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Dynamic Processes in Regulation and Some Implications for Biofeedback and Biobehavioral Interventions

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Abstract

Systems theory has long been applied in psychology, biology, and sociology. This paper applies newer methods of control systems modeling to the assessment of system stability in health and disease. Control systems can be characterized as open or closed systems with feedback loops. Feedback produces oscillatory activity, and the complexity of naturally occurring oscillatory patterns reflects the multiplicity of feedback mechanisms, such that many mechanisms operate simultaneously to control the system. Unstable systems, often associated with poor health, are characterized by absence of oscillation, random noise, or a very simple pattern of oscillation. This modeling approach can be applied to a diverse range of phenomena, including cardiovascular and brain activity, mood and thermal regulation, and social system stability. External system stressors such as disease, psychological stress, injury, or interpersonal conflict may perturb a system, yet simultaneously stimulate oscillatory processes and exercise control mechanisms. Resonance can occur in systems with negative feedback loops, causing high-amplitude oscillations at a single frequency. Resonance effects can be used to strengthen modulatory oscillations, but may obscure other information and control mechanisms, and weaken system stability. Positive as well as negative feedback loops are important for system function and stability. Examples are presented of oscillatory processes in heart rate variability, and regulation of autonomic, thermal, pancreatic and central nervous system processes, as well as in social/organizational systems such as marriages and business organizations. Resonance in negative feedback loops can help stimulate oscillations and exercise control reflexes, but also can deprive the system of important information. Empirical hypotheses derived from this approach are presented, including that moderate stress may enhance health and functioning.

Keywords

psychophysiology; heart rate variability; biofeedback; chaos; systems theory; stress

Introduction

Concepts of ‘cybernetics’, ‘systems’ (dynamic and otherwise), ‘complexity’, ‘chaos’, ‘catastrophe’, and ‘oscillation’ have long been part of discourse in the behavioral, social, and biological sciences. Without the ready availability of mathematical models for the social and biological sciences, a nonmathematical approach to systems theory was prominent in early biofeedback work, and was well articulated by Schwartz and colleagues (Schwartz, 1981; Schwartz et al., 1979). However, a mathematical approach for aircraft communication and control systems had been articulated by Wiener as early as the 1940s (Wiener, 1948, 1961). This model served as a heuristic for describing behavioral, economic, biological, and astronomical systems, among others (Mindell, Segal, & Gerovitch, 2003; Wiener, 1948). In recent years, mathematical versions of systems theory have been applied in biology and behavioral science, as described below.

Because Wiener's theory had limited predictive power, it was soon combined and supplanted by theoretical systems with greater complexity, such as Shannon's *information theory* (Shannon & Weaver, 1949), which incorporates concepts of channel capacity, noise, and *entropy* (here reflecting the uncertainty in prediction rather than the conventional meaning implying dissolution of order), as well as *chaos theory* (Gleik, 1987; Kellert, 1993), which emphasizes deterministic nonrandom but complex nonlinear relationships among a large number of co-occurring processes, for which statistical prediction is possible. Applications of both information theory (Attneave, 1959; Yockey, 2005) and chaos theory (Elbert et al., 1994; Guastello, Koopmans, & Pincus, 2009; Rossler & Rossler, 1994; Weiss, Garfinkel, Speno, & Ditto, 1994) have been made to the biological and behavioral sciences, and the present article draws upon insights from this work.

For the purposes of this article, we define a system as a variety of elements that interact with one another to form a whole entity. A system's distinct parts are not isolated from each other, thus the characteristics of the whole entity cannot generally be deduced from each of its components. A stable system retains important characteristics even in the face of perturbations that disturb the behavior of specific elements. *Dynamical* systems show changing patterns of action over time, but retain characteristics of an integrated whole. *Cybernetics* is the study of such regulatory processes, including system characteristics like stability, feedback, adaptation, information, and the relationships among them. Dynamical systems have been described as "organized" or "disorganized" and of greater or lesser complexity. Simpler organized systems can often be described and modeled in linear terms, although nonlinear approaches usually are more appropriate for more complex systems.

A *control* system is defined as a stable system, in which system elements interact to preserve system stability, both for internal control and in response to perturbations caused by external influences. Systems can be modeled as *closed-loop* or *open-loop*. An open-loop system involves only a system response to an outside event. It does not provide an internal mechanism for monitoring system performance or preserving system stability. For example, open-loop models have been used to biomimetically describe the flying patterns of *drosophila melanogaster* after stimulation (Fry, Rohrseitz, Straw, & Dickinson, 2008). Behavioral and chemical interventions designed to change system behavior are examples of open loop control processes, such as when we teach a person to lower muscle tension or blood pressure directly, rather than by using natural feedback mechanisms.

A closed-loop model includes internal regulation, whereby system responses to outside stimulation are processed through internal feedback loops that monitor and adjust the response of the system itself. As a discipline, biofeedback is particularly concerned with closed-loop, internal regulatory systems, and tries to maximize their effectiveness. A good example of a closed loop system is the baroreflex (Vaschillo, Lehrer, Rishe, & Konstantinov, 2002), as will be described in more detail later in this article. However, when biofeedback or relaxation is used as a strategic intervention to control acute symptomatology, the resultant process can be described as an open-loop system.

A common control mechanism leading to system stability in closed loop systems is the negative feedback loop. Negative feedback loops preserve stability by activating opposing processes that act to modulate change, though importantly, stable systems tend to contain both positive and negative feedback loops (Cinquin & Demongeot, 2002; Pigolott, Krishna, & Jensen, 2007), as will be described below. Negative feedback systems usually have inherent delays caused by the time needed for opposing system elements to effect change in each other. Negative feedback loops with delays cause oscillations at particular frequencies Cinquin & Demongeot, 2002). A very simple negative feedback system is the thermostat, which responds to changes in ambient temperature by switching a heating or air conditioning system on and off. Here the delay is dependent on such factors as outside air temperature, insulation, and volume of inside air. Thus, room temperature oscillates around the thermostatic setting, but is rarely constant. The negative feedback loop in the baroreflex system also contains delays, as will be described below.

Oscillatory properties have been observed in systems as small as the cell, and as large as societies. For example, at a cellular level, oscillations have been used to map various negative feedback loops in protein concentrations, and circadian gene expressions in bacteria (Pigolotti, Krishna, & Jensen, 2007). In social systems oscillations describe patterns of voting, marital relationships, and mood.

The baroreflex system is a good example of a stabilizing oscillatory process. It produces periodic fluctuations in blood pressure, heart rate, and vascular tone that reflect modulatory control. External influences on blood pressure (e.g., aperiodic stress or exercise) induce blood pressure changes that, without a control mechanism, could burst blood vessels or cause circulatory insufficiency, depending on the direction of blood pressure change. The baroreflex responds to blood pressure increases by slowing heart rate and causing vasodilatation, which, in turn, produces a decrease in blood pressure. Each time blood pressure decreases, the same mechanism produces vasoconstriction and heart rate acceleration, which causes blood pressure to rise again. Changes in blood pressure are delayed by a number of factors, including inertia in blood flow and blood vessel plasticity (Vaschillo et al, 2002; Vaschillo, Vaschillo, & Lehrer, 2006). The delay in blood pressure changes following heart rate change averages about five seconds, thus yielding the ubiquitous heart rate oscillation of about 10 seconds (Vaschillo et al., 2002), i.e., five seconds for the baroreflex to cause an increase in blood pressure when the baroreflex responds to a decrease in blood pressure, and five seconds to cause a decrease in blood pressure following a baroreflex response to a blood pressure increase. In actuality, however, the baroreflex system is composed of *two* closed linear systems with negative feedback loops – it also contains a slower vascular tone loop with a rhythm of approximately 0.02–0.03 Hz, which has a slower response time than the heart rate loop (Rahman, Pechnik, Gross, Sewell, & Goldstein, 2011; Vaschillo, Vaschillo, Buckman, Pandina, & Bates, 2012).

It should be noted that a full description of baroreflex control would not be restricted to purely mechanical properties of the reflex. The baroreflex system shows characteristics of neuroplasticity. Dworkin (Dworkin, 1993) demonstrated that the baroreflex can adapt to changing environments through classical conditioning. Consistent with Dworkin’s findings, Lehrer and colleagues demonstrated that regular stimulation of the baroreflex through biofeedback can increase baseline baroreflex gain, suggesting an improvement in regulatory capacity over blood pressure changes (Lehrer et al., 2003).

Complex control of systems

Most psychological and biological systems are much more complex than thermostats, with multiple control mechanisms, and multiple overlapping oscillations, the quantitative characteristics of which depend on the frequency and phase of each component oscillator, as well as the interactions among them (Hyndman, 1974). Changes to one system component (control mechanism) affect others, so the individual control mechanisms are interdependent, thus promoting biological vitality and complexity. Additionally, it should be noted that closed loop systems with negative feedback loops often require simultaneous open loop processes in order to function properly, to provide sufficient stimulation to stimulate negative feedback loop activity (Feigl, 1998). This adds to the complexity.

Simple control, such as control of room temperature, can typically be described with linear mathematical models, but when multiple controllers operate, each with a characteristic frequency, attendant mathematical computations become more complex. Existence of multiple overlapping control systems assures system stability in the face of various perturbations by providing multiple “backups”. A high degree of entropy, reflecting a high degree of nonlinearity and/or a need for multiple linear formulas to describe the system, is often related to health and biological system stability. Conversely, simple periodicity or random variability (“white noise”) often underlies pathology in disordered systems (Goldberger, Peng, & Lipsitz, 2002), reflecting, respectively, either the presence of only a single control oscillator, or absence of any regulatory activity.

Oscillatory patterns with greater complexity, such as those that occur when a number of oscillatory patterns overlap, are described as “chaotic”. Chaos reflects the simultaneous operation of numerous control processes. Although the healthy cardiovascular system can be effectively modeled using linear statistics (Berntson, et al., 1997), it also has chaotic properties, which diminish when cardiac function is impaired or an individual is in danger of dying from physiological decompensation (Arzeno, Kearney, Eckberg, Nolan, & Poon, 2007). Similarly, healthy adjustment is characterized by chaotic rhythms in appetite (Berthoud, 2006) and mood (Haffen & Sechter, 2006), among other biobehavioral dimensions. Also, negative feedback loops often work in concert with open loops as described above, and with positive feedback loops and resonance characteristics, as described below, to maintain optimal functionality.

Oscillation, control, and health

Many oscillatory systems in the body, such as neural (Berthouze, James, & Farmer, 2010), cardiovascular (Berntson et al., 1997), and circadian (Garau, Aparicio, Rial, Nicolau, & Esteban, 2006) tend to degrade with age, reflecting a decrease in adaptive capacity. In addition, there are also pronounced age-related decreases in baroreflex gain (Brown, Hecht, Weih, Neundorfer, & Hilz, 2003), while blood pressure oscillations tend to increase with age (Cugini et al., 2003), perhaps reflecting degrading of control over this otherwise tightly regulated function. Generally speaking, oscillatory patterns in a variety of biological control systems tend to be a characteristic of youth, fitness, and health.

Oscillatory properties do not only represent activation of specific control reflexes (e.g., the baroreflex). They provide information as well. Periodic stimulation is required for system control in feedback networks. This principle has been proposed for cellular behavior (Klevecz, Li, Marcus, & Frankel, 2008) as well as macro biological and behavioral systems, as in discussions of open loop processes described above, and both resonance and stochastic processes, described below. External stimulation “perturbs” a control system causing it to oscillate. Without such oscillations, and hence, without noise (which can function as the perturbation that pushes the system to oscillate), systems may fail to get the information they need to function properly. The tendency for noise to stimulate system oscillation is called *stochastic resonance*. There is evidence that interoceptive and exteroceptive noise enhances the sensitivity of a variety of control processes, from micro to macro levels (Wiesenfeld & Moss, 1995). Studies of stochastic resonance show that noise can facilitate control functions, as in optimization of monosynaptic afferent reflexes in the motor system of the cat by noisy stretching of a synergistic muscle (Martinez, Perez, Mirasso, & Manjarrez, 2007). In humans, extreme absence of system perturbation, as in sensory deprivation, can cause regulation go awry, resulting in psychotic-like sensory and emotional symptoms (Mason & Brady, 2009).

One could, therefore, speculate that psychological stress may have some beneficial effects, by introducing noise into neural regulatory processes, just as exercise helps maintain many physiological processes. Since, in biological systems, oscillations tend to reflect the operation of reflex systems involved in modulation and self-control, presumably a complete lack of stimulation would deny exercise to these reflexes, causing them to atrophy. Under normal circumstances, however, the environment provides sufficient perturbations in biological and behavioral systems to preserve their normal function. In psychophysiological theories of stress effects, this formulation overlaps with the more recent concept of “allostasis” and “allostatic overload” (Juster, McEwen, & Lupien, 2010). *Allostasis* refers to stability achieved through variability, and is analogous to the activity of oscillating control processes stimulated by stochastic noise, or general unorganized environmental stimulation. A well functioning personality or biological system responds well to moderate environmental stressors, and, in fact, may be energized by them, as in Yerkes and Dodson’s model of stress and performance, wherein moderate stress enhances performance in moderately difficult tasks, while very low or very high levels of stress can be detrimental (Yerkes & Dodson, 1908). *Allostatic overload* (McEwen, 2004) occurs when environmental stresses are either too great or too prolonged, or when various control reflexes become exhausted.

Resonance: A source of stimulation and simplicity in system oscillation

In addition to oscillation, another characteristic of negative feedback systems with a delay, is resonance (Grodins, 1963). When outside stimulation causes a system oscillation at a particular frequency, and no other forces are at work to dampen the oscillations, negative feedback loops can themselves destabilize the system by causing increasingly large resonance frequency oscillations, to the point where information from other frequencies no longer gets processed. A common example of a ‘run-away’ negative feedback loop, resonance effect is the “Larsen effect” that occurs when a microphone is placed near a speaker, causing a high-pitched squeal at a single frequency (Weaver & Lobkis, 2006). In such a case, a single high-amplitude oscillation, triggered either by noise (stochastic resonance) or by pulsatile stimulation close to the resonance frequency, can obscure the effect of otherwise meaningful perturbations. In the human body, resonance effects in the postural control loop have been implicated in postural impairment in Parkinson’s disease (Maurer, Mergner, & Peterka, 2004). Resonance has been similarly implicated in age-related impairment in gait control (Thurner, Mittermaier, & Ehrenberger, 2002).

In terms of psychophysiology, it is conceivable that resonance effects might inhibit the fight-or-flight reflex because a single homeostatic process may overwhelm reflexes needed to confront an environmental stressor. One could speculate that resonance effects, stochastic and otherwise, might deprive the system of information from various internal control mechanisms, as when resonance-frequency oscillations are at such a high amplitude that they obliterate information from reflexes operating at different frequencies. Thus, it is possible that resonant oscillations in the heart rate baroreflex system at 6/minute could weaken the effects of other control reflexes, by greatly diminishing their relative size and depriving the system of information. This is a hypothesis for future research. To prevent a ‘run-away’ resonance process, systems must be dampened (Siebert, 1986). Dampening effects on heart rate amplitude during heart rate variability biofeedback probably stem from inherent limitations in the ability of the heart to respond at extreme levels.

The literature on heart rate variability biofeedback, however, shows that not all resonance effects are detrimental. Resonance in the cardiovascular system produced by a rhythm in the baroreflex is the basis of the beneficial effects of heart rate variability biofeedback. The baroreflex provides a negative feedback loop for controlling blood pressure, such that heart rate falls when blood pressure rises, and vice-versa when blood pressure falls, thus modulating blood pressure fluctuations. The resonance frequency of this system appears to be related to the individual's blood volume (Vaschillo, et al., 2006), with a lower resonance frequency among people with a larger blood supply (men and taller people, vs. women and shorter people). The resonance frequency appears to be determined by changes in hemodynamic inertia resulting from fluctuating heart rate. When this resonance system is activated by a respiration rate close to the resonance frequency, oscillations in heart rate become very large. This high-amplitude stimulation of the baroreflexes appears to strengthen them (Lehrer et al., 2003), and is perhaps the cause of the various salutary effects of heart rate variability biofeedback.

Heart rate variability biofeedback has been shown to restore autonomic control that has been acutely repressed by experimental exposure to inflammatory cytokines (Lehrer et al., 2010), and appears to ameliorate a number of disorders characterized by autonomic and/or emotional dysregulation (Lehrer, 2007), including hypertension (Lin et al., 2012; Nolan et al., 2010; Reineke, 2008), asthma (Lehrer et al., 2004), anxiety/stress (Hallman, Olsson, von Scheele, Melin, & Lyskov, 2011; Henriques, Keffer, Abrahamson, & Horst, 2011; Shenefelt, 2010), depression (Beckham, Greene, & Meltzer-Brody, 2013; Karavidas et al., 2007; Patron et al., in press; Siepmann, Aykac, Unterdorfer, Petrowski, & Mueck-Weymann, 2008), and chronic pain (Hallman et al., 2011; Sowder, Gevirtz, Shapiro, & Ebert, 2010; Strine, 2004; Yetwin, 2012), while improving athletic performance (Paul & Garg, 2012). We might, however, theorize that the effects of constant breathing at resonance frequency would not be advantageous. Chronic resonance frequency breathing could theoretically weaken or obstruct reflexes dependent on oscillations at other frequencies. Thus, individuals practicing heart rate variability biofeedback are instructed to practice for a relatively brief period of time daily (usually about 20 minutes) and to use the technique strategically when symptomatic.

Positive feedback loops

The body also contains multiple positive feedback loops, whereby change in a particular direction facilitates greater change in that direction. Although positive feedback can provide a stimulating effect in an open loop system, it also plays a role in closed loop systems. In psychophysiology, positive feedback loops often are involved in maladaptive processes (Thayer & Lane, 2000). A prime example is anxiety and depression's propensity to amplify their inherent symptomology by triggering greater sensitivity to anxious or depressive thoughts, thus creating a vicious cycle. On the cellular level, positive feedback loops may be necessary to stimulate modulatory negative feedback loops (Kurbel, 2012; Nishi et al., 2000; Pomerening, Kim, & Ferrell, 2005; Prochazka, Gillard, & Bennett, 1997; Tsai et al., 2008).

However, positive feedback loops can also play an important role in enhancing emotional control. The psychological augmenting effects of positive feedback may add to oscillation amplitude during HRV biofeedback, or the sympatholytic effect of muscle relaxation. This may result from a spiraling relaxation effect. Just as anxiety begets more anxiety by sensitizing anxiogenic brain circuits (a positive feedback loop) (Bos, Hoenders, & de Jonge, 2012; Chemtob, Roitblat, Hamada, Carlson, & Twentyman, 1988; Krantz et al., 1987; Thayer & Lane, 2000), heart rate variability biofeedback or muscle relaxation therapy may compound relaxation effects.

Positive feedback loops can also play a role in creating system complexity, which may increase stability by creating a multiplicity of stable states (Plahte, Mestl, & Omholt, 1995), as well as by maintaining oscillation amplitude during frequency adjustment (Tsai et al., 2008). Positive feedback loops have been shown to promote load compensation in control of movement (Prochazka et al., 1997), and to be necessary to prevent dampening of oscillations in cellular function (Pomerening et al., 2005). Positive feedback loops also are important for the maintenance of the ovulatory cycle (Kurbel, 2012), and for propagating dopaminergic signaling (Nishi et al., 2000). Without some form of regular perturbations, oscillations will gradually decline in amplitude and disappear. Positive feedback loops can provide these perturbations.

Simplicity, complexity, and randomness

The dimensions of simplicity and complexity are important for understanding psychobiological control, and can be usefully incorporated into theories of applied psychophysiology. Simplicity in a biological or behavioral control system can have multiple sources. In addition to reflecting the effects of resonance, simplicity may result from system fatigue due to allostatic overload (Juster et al., 2010), or from biological damage to system components, such as when heart failure leads to diminished entropy in heart rate (Ho, Lin, Lin, & Lo, 2011; Isler & Kuntalp, 2007; Liu et al., 2011). Simplicity in heart rhythms as a sign of cardiac pathology was discussed earlier. Emotional rigidity, or simplicity, is well described in DSM-IV (American Psychiatric Association, 2000) as a sign of psychopathology, which is characterized by a tendency to respond to a wide variety of situations with a stereotyped response: sadness, anxiety, suspiciousness, anger, etc. However, just as simplicity is a sign of poor adaptation, so is random variation, suggesting lack of modulatory control. Pathological examples of random fluctuations include manic or depressive episodes in bipolar disorder, as well as certain cardiac arrhythmias such as preventricular or preatrial contractions, asthma exacerbations, and so on.

Work in the tradition of chaos and information theories has provided mathematical tools for describing organized complexity of temporal patterns in terms of entropy, as described in information theory, including Shannon's "spectral entropy" calculations (Shannon, 1948), Pincus' "approximate entropy" (Pincus, 1991, 1998), Lempel and Ziv's method for evaluating "randomness" (Lempel & Ziv, 1976). These measures represent various approaches to calculating relative unpredictability of fluctuation patterns in a time series, or the number of dimensions, or fractals (Mandelbrot, 1983) necessary to describe a data set mathematically.

Autonomic regulation

Healthy regulation is often characterized as sympathetic and parasympathetic activity converging in a limit cycle around a critical value, such as is the case of cortisol-vasopressin or acetylcholine-epinephrine reactions, where each process induces a compensatory reaction in the other (Bernard-Weil, 1986). Thus, sympathetic activity may simultaneously suppress parasympathetic activity, but increase parasympathetic *reactivity*, thereby producing an oscillation . During extremely stressful stimulation, an individual may show wild oscillations in various autonomic functions, both sympathetic and parasympathetic (e.g., bronchodilation and constriction, increased and decreased blood pressure, energy and fatigue, high versus low rates of peristalsis as in constipation and diarrhea, etc.), although these oscillations are sometimes paradoxically suppressed in severe emotional reactions (Gellhorn, 1969, 1970).

Heart rate changes in response to stimulation appear to be important modulators of systemic response. Reduced cardiac variability in response to stimulation is related to a variety of pathophysiological states (Montano et al., 2009), while increased heart rate variability and vagal influence on the heart are positively correlated with recovery after physical exercise stress (Chen et al., 2011). Thus flexibility in cardiac response to stimulation, and higher vagal influence on the heart (measured as high-frequency heart rate variability, reflecting both baroreflex control and modulation of respiratory function) are related to better adaptation to interoceptive and exteroceptive demands (as evinced by rapid recovery). This is another example of ways in which complexity and oscillatory function are related to health and adaptability.

Thermoregulation

Thermoregulation is another system in which several systems converge around a critical value. Until the mid 20th Century, stability and circadian variability in core body temperature were considered homeostatic responses to environmental triggers, such as light intensity or daily routine. In fact, core body temperature is partially regulated by an endogenous clock in a central control mechanism, which integrates multiple systems including thermoreception of ambient temperature, systems for conserving or dissipating heat, as well as those for generating heat, and endogenous circadian regulators. As with heart rate variability, circadian thermal variability decreases with age (Weinert & Waterhouse, 2007). A relationship between circadian thermal oscillation amplitude and general homeostasis can be hypothesized, but further evidence is needed to confirm its existence.

Oscillation, complexity, and disease

Heart rate variability complexity is indicative of cardiac and neurocardiac flexibility and adaptability, and may be diminished significantly by pathology. A healthy heart can respond to various moment-to-moment physical and emotional demands, while the diseased heart does not exhibit such flexibility. Although oscillations may persist in the diseased heart, aging and disease cause increasingly more regular oscillatory patterns reflecting a decrease in mechanisms of cardiac control (Goldberger et al., 2002). Such noncomplex patterns of variability ultimately predict death in the critically ill (Arzeno et al., 2007; Norris, Anderson, Jenkins, Williams, & Morris, 2008; Norris, Stein, & Morris, 2008) .

Similarly, a disturbance of complementary oscillatory patterns in pancreatic islet beta cells is associated with impaired glucose tolerance and diabetes mellitus (Polonsky, Sturis, & Van Cauter, 2000). Under normal conditions, oscillations in nervous output from pancreatic ganglia cause pancreatic islet beta cells to secrete insulin in a coordinated pulsatile manner, at two distinct periodicities, 1) in small amplitude oscillations with a periodicity of 5–15 minutes, and 2) in larger amplitude ultradian oscillations ranging from 80 to 150 minutes, particularly in response to the ingestion of food or intravenous glucose perfusion (Polonsky et al., 2000). This oscillatory rhythm operates through an insulin-glucose negative feedback loop, with a delay between plasma insulin and hepatic glucose production. Compared with steady-state infusion, this oscillation promotes more efficient glucose utilization (Tolic, Mosekilde, & Sturis, 2000). When these oscillatory rhythms are disturbed, such as in diabetes mellitus type II, decreased oscillatory complexity is associated with system decompensation (Bertram, Sherman, & Satin, 2010).

Mental illness

Mood and behavior appear to be governed by many of the same concepts used to describe oscillatory behavior in physiological processes. As with physiological systems, organized complexity is the hallmark of healthy psychological behavior. Both hyper and hypo-stabilities may characterize a breakdown in normal mental functioning, and leave a person psychologically vulnerable to the deleterious effects of stress. Bauer and Whybrow (1995) found that while participants with bipolar disorder showed some brief periods of fairly well defined cycling in mood, their overall pattern of mood changes were less complex than controls. Paulus et al. compared patients with schizophrenia to healthy individuals in a binary choice study, and found that participants with schizophrenia showed a simpler and more predictable pattern of response, apparently reflecting decreased adaptability in cognitive processing (Paulus & Braff, 2003; Paulus, Geyer, & Braff, 1996). A study of laterality in electrodermal activity found decreased activity and complexity in the left hand, compared with the right, among depressed patients, and decreased activity and complexity in the right hand, compared with the left, among patients with schizophrenia, while there were no laterality differences among healthy individuals (Bob, 2007). These results are consistent with theories of right hemisphere dysfunction in depression (represented by decreased adaptiveness in this instance), and left hemisphere dysfunction in schizophrenia. However, even some psychopathological states appear to possess chaotic organization. Tschacher, et al. (Tschacher, Scheier, & Hashimoto, 1997) recorded occurrence of psychotic symptoms among 14 patients with schizophrenia over time, and found a complex, nonlinear time course in eight of them. Others showed more random psychotic behavior, suggesting that the patients were responding to environmental cues, not modulated by control processes.

EEG oscillations reflect system functions

Systems theory also applies to neurons' activity in the brain, whose functioning has been shown to be interdependent with other nearby neurons and even neurons in different brain regions. The complexity and chaotic characteristics of brain function, particularly as studied by electroencephalogram (EEG), has been thoroughly reviewed elsewhere (Buzsaki, 2006). Briefly, EEG reflects summations of excitatory postsynaptic potentials that neurons emit as discrete events. When neurons fire synchronously, relatively high-amplitude slow waves occur, in a relatively simple pattern; when they fire desynchronously, the numerous potentials can both augment and cancel each other out, generally resulting in lower-amplitude, more complex signals at higher frequencies (Onton, Westerfield, Townsend, & Makeig, 2006). Fast-firing cells in the cortex may contribute to these effects, as does the interaction between excitatory and inhibitory processes. Faster, low-amplitude oscillations tend to predominate during states of arousal, attention, and cognitive processing (Timofeev & Chauvette, 2011), and in general, during periods of greater cortical activity (Klimesch, 1996).

Oscillations in EEG signal reflect the interplay of various brain processes involved in cortical integration, such that specific kinds of mental activity may be reflected in definable patterns of activity at specific frequencies, and at specific electrode locations (Gottesmann, 1999; Jacobs, 2001). Slower waves from the cortex reflect decreased arousal at the measured EEG sites (i.e., fewer simultaneous processes producing potentials at various frequencies). Low levels of alpha and beta activity (the faster, higher-frequency ranges) and/or increased waking slow-wave activity are associated with a lack of inhibitory control over behavior (Knyazev, 2007). Similarly a greater frontal theta beta ratio is related to decreased emotional response inhibition (Putman, van Peer, Maimari, & van der Werff, 2010). Greater delta and theta activity and lower alpha activity have been found in the EEGs of children with fetal alcohol syndrome (Kaneko, Phillips, Riley, & Ehlers, 1996). This pattern is also found in attention deficit disorder, lower cognitive abilities, impaired motor control, hypoglycemia, and antisocial behaviors. It is even found during deep relaxation and sleep, while exposed to hypoxia, fasting, and in sexual arousal and orgasm (Knyazev, 2007). Conversely, delta, theta, and lower-frequency alpha activity are inhibited when people are awake and cognitively active. A recent study found that, during tasks with increased cognitive demand, increases occurred in the EEG frequency with the greatest activity across electrode sites, but a decrease in EEG entropy (Zarjam, Epps, & Chen, 2011).

Oscillations are not smoothly distributed across the frequency spectrum. Resonance structures have been identified at frequencies of 4, 10, 20, and 40 Hz (Erol Basar, 1999) with the largest body of research on the 10 Hz rhythm, the center of the alpha frequency band (8 – 12 Hz). Resonance properties can be determined by a variety of methods. For instance, one can stimulate the system at specific frequencies with photic stimulation, and determine the frequencies at which high-amplitude oscillations are obtained (Fedotchev, Bondar, & Konovalov, 1990; Herrmann, 2001; Spiegler, Knösche, Schwab, Haueisen, & Atay, 2011). One may also use computer simulations based on known frequency characteristics of particular nerve cells (Kasevich & LaBerge, 2011) or from evoked potentials (Basar, Gönder, & Ungan, 1976; Bayram et al., 2011; Winterer et al., 1999). Alternatively, one can stimulate an individual with audible noise and measure the obtained frequency peaks (stochastic resonance) (Ward, MacLean, & Kirschner, 2010). Resonances at these frequencies suggest the existence of specific positive feedback reflex arcs at each resonance frequency, related to particular neural processes contributing to each resonance frequency.

Thalamocortical processes have been studied and modeled, and rhythm bands containing each of these frequencies have been described in a large literature (theta or delta for 4 Hz, alpha for 10 Hz, beta for 20 Hz, and gamma for 40 Hz) (Knyazev, 2007). It has been theorized that delta oscillations reflect activity of motivational systems, while theta oscillations reflect emotional regulation, and alpha oscillations reflect inhibitory processes (Knyazev, 2007). Some theorists have related specific resonance frequencies to the period length of experimentally evoked action potentials, event-related potentials, synchronies, or asynchronies (Pfurtscheller & Lopes da Silva, 1999). Patterns of theta and alpha-frequency resonances triggered by memory consolidation processes have been identified (Klimesch, Schack, & Sauseng, 2005). It is also known that memory consolidation occurs during sleep (Fogel & Smith, 2011), which is characterized by high-amplitude slow EEG waves primarily stemming from the brain stem, with cortical modulation of lower centers, perhaps from a single oscillator (Crunelli & Hughes, 2010).

Phase relationships in EEG activity among various brain areas have also been studied, appearing to vary systematically. For example, occipital phase synchrony in the alpha rhythm tends to be greatest during relaxation with eyes closed, and decreases with greater arousal (Gengerelli, 1978). Experience of “pure consciousness” in transcendental meditation appears to be characterized by alpha phase synchrony from the frontal and central areas (Orme-Johnson & Haynes, 1981). Although phase synchrony may reflect tight coordination among brain sites, more complex forms of coordination have also been modeled, often involving varying frequencies, varying orderly phase relationships, and nonlinear relationships, where frequent changes in phase relationships among brain areas reflect complexity of cognitive processing (Basar, 2006; Panzeri, Brunel, Logothetis, & Kayser, 2010; Tognoli & Kelso, 2009).

Measures of chaos and complexity applied to EEG data suggest a simpler pattern of brain organization, with, fewer control processes, among patients with schizophrenia (Roschke, Fell, & Beckmann, 1995) and depression (Nandrino et al., 1994; Pezard et al., 1996). Pezard et al. found that EEG patterns became more complex among depressed patients, whose depression improved, becoming indistinguishable from those among healthy individuals, while the pattern of decreased complexity persisted among individuals whose depression did not improve (Pezard et al., 1996). Other studies have found risk for autistic spectrum disorder (Bosl, Tierney, Tager-Flusberg, & Nelson, 2011) and the presence of attention deficit hyperactivity disorder (Sohn et al., 2010) to be related to decreased average EEG complexity.

Social systems

Humans live as couples, in families and in neighborhoods or larger social and economic networks. Systems theory has been applied to social systems, and, indeed, oscillatory patterns of social system behavior can reflect negative feedback loops, which could contribute to stability. Stability in a social system generally represents a stable pattern of interaction, implying the action of mechanisms that resist change. Oscillatory patterns of openness and closedness to new ideas have been described in societies (Klapp, 1975), as have variations in societal norms about expression of emotion (Cancian & Gordon, 1988), although presumably extremes in either of these characteristics trigger a consequent tendency in the opposite direction. Voter patterns appear to have oscillatory characteristics, which, in the United States, have been quantified as thirty-year oscillatory patterns in party alignment (Mayhew, 2002). The cause for this oscillation period may reflect generational change. Perhaps people see the problems caused by results of their parents' voting patterns, and react to this by changing course. Although delays, chaos, and resonance characteristics in social feedback loops have not been measured, the existence of specific frequency patterns in some of them suggest that these characteristics may be present.

Dyadic systems may also have oscillatory qualities. Gottman and his colleagues have taken a mathematical approach to assessing marital systems (Gottman, Murray, Swanson, Tyson, & Swanson, 2002). They have applied concepts of nonlinear dynamics and catastrophe theory, which posit complete periodic restructuring of systems when perturbed by certain forces. They propose that marriages have one or more "set points" for nature and style of interaction, some of which may be favorable to marital satisfaction and stability, and others unfavorable. From this perspective, they have developed formulas that predict marital stability and divorce. They record verbatim transcripts of marital interactions, where they note the number of times that individuals respond to each other's content with specific affect, including such variables as threshold for negativity, and frequency of positive and negative interactions. In marriages characterized by reciprocal negativity and paucity of positivity in interactions, couples can be trained to modify their individual behavior. Thus, based on positive feedback loops, marital systems, wherein negativity begets negativity, may be altered so that positivity begets positivity. The overarching goal is to move the interaction system from a negative steady state to one that is more positive. Repair and dampening functions have been calculated, which can modify the positive or negative influence of one partner on another in various steady state conditions. The investigators report conflicting data about whether rigidity in behavior predicts poor marriage outcome, but show how intervention can affect the system of interaction and, ultimately, marital satisfaction. Their model includes the interaction of perception of well-being in the relationship, the flux over of negative and positive behaviors, and physiological responses.

Systems theory has also been applied in analysis of corporate structures (Weick, 2009), but concepts of oscillation, delay, and influences of positive and negative feedback loops have not been studied. Corporations are systems, just as those defined above. They are constantly bombarded by changes in market conditions, competition, etc., and need to maximize the adaptiveness with which they respond to changing conditions, while still maintaining their structure. Information and communication, both from outside of and within the organization, has been proposed as a medium for achieving these ends. Utilization of feedback from information allows an organization to monitor both external events and internal processes. For example, if an organization's norms do not allow for transmission of bad news to its CEO, then poor, uninformed decisions are likely to be made. Various feedback mechanisms can prevent change from happening (e.g., not heeding information identified as coming from the “wrong channel”). Although we have found little research using time series analysis to discover patterns of oscillations in negative feedback loops comprising organizational structures, examples of feedback loops in organizational behavior have been described (Weick, 2009). Presumably oscillations occur in organizational communication as well as in other control systems, and might be quantifiable on a number of dimensions, such as commands to change operational procedures to adapt to external pressures, oscillating with instructions to follow internal protocols, pressured work versus relaxation, and supportive versus critical communications from superiors.

Implications for research

In psychophysiology, linear models are frequently employed to predict one variable from another. However, because physiological systems are so complex, such prediction does not truly characterize physiological states. Time series models have become available that can be used to better model these systems. The complexity of biological and behavioral systems and the fact that complex systems can be mathematically modeled present a challenge to psychobehavioral research. This paper proposes that we re-examine the systems approach, in light of methodologies recently proposed. Cybernetic systems approaches in biology and psychology present practical challenges such as in the assessment and measurement of multiple systems, and large quantities of time series data. Nevertheless, quantification of complex systems involved in personality, illness, marital or social harmony, and stress reactivity may give us greater insight into ways of promoting health and managing disease, and are thus amply justified.

Hypotheses generated by this review

This review would lead us to posit certain hypotheses. These include:

1. Any stable system can be modeled using time series analysis.
2. Internal control mechanisms can be modeled as closed negative feedback loop systems with oscillatory properties. Decreases in oscillatory properties will be associated with less adaptability to perturbations (stressors), and greater vulnerability to system failure.
3. Stable systems are complex, indicating a multiplicity of control mechanisms; however, they are not random.
4. Adaptability of a system can be modeled from the effect of perturbations on its various closed-loop systems of internal control. Changes in any elements due to system perturbations will return toward a pattern of stable equilibrium.
5. A stable system does not necessarily have a single level of stability. This may change depending on demands placed on the system.
6. Disease, injury, stress, and older age all reduce adaptability, and will be reflected in decreases in oscillations of control systems, complexity of oscillations, and ability to return to equilibrium after perturbation. They may also be characterized by greater periods of randomness.
7. This model can be applied to all systems: biological, behavioral, cognitive, emotional, social, organizational, etc. Elements of systems could be quite varied, and include such diverse phenomena as behaviors, communications, and biochemical or physiological functions.

Particular implications for applied psychophysiology and biofeedback

The present analysis indicates that further investigation of patterns of oscillation in various psychobiological systems is warranted. Better identification of oscillatory systems may lead to the elucidation of homeostatic or allostatic control mechanisms in such systems, and may ultimately lead to the development of ways to exercise and strengthen reflexes that strengthen allostatic capacity. Ideally, these exercises could render an individual more resilient to effects of environmental stressors, improve performance, and strengthen resistance to psychological and physical disease. Systematic use of various quantitative approaches to assessing oscillation and complexity could contribute to advances in this field.

Work in this direction has already begun in studies of heart rate variability and EEG biofeedback. Heart rate variability biofeedback is based on the explicit mechanism involving stimulation and exercise of modulatory reflexes by stimulating resonance characteristics of an oscillating system. For this method, the theory proposed in this paper predicts that only *periodic* practice of the technique would be beneficial, while *constant* practice of the technique might actually be iatrogenic, since the resonance frequency oscillations would prevent chaotic variability in heart rate, and possibly decrease adaptability, if they were *continuously* present. However, strengthening of homeostatic reflexes, with a consequent increase in chaotic variability, appears to be beneficial. Periodic stimulation of a reflex seems to improve its efficiency. We have found this to be the case with the baroreflex (Lehrer et al., 2003). As yet, no studies have reported changes in chaotic variability in the resting state after a course of heart rate variability biofeedback; although other measures of variability do appear to increase.

It is possible that biofeedback used to increase other sources of periodic variability in the cardiovascular system might also be explored. One such possibility is biofeedback targeting the vascular tone baroreflex, following research by Vaschillo and colleagues (Vaschillo et al., 2012; Vaschillo, Vaschillo, Pandina, & Bates, 2011).

Neurofeedback is another biofeedback modality that explicitly addresses oscillations by stimulating and exercising modulatory reflexes in the central nervous system. Alpha rhythm and theta: beta rhythm biofeedback have been used to enhance relaxation, memory consolidation, and attention, and appear helpful for such disorders as attention deficit hyperactivity disorder (Ramirez, Desantis, & Opler, 2001; Rossiter, 2004), and anxiety disorders (Moore, 2000), as well as intellectual performance enhancement (Angelakis et al., 2007; Gruzelier, Egner, & Vernon, 2006; Moore, 2000; Ramirez, Desantis, & Opler, 2001; Rossiter, 2004). This feedback may strengthen reflexes involved in conscious attention and memory consolidation, depending on the particular frequencies and brain regions that are trained. Pulsatile stimulation by electricity (Schindler, Elger, & Lehnertz, 2007) and light flicker have also been used (Jain, Woodruff, & Bissessar, 2001).

Chaotic and oscillatory properties of various psychophysiological measures suggest that there may be many more potential control reflexes that can be trained, perhaps one on each fractal plane. This raises a host of other possibilities for future biofeedback research. Future research may bear fruit by examining various sources of oscillation in the body and in behavior, to determine whether periodic stimulation of these oscillations may similarly exercise modulatory reflexes, and improve health. In particular, resonance and positive feedback loops could be considered, such as in heart rate variability biofeedback, wherein positive feedback can promote complexity and maintain oscillatory activity caused by negative feedback, helping individuals adapt to environmental demands.

Applications of systems theories to social and organizational structures, other than for Gottman's approach to marital interactions, have tended to be nonmathematical, focusing primarily on norms, beliefs, and behaviors that preserve a particular pattern of social interaction. Time series analysis of these interaction patterns may yield important information that could be used as instruments for increasing social stability or social change.

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