}	0.029	0.90^{ns}
Low Band LH Mu	-0.402	0.071^{ns}	0.117	0.61^{ns}
Low Band RH Mu	-0.576	0.006^{**}	-0.06	0.80^{ns}
High Band Mu	-0.504	0.02^{*}	-0.089	0.70^{ns}
High Band LH Mu	-0.381	0.088^{ns}	0.041	0.86^{ns}
High Band RH Mu	-0.594	0.004^{**}	-0.215	0.35^{ns}

* $p < .05$

** $p < .01$

LH = left hemisphere, RH = right hemisphere

Low Band = 8-10 Hz , High Band = (10-12 Hz)

Table 2

Factor Analysis evaluating Low Alpha Band Activity

Component	*Factor 1*	*Factor 2*	*Factor 3*
Coherence		-0.853	
Period Difference			-0.583
LH AF	0.877		
LH F	0.87		
LH FC	0.844		
LH C	0.879		
LH CP	0.774		0.518
LH P	0.532	0.725	
LH PO	0.447	0.833	
RH AF	0.807	0.409	
RH F	0.718	0.545	
RH FC	0.42	0.527	0.542
RH C	0.413		0.814
RH CP			0.849
RH P	0.432	0.698	0.442
RH PO		0.853	

LH = left hemisphere, RH = right hemisphere

AF = anterior frontal, F = frontral, FC = fronto-central, C = central, CP = centro-parietal, P = parietal, PO = parieto-occiptal

Table 3

Factor Analysis evaluating High Alpha Band Activity

Component	*Factor 1*	*Factor 2*	*Factor 3*
Coherence		-0.853	
Period Difference			-0.583
LH AF	0.877		
LH F	0.87		
LH FC	0.844		
LH C	0.879		
LH CP	0.774		0.518
LH P	0.532	0.725	
LH O	0.447	0.833	
RH AF	0.807	0.409	
RH F	0.718	0.545	
RH FC	0.42	0.527	0.542
RH C	0.413		0.814
RH CP			0.849
RH P	0.432	0.698	0.442
RH O		0.853	

LH = left hemisphere, RH = right hemisphere

AF = anterior frontal, F = frontral, FC = fronto-central, C = central, CP = centro-parietal, P = parietal, PO = parieto-occiptal

Figure 1. Depiction of experimental set-up. Participants were seated side-by-side in arm-chairs and rested the swinging arm on the edge of the arm rest to allow the wrist pendulums to swing freely while the arm was supported. The participant with the EEG cap swung the pendulum with the right hand, the partner used the left hand. Goniometers recorded the wrist movements during pendulum swinging.

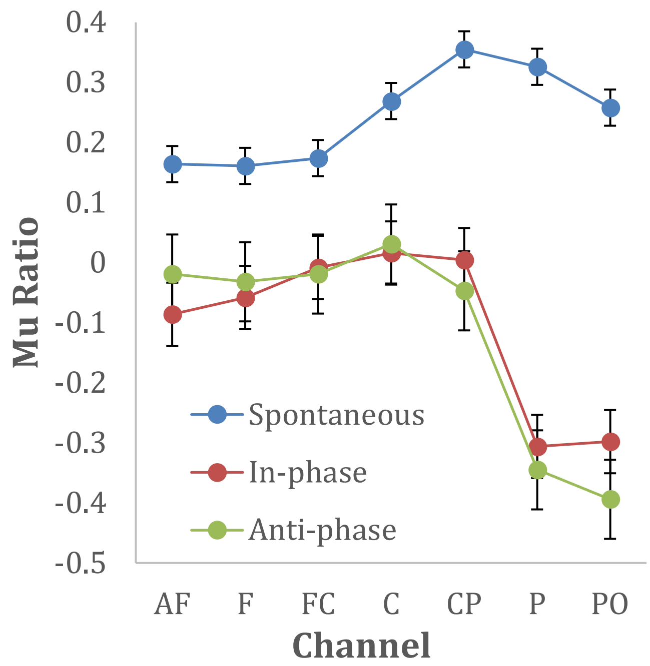

Figure 2. Alpha band enhancement (mu ratio greater than 0) was found for the spontaneous coordination condition. In contrast, mu suppression (mu ratio less than 0) was found for the intentional coordination conditions (in-phase and anti-phase coordination).

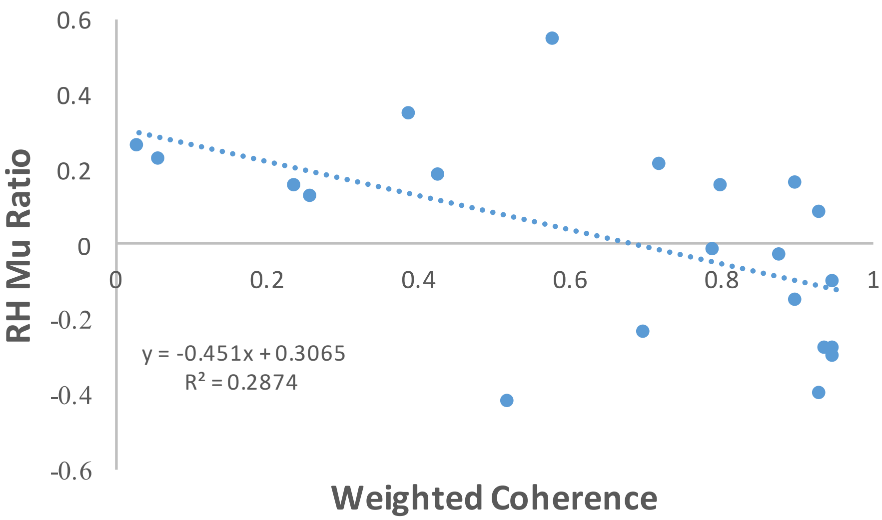

Figure 3. The relationship between coordination strength (weighted coherence) and the average alpha band enhancement and suppression (mu ratio) for the right hemisphere.