The Blue Collar Brain

Guy Van Orden*1, Geoff Hollis2, Sebastian Wallot3

1CAP Center for Cognition, Action & Perception, Department of Psychology, University of Cincinnati, Cincinnati, OH, USA.
2Department of Psychology, Grant MacEwan University, Edmonton, AB, Canada.
3MINDLab, Aarhus University, Aarhus, Denmark.

Correspondence:
Guy Van Orden
CAP Center for Cognition, Action & Perception
Department of Psychology
University of Cincinnati
Cincinnati, OH, 45221-0376, USA
guy.van.orden@uc.edu

Keywords: control, synergetics, self-organization, 1/f scaling, mind and body,

Acknowledgment: Supported by NSF grants BCS #0843133 and DHB #0728743 to Guy Van Orden. Sebastian Wallot acknowledges funding from the Marie Curie TESIS network
Abstract

Much effort has gone into elucidating control of the body by the brain, less so the role of the body in controlling the brain. This essay develops the idea that the brain does a great deal of work in the service of behavior that is controlled by the body, a blue collar role compared to the white collar control exercised by the body. The argument that supports a blue collar role for the brain is also consistent with recent discoveries clarifying the white collar role of synergies across the body's tensegrity structure, and the evidence of critical phenomena in brain and behavior.
1. Introduction

In the 1940s, Lloyd Olsen shared his fifteen minutes of fame with Mike the celebrity headless chicken. Mike’s head was lost when he was five and a half months old while being prepared to become chicken dinner. Mike lived on without a head for 18 months, fed through an eyedropper and growing from two pounds at his beheading to eight pounds at his death. In the mean time he traveled widely performing in New York City, Los Angeles, Atlantic City and elsewhere.

Our interest in Mike is that he demonstrated coordination among the processes of his body despite lacking a central nervous system (except, probably, he still had a brainstem). What was left of Mike’s central nervous system would mark a handkerchief somewhat less than a healthy sneeze. But he nevertheless retained coordination among organ systems, facia, muscles, tendons, skeleton, and his peripheral nervous system, producing locomotion that could appear indistinguishable from intact locomotion, even walking around and “pecking” immediately after losing his head. To us Mike demonstrates that control of the body and behavior has sources apart from or in addition to the central nervous system.

In another demonstration, some feckless chickens were kept in an environment of constant red light. In this environment, the chickens lost their connection to the daily cycles of sunrise and sunset, and the pace markers or zeitgebers of the body’s circadian rhythm. Consequently the chickens suffered a breakdown of healthy coordination among the rhythms of physiology, including heart rate and cycles of deep body temperature, and the coupling of physiology with locomotor activities (Winget, Card, & Pope, 1968). Apparently, chicken physiology and behavior include necessary sources of control in the daily cycles of a circadian environment.

Seasquirts start life as rather simple tadpole-like creatures, possessing a simple nervous system, capable of locomotion and light detection. However, finding a surface upon which they can affix themselves, they do so, and promptly ingest their nervous system (Marsh, Richardson, & Schmidt, 2009). The seasquirt and the chicken examples speak to sources of control of the body and behavior in addition to the central nervous system. The example of the feckless chickens illustrates as well a basic tenet of control theory.

The more slowly changing circadian rhythm constrains the faster changing processes of physiology—slower dynamics constrain faster dynamics and not vice versa (Simon, 1973; Newell, 1990). Deprivation of sleep cycles or nutrients likewise destabilizes human emotional control, increasing emotional lability. The effect is sufficiently reliable to have become a mainstay of the weekend initiation rituals of cults and extreme self-help programs. Initiates are kept awake in a common room without food for 24 hours, which opens them up emotionally to be more receptive to the program being sold.

The previous tenet of control theory supplies an important clue about how control unfolds between the brain and the body. The pacing of the phenomena of the body during behavior, with respect to the concurrent pacing of the phenomena of the brain, tell us which of these processes
constrains which in enacted behavior. The thesis that we develop in this essay derives from the more slowly changing processes of the body and the faster changing processes of the brain and allows us to sketch out an outline of control in broad strokes.

This issue of *Frontiers of Fractal Physiology* is about critical phenomena of the brain, and we use this venue to explore the circumstances under which the body controls the brain to serve a blue collar role in on-going behavior. Next we introduce the basic idea of measurement of human performance plus the idea of critical states separating qualitatively different behavior at bifurcation points. Following that we introduce the critical phenomena observed in brains and behaviors and describe the body as an excitable medium of self-organizing synergies that constrain the brain during behavior. Finally, we summarize conclusions that appear to us to be the logical consequences of a blue collar perspective on the brain.

2. Human performance data

Cognitive scientists may tell you that they study specific cognitive functions such as memory, language, or motor control. In actual practice we study measurements of a person performing a “memory” task, a “language” task, or a “motor” task. Yet all task performances are motor performances and language is ubiquitous in the instructions to participants, which must tax memory to be remembered while performing a somewhat arbitrary laboratory task. So most of the time, and maybe all of the time, the scientists who study cognitive activities study a coordination over time among memory, language and motor activities.

All scientists are concerned with the reliable changes that they observe in the measurements that they take, which is true of cognitive scientists as well. The measurements that we take in cognitive science range from millisecond-precise durations of event times in human activities to nominal measurements that tally which category an observed behavior is assumed to represent. In all cases it is patterns of change or variation in the measured values that are scrutinized and interpreted to motivate interesting conclusions and to test the hypotheses that stem from scientific theories.

Early in the 20th century scientists derived powerful statistical tools with which to carve out the patterns in data, based on idealized assumptions about the central tendencies of data and uniform dispersion of data values around a central tendency—as though the average behavior of a system were a magnet drawing in the noisily dispersed measured values equally from all sides toward the middle. By the end of the 20th century the “magnet” picture of data had been generalized within chaos theory or nonlinear dynamical systems theory. Linear patterns of change in data, in which related changes were always strictly proportional to one another, were neatly absorbed as special cases of broader categories of nonlinear proportional change, discontinuous abrupt changes, and changes out of all proportion to one another.

In chaos theory, a tiny increment of change can result, all of a sudden, in qualitative changes in the data portrait of a system’s behavior. The locally tiny change breaks the balanced symmetry of
possible outcomes while reliably predicting a larger qualitative change called a bifurcation, which is studied in the mathematics of topology theory. Bifurcation theory concerns the relation between locally continuous or incremental changes and the abrupt qualitative changes that they may provoke. The tipping point of a bifurcation is a critical point and the behavior of systems near critical points is called criticality. The empirical focus of this essay is the scale-free behavior predicted to occur near the critical bifurcation points of complex systems.

3. Scale-free behavior of the brain and the body

Multicellular living things comprise nested structures. The toes and fingers at the small-scale periphery of the human skeleton are composed of small toe and finger bones coupled by small articulating joints. Toes and fingers are nested within the next scale of rigid bones of arms and legs that are coupled by larger articulating joints. Arms and legs in turn sprout from the trunk of the human body and are connected to the trunk by rotating joints at the hips and shoulders. Similarly, viewing a tree we can see that leaves are nested within the structure of small branches that are nested, in turn, within the structure of larger and yet larger branches that culminate in its largest branches, sprouting from the tree trunk.

The anatomy of blood vessels throughout the body, the detailed anatomy of a kidney, and the airways of a lung all comprise nested tree-structures across multiple scales—an arrangement called fractal structure that is studied using the mathematical tools of fractal geometry. The fractal composition is indicated by scaling relations that define the spatial organization of living things. In a scaling relation, the size of a structure is inversely proportional to how often structures of that same size recur. For example, within limits, the diameter of each blood vessel is inversely proportional to the total number of blood vessels of that same diameter that will be found in the body (West, 2006).

Scaling relations in space are complemented by scaling relations in time; event times of both human physiology and human behavior compose temporal scaling relations. In the scaling relations of event times, the magnitude of changes in the duration of event times is inversely proportional to how often a change of that magnitude recurs. Figure 1 portrays a physiological data series of brain activity to illustrate a scaling relation of fractal time. Across the top of Figure 1 we present raw electroencephalogram (EEG) data from a volunteer, collected from an electrode on his scalp while he performed the task of repeatedly estimating a one second time interval.

The bottom, left side of Figure 1 portrays a subset of the periodic sine waves used to simulate the aperiodic EEG signal. Arrows extend from each sine wave to its paired coordinate point in a power spectral graph, appearing below the raw EEG data. The amplitude and frequency of each sine wave become the two coordinates of a single point in the power spectral graph. The amplitude of the sine wave (squared) corresponds to the power or magnitude of changes in the data values that the sine wave simulates. The frequency of the sine wave estimates how often the changes of that magnitude recur.
Frequency of change and magnitude of change are the coordinate X- and Y-axes of the power spectral graph (after logarithmic transformations). Thus the power spectral graph presents a relation between the magnitude or power of the changes and the corresponding frequency of changes of that magnitude. This relationship is summarized by the slope of a regression line, also portrayed in Figure 1. The slope of the line in Figure 1 indicates scale-free behavior because power is proportional to frequency. Data like these are called scale-free because the data pattern will look similar whether the vantage point of the analysis zooms in, to a finer scale, or zooms out, to a coarser scale.

![Figure 1](image)

Figure 1. The ordered series of a single EEG-electrode record, sampled at 500 Hz (top) and the illustration of a spectral analysis of this record (bottom, right). Specific frequencies and magnitudes of change (bottom, left) are used to approximate the rough graph of the EEG-data (top), and the outcome is the spectral portrait (lower right) on log-log axes. The spectral slope $-\alpha = -1.08$ is close to idealized $1/f$ noise ($-\alpha = -1.00$). The Y-axes in the illustrated sine waves have been adjusted to make smaller amplitude sine waves visible.

The scale-free pattern of the data in Figure 1 is further illustrated in Figure 2 by repeatedly zooming in to examine the middle half of the time series of the EEG data. Each tighter frame on the EEG data reveals another self-similar pattern in the variation, which brings us back to a point of the previous section: This self-similar pattern is the predominant pattern of variation in EEG
data and begs to be explained with a high priority (Gilden, 2001). An explanation may begin with the apparent fact of the fractal pattern, that the same pattern is observed whether the focus is one half of the original data, one fourth of the original data, one eighth of the original data, and so on.

![Figure 2](image.png)

Figure 2. Ordered series of the single EEG-electrode recording from figure 1 (top, left) and the resulting spectral plot (right) on log-log axes. The top panel includes 16 minutes of continuous EEG recordings. All other panels are subsets of the original data series. The first and last quarters of each data series are deleted in each iteration, yielding eventually a data series that ran for 2 minutes (bottom). The scaling relation remains very similar for each nested series, close to idealized $1/f$ noise, and demonstrating the statistical self-similarity of the data series.

Another fact begging for explanation is that human performance data reveal a scale-free pattern similar to the brain data. The performance data of the same volunteer, whose brain data appear in Figures 1 and 2, are portrayed in Figure 3. Each Y-value of a data point in the raw data series of Figure 3 is the estimate produced by the volunteer of the duration of one second—the volunteer pressed a key to mark the time of each second’s passing. The raw data are portrayed across the top of Figure 3. Each datum is portrayed in the order in which it was collected; the data value from the first estimated event time is leftmost on the X-axis of the raw data and the data value of the last estimated event time is rightmost on the X-axis.
Figure 3. The ordered trial-series of 1000 intervals between the button presses defining time estimates of one second (top) and an illustration of a spectral analysis of this time-series (bottom, right). Specific frequencies and magnitudes of change (lower left) are used to approximate the rough graph of the behavioral button-press data (top), and the outcome of the spectral analysis (lower right) on log-log axes. The spectral slope $-\alpha = -0.99$ is close to idealized $1/f$ noise ($-\alpha = -1.00$). The Y-axes in the illustrated sine waves have been adjusted to make smaller amplitude sine waves visible.

A subset of the sine waves that were used to simulate the raw behavioral data series is portrayed on the left side of Figure 3. Each sine wave yielded two coordinates defining a point on the power spectral graph, again below the data series graph. Arrows connect each sine wave to its point coordinates. The amplitude of each sine wave (squared) estimates the size of changes in data values, and the frequency of the sine wave estimates how often changes of that size recur. The logarithms of frequency and size of change (power) are again the respective coordinate X- and Y-axes of the power spectral plot, and the summary regression line again has a slope near minus 1, which translates into a scaling exponent $a$ close to positive 1.

Repeatedly measured data values, whether from brain activity or behavior, are generally scale-free with exponents $a \sim 1$, consistent with our examples (for brain see Buzaski, 2006; for behavior see Gilden, 2001; 2009; Riley & Turvey, 2002; Newell et al.). This fact, plus the idea of intuitive brain-to-body white collar control, has led to speculation that the scale-free behavior of the brain causes the scale-free variation in behavior, in whole or in part (Raichle & Gusnard,
2005). This speculation is likely false however because the priority of control, as understood within control theory, flows from slower changes to faster changes and the scale-free behavior of the body includes orders-of-magnitude slower changes than the co-occurring brain activity. White collar control would thus require an extra source of control, in addition to brain dynamics, to amplify the activity of the brain in such a way that it could affect the dynamics of behavior.

We created an idealized illustration of how the time scales of behavior and brain might look together on the same graph, using the duration of the sine wave periods that would suffice to simulate the time scales of variation in repeated measurements of behavior and brain. The idealization appears in Figure 4. The behavioral data fill out the slower region of low-frequency high-power change on the logarithmic X- and Y-axes. The powerful amplitudes of change in the behavioral data are orders of magnitude larger than those of the brain data. The low amplitude changes of the brain are thus too weak and change too fast to be the causes of the much slower and more strongly varying changes of the body in behavior. Perhaps then the activities of the body somehow “cause” those of the brain.

![Time Scales of Behavior and Brain](image)

**Time Scales of Behavior and Brain**

Duration of Sine Wave Periods in $\log_{10}(\text{Sec})$, Approximating Empirical Variation

Figure 4. Time scales of behavior and brain were estimated from the time scales implicated in sine wave simulations of variation across repeated measurements (as in Figures 1 and 3). Landmarks of durations (Day, Week, etc.) or brain activity (Alpha, Gamma) are placed near their values in $\log_{10}(\text{Sec})$. Figure 4 also includes the span of brain activity observed in the BOLD signal of brain metabolism used in fMRI studies, all to give context to the contrast between the span of time scales observed of behavior and the span of time scales observed of the brain (for reviews see Buzáki, 2006; Gilden, 2001; Van Orden et al., 2011; van Roij & Van Orden, 2011). The question mark to the right of the behavioral span symbolizes the fact that no upper bound short of death has yet been discovered in longitudinal studies estimating the presence of scaling relations in the variation across measurements of behavior.
4. Presence of mind

Low amplitude changes of the brain are too weak and change too fast to be causes of the much slower and much more strongly varying changes in the body of the behavior. This claim might sound odd when adopting an overly exclusive, white collar, ‘the brain controls the body’ way of thinking. But it is not odd at all from an engineering perspective. Some engineered systems produce scaling relations in their behavior and the scaling relation characterizes a kind of marriage among different functions of ‘memory’ and ‘context.’ The consequences concern how engineered processes on very different time scales affect each other in their interaction.

Very slowly changing processes would appear almost static if seen from the perspective of a very rapidly changing process. But the changes in the slow and fast processes are of course co-occurrent. On the one hand, co-occurrence allows a very slowly changing process to serve a kind of memory function for the more rapidly changing process. The slowly changing process reminds the rapidly changing process of the influence coming from the slow timescale process which may change only slightly, or not at all, from the way it influenced the faster process during previous cycles. Slower changes are in this way a means for faster changing processes to ‘remember’ what they need to know about the status of all the more slowly changing processes of the system (Keshner, 1982).

On the other hand, very slowly changing processes also function as relatively stable contexts, as slowly changing or unchanging platforms within which rapidly changing processes are staged. In this emphasis, the very slowly changing processes constrain what can happen on faster time scales. As context, the very slowly changing processes interact with the rapidly changing processes to limit the degrees of freedom allowed to the rapidly changing process. All rapid changes must be made within the limited degrees of freedom that the context platform leaves available for changes.

The crucial importance of memory and context is reflected in how the brain consumes energy. The brain alone accounts for 20% of the body’s energy consumption (Clarke & Sokoloff, 1999). Yet in a task performance the range of changes in energy consumption in the brain’s activity is less than 5%—less than 1% of total bodily energy consumption (Raichle, 2010). In other words, our present state of knowledge about energy consumption suggests that a complex brainy task requires little- or no-more energy than simply relaxing with eyes closed. This pattern of energy use is consistent with a brain that is primarily about updating and maintaining predictive aspects of history and current events from the lived perspective of the actor.

The facts about energy consumption make clear the importance of the brain “knowing” its place in the world, at any given time. This knowledge could be sustained in positive feedback loops of glutamate cycling (Davia, 2005), and it is estimated that between 60% and 80% of the overall energy consumption of the brain occurs in glutamate cycling (Raichle, 2010). If an actor’s history and context—presence of mind—are sustained in the energy patterns of feedback loops,
then the amount of energy dedicated to this task is consistent with the importance of the blue collar work that supports ongoing perception and action.

Slower time scale dynamics are thus controlling of faster time scale dynamics, which allows the flow of changes in visible or audible, or otherwise available, context to constrain the dynamics the brain. The residual degrees of freedom allowed by a visible checkerboard, for example, slowly changing its position across the visual field on which flickering rings create expanding or contracting traveling waves (1/32 or 1/48 Hz), gives structure to the activity in visual cortex. The traveling wave supplies slowly changing constraints that give a more efficient and spatially precise picture of retinotopic organization, compared to previous attempts using static stimuli (Engel et al., 1993; 1994; Engel, Glover & Wandel, 1997).

Whether viewed as history or context, the slower the time scales of change, the more constant or stably constraining is the influence of the past. Invariant patterns of flow across the perceptual array sustain presence of mind and set the stage for perception, as James Gibson (1979) explained. The flow of context across perception occurs on the slower time scales of change in brain activity (see Figure 4). Slow changes in context (compared to the faster brain dynamics) supply constraints that reduce the degrees of freedom for what may happen next.

We suggest that the brain is primarily about maintaining presence of mind. In our meaning, ‘presence of mind’ includes the current configuration of the body as it is currently entwined in meaningful relations with the present configuration of the world. Relations among configurations are all themselves changing relatively slowly (compared to the brain). Slower time scales of change provide constraints to the brain in the shape of the pattern of energy flow in the brain. Constraints provide knowledge about possible futures, and they are had for free in the immediate status of relations between the body and the world.

5. A third category of phenomena

Behavior and brain share the same scaling relation, which they also share with other measured signals of physiology such as heart rate, colon contraction, transduction at the retina, neural firing, and many others (Glass, 2001). We believe there are fundamental consequences of this shared scaling relation. There are practical advantages for a system to maintain scaling relations in its patterns of change, these advantages place practical constraints on the development of species and organisms, and in turn this has staggering consequences for cognitive science.

An empirical scaling relation with scaling exponent $a \sim 1$ is approximately the mathematical scaling relation called fractal time, $1/f$ scaling, or pink noise. It is called pink noise due to a resemblance to the empirical spectral portrait of pink light, which concentrates power in the lower frequencies of red light relative to the higher frequencies of blue light. Pink noise is observed of complex systems near the critical points of bifurcations. By staying near its critical points, a system can immediately change the organization of its behavior.
Subtle changes in the relation between the task and the performer are often met by qualitative changes in the organization of performance. The relation between task and performer even shapes the expression of learning disabilities (Hendriks & Kolk, 1997). Encouraged to read aloud very quickly, developmental dyslexics make errors consistent with a deficit in the “lexical” process in reading, producing symptoms of a type of dyslexia that is defined by visual/phonological errors (e.g., CAMPAIGN → /camping/) and semantic errors (e.g., CARNATION → /narcissus/). When encouraged to read aloud accurately, the same dyslexics produce symptoms of a different type of dyslexia, exhibiting the ponderous letter-by-letter or syllable-by-syllable reading associated with a “nonlexical” process of reading.

Cognitive performance may undergo a bifurcation between speed versus accuracy conditions, self-organizing a different dynamical system suited for speed rather than accuracy (cf. Dutilh, Wagenmakers, Visser, & van der Maas, 2011). This hypothesis is consistent with the two types of dyslexic performance, one under speed conditions and the other under accuracy conditions. These speed versus accuracy types also closely parallel the two types of acquired dyslexia that were featured conspicuously in a double dissociation of reading processes that kicked off modern cognitive neuropsychology (Marshall & Newcombe, 1973, 1977). And extreme speed conditions also induce errors by intact readers that resemble the errors defining acquired dyslexias (Kello & Plaut, 2000).

Different task demands elicit the symptoms of different types of aphasia from the same brain-damaged individual(s) (Hofstede & Kolk, 1994; Kolk & Heeschen, 1992; Kolk & Hofstede, 1994; Kolk, van Grunsven, & Keyser, 1985). This would seem to require white collar brain-to-body control, if only to guarantee performance will satisfy the task requirements described in instructions to a brain-damaged individual. White collar control could occur if the weaker and faster changes of the brain could be quickly amplified. Rapid amplification could perturb or usurp the stronger and slower dynamics of the body to set or change the course of behavior. This is a reasonable way to imagine the white collar control of behavior by the brain, capitalizing on the relatively unstable dynamics near critical points. The instabilities near critical points could allow the brain to destabilize ongoing behavior and change its course.

But white collar control is not the topic of this essay. Our aim is to shine more light on the blue collar work of the brain. Blue collar work exploits the relatively stable dynamics near critical points, which may at first seem to contradict what we just supposed to be the basis for white collar control—that is, relatively unstable dynamics near critical points. Yet a critical state has the unique feature of being simultaneously the locus of stability and instability, regular and random variation, universal and singular structures—both together or neither alone—a third kind of behavior (Keshner, 1982; Nicolis & Rouvas-Nicolis, 2007; Sporns, 2007; Tsonis, 2008; Ulanowicz, 2006; Van Orden, Kloos & Wallot, 2011).

Before complexity science the variation in measured values was divided exclusively between the regular changes of explainable variance and the random changes of measurement error, signal versus noise. But pink noise is neither signal nor noise, or it is both, as already noted, and so it
cannot be classified within the conventional dichotomy. Pink noise is a third category of behavior, a widely acknowledged game-changing phenomenon of complexity science.

It is the simultaneous presence of instability together with stability that is defining of critical states. Thus our thesis: If white collar control can be said to exploit a propensity toward instability in behavior then blue collar work depends upon a propensity toward stability in behavior. White collar control by the faster changing dynamics of the brain exploits the instability of behavior near a critical state to change the course of the slower dynamics of the body.

Blue collar work depends upon constraints supplied by the more slowly changing dynamics of the body that lend stability to the faster changing dynamics of the brain. Sources of stability for brain dynamics include the repetitively similar behavioral trajectories of organ systems, the expressed modes of physiological processes, and the repetitive movements of human gait, for example. But sources of stability in constraints are also generally present in the generally more slowly changing dynamics of behavior compared to brain. We next describe the structural composition of the body that self-organizes the movement trajectories of the body in behavior.

6. Tensegrity structure of the body

A mollusk’s body naturally self-organizes survivable relationships with its environment. While slowly treading water, for instance, the mollusk abruptly recruits interneurons within a self-ordering central pattern generator, allowing a rapid escape from a predator (Nishikawa et al., 2007). The central pattern generator illustrates soft-assembly of a synergy.

Synergies are “softly” (temporarily) assembled dynamical processes. Temporary soft assembly allows changes in control to stay apace with the changing demands for reorganization of behavior. Perpetually changing demands exist at the perpetually changing interface of an organism with its environment. Central pattern generators may stay apace by re-organizing their network connectivity (Harris-Warrick & Marder, 1991; Hooper, 2001; Morton & Chiel, 1994). The changing relationship with an environment is sometimes served by previously inhibitory connections that now become excitatory connections, by neurons that are recruited into networks in which they did not participate before, or by the fusion of previously separate networks.

The spontaneous dynamics of the so-called default network change depending on what the participant just heard. The volunteer’s investment of attention to the task and other task demands change the functional organization of brain activity among the regions of the default network (Hasson, Nusbaum, & Small, 2009). The organism at its changing interface with the environment requires this flexible control, and temporary context-sensitive soft-assembly appears to be the vital organizing principle of brain architecture (Nikolić, 2010).

Almost any change pertaining to a standing person will yield uniquely configured postural dynamics (Riley et al., 2012). The body thus creates of itself unlimited postural solutions, apace
with the idiosyncratic local environments in which it finds itself (Riccio & Stoffregen, 1988). Organism-wide synergies enact this ordinary behavior. And the organism-wide synergies emerge across a tensegrity structure. The tensegrity structure is formed by a taught web of muscles and fascia to fully connect the parts of the skeleton, appearing to wrap it like a mummy.

Similar to tensegrity structures in architecture (Tomassian, 1997) or robotics and biology (Tur & Juan 2009), the skeleton supplies struts while the muscles, ligaments and fascia form tension lines that eliminate the slack across the tensegrity structure (Levin, 2002). The taught web of tension lines ensures that movement at any one place in the tensegrity structure has consequences throughout the tensegrity structure, creating a robust mechanical holism that even survives brain damage that leaves the body paralyzed (Carello, Silva, Kinsella-Shaw, & Turvey, 2008). The neuromusculoskeletal structure of the body, in the guise of this tensegrity structure, is an excitable medium that self-organizes constraints among the coordinated movements of the body. As constraints, synergies allow the tensegrity structure to behave in some ways but not others.

Synergies are webs of constraints that limit how the body can change in coordination. Respiratory and cardiovascular processes change together with a change of locomotor gait, for example, ensuring the right amount of oxygen to the cells at the right time. Behavioral processes in a skilled tennis player are constrained to run for the ball and make forehand shots, backhand shots, and to serve and return serves. A swimmer is constrained by synergies to breath out through the nose and breath in through the mouth apace with the strokes of swimming. A web of constraints in each case delimits the possibilities for coordination among the processes of the body, in the actions at hand.

Synergies and tensegrity structure also harvest energy from the temporary contexts of the body (Kugler & Turvey, 1987). Some good configurations of the body with its environment exploit potential energy from inertial forces or from gravity in ongoing movement (Bernstein, 1967; Dickinson, Farley, Full, Koehl, Kram, & Lehman, 2000; Kugler & Turvey, 1987; Turvey, 2007; Wijnants……, in press). Other good configurations knit the body together, head to foot, in the endlessly novel solutions of postural control. We are two legged creatures who must balance a large heavy head on a thin neck and to maintain balance our center of mass should not exceed its base of support, approximately circumscribed by a perimeter around the feet. To sustain balance, all overt movements must be anticipated by remote preflexes lest we tip over (Belen’kii, Gurfinkel, & Pal’tsev, 1967). And yet walking is also falling because the body moves outside of its center of mass in each step, exploiting the potential energy from gravity in the process.

7. Evidence of synergy

The body exploits the locally changing details of its own configuration along its own trajectory. In this way the body contributes to presence of mind, supplying always contemporary constraints penultimate to an action itself. In the example of saying the /b/ in /bob/, control by constraint and exclusion of unlikely configurations retains sufficient degrees of freedom, nevertheless, prior to
action, to allow the lips to compensate for each other if something goes wrong (e.g., Latash, Scholz, & Schöner, 2002; Riley et al., 2012; Scholz & Schöner, 1999).

The taught tension-line coupling across the tensegrity structure allows the body to perform as a single functional unit. In addition, synergies further tailor the available degrees of freedom for coincident changes in the coordinated changes among the processes of the body. The lips must be in contact to say the /b/ in /bob/, for example. A synergy ensures this contact by coupling neuromuscular processes to exclude all non-contact relations between the lips at the time that contact is required.

To test for control by synergy, perturb on-going speech and look whether compensation occurs in the coupled articulators. In a classic study, a speaker’s attempt to say the /b/ in /bob/ was perturbed by a sudden, unexpected, downward tug on the speaker’s jaw. Ultrafast compensation began within 5-10 ms—faster than the brain can compute and return a new plan of articulation (Wallot & Van Orden, in press)—and the lower lip, not the jaw, stretched upward to form a new configuration of contact, producing a fully intelligible pronunciation of /bob/ with no audible distortion (Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984; see also Abbs & Gracco, 1984; Folkins & Zimmermann, 1982).

Ultrafast compensation reconfigured the bilabial and laryngeal gestures (at least), producing compensatory lip gestures to respect abstract phonology plus compensations in the kinematics of the larynx (Saltzman, Löfqvist, Kay, Kinsella-Shaw, & Rubin, 1998; see also Bauer, Jancke, & Kalveram, 1995). In the theoretical language of cognitive psychology, bi-level coupling of kinematic micro-dynamics and linguistic macro-dynamics is a coupling between body and mind. Synergies in speech generally include coupling across different levels of organization (van Lieshout, 2004) and coupling across multiple levels of organization solves the essential problem of speech production—the on-line coordination of about 70 muscles to stay within narrow trajectories of legible meaningful speech (e.g., van Lieshout, Bose, Square, & Steele, 2007).

In other evidence of synergetic control, the perturbation is again sufficient to prompt a reorganization of human performance. Dual-task paradigms can be interpreted according to whether performing one task perturbs the performance of another task (Riley et al., 2012). For instance, pressure to respond quickly in a cognitive task perturbs and decreases the stability of motor-task performance, compared to performing the motor task by itself (Temprado, Zanone, Monno, & Laurent, 1999, 2001). Other times, a concurrent cognitive task is sufficient to change the organization of the motor performance (Pellecchia, Shockley, & Turvey, 2005; Shockley & Turvey, 2005, 2006).

In the latter case, dynamical models suggest a higher-order synergy emerges to integrate cognitive and motor performance (Fuchs, Jirsa, Haken, & Kelso, 1996). However, the motor task of walking on a treadmill takes priority over a concurrent cognitive performance, lest the participant fall, yielding a reorganization of cognitive performance. The same dynamics of
locomotion are present with or without the cognitive task, while cognitive dynamics are reorganized in the dual task (Kiefer, Riley, Shockley, Villard, & Van Orden, 2009).

In concurrent observations of brain and behavior, changes that anticipate reorganization are seen in the repeated measurements of both brain and behavior, and the coincident changes strictly resemble those that precede physical examples of bifurcations called phase transitions (Fuchs, Kelso, & Haken, 1992; Kelso & Fuchs, 1995). Reorganization across a bifurcation point is preceded by patterns of change called *critical slowing*, *critical instability*, and eventually the *sudden jump* in a bifurcation. The time delay from the sudden-jump reorganization of the brain to the sudden-jump reorganization of behavior is also about right, given our speculation about white collar control, occurring within the time required for a single jolt of activation running from brain to behavior (Fabre-Thorpe, Delorme, Marlot, and Thorpe, 2001; Riley et al., 2012; Thorpe 2002; Wallot & Van Orden, in press).

The coupling of processes in synergy is a refinement of the idea of coordinative structures in motor coordination, the previous solution to the notorious degrees of freedom problem of behavior (Turvey, 2007): There exist incalculably more possible configurations of the possible states of the body than there are smoothly and appropriately coordinated ways to make behavior (Bernstein, 1967). Tensegrity structure and synergies reduce the degrees of freedom of the body, limiting the possible configurations to task and context appropriate “symphonies” of movement as coordinated change in behavior (Haken, 1977; Juarrero, 1999; Kelso, 1995, 1998, 2009; Kugler, Kelso, & Turvey, 1980, 1982; Riley et al., 2012; Van Orden et al., 2011).

Another test for the presence of a synergy is to look for reduced degrees of freedom in the processes that are entailed in a behavior (e.g., Riley, Richardson, Shockley, & Ramenzoni, 2011). For instance, the reduced degrees of freedom observed of one process may anticipate the reduced degrees of freedom of another process not yet enacted. Raising an arm requires anticipation by remote muscles on the opposite side of the body, for instance, prior to any change in the arm’s position—else the body would tip over. If the arm movement is made to signal a cognitive choice then the preflex of the remote muscles would “signal” the same choice. If so then the fact of the reduced degrees of freedom in the anticipatory preflex corroborates the synergy of the soft-assembled choice response.

One widely used cognitive task includes a judgment of whether a visually presented letter string correctly spells a word in a reference language—that is, standing before a screen on which letter strings will appear, raise one arm for each American English ‘word’ and the other arm for ‘nonwords.’ Event times as ‘response times’ by anticipatory preflexes can be measured in the onset of electromyographic activity in the right or left thigh, the right or left paraspinal muscles of the lower back, or the right or left shoulder muscles. If the preflexes reliably distinguish words from nonwords instead of leaving the available degrees of freedom open, to accommodate either arm response, then the predicted, anticipatory, synergetic reduction in the degrees of freedom is confirmed.
Moreno, Stepp, and Turvey (2011) conducted this experiment, observing typical average ‘word’ decision times of about 649 ms in the arm movement data and an identical advantage for ‘word’ over ‘nonword’ response times in each of the anticipatory preflexes. Word letter-strings were reliably distinguished by the side of the body of the activated preflex. On average, the preflex ‘word’ response times preceded the arm ‘word’ response time by 120 ms at the shoulder, 189 ms at the trunk, and fully 225 ms at the thigh. The anticipatory reduced degrees of freedom in the corresponding preflexes corroborates synergetic control. Synergies soft-assemble a multilevel whole-body ‘American English word versus nonword judgment device’ (cf. Carello & Turvey, 1980; Hollis, Kloos & Van Orden, 2009; Kello & Van Orden, 2009; Kloos & Van Orden, 2009; Turvey, 1990; 2007).

Synergies that self-organize apace with the flow of context and behavior will organize and update on-going constraints that anticipate the requirements for oncoming behavior. Invariant or smoothly changing aspects of the world yield invariant or smoothly changing constraints at a pace that is slower than brain dynamics. These constraints inform behavior by limiting the degrees of freedom about what can happen next, leaving open the possible kinematic changes that the body may enact in behavior. A muscle contraction here or a postural adjustment there are nonetheless always constrained by, and constraining of, the total configuration of the behaving body—the organism as an integrated whole.

8. Summary conclusions

We began this essay with several examples of control that did not require an intact central nervous system. Mike the celebrity chicken may now be seen to illustrate the importance of tensegrity as an organizing principle of behavior. Taught tension lines across skeletal struts imbue the body with self-organizing properties of excitable media. Chickens who lose their circadian coordination among physiology and behavior illustrate a coupling to the environment that contributes to control and regulation of health and well-being. The seasquirt is perhaps the ultimate illustration of how a nervous system can be necessary (although not sufficient) for some aspects of being, and dispensable for other aspects. No doubt even stranger examples exist of organisms and the blue collar tasks of their nervous systems.

We speculate that criticality is essential to both the white collar and the blue collar functions of the nervous system. It is no accident that the body and the brain stay near to critical states. Systems that stay near critical states are called metastable systems and the advantages of metastability are legion. A metastable system can commit to a region of the state space of possibilities for action, without otherwise narrowing its options. This allows a healthy codetermination of action both by the history and context that define the possibilities for behavior together with the momentary contingencies that “choose” the behavior that is observed. This codetermination is also another pairing of regularity and randomness or order and disorder, like those that characterize pink noise and other aspects of complex systems.
At any given moment in time, the available constraints are self-organized in synergies, which reduce the degrees of freedom for the mind and body, defining the possibilities for action. Synergies also allow the body to change altogether as a single entity. To do so, anticipated behaviors can be pre-constrained or poised, lacking only a single bit of contingent circumstances to enact one of the possible actions that are anticipated (Järvilehto, 1998; Riley et al., 2012; Wallot & Van Orden, in press). The anticipation of behavior by excluding actions that will not occur requires neither rules nor explicit expectations about what will occur next (Stepp & Turvey, 2010), which is a good thing because rules and expectations are too parochial in their anticipations about possible behaviors (Dreyfus, 1992; Van Orden, Kello, & Holden, 2010).

In contrast to rules and expectations, synergies directly couple anticipation to context, ensuring that the history of the organism and the on-going changes in context are constitutive of cognition and action. Anticipation is possible because processes linked in positive feedback create a centrifugal attraction to the activities that may emerge in their collective (Kelso, 1995; Strogatz, 1993; Ulanowicz, 2006). In the collective, the possible activities are specified or delimited in the reciprocal context that each process provides for the others. Mathematically this might be formulated as an intersection among all of the possible action trajectories that each process entails. Imagine their entailed propensities to act as Venn diagrams yielding a crosshatched overlap as the set of anticipated future solutions to behavior.
9. References


