Complexity in Neuroscience and Collective Behavior

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This is a brief review of some complex systems concepts written as a final paper for PSY 5001 - Biological Bases for Clinical Practice

While essentialism is alive and well in pharmacology and molecular biology, the general trend in neuroscience is away from reductionistic analysis of the brain and toward models which use concepts of distributed functionality and interconnectedness (Sieglemann, 2010; Mattei, 2014; Bassett & Gazzaniga, 2011). This move is a reflection of the inability for conventional science to tackle problems of complexity, and of the strength in systems philosophy which actually has its modern roots in the field of biology during early part of the 20th century (Bertalanffy, 2015). This rather broadly dis-jointed paper will survey some of the ways that non-localized complexity is handled in neuroscience, the overlap with multidisciplinary studies of complexity in some other natural systems, and how this relates to progress in the science of human behavior.

Systems Philosophy

The classical roots of “systems philosophy” in the West begin with Aristotle and Democritus, but Bodganov was probably the first to publish modern systems ideas sometime between 1910 and 1913 under the guise of *Tektology* (Midgley, 2003). Bodganov was interested in social change and making sure that it happened thoughtfully with the consideration of many variables. Bodganov suggested the concept of *organization* as pervasive in nature, which implies all existence is the result of the interaction of different forces of situating matter with other matter. An early human tearing apart a fellow predator’s bone marrow is deorganizational from one perspective, but from another perspective the human is organizing the tissue “according to his own physical constitution” (Bodganov, 1996, p. 2). Bodganov was adamant in the absolute law of organization,

> All the interests of mankind are organizational. From this it follows that there cannot be, and there should not be, any other view of life and the world, than the organizational one. And that this is still not properly understood is due to remaining fetishism distorting the process of the intellectual development of mankind. (pp. 3).

He writes of human’s role in the world as organizer, but quickly broadens the question to wonder of organization in the natural world and the place of the human within it:

> So far so good…But what of nature? Would it not be a naïve subjectivism or poetic fantasy to apply the same view to its events and actions?...Nature is the *first* and greatest organizer; and a human being just one of its organized creations. (p. 2)

Contemporary systems thinkers often write of a pragmatic reintegration of philosophy to understand the limitations of the current way of thinking about scientific problems. Erwin Laszlo (1971) argued for the return of philosophy the most important problems of the day, in that philosophy has lost its grounding in substantive questions about nature and the sciences through increased specialization of science: “Lest philosophers analyze themselves out of philosophy, a return must be effected to synthesis. . . . Synthesis can mean the conjoining various sets of non-philosophically researched data, to furnish new avenues toward the constructive discussion of substantive philosophical issues” (p. 55). Frodeman (2013) writes “The institutional status of philosophy—e.g., its functioning as a discipline—was the great blind spot of twentieth (and now twenty-?rst) century philosophy. This is part of what has led philosophy, potentially the most relevant of subjects, to become a synonym for irrelevance” (p. 1918). These authors suggest that it is *uncoordinated* specialization which detracts from the meaning-making which can occur through synthesis, both at the level of science and the level of the human soul. Laszlo suggests that reductionism is the new nihilism. People need to feel as though they have a purpose, as though their existence plays some role in the big picture. Laszlo (1971) writes,

> In earlier epochs they were guided by synthetic modes of thought which rested in part on faith and imagination; but the great myths of former ages and the religions of our immediate heritage have lost their cogency to millions. According to “ideologues,” they are capable of being replaced by action-oriented ideologies, like Nazism and Communism, which present a total world-view with explicit directives for action. (p. 112)

Laszlo argues that the obsession with analysis and subsequent loss of meaning partially accounts for the surging popularity of “Eastern sacred texts, astrology, reincarnation, states of consciousness, and the like” (p. 112). Thus, science, the humanities, and spirituality are intimate bedfellows through the common “demand to ‘see things whole’” (p. 112). “All this requires the resuscitation of a mode of rational and systematic thinking which has fallen into disrepute through over-insistence on detailed investigation and specialization” (p. 113).

This dilemma of isolation and ignorage as a result of reductionism was as alive in the 19th century as it is today, when Nietzsche (1886, as cited in Frodeman, 2013) wrote of the domination of a purely serialized and rationalized worldview,

> The dangers for a philosopher’s development are indeed so manifold today that one may doubt whether this fruit can still ripen at all. The scope and the tower-building of the sciences has grown to be enormous, and with this the probability that the philosopher grows weary while still learning or allows himself to be detained somewhere to become a ‘specialist’:–so he never attains his proper level, the height for a comprehensive look, for looking around, for looking down. Or he attains it too late, when his best time and strength are spent—or impaired, coarsened, degenerated, so that his overall value judgment does

> not mean much anymore. It may be precisely the sensitivity of his intellectual conscience that leads him to delay somewhere along the way and to be late: he is afraid of the seduction to become a dilettante… (Nietzsche 1886, p. 134)

"The world has problems, but universities have departments" (Brewer, 1999, p. 328, as cited in Cronin, 2008). All of the above propose the solution of philosophy's return as a binding force in the application of science to human life. "Philosophers need to get out of the study, and into the field," Frodeman writes, (2013, p. 1918), and begin to combine the fruits of analytical science for the good of human life. Wilson believes that the thinkers of the enlightenment "got it mostly right the first time" assuming a "unity of knowledge" (Wilson, 1999, p. kpp 20) as in Sir Francis Bacon utopian *Solomon's House*, a loom weaving together the threads of knowledge contributed by different scholars of different problems (Pihlaja, 2012).

The study of *complexity* is one area where hard science meets the mystery and challenge of synthesis. It requires systematically understanding the order within the disorder of phenomena which cannot be pinned down to a single cause, or even a few mediated relationships between discrete variables. The study of complex systems requires utilizing the brain's "pattern-seeking" function (Lilienfeld, Ammirati, & David, 2012, p. 17) to make *meaning* out of mounds of reduced data by combining the slow, ordering process of the logical left hemisphere with the associating, "intuitive" processes of the right.

Complexity in Neuroscience

Systems Philosophy as the study of *complexity* in dynamical biological systems is taking root in the increasingly multidisciplinary fields of neuroscience and collective behavior, to name only two. The multidisciplinary aspect of these fields falls in line with Von Bertalanffy's (2015) *general systems* vision of uniting the sciences through a common language; concepts such as *hierarchy*, *modularity,* and *connectivity*, *reciprocation*, *autopoiesis*, *equifinality*, which focus on relationships instead of essential elements and transfer across natural systems from cellular mitosis to migration of germ cells and wildebeests (Guttal & Couzin, 2011; Meunier, Lambiotte, & Bullmore, 2010). What is it that patterns of change in immunological therapies, addiction withdrawal, and taming a wild stallion, have in common? Could there be an agitated introductory period, followed by a phase of extreme chaotic protest, ending with spindled peaks among a gradual titration of habitual behavior before finally resting in a new equilibrium? (Gleick, 2011). What do these patterns have in common with the transition and out of sleep? How might commonalities across these systems allow heterogeneous data in one area to be transferred to another? These are the types of questions that require the synthesis of data from multiple levels of analysis (i.e. special, temporal, hierarchical, etc.) which is common in systems approaches (Bassett & Gazzaniga, 2011).

While the study of non-linear patterns in dynamical systems has been part of physics for some time (Gleick, 2011), it has only recently made its way into the fields of neuroscience (Mattei, 2014; Siegel, 2012). Building on Bodgonov's "organization" as a fundamental principle in nature and building on Bertalnaffy's (2015) concept of an *open-system*, Mattei (2014) writes, "the concept of self-organization has been able to offer a proper account of the phenomenon of evolutionary emergence of new complex cognitive structures from non-deterministic random patterns, similarly to what has been previously observed in nonlinear studies of ?uid dynamics" (p. 1).

Though a rudimentary search through the literature will reveal a rapid increase in non-essentialist models of organization in neuroscience, some branches of neuroscience research continue from constructivist assumptions ultimately derived from Freud's positivist science of the unconscious (Freud, 1915), typically hypothesizing physiological bases for a priori psychological concepts social cognition, emotion, etc. (Barrett, 2013; Jaegher, Paolo, & Adolphs, 2016; Siegel, 2012). While the clinically-inspired fields of "affective neuroscience" or "social neuroscience" generate vital knowledge on the physiological basis for emotion and affect regulation in humans, it unfortunately may suffer from the same limitations as the psychological assumptions that generate its hypotheses; namely that intuited psychological concepts like *anger*, *ego*, *object*, *abandonment, attachment*, *object*, *relational matrix, empathy,* etc. are difficult to define and also difficult to refute in postpositivist experimentation (Barrett & Satpute, 2013; Decety & Jackson, 2006; Ibanez, et al., 2016). Thus, the inductive potential of this domain may remain limited to a speculative subjective realm and cannot *directly* benefit from overlapping research in other hard biological realms such as ecology, microbiology, entomology, etc., and non-biological realms such as physics, meteorology, paleontology, astronomy, etc. The concepts relate to humans and often only to humans.

Models based on complex systems concepts do not suffer this limitation, but require unlearning old ways of thinking about the brain and the mind in order to grasp the subtle relationship between analysis and synthesis while still remaining within the postpositivist realm (Bowen, 1980). Complex systems possess emergent properties which occur as a function of the relationships with the elements in the system ("the whole is greater than the sum of its parts"), and it is the emergence of higher-level patterned activity in neuronal networks that organizes systems-oriented theories of the brain (Bassett & Gazzaniga, 2011; Sieglemann, 2010; Telesford, Simpson, Burdette, Hayasaka, & Laurienti, 2011). For example, one way of answering the question of how the *concept* of mind relates to the physical brain is by looking at "mind" as an emergent property of the complex interactions of the physical components of the brain, body, and environment (Bassett & Gazzaniga, 2011; Duncan, Chylinski, Mitchell, & Bhandari, 2017; Doursat, 2013; Sieglemann, 2010). Seen in this light, the process we call "mind" could possess similar properties as other *strange attractors* (Gleick, 2011) which may be called "self." This "self" may possess something akin to the feeling of "personality" in a finicky autopilot on a sailboat or laptop computer which seems to have "a mind of its own", or unforeseen organic-appearing "noise" in electronic modular synthesis or guitar distortion pedal which speaks to a "deeper part of us."

A relatively simple way to visualize the mechanics of these sorts of strange attractors is using the *double-rod pendulum,* a simple deterministic device which never repeats the same pattern of oscillation twice due to the non-linear effect of two dynamic coefficients (in this case the positions of the two joints) interacting with each other through one simple binomial equation. All of these examples follow simple deterministic rules yet exhibit an ordered-disorder in their behavior that makes them appear *alive* due to their reciprocal feedback relationships *(Fleischman, 2012)*.

If a property such as strange attraction is *emergent* then there is no evidence of the property derived from properties of individual components alone. Telesford (2011) writes,

> the dynamic nature of a complex system cannot be understood by thinking of the system as comprised of independent elements. This concept also highlights the limits of reductionism; one cannot fully understand a complex system by only understanding its constituent parts (e.g., understanding the brain via knowledge about individual neurons). (p. 295)

Because of the portability of these kinds of concepts across large classes of natural systems, lessons from research in one type of complex system can inform research in other complex systems. Bassett (2011) writes,

> The concept that emergence of complex behaviors might occur through the interaction of multiple temporal scales is one that, perhaps unsurprisingly, is not confined to neuroscience. Recent work characterizing power structures in animal societies suggests that emergence or the development of aggregates is a direct consequence of temporally dependent system uncertainty which, in social systems can be based on misaligned interests. (p. 9)

Swarming behavior in fish (Tunstrøm, et al., 2013) and locusts (Guttal, Romanczuk, Stephen, Sword, & Couzin, 2012) is highly predictable at the group level using a few simple variables, and there is no evidence for these variables found in the individuals. While consistent individual differences (i.e. “animal personalities” (Jolles, Boogert, Sridhar, Couzin, & Manica, 2017)) are found to determine group performance (e.g. speed to find safe areas or areas with food) and factors such as individual tendency toward leadership positions (Couzin, Krause, Franks, & Levin, 2005), the overall emergent patterns of group states (such as swarming, milling, and group polarization (Tunstrøm, et al., 2013) remains the same regardless of individual differences (Couzin, et al., 2011; Jolles, Boogert, Sridhar, Couzin, & Manica, 2017; Killen, Marras, Nadler, & Domenici, 2017; Strandburg-Peshkin, Farine, Iain, & Crofoot, 2015),.

Research in fish shoaling behaviors has produced reliable theories which show how a few simple variables (e.g. proximity to a neighbor, proximity to a safety gradient, and proximity to a predator) generate a pattern of aversive behavior in a school of fish to a predator which *appears* to be highly coordinated *at the group level*, as if each fish had knowledge of the grand plan of changing trajectory and more or less executed the change in direction to suit it (Katz, Tunstrøm, Ioannou, Huepe, & Couzin, 2011; Schaerf, Dillingham, & Ward, 2017; Tunstrøm, et al., 2013).

However, individuals are found to have relatively little knowledge of emergent group properties and in fact behave primarily in their own self-interest (Hein, et al., 2015). Each fish will simply move to maintain within a comfortable window of distance to one other fish, and the proximity of a predator initiates the aversive movements in a few fish at the front of the school which triggers changes in enough other fish to initiate a phase transition where the entire school is moving in the newly emergent trajectory pattern.

The area where most of the complex systems research is taking place in humans is in mapping structural and functional modularity and emergent properties of the brain using models based on network graph theory. “Brain networks are increasingly understood as one of a large class of information processing systems that share important organizational principles in common, including the property of a modular community structure” (Meunier, Lambiotte, & Bullmore, 2010, p. 1). The principles of collective behavior overlap in that they involve the abstract relationships between uninformed parts into wholes which exhibit emergent properties. The brain *as a unit*, in this sense, can be studied somewhat similarly to a school of fish *as a unit*, where what we call “mind” may emerge from the interactions of individual neurons and feedback mechanisms in the rest of the body which are otherwise uninformed of the beautifully coordinated behavior that they are taking part.

Systematic methods of studying complex systems are now emerging as a combination of mathematics and lessons learned through the study of complexity in physics. One method rapidly growing in popularity in neuroscience is *network graph theory*, which comes from the field of computer science through the analysis of Bayesian decision networks in software reliability and artificial intelligence. Graph theory itself has been around since the time of Euclid (18th century) and organizes processes around a complex unit of nodes (e.g. neurons, organs, or conspecific social individuals) who’s relationships are described by edges connecting the nodes (Power, et al., 2011). The focus is not so much what each node *is* (although demarcating where each node begins and ends remains a fundamental challenge) but how often one node communicates with each other node, usually limited by some sort of arbitrary salience threshold. “Centrality metrics such as degree, betweenness, closeness, and eigenvector centrality determine critical areas within the network” (Telesford, Simpson, Burdette, Hayasaka, & Laurienti, 2011, p. 295). Mapping at this level allows for synthesis (observing overall relationships) of analytical data (reducing the whole into individual parts) at multiple levels of analysis (by constructing relationships among hierarchies of modules, sub-modules, sub-sub-modules, etc.).

Network graphs are employed to assist in determining the relationship between *structure* (this piece over here and that piece over there) and *function* (processing this information and processing that information) of the brain. The brain may be divided into voxels (three dimensional units of brain tissue) where each voxel is a node on the graph. fMRI data would then be analyzed to determine the degree to which each node fires with each other node on the graph, quantifying the strength of their relationships (Bassett & Gazzaniga, 2011). A rectangular matrix called a *dendrogram* could then be used to visualize how each node is connected to each other node (Zemanova, Zhou, &

Kurths, 2006). The structure of connections described in the dendrogram is often referred to as a *connectome* (Krakauer, Ghanzanfar, Gomez-Marin, MacIver, & Poeppel, 2017). Connectome matrices show strong relationships down the line from top-left to top-right when the nodes are listed in order of proximity, indicating the *small-world* nature of brain networks (nodes are typically connected to close-by neighbor nodes for speed of transmission). Groups of nodes may fire so often together that they are designated as *communities*, or groups of nodes, or groups of groups of nodes (Zemanova, Zhou, & Kurths, 2006). Activity in neural communities correlate with specific functions, supporting the notions of functional *modules* in a network. Modules are organized into hierarchies where modules in similar taxa have stronger relationships, and sub-modules in differing taxa have weaker relationships (Bassett & Gazzaniga, 2011). Network models are usually controlled using a t-statistic by comparing models against synthetic *null models* which express randomized connections between nodes. Relationships in null models are random and so are assumed to illustrate no or little organization (Nelson, Bassett, Chamchong, Bullmore, & Lim, 2017). The use of randomized networks as null models as a sort of white-noise comparator is not ideal, but is the best control available as of this writing.

Brian networks can contribute to an understanding of complex pathology in terms of change in the interrelatedness of modules. While studies in schizophrenia in the last 40 years have mostly focused on isolated brain areas or singular genetic causes or predispositions with pharmacological remedies, large-scale network graph research of the brain reveals that schizophrenics may show a breakdown in holistic integration of brain modules at both the structural and functional levels (Nelson, Bassett, Chamchong, Bullmore, & Lim, 2017). Because network approaches normalize data across domains, more holistic connectivity research can integrate analysis from many levels, for example both structural and functional data (Meunier, Lambiotte, & Bullmore, 2010). Unifying neurological data from different levels under a common mathematical framework such as network graphing is a relatively new concept to the field, and shows promise for more integrative methods to come in the future.

Implications for Psychology as a Science

The above findings using complex systems models support the importance of the integrative study of natural phenomena as opposed to assuming that causal relationships between essential individual differences which has been the norm in psychology since Freud. But applications of complex systems concepts to research in biogenetic factors on human behavior have a long way to go before reaching the level of sophistication already reached in other species. For example, as of this writing there is very little research on human groups which produce this sort of predictive models. A search on the literature using google scholar on July 23rd, 2017 using the keywords "'collective behavior' humans" revealed a striking scarcity of literature on human collective behavior when compared to research on other social swarming species. The results show numerous speculative books on the philosophy of collective behavior in the past 15 years, sometimes applied to humans, and a single study (Silverberg, Bierbaum, Sethna, & Cohen, 2013), coincidentally of human flocking behavior, observing humans concert *mosh pits* produced a model which simulated two stable “gaslike” and “circular vortex” states similar to Tunstrøm’s (2013) “swarm” and “milling” states. However, limited access to the article content prevented determining whether the model was inferential (i.e. speculative) or based on real-time data from actual cases as is common collective behavior research on other species.

There is more research on the concept of collective intelligence in humans, a construct based on models of individual general intelligence used to determine differences in group’s abilities to solve problems. Collective intelligence, as defined by Wolley et al (Wolley, Chabris, Pentland, Hashmi, & Malone, 2010), is found to be only moderately correlated with individual intelligence (i.e. a group of smart people VS a group of not-smart people), and more strongly correlated with individual’s abilities to determine the emotions of other individuals through visual facial cues. Interestingly, the proportion of women in a particular group was a strong determinant of collective intelligence, probably due to the fact that women score higher on scales which measure ability to determine emotions in others. Where the women score lower on these scales the difference is unnoticeable. Some research reveals the predictability of democratic consensus in animal groups (fish and baboons) based on proportions of informed and uninformed individuals (Couzin, et al., 2011), yet only makes inferences about the outcomes of human decision making, and frequently makes anecdotal reference to this inference in relation to other data on election outcomes in his in-person talks.

This suggests that we know much less about collective behavior in humans than we do other species. The above described research in other species as well as early pioneering systems-based research on human behavior (Bowen, 2015) suggest that many properties of individual behavior are not evidenced at the level of that individual but at the level of some emergent property in the collective. Perhaps it is the complexity of human behavior, or our inability to *see* the simplicity in our behavior beyond our biases. And perhaps this points to a deficiency in the current value system of psychologists and medical researchers in general which almost completely focuses on the relationship of pathology to psychological or physiological variables found in the individual. Further, the majority of clinical theory remains derived from the subjective positivist realm of science pioneered through Freudian theory which is almost entirely bound to variables in the individual. These theories also cannot be refuted through empirically generalized experiment, which prevents them from being affectively compared to objective data, and even to each other (Zepf, 2010) which erodes the popular meaning of the research term “theory” to mere opinion in the clinical space. Perhaps future experimental research could include asking questions about the impact that group variables have on normal behavior and the relationship of these group variables to the enormous canon accumulated on individual differences. Further, this type of research could explore relationships of group variables not just to normal behavior but to pathological behavior, and possibly even medical symptoms related to the automatic emotional processes that are already found to emerge from the complexity of the relationship systems described in this paper, emotional processes that we (Kerr & Bowen, 1988), and other species like Couzin’s locusts (Guttal & Couzin, 2011), depend on for survival.

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