Much of the research involving the quantitative EEG (QEEG), in terms of scientific research and clinical interventions, has focused on the four frequency ranges (Delta, Theta, Alpha, Beta) and their respective amplitudes (microvolt levels). The Beta frequency has typically been separated into segments defined by frequency. These measures can be conceptualized as involving different measures of the brain’s arousal level. The other conceptual measure is focused on the communication patterns within the brain and involves coherence and phase measures. These communication measures have revealed scientific and clinically relevant information regarding the brain’s functioning. This paper examines the communication problems and patterns in the brain in different clinical conditions: autism, Asperger syndrome, schizophrenia, bipolar disorder, Alzheimer’s disease/dementia, depression, traumatic brain injury, and cognitive performance. The consistent pattern across all of these conditions is that a decrease in the communication values is related to an increased probability of the presence of the diagnosis.

**Background**

The EEG biofeedback intervention methodology initially focused on the sensorimotor rhythm (SMR; 12–14 Hz) along the sensorimotor strip of the cortex (C3–Cz–C4) for the inhibition of epilepsy (Sterman, 1973). Many of the variations of this initial intervention model were focused on inhibiting microvolt levels of Theta and rewarding Beta microvolts, with exact frequency ranges varying by author. Encouraging research results kept the research focused on these variables. This article is a nonexhaustive review of the literature on specific clinical conditions and the relevance of coherence and phase to these conditions. The general pattern is that the coherence and phase values are lower in patients with the clinical conditions reviewed, with differences between frequencies, locations, and short-versus long-range connections.

There are three problems in understanding this research. First, the coherence and phase variables have been formulated through a myriad of mathematical algorithms in attempts to obtain numbers that accurately represent the presumed activity in the white matter. Second, there is little research that has attempted to understand the relation between these difference algorithms. Third, there have been limited attempts to directly link the connection activity (coherence, phase) to simultaneously occurring behavioral and cognitive measures. The clinical areas that will be reviewed include autism, Asperger syndrome, schizophrenia, bipolar disorder, Alzheimer’s disease/dementia, depression, traumatic brain injury.

**Autism**

The research on connectivity issues and autism spectrum disorder (ASD) has consistently reported a pattern of under- and overconnectivity. The coherence issues involve short-, medium-, and long-distance connections and frequencies. A relatively consistent finding is hyperconnectivity within frontal locations and hypoconnectivity in long-range connection patterns.

Atypical developmental trajectories of cortical fiber tracts in at-risk infants who displayed ASD features at 2 years of age have been reported. The development of fiber tracts studied in the infants who later developed ASD was characterized by higher fractional anisotropy (FA) values at 6 months. At 2 years of age, those with ASD had lower FA values. These data provide a basis showing the hypoconnectivity in the ASD child (Wolff et al., 2012). Additional support comes from diffusion tensor imaging studies, which have shown decreased white matter integrity and connectivity in ASD subject (Barnea-Goraly et al., 2004; Haueisen et al., 2002; Lee et al., 2007; Sahyoun, Belliveau, Soulieres, Schwartz, & Mody, 2010; Sundaram et al., 2008).

The Wang et al. (2013) review reported that the literature “suggests a U-shaped pattern of power abnormalities, overall local overconnectivity and long range underconnectivity, and
enhanced power in the left hemisphere of the brain in individuals with ASD" (from the abstract). While not a connection issue, the U-shaped pattern is an important finding in frequency issues. The pattern reflects higher microvolt/relative power values in the lower and higher frequencies with a reduction in the Alpha frequency. Machodo et al. (2015) replicated the finding of reduction of Alpha and increased Beta and Gamma (25–55 Hz) in the ASD subject.

The “overconnected” hypothesis has focused on the temporal and frontal lobes (e.g., Courchesne & Pierce, 2005; Murias, Swanson, & Srinivasan, 2007), while other reports indicated that there is decreased long-range communication between the frontal lobes and more posterior parts of the brain (Coben & Myers, 2008; Courchesne & Pierce, 2005). Duffy and Als (2012) found underconnectivity in the ASD population as compared with controls (ages 2–12 years). The left-hemisphere language areas stood out with lower coherence values for short-range connections and lower and higher long-range connections compared to the normative group.

Three studies reported reduced long distance connectivity (Cantor, Thatcher, Hrybyk, & Kaye, 1986; Coben & Myers, 2008). The frontal and local (short neuronal paths) hyperconnectivity has been shown to be present in autistic samples (Wass, 2011; Li et al., 2014). However, there is other data showing hypoconnectivity in long distance and posterior to anterior or temporal regions in autistics. EEG technology has been able to demonstrate long-range, anterior to posterior and temporal and frontal lobes (e.g., Courchesne & Pierce, 2005; Murias, Swanson et al., 2007). Coben and Myers (2008) reported findings consistent with frontal hyper-coherence and bilateral posterior-temporal hypo-coherences. Similarly, high frontal coherence has been observed in other studies (Murias, Swanson et al., 2007). Coben, Mohammad-Rezazedeh, and Cannon (2014) examined three different approaches to the analysis of the coherence issues in ASD involving principle components analysis, sLORETA source coherence, and Granger causality, and proposed a theory of mixed under- and overconnectivity in a single case study.

**Locations**

Other researchers have drawn attention to location issues. Orekhova et al. (2014) reported “As a group, high-risk infants who were later diagnosed with ASD demonstrated elevated phase-lagged Alpha-range connectivity as compared to both low-risk infants and high-risk infants who did not go on to ASD. Hyperconnectivity was most prominent over frontal and central areas. The degree of hyper-connectivity at 14 months strongly correlated with the severity of restricted and repetitive behaviors in participants with ASD at three years” (from the abstract). Alpha was defined as 7–8 Hz. Coben and Myers (2008) reported findings consistent with frontal hyper-coherence and bilateral posterior-temporal hypo-coherences. Similarly, high frontal coherence has been observed in other studies (Murias, Swanson et al., 2007). Coben, Mohammad-Rezazedeh, and Cannon (2014) examined three different approaches to the analysis of the coherence issues in ASD involving principle components analysis, sLORETA source coherence, and Granger causality, and proposed a theory of mixed under- and overconnectivity in a single case study.

**Asperger Syndrome**

Clarke et al. (2016) reported reduced anterior interhemispheric coherence in the Alpha and Beta bands in Asperger’s syndrome (AS). Lázár et al. (2010) reported intrahemispheric coherence measures were markedly lower in AS in the frontal areas and the right hemisphere over all EEG channels. The most prominent reduction in intrahemispheric coherence involved the fronto-central areas in Delta, Theta, Alpha, and Sigma (12.50–15 Hz) frequency bands. Duffy, Shankardass, McAnulty, and Als (2013) studied coherence relationships in the ASD and AS population and found distinct differences between the groups. The authors concluded that the Asperger’s participants were a “neurophysiologically identifiable, normally distributed entity within the higher functioning tail of the ASD population distribution” (from the abstract).

**Schizophrenia**

The research on schizophrenia (Sz) and coherence shows a pattern of decreased coherence values (Alpha, Beta, and Gamma) related to increased symptoms on symptom inventory scales. Diffusion tensor imaging has suggested that changes occur in the integrity of the white matter tract in schizophrenia. These findings are supported by post-mortem analysis of white matter pathology reported by

Higashima et al. (2007) examined Sz’s acute psychotic symptoms in reference to Beta (13–20 Hz) coherence (at F7–T3) versus right hemisphere (F8–T6) coherence, and the Brief Psychiatric Rating Scale (BPRS) to examine the effect of medication intervention. The intervention resulted in increased Beta coherence (F7–T3), which correlated negatively with the total BPRS score. John, Khanna, Pradhan, and Mukundan (2002) reported that lower interhemisphere Alpha coherence values were related to higher psychomotor poverty scores but had no relation to reality distortion or disorganization scores. Tauscher, Fischer, Neumeister, Rappelsberger, and Kasper (1998) showed that Sz patients had lower left frontal intrahemispheric Alpha coherence (vs. normal in EC condition). The Positive and Negative Syndrome Scale (PANSS) showed an inverse relation between delta coherence (F7–F3) and the positive symptom subscore, and a negative relation between the negative symptom score and Alpha coherence (intra- and interhemisphere) in the EO condition in medication-free Sz patients (Merrin & Floyd, 1989). Norman et al. (1997) found a negative correlation between fronto-temporal Alpha coherence and reality distortion in a chronic, medicated Sz patient while performing a left hemisphere activation task. No significant correlations were observed in the resting EC or EO conditions. However, other frequencies and frontal locations have been implicated in the Sz condition. Merrin, Floyd, and Fein (1989) studied unmedicated schizophrenics, affective disorders, and normal controls. They reported higher values of Theta coherence in the schizophrenic group compared to affective and normal controls.

Gamma band activity has received some attention in the Sz research area. Kikuchi et al. (2011) employed the concept of Omega complexity (OC), which is defined as a “global estimate of the number of uncorrelated brain processes active during the analysis period” (p. 187), and examined Gamma (30–50 Hz) in drug-naive Sz patients. The Gamma OC was higher in the drug-naive Sz group compared to normal with a major contribution of Fp2 to the OC results (EC condition). After medication treatment there were reductions in the frontal Gamma (as well as the 1.5–30 Hz frequency) contribution to the OC measure, which correlated with the symptom improvement. The authors noted that “aberrant

\[ F4, F7, F8, T3, T6, \text{and} Fp2 \] are all referenced in this section and are sites in the international 10–20 system. F designates sites over the frontal cortex, Fp the prefrontal cortex, and T the temporal cortex. Odd numbers designate left hemisphere placements and even numbers the right side. Gamma phase-locking and coherence between task relevant regions has been reported in schizophrenia during cognitive tasks or attentional loads” (p. 187). Yeragani, Cashmere, Miewald, Tancer, and Keshavan (2006) showed lower Gamma coherence between F4 and C4 in unmedicated Sz patients (awake condition). These results support the “disconnection hypothesis,” which states that Sz disrupts cellular circuits (Andreasen et al., 1996; Friston, 1998).

Shin, O’Donnell, Youn, and Kwon (2011) noted that Sz research has shown that the condition is characterized by alternations in synchrony, particularly in the Gamma frequency range. Gamma phase locking was consistently reported to be lower in schizophrenia during visual (Spencer, Niznikiewicz, Shenton, & McCarley, 2008) and auditory oddball tasks (Light et al., 2006; Roach & Mathalon, 2008). Symond, Harris, Gordon, and Williams (2005) concluded that first-episode Sz patients have a decrease and delay of temporal connection activity in “early sensory response to task-relevant stimuli” (p. 459). The present findings of reduced early frontal synchrony in first-episode schizophrenia are consistent with the “hypo-frontality” hypothesis of schizophrenia (Levin, 1984).

Duffy, D’Angelo, Rotenberg, and Gonzalez-Heydrich (2015) searched for an EEG biomarker in participants at risk for developing Sz with EC data. The researchers reported the primary result of reduced long distance coherence patterns in the Sz group (compared to the normal group) predominantly involving T5 and T6, although there were some instances of increased coherences. Jalili et al. (2007) developed a new method of multivariate synchronization analysis called S-estimator and employed a 128-channel EEG system. The authors reported that the S-estimator showed increased synchronization over temporal locations and decreased synchronization over postcentral/parietal locations near the midline in the Sz group. The pattern was stable (several months) and correlated with the severity of symptoms. The hyper-synchronized temporal activity was positively correlated with positive, negative, and general psychopathological symptoms while the hypo-synchronized postcentral location negative correlated with general psychopathological symptoms.

**Bipolar Disorder**

Kam, Bolbecker, O’Donnell, Hetrick, and Brenner (2013) studied coherence values in bipolar (BP), schizophrenia (Sz), and controls (NC). The Sz patients showed higher delta coherence than the NC and BP. The BP and NC showed higher coherence values within hemispheres (vs. Sz) for Beta1. The Sz and BP showed higher Alpha coherence values compared to NC at temporal locations.
Alzheimer’s Disease/Dementia
The coherence pattern in the Alzheimer’s disease/dementia (AD) research is one of reduced coherences across all frequencies, with the exception of some research indicating increased Theta coherences. Adler, Brassen, and Jajcevic (2003) studied AD and reported decreases in Alpha (left temporal) coherence, decrease in interhemispheric Theta coherence, and increase in global Theta. Another research report (Sankari, Adeli, & Adeli, 2011) reported the AD group increased left intrahemispheric frontal coherence in the Delta, Theta, and Alpha frequencies, increases in left intrahemispheric temporo-parietal coherence in all bands, and decrease in right temporo-parieto-central coherence in all bands. The increases were most pronounced in the Theta band.

Locatelli, Cursi, Liberati, Franceschi, and Comi (1998) examined Alzheimer’s patients and found decreased Alpha coherence in temporal–parietal–occipital locations, which was more evidenced in the more severely cognitively impaired patient and increases in Delta coherence between frontal and posterior locations. Chen, Hsu, Chio, Hu, and Lee (2015) studied Alzheimer’s and found that patients with advanced AD had a greater slow-to-fast wave power ratio. Patients with advanced AD had decreased coherence in multiple brain regions. The phenomenon was most prominent in the centroparietal region (p < .05) between any two patient groups. Besthorn et al. (1997) reported decrease (in AD patients) of coherence in Theta, Alpha, and Beta bands versus control subjects in central and frontal areas. Their findings were comparable to results of Locatelli et al. (1998) who showed an Alpha band coherence decrease in AD in left temporal–parieto–occipital areas.

Depression
Interhemispheric Beta and Theta coherence and intrahemispheric coherence between Beta and Delta rhythms were significantly lower in depressed patients. Coherence measures were lowest in women with depression and highest in men in the control group (Armitage, Hoffman, & Rush, 1999).

Traumatic Brain Injury
Thornton (2014) conducted a discriminant function analysis of the difference between traumatic brain injury (TBI) and normal individuals employing the high frequency (32–64 Hz) values of relative power in frontal locations and the coherence and phase values of the high frequency across all 19 locations in five tasks (EC, visual attention, auditory attention, auditory memory, and reading memory). The results of the analysis indicated an accuracy rate of 100% with no false negatives or positives. Fifty subjects were deliberately misclassified to determine if the algorithms could discern the misclassifications. The discriminant was able to correctly identify the misclassification in all 50 cases.

Cognition
The coherence and phase variables reflect the connectivity of the brain, which involves 100 billion neurons and many trillions of synapses. On the medical side, the diffusion tensor imaging technology (DTI) has been able to visually capture the complex, intertwining myelinated fibers connecting brain regions. It is an operational assumption that the coherence and phase algorithms capture the activity of the myelinated neurons in a numerical format.

The author has addressed the problem of the relationship between the QEEG variables and performance while QEEG data was recorded across a diverse set of cognitive tasks. Each cognitive task presented a different set of QEEG correlates, which related to performance. The results are consistent with the author’s proposal of a coordinated allocation of resource model (CAR) of brain functioning, which asserts that different specific cognitive tasks rely upon different (albeit overlapping in some cases) sets of resources to be successful. The overall conclusion from these research efforts is that phase and coherence variables are the major contributors to successful performance.

Three Case Examples
The discussion presented in this article addressed coherence (not phase) in clinical groups, not individual cases. The first case example involves a teenaged girl for which a full activation QEEG evaluation was available one year after the
original evaluation. During the intervening year, she reported that she had, on multiple occasions, had a tennis ball hit the left side of her head (T3). She was not rendered unconscious. The value of this clinical case is that it demonstrates that even minor appearing head injuries can produce effects on the QEEG variables.

Memory Score Changes?
Figure 1 presents the changes in the standard deviation values emanating from T3 in the Beta2 (32–64 Hz) frequency during the reading task. The star figure represents the origin of a metaphorical flashlight, which sends a “beam” to all other locations, within a specific frequency. The white circle color coding addresses those values within ±0.50 standard deviations (SD) of the normative value, light gray between either −0.50 to −1.50 SD or between +0.50 to +1.50 SD, and dark gray lower than −1.50 SD or higher than +1.50 SD.

The subject was engaged in an EEG biofeedback program. Her auditory memory (immediate and delayed recall score summed) increased from the initial baseline value of 14.87 to 32.5. Reading memory performance is calculated by the memory score divided by 10. The initial reading task allows 100 seconds for reading, while the reevaluations typically take less time, so the memory performance is calculated according to how much information is recalled for every 10 seconds of reading. The subject’s value increased from 1.8 to 4.37 at the end of the program.

Second Case Study
The second case is of 22-year old man with a history of encephalopathy at birth. It is presented because of the extreme values in the coherence and phase values. It is the most deviant case the author has observed during his years of practice. Note in Figure 2 the extreme differences emanating from P3 in the left head figures between P3 and Fz—17 SD below normative values. The figure on the right (O1 flashlight effect) show extremely low values (O1–P3, −14 SD; O1–Pz, −9.5 SD), while frontal connections were above normative values (O1–F3, +5 SD; O1–F4, +4.8 SD).

Third Case Study
The third case study is intended to demonstrate the pattern of decreased values of coherence variables to frontal lobe locations (see Figure 3). Note that all relations between T3 and C3 and the frontal locations were significantly below normative values, while the relations with posterior locations were above normative values. The F7–T3 connection is the weakest connection. For this specific participant there were also problems within the frontal lobe connection patterns. The participant had a history of several minor head injuries.

The value of looking at individual cases with the activation database is that specific patterns of disconnection can be readily observed that are critical for effective clinical intervention.

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3 P3, Fz, O1, Pz, F3, F4, F7, and T3 are all referenced in the case studies. These are locations in the international 10–20 system for electrode placement. Prefers to the parietal cortex, O to the occipital cortex, F to the frontal cortex, and C to the central cortex. Odd numbers refer to left-sided, left hemispheric placements, and even numbers to right, and z refers to the cortical midline (as in Fz and Pz).
References


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