

Voluntary Behavior in Cognitive and Motor Tasks

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Abstract

Many previous treatments of voluntary behavior have viewed intentions as causes of behavior. This has resulted in several dilemmas, including a dilemma concerning the origin of intentions. The present article circumvents traditional dilemmas by treating intentions as constraints that restrict degrees of freedom for behavior. Constraints self-organize as temporary dynamic structures that span the mind-body divide. This treatment of intentions and voluntary behavior yields a theory of intentionality that is consistent with existing findings and supported by current research.

1. Dilemmas with Traditional Views of Intention

Extensive catalogs of empirical data stand behind contemporary theories of mind, body, and behavior. However, one important fact, common to all experiments with human participants, is rarely considered: Before meaningful data can be collected, a participant's intentions to perform as instructed must be solicited (Lindworsky 1923). In other words, the backbone of what scientists know about mind and behavior – experimental data – depend fundamentally on the will, purpose, and goals of participants. But despite its prevalence, an agreed-upon coherent understanding of intentionality is not available. This is not for lack of data, given that every study of human behavior solicits human intentions. Instead, theoretical progress has been hamstrung in the dilemmas of a dualist mind-body separation.

The current essay addresses these dilemmas under the umbrella of complexity science, emphasizing intentions as constraints on emergent behavior. We start by describing the dilemmas inherited from the perspective of mind-body separation. We then provide a view of intentionality that transcends the mind-body divide. Along the way, we explain how contents of intentions accomplish selective attention, and how voluntary control reveals its presence in behavior.

Consistent with the masthead *Mind and Matter*, mental events have abundant and reliable material consequences for the body and behavior

(Markman *et al.* 2005), and they permeate all human activities (cf. Gibbs 1994, Lyons 1995, Mandler 1997, Mitchell *et al.* 2009). The mere expectation of an adverse effect can lead to strong bodily reactions (known as *nocebo effects*; e.g., Barsky *et al.* 2002). And mental imagery can improve sports performance, especially when images are enacted repeatedly (Wakefield and Smith 2009, Weinberg 2008). Intentions are one kind of those mental events – with similarly remarkable effects on the body. For example, an intention to act results in muscle tensions across the body, including “heightened tonicity of the reactive mechanisms ... widespread contraction of skeletal muscles ... marked changes in breathing, heart rate, and vascular processes ... and an increased readiness of arousal for associations within a given sphere” (Bills 1934, p. 408).

Even more striking effects of intentions come from classical-conditioning research on autonomous bodily reactions of human participants (for a summary see Woodworth and Schlosberg 1954). In a Pavlovian-type paradigm, a sound was paired with eating food, while the amount of secreted saliva was measured. Or a light was paired with an electric shock, while psycho-galvanic reflexes were measured. Notwithstanding the fact that people can be classically conditioned, neither conditioning nor extinction proceeded in a regular fashion. For example, the conditioned sound sometimes led to a decrease, rather than an increase, in the level of saliva secretion, depending on the intentional stance (Razan 1935). Or in the case of shock conditioning, the conditioned reflex in response to the light disappeared immediately after the participant was told there would be no more shocks (Cook and Harris 1937, Mowrer 1938). Changes in the intentional set, in effect, turned the participant into a differently conditioned animal (Razan 1939).

Finally, the intentional stance in one task can infect performance of another task that requires a different intention altogether (for a summary see Bills 1943). For instance, performing a task that demands high accuracy will improve accuracy in a subsequent task. Likewise, performing a task that emphasizes speed will speed up performance in a second task. Even intended rhythm is infectious across tasks. A skilled pianist, for example, after playing a composition with a fast tempo, will then play a slower-tempo composition closer to the pace of the first piece, or vice versa (Cathcart and Dawson 1928). It is even possible to fatigue the participant’s goal to pay attention in voluntary behavior and transfer that fatigue to a second task.

Immediate effects of intentions on bodily reactions create dilemmas for theories of mind and body because theories lack the necessary bridging concepts to connect mind and body (Mandler 1984). How does intentionality affect a body reflex that lives outside of voluntary control (cf. Fearing 1970)? And how does the intentional stance elicited for one task reappear in the performance of a different task? The traditional solution to these

dilemmas is to assume a special causal status for intentions: a capacity of intentions to bring into existence behavior across the mind-body divide, and from one task to another. There are several problems with this view, however, whether on methodological, theoretical, or empirical grounds.

On a methodological level, the muscle tensions that result from intentions will vary in quality from person to person and from task to task. While muscle tensions can reliably predict a host of factors (e.g., task difficulty, fatigue, quality of performance, even broad content of thought; Woodworth and Schlosberg 1954), idiosyncratic muscle tensions across participants and tasks prevent aggregating data to discover common causes. In other words, methodological attempts to isolate the causal power of intentions are bound to fail, given the idiosyncratic variability in embodied content from person to person, or task to task (cf. Molenaar 2008).

On a theoretical level, conceiving of intentions as causal entities inevitably raises the question of the cause of intention. If the origins of nocebo effects, effects of mental imagery, paradoxes of conditioning, and the embodiment of the intentional stance are explained by an intention, then what caused the intention in the first place? Intentions must either acquire a magical status, as *prime movers*, or we enter an endless logical regress of seeking the cause of the cause of the intention to behave (Juarrero 1999).

Finally, on an empirical level, if the origin of voluntary behavior is explained by intentions, it is not clear why intentions sometimes have so little effect on behavior. It is well known, for example, that a dieter forbidding himself to eat his favorite non-diet foods will likely fail with that diet solution (Baumeister and Heatherton 1996, Rachlin 2000). In general, mindful, forbidding self-control is notoriously difficult to put into action, leaving us vulnerable to temptation (Nordgren *et al.* 2009). If intentions are prime movers, why do they fail to move us when it matters?

One solution to the dilemmas is to deny intentions any status in bringing about behavior. In fact, experiments are frequently thought to tap into involuntary, automatic, or unconscious processes exclusively (Science Watch 1999). This solution not only ignores the role of participants' intentions in data collection (Vollmer 2002), but it also creates new dilemmas. Most prominent is the mind's ability to attend selectively to relevant factors. Take for example the well-known finding that participants – instructed to focus on the ball handling in a basketball game – fail to notice a man in a gorilla suit pounding his chest on the basketball court (Simons and Chabris 1999). How could such striking selective attention be explained without reference to the focus of the participant or the intentions to perform as instructed? In other words, how does the mind stay open to the outside factors that are necessary to promote intended goals, while at the same time ignoring irrelevant factors that might derail them?

In sum, the mind-body divide has led to dilemmas about how to understand the role of intentions in behavior. Conspicuous in the protracted failure to connect mind to body, intentions can either take the role of functional causes of behavior; or they become irrelevant facets without causal impact. Neither of these options fit the existing data – data that show strong influences of intentions. In the remainder of the essay, we describe a way to bridge the mind-body divide that escapes these dilemmas. To build this bridge, we borrow concepts from complexity science, developed over decades of research with living and non-living nonlinear systems.

2. Intentions as Constraints

Complexity science offers a framework for an integrated understanding of intentionality, one that avoids isolable functional causes of cognitive activities (for contemporary issues of the functional view, see Bechtel 2009, Lyons 1995). We align ourselves with the idea that intentions are not effective causes in the sense of billiard-ball causality, but function instead as constraints in emergent coordination (e.g., Juarrero 1999, Riley and Turvey 2001). To unpack this claim, we first discuss constraints and emergent coordination more generally and then turn to how control parameters bring about selective attention.

2.1 Constraints and Emergent Coordination

Constraints are relations among a system's components that reduce the degrees of freedom for change. An intuitive example of constraints comes from the arrangement of muscles and bones across the skeleton. Similar to tensegrity structures in architecture and robotics (e.g., Tomasian 1997, Tur and Juan 2009), the skeleton supplies struts, while the muscles (ligaments and fascia) form tension lines, which together eliminate slack across the musculoskeletal structure (Levin 2002). The limits on degrees of freedom of this tautly poised arrangement limit the range of motion of body parts, such that they can move in some directions, but not others.

Other examples of constraints on body motion, less constant than musculoskeletal tensegrity, are *temporary coordinative structures* (Turvey 1990). They comprise webs of constraints across the body, which constrain how the parts of the body will change together, in coordination. Playing tennis, for instance, is constrained by coordinative structures to run for the ball, forehand shots, backhand shots, serves, and return a serve. And swimming is constrained by coordinative structures to enact the strokes of swimming. The web of constraints of a coordinative structure delimits the possibilities for coordinated movement of the body in the actions at

hand. As a result, the coordinative structure will temporarily constrain the body to move in some ways but not others.

Like coordinative structures, intentions can be conceived as temporary sources of constraint that concern the specific needs and goals of an actor. For example, the instructions about how to act as a participant in an experiment are temporary sources of constraint that the participant takes on. Thus intentions contribute self-control by limiting the options for behavior to suit the immediate requirements of the task. They are temporary dynamical structures that emerge to constrain mind and body and sustain purposeful behavior. In this sense, intentions are ordinary ingredients of nature, as commonplace as causes. It even becomes plausible that emergent structures of physical systems express a kind of proto-intentionality or proto-mentality (Shaw 2001).

Temporary dynamical structures have several important features that apply to intentions. In particular, a temporary structure constrains local interactions at the same time as the local interactions sustain it. A model physical system to intuit this constrain-sustain feature is a layer of fluid, heated from below (e.g., Kelso 1995). At a critical difference between heat coming in at the bottom and heat going out at the surface, the fluid molecules self-organize into orderly Bénard convection cells to transport heat through the fluid (Nicolis 1989). A hexagon pattern forms across the surface of the fluid such that each cell of the hexagon circulates fluid molecules in a direction opposite from its neighbors. This pattern of convection cells constrains the motions of its component molecules (i.e., each molecule moves in the direction of the convection roll that it happens to be part of). At the same time, the interdependence of motion across the entire fluid is sustained by local interactions among the motions of neighboring molecules.

This relation between the hexagon of Bénard convection cells and the molecules that sustain them is called a *strange loop*. It refers to the constrain-sustain relation in which local mutually reinforcing motions sustain an emergent global structure in their collective activity, which “loops” back to constrain the local motions within the global structure. Such a relation is present in all strongly emergent phenomena. In fact, interdependent strange-loop behavior is at the heart of complexity science. Strange loops short-out the logical regress of searching for ultimate causes because local changes are constrained by the global coordination they sustain (Juarrero 1999). Thus temporary dynamical structures respect the local physics of cause and effect while, at the same time, they acquire dynamical properties in their global organization (that constrain the local dynamics).

An intention is analogous to the emergent coordination of a Bénard cell, part of a temporary coordinative structure of the entire system. As a Bénard cell self-organizes within a hexagonal pattern, spanning the system

of heat and fluid, so do intentions self-organize within dynamics spanning the system of mind, body, and context. Like Bénard cells constrain the movements of molecules, intentions constrain the changes in their embodied elements. And like Bénard cells are sustained in the interdependent interactions of molecules, intentions are sustained by interdependent interactions among their embodied elements. In both systems, elements change on faster timescales than the coupling that sustains the pattern emerging among them. And in both systems, the emergent pattern constrains the local behavior of the elements.

2.2 Control Parameters and Critical States

Relevant constraints are summarized in control parameters. In a simplified illustration of the heated fluid, a control parameter is the ratio between heat entering the bottom layer of the fluid, and heat dissipated at the surface:

$$\text{simplified fluid dynamics : } \frac{\text{incoming heat}}{\text{outgoing heat}} \quad (1)$$

This ratio of incoming heat and outgoing heat predicts the observed global behavior of the molecules. When the ratio is less than 1, disorderly movements of molecules are sufficient to dissipate heat. And if the ratio becomes greater than 1 (all else equal), orderly Bénard cells emerge.

Applied to human behavior, a control parameter has been illustrated in infants' voluntary stepping behavior (Thelen and Smith 1994). Sources of constraint include the weight of an infant's leg and the strength of the infant's leg muscles. The control parameter combines these constraints, again in a ratio:

$$\text{simplified stepping : } \frac{\text{weight of leg}}{\text{strength of leg}} \quad (2)$$

Weight of the leg is in the numerator, and strength of the leg is in the denominator. Stepping behavior is possible when the strength of the leg exceeds its weight, and stepping behavior disappears when the weight of the leg exceeds its strength, which correctly predicts typical and atypical patterns of development.

In more general terms, the numerator of the control parameter – e.g., leg weight – summarizes constraints that embed the infant in her environment. Such embedding constraints delimit *affordances*, the dispositions of the surrounding environment that are directly relevant for action (Gibson 1979). Conversely, the denominator – e.g., leg strength – concerns embodied constraints of the actor, constraints supplied by the body itself. Embodied constraints delimit *effectivities*, the capacities and capabilities of the actor to exploit the available affordances (Shaw *et al.* 1982). Thus,

the control parameter of voluntary stepping captures the relations between the infant and its environment:

$$\text{simplified behavior : } \frac{\text{affordances}}{\text{effectivities}} \quad (3)$$

Working out the details of the control parameters allows us to discuss the concept of *critical states*, a concept with special significance for our understanding of intentions. When numerator and denominator of the ratio are equal, the control parameter reaches a *critical value*, and the system enters a critical state. In the example of the heated fluid, the critical value is reached when the incoming heat equals the outgoing heat. The opposing actions that are equally available in this state are random dispersion vs. clockwise or counter-clockwise movement within convection cells. In infant stepping, the critical value is reached when the pull of gravity exactly equals leg strength. In this state, two opposing behaviors (e.g., stepping and not stepping) are in precise balance, and therefore equally likely.

The simultaneous presence of opposing actions creates a symmetry that can be broken by the smallest perturbation. Even tiny changes – with seemingly miniscule causal power – can tip the balance of the poised alternatives and enact behavior. In the heated-fluid analogy, just before molecules self-organize as convection rolls, any relevant contingency, even a single molecule’s movement, can determine whether a particular Bénard cell will roll clockwise or counter-clockwise within the global pattern. And in the example of body motion, a very local change in musculoskeletal position can be amplified through the tensegrity structure and, as a result, change the movement of the entire body (Carello *et al.* 2008, Turvey 2007, Turvey and Fonseca 2008). Even the spontaneous contraction of a single muscle at the critical point of movement may bring about a movement that was not possible before.

Selective attention, one of the dilemmas of intentionality, is resolved in critical states. This is because critical states can only be perturbed by events that favor an available action alternative. For example the next meal of a hungry dieter may be enacted by finding a candy bar, but not by finding a toy car. The toy car is not sufficiently relevant to the specified critical state, like the color of her mother’s blouse may be irrelevant to a baby’s stepping behavior. In this way, critical states allow the actor to stay open to even the smallest changes in events relevant to the critical state, without being captured by irrelevant contingencies.

Taking this idea a step further, it is the intentional content of the critical state that determines which contingencies may sway the system one way or another (cf. Mandler 1984, 1997). A dieter’s focus on healthy versus unhealthy edible things creates a critical state in which foods – whether healthy or unhealthy – become part of the relevant contingencies.

It therefore leaves the dieter susceptible to eating candy bars despite the intention not to. A more effective strategy might be to concentrate on more abstract end-goals of dieting, such as personal wellbeing, to better disconnect candy bar contingencies from critical states of behavior (Fujita and Han 2009).

Before a contingency can enact behavior, the system must already be in a relevant critical state. Available constraints must first specify propensities to act. Only then do contingencies have the power to cause behavior. Absent a relevant critical state, neither voluntary nor involuntary behavior will occur. And once a relevant contingency occurs, the specific critical state ceases to exist, dissipating the causal powers of the contingency. Eating a candy bar, for example, may rob the next candy bar of the power to enact behavior. Instead, new constraints for behavior emerge.

3. Evidence of Complexity in Human Performance

We have suggested that intentions are best conceived as temporary dynamic structures. Intentions are emergent constraints that span the mind-body divide and shape the critical states that anticipate purposeful behavior. But how would we know that voluntary performance is the product of emergent coordination? The answer lies in the fact that emergent coordination requires positive feedback among a system's components (e.g., Camazine *et al.* 2001). Positive feedback of this sort predicts a specific pattern of intrinsic variation in measurements of a system's behavior, known as a *scaling relation* (Van Orden *et al.* 2003). In this section, we elaborate on these ideas.

3.1 Scaling Relations

In an emergent coordinative structure, changes in any relevant part of the body are correlated with changes in every other relevant part. This appears as long-range correlations in a repeatedly measured human performance. A scaling relation reflects such long-range correlations. It pertains to the relation between the size of changes in repeated measurements and how often changes of that size occur. The scaling relation at issue has been called *pink noise*, but has also been referred to as *flicker noise*, *1/f noise*, *1/f scaling*, *multiplicative noise*, *edge of chaos*, *fractal time*, *long-range correlations*, *red noise*, or *self-affinity*. The many names reflect the many phenomena and disciplines in which scaling relations have been observed. We will use the term "pink noise" throughout (but see Ihlen and Vereijken 2010).

Pink noise can be portrayed in a spectral plot that results from decomposing a data series into sine waves of different amplitudes. Figure

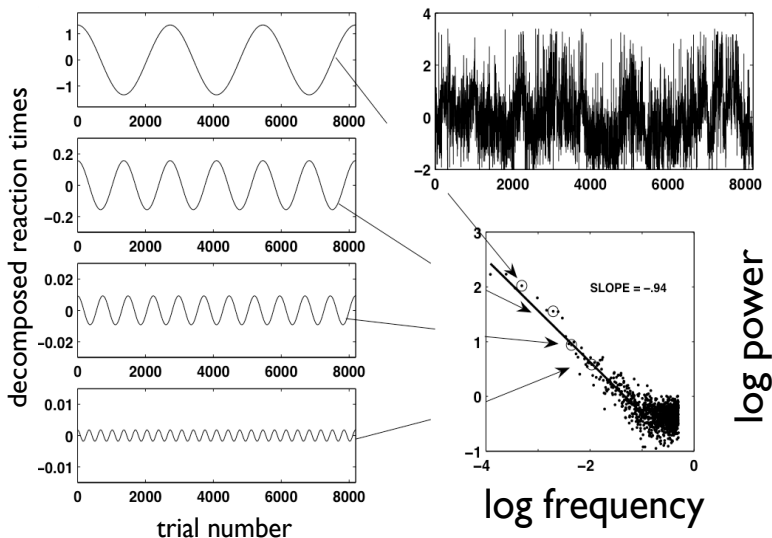


Figure 1: upper right – reaction times of one subject versus trial number; left – reaction times decomposed into sinusoidal components of different wavelength; lower right – spectral plot of reaction times with an average slope of -0.94 and four marked points referring to the sinusoidal components indicated.

1 shows such a data series (top right) and how it can be decomposed into sine waves of particular amplitudes. Slow changes in the data series are captured by low-frequency high-amplitude sine waves (top left of Fig. 1), and fast changes are captured by high-frequency low-amplitude waves (bottom left of Fig. 1). A power spectrum is then constructed, with relative amplitude on the vertical axis, and frequency f of change on the horizontal axis (on log-log scales). The amplitude represents the relative size of change $S(f)$, also referred to as power. The slope of the regression line in the spectral plot defines the scaling relation between amplitude and frequency. In Fig. 1, the size of changes $S(f)$ is inversely proportional to their frequency f :

$$S(f) = 1/f^\alpha = f^{-\alpha},$$

with scaling exponent $\alpha \approx 1$, the scaling exponent of pink noise.

Pink noise is so commonly observed in cognitive and motor task performance that it has been claimed to capture a universal feature of human performance (for reviews see Gilden 2001, 2009, Kello and Van Orden 2009). Furthermore, the universality of pink noise beyond human performance supports the idea that common dynamical organizations appear in systems of different material construction, in living as well as nonliving matter. However there is some difficulty related to pink noise. This is

because pink noise is both a regular and an irregular phenomenon: Regularity is seen in the stable scaling relation of a power spectrum, while irregularity is seen in the unstructured aperiodic waveform in a data graph. In truth, empirical pink noise is neither regular nor irregular. Instead, it is a strongly nonlinear pattern that exists between the two extremes (Nicolis and Rouvas-Nicolis 2007, Sporns 2007, Tsonis 2008).

A physical system provided the analogy for our interpretation of pink noise: avalanches of sand or rice piles. In actual experiments, sand granules were dropped, one at a time, to build a pile in which eventually the next dropped granule triggered an avalanche (for a review see Jensen 1998). Time between avalanches of different sizes was measured repeatedly. Initial results showed that sand pile avalanches never became sufficiently large to reproduce the very large avalanches predicted in a scaling relation. They instead yielded overly random avalanche behavior driven by the inertia of sand granules.

Results changed after grains of sand were replaced with rice kernels (Frette *et al.* 1996). The rice kernels varied in their aspect ratio of kernel length to kernel width. Kernels of low aspect ratio (less surface area) behaved like sand; too little friction resulted in over-random avalanche behavior. Kernels of higher aspect ratio (more surface area) allowed more friction among kernels, and thus more regular avalanche behavior. More friction made it possible for small piles of rice to form throughout the larger pile, at or near their toppling threshold. With so much rice poised to topple, rice piles could produce the rare large avalanches to fill out a scaling relation between size $S(f)$ and frequency f of avalanches.

Taking the rice- and sand-pile results together, granules with too little friction were too strongly governed by inertia. Although inertia itself is a highly regular phenomenon – i.e., the tendency of a particle to maintain its current state trajectory – inertia is a source of over-random behavior in the case of avalanches. This is because too little friction, relative to inertia, minimizes the tendency to build local structure in a sand pile, necessary for scaling behavior. In order to capture granules in local piles, poised near their toppling threshold, more friction is needed, relative to inertia. On the other end of the spectrum, too much friction (or too little inertia) would produce piles that are too coherent and too over-regular in their behavior. This is the case in a mud-pile in which rare large-avalanche mudslides dominate behavior. Only when friction and inertia are in relative balance do avalanches reveal scaling relations.

The tradeoff between friction and inertia can again be represented as a control-parameter ratio:

$$\text{variation in avalanche behavior} : \frac{\text{inertia}}{\text{friction}} = \frac{\text{over-random}}{\text{over-regular}} \quad (4)$$

Inertia contributes to over-random behavior, and friction between gran-

ules contributes to over-regular behavior. When these two factors are in balance, a pink-noise scaling relation can be observed. As such, pink noise is neither over-random nor over-regular but balanced between the two. Applied to cognitive and motor performance then, pink-noise scaling relations might be indicative of a mind-body-context system that is poised at a critical state in which over-random tendencies are balanced with over-regular tendencies.

3.2 Attraction to Critical States

As we discussed earlier, a balance between numerator and denominator in the control parameter is constitutive of critical states – a state in which opposing options are available simultaneously. And so far, we have shown how a pink-noise scaling relation is also a form of balance, namely between over-random and over-regular tendencies. A new dilemma arises, however. Absolute symmetry in critical states is behaviorally unstable, given that the smallest relevant contingency will collapse the symmetry. Yet pink noise is common in nature. How can empirical critical states be unstable while at the same time be associated with behavior as commonly observed as pink noise? The solution is a system that is attracted toward critical states (Bak 1997, Bak *et al.* 1987). What is the evidence that intentional acts are poised at criticality?

Suggestive evidence comes from speech experiments in which participants repeated the same word again and again (Kello *et al.* 2008). Each recorded instance of the word was then parsed identically into dozens of frequency bins, and the amplitude of each frequency-bin was tracked across a participant’s tokens of the spoken word. This resulted in dozens of separate data-series per participant, each with a spectral exponent. Aggregating the estimated scaling exponents in a histogram revealed a normal Gaussian distribution with a central tendency near the pink-noise scaling exponent of $\alpha \approx 1$. In other words, taking into account variations in scaling exponents, their central tendency in a repetitive speech task appears to be pink noise.

More direct evidence for attraction towards pink noise was observed as adults gained practice with a Fitt’s tracing task (Wijnants *et al.* 2009). Participants used a stylus to repeatedly trace between two dots on an electronic tablet. The measurement was the time required to trace from one dot to the other, yielding a trial series of trace times. Across practice blocks, the central tendency of spectral plots approached $\alpha \approx 1$ of pink noise. Interestingly, in the earliest practice block, the trace-time exponents were distributed below $\alpha \approx 1$, reliably toward $\alpha \approx 0$ (see Figure 2). A scaling exponent of $\alpha \approx 0$ would reflect *white noise*, an over-random coordination in which changes of every size $S(f)$ are equally frequent. As participants acquired practice across blocks, over-random whiter noise gradually approached pink noise.

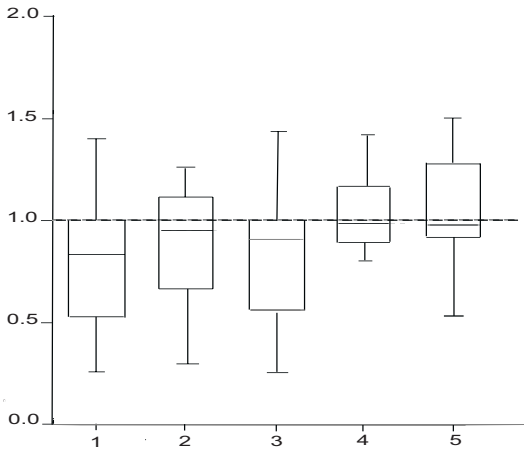


Figure 2: Change in participants' dispersion of spectral exponents α (vertical axis), moving from white noise ($\alpha < 1$) to center on pink noise ($\alpha \approx 1$), across five consecutive blocks of practice of a Fitt's tracing task.

Attraction to pink noise has also been observed across development, in a cross-sectional study of 4- to 12-year-olds and adults who estimated a short time-interval repeatedly (Kloos *et al.* 2009). Participants pressed a button each time they thought the particular time interval had passed, yielding a trial series of durations between button presses. Scaling exponents were then determined, one for each trial series, to describe the variation in time estimates. As was the case with the Fitt's tracing task, there was a reliable trend toward pink noise. While younger children exhibited white-noise scaling exponents, the scaling exponents of older children and adults were attracted to pink noise.

What changes in a system, as it departs from white noise toward pink noise? To answer this question, recall that the proposed control parameter of human performance is a ratio between affordances (opportunities for action) and effectivities (capacities or capabilities for action). Also recall that the control parameter of the pink-noise scaling relation is a ratio between over-random and over-regular tendencies:

$$\text{human performance variation} : \frac{\text{affordances}}{\text{effectivities}} = \frac{\text{over-random}}{\text{over-regular}} \quad (5)$$

Younger children performing an estimation task (or novice adults performing a tracing task) may lack capacities to sufficiently control the degrees of freedom afforded within these idiosyncratic and unusual tasks. For example, younger children may have a reduced capacity to sustain voluntary control, while they also remember a time interval. With development and practice children accrue effectivities to better coordinate their

bodies with cognitive tasks. They can better accommodate arbitrary and idiosyncratic tasks, and they can sustain the intentions that follow from experimental instructions. Consequently, whiter, over-random, scaling relations, reflecting underdeveloped effectivities and uncontrolled degrees of freedom in task performance, eventually give way to pinker scaling relations in which available and controllable degrees of freedom are more in balance.

Attraction toward criticality can also converge on pink noise from the other direction: going from over-regular behavior toward pink noise. This was observed, for example, in a cross-sectional study of gait development (Hausdorff *et al.* 1999). Stride-interval times were measured while children and adults walked on a treadmill. A detrended fluctuation analysis was performed on the resulting data, yielding values that are equivalent to scaling exponents (after a transformation). Gaits of 4 and 5 year-olds produced exponents distributed toward *brown noise*, reliably above $\alpha \approx 1$, toward $\alpha \approx 2$. This scaling exponent reflects over-regular coordination: A young walker, inexperienced with walking on the treadmill, might lock out degrees of freedom in the body to avoid falling. With development and practice, this over-rigid control is relaxed toward more flexible control. Indeed, gaits of older children and adults converge, with development, on the over-random side of pink noise.

Figure 3 shows the three kinds of scaling exponents that we have discussed: over-regular (brown noise), over-random (white noise), and between the two (pink noise). Both development and training have re-

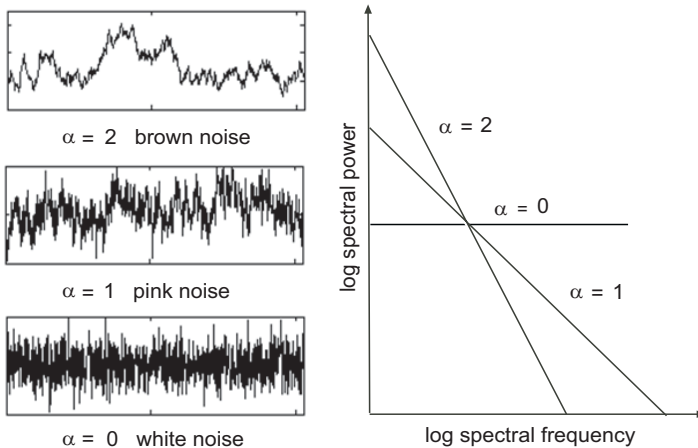


Figure 3: Illustration of brown noise, pink noise, and white noise. Typical data series appear on the left, spectral plots with their characteristic slopes $-\alpha$ appear on the right.

vealed attraction toward balanced pink noise, whether by accruing additional constraints (departure from white noise) or by loosening over-rigid constraints (departure from brown noise). Rigid over-regular control can produce stable behavior in an environment of very predictable affordances, but fails as affordances becomes less predictable. Vice versa, over-random control makes flexible changes possible when affordances are unpredictable, but over-random changes will fail to track the predictable features of the environment. Thus pink noise variation in behavior may reflect an optimal combination of stability and flexibility in control, to accommodate both commonplace and idiosyncratic changes in affordances. Indeed, variations in data across development and training show an attraction toward this balance of stability and flexibility in the attraction toward pink noise.

3.3 Soft-Assembly of Idiosyncratic Mechanisms

Temporary dynamical structures, rather than drawing on hard-assembled static origins in the brain or body, must be soft-assembled to reflect the temporary particulars of task contexts and the idiosyncratic states of individuals. This is because participants in cognitive and motor tasks produce idiosyncratic distributions of response times, differing in quality as well as quantity (Ashby *et al.* 1993, Balakrishnan and Ashby 1992, Holden *et al.* 2009, Luce 1986, Maddox *et al.* 1998). Can such task-specific soft-assembled mechanisms be demonstrated empirically?

One demonstration used a key-press task in which two measurements were taken: (1) the time between seeing a signal to respond and pressing the response key, and (2) the time between pressing the key and releasing it again, to get ready for the next signal (Kello *et al.* 2007). The interleaved trial series of key-press and key-release times were recorded for each participant, and each data series was subjected to a spectral analysis. As expected, spectral analyses revealed pink noise in each separate data series. The crucial finding, however, was that the two interleaved data series were not correlated with each other. That is to say, while each measured key-press time was long-range correlated with all other key-press time, and while each measured key-release time was correlated with all other key-release-time, key-press times were not correlated with key-release times – even though they followed each other immediately.

A lack of correlation between behavioral measurements is typically taken as evidence of separate and independent mechanisms, one deciding when to press a key and the other deciding when to release a key. Under the framework of soft-assembly, however, the mere fact that the two tasks differ in their constraints suffices to elicit independent coordinative structures. Even though the key-press movement and the key-release movement are interleaved in time, constraints entailed in pressing a key

vary independently from the constraints entailed in releasing the same key.

A subsequent key-press experiment further demonstrated that these are indeed independent coordinative structures (Experiment 2 in Kello *et al.* 2007). Again, key-press response times and key-release response times were collected, and each trial series was subjected to a spectral analysis. This time though the signals to press a key were alternated unsystematically across trials, producing uncertainty about which key to press. The uncertainty about which key to press produced spectral exponents in key-press times that were closer to white noise, reflecting over-random variation. But spectral exponents in key-release times were unaffected, retaining their pink noise pattern like before.

The unsystematic signals supplied unsystematic perturbations to the soft-assembly of key presses, resulting in the unsystematic whiter-noise series of key-press times. Yet there was no uncertainty about which key to release, resulting in a pink-noise series of key-release times, just like before. Soft assembly explicitly predicts these dissociations of temporary mechanisms, because performance is the coming into existence of a temporary performance device entrained to specific task demands. Even tasks that differ trivially, say in the uncertainty about which key to press, or say in the direction of the finger's motion, entrain distinct specialized devices that accommodate the trivial differences. Even the change in intentional stance upon being told "there will be no more shocks" changes the organization of the participant, to now exclude the "conditioned" psychogalvanic reflex. A mere change in context and participants' intentions creates a differently conditioned human being.

4. Weighing the Evidence

Evidence provided so far agrees with the idea that voluntary behaviors are soft assembled near critical states in which over-random tendencies are balanced with over-regular tendencies. The implied control parameters demonstrably predict the structure of variation in behavior. In this final section, we critically evaluate the general form of the control parameters that we have introduced and illustrate how contradictory evidence may refine this hypothesis.

Recall that the control parameter in (5) was defined as the ratio of over-random and over-regular tendencies in behavior. We equated the numerator of over-random tendencies with affordances: the opportunities for behavior within a task environment. And we equated the denominator of over-regular tendencies with effectivities: the capacities and capabilities of an actor to exploit opportunities for behavior. Put differently, the numerator reflects the available degrees of freedom (DOF), while the de-

nominator delimits controllable DOF. We can now subject these ideas to less favorable contrasts with evidence.

4.1 A Dilemma of Exogenous Control

In light of the evidence described earlier, the control parameter in (5) could be described more loosely as a ratio between task difficulty and participant skill:

$$\text{human performance variation} : \frac{\text{avail. DOF}}{\text{control. DOF}} \approx \frac{\text{task difficulty}}{\text{participant skill}} \quad (6)$$

As participant skill comes to match task difficulty, scaling exponents of coordination move toward pink noise. Likewise, the more difficult the task or the more novice the participant, the more scaling exponents of performance move away from pink noise (e.g., Correll 2008, Clayton and Frey 1997, Gilden 1997, Kello *et al.* 2007, Kiefer *et al.* 2009, Ward 2002).

However, some findings do not fit with this monotonic relation between task difficulty and the direction of change in scaling exponents. Consider the task of tapping to a metronome, for example. Tapping continuously to a metronome is intuitively an easier task than tapping to a remembered beat, after the metronome has been switched off. Relation (6) therefore predicts pinker noise when the metronome is on, compared to when the metronome is switched off. In fact, given that the beats of the metronome are so regular, one might predict over-regular browner noise.

Counter to the predictions, tapping from memory yielded scaling exponents close to pink noise, $\alpha \approx 1$, while tapping in synch with a metronome yielded exponents moves toward white noise, $\alpha \approx 0$ (Chen *et al.* 2001). Tapping in synch with the metronome, though a very easy task, resulted in over-random behavior, rather than in behavior that balances over-random and over-regular tendencies. To further contradict predictions, the same study reported pinker signals in a difficult syncopated-tapping condition (when tapping had to occur between the beats of the metronome), compared to the easy task of tapping on the beats of the metronome (see also Delignières *et al.* 2009).

Another contradictory outcome has been observed in repeated time-estimation with accuracy feedback. Accuracy feedback is a source of external constraints and exogenous control – like a metronome beat. It should therefore reduce the available DOF for performance and decrease the affordance numerator. In turn, this should amplify the over-regular tendencies of the denominator. Yet, while time-estimation without feedback yields an exponent close to pink noise, $\alpha \approx 1$, accuracy feedback produced an exponent closer to white noise, $\alpha \approx 0$ (Kuznetsov and Wallot 2009). Thus, despite exogenous support to reduce over-random tendencies, the structure of variability in these examples showed an increase in the over-random variation in performance.

A solution to these dilemmas of exogenous control would be to assume that external constraints affect not only affordances but also effectivities. The regular beat of a metronome, or constraints due to accuracy feedback, might reduce controllable DOF in the denominator, to a greater degree than they reduce available DOF in the numerator. This would yield a net increase in uncontrolled DOF, and thus a whiter behavioral signal. However, this solution is not only inelegant, but it is also contradicted by findings of endogenous control.

4.2 A Dilemma of Endogenous Control

An elite dancer trains her posture to hold her torso rigidly upright over her body's center of balance, which creates the appearance of gliding across the stage for example. Training to reliably constrain posture will increase embodied constraints to control DOF – it will increase effectivities in the denominator. The resulting increase in over-regular tendencies in the denominator should increase the dancers' scaling exponents in the direction of brown noise. But the opposite is the case: Observed scaling exponents of posture (measured by deviations around a center-of-pressure on a force plate) move in the direction of white noise, compared to ordinary adults or elite athletes who are not dancers (Schmit *et al.* 2005). In this example, external constraints stay the same. Training of posture yields an increase in internal constraints only, which reside in the denominator. And yet, the findings are neither predicted by the control parameter of (6), nor by the modified control parameter in which external control is added to both the numerator and the denominator.

Maybe postural variation is special, in that it has a kind of fail-safe character. After all, over-regular control of posture (and its associated brown-noise variation) would imply large sway and large deviations around the center of balance, decreasing the stability of upright standing and possibly inducing falling. Maybe pink-noise coordination is the outer limit of the scaling exponent in postural sway, forcing us to redefine the meaning of white noise in postural sway. But this suggestion does not fit with observed brown-noise variation in the postural sway of Parkinson's patients. Parkinson's patients, asked to stand balanced on a force plate, produce a brown-noise pattern of over-regular control, compared to healthy participants who produce pinker variations (Schmit *et al.* 2006). To stay upright and not fall down, Parkinson's patients apply over-rigid control, with large deviations around the center of pressure.

Taken together, the findings suggest that the control-parameter ratio of affordances and effectivities needs to be refined. While the affordance/effectivity ratio has sufficed to predict the direction of change in exponents in some examples of training and development, it appears to lack overall support in evidence, especially when it comes to predicting

the effect of endogenous control. Therefore, despite its success so far, we appear to have abducted the wrong control parameter, with potential consequences for our theory of intentionality and voluntary control.

4.3 An Elegant Solution

In addressing the dilemma of endogenous control, the new solution must remain consistent with our root assumptions about intentions: They include the notion that intentions affect behavior as constraints and not causes; and they include the notion that intentions are temporary dynamical structures, soft assembled to contribute constraints to control parameters. The solution to endogenous control must also incorporate the findings of exogenous control (i.e., entrainment to a metronome and accuracy feedback). How can the control-parameter ratio be modified to accomplish this?

Notice that all of the contradictory findings, whether of endogenous or exogenous control, are cases in which enhanced sources of constraint reduce voluntary control as they shift scaling exponents toward white noise. For example, voluntary control was reduced in the case of entrainment to a metronome – more so than having to sustain a beat from memory, or tapping between the beats of a metronome. And voluntary control was reduced in the case of accuracy feedback provided from one trial to the next – more so than performing without feedback. Finally, voluntary control was reduced in the posture of an elite dancer, over-trained to sustain a rigid torso position – more so than in elite athletes with no posture training. The common denominator therefore appears to be the degree to which behavior is under moment-to-moment voluntary control.

Given the prominent role of voluntary control in predicting changes in scaling relations, the denominator of a more appropriate control parameter might contain voluntary control exclusively. All other sources of constraint, whether affordances (including the metronome and accuracy feedback, for example) or effectivities (such as over-trained posture), might be better represented together in the numerator. Together, they constitute all the constraints that pertain to involuntary control, the sources of opportunity and capability in behavior that are not under voluntary control. As before, however, the numerator still delimits the available DOF that remain after sources of involuntary control have been taken into account. Accordingly, the new control parameter of human performance is:

$$\text{human performance variation} : \frac{\text{invol. control}}{\text{vol. control}} \approx \frac{\text{uncontrol. DOF}}{\text{control. DOF}} \quad (7)$$

This refined parameter explains all of the scaling-exponent findings known to us. First, it anticipates change to an over-random pattern of gait when walking to a metronome (Hausdorff *et al.* 1996). Stepping to

a metronome reduces voluntary control for step frequency, yielding an exponent closer to white noise, just as tapping to a metronome yielded whiter noise. Step length is unaffected, however (Terrier *et al.* 2005). The reduction in voluntary control is specific to the frequency of gait, because the metronome constrains only the soft-assembly of frequency, impacting step length indirectly. A different task manipulation would be needed to entrain step length as well (see also Jordan and Newell 2008).

Second, relation (7) is consistent with findings that over-random variation decreases with increasing voluntary control. Take, for example, the palsy tremor in Parkinson's patients: a grossly amplified form of the over-random tremor that results from ordinary relaxation of voluntary control (cf. Woodworth and Schlosberg 1954). In the early stages of Parkinson's disease, an intention to move eliminates the palsy; and voluntary control will continue to dampen the palsy, at least, even into later stages. Another example comes from adult gait. Walking at speeds slightly faster or slower than the preferred pace produces pinker noise than walking at the preferred speed (Hausdorff *et al.* 1996). This holds up for a wide range of deviations from the preferred pace, in both walking and running, and across a variety of measurements (e.g., stride interval, stride length, step interval, step length; Jordan *et al.* 2007a,b). Preferred pace for locomotion is a pace that requires least effort, and therefore less effortful voluntary control.

Third, the new control parameter (7) is consistent with observations of brown-noise scaling exponents. As we mentioned already, they are found in the postural sway of Parkinson's sufferers, and they are found in the gaits of young children. Scaling exponents close to brown noise also appear in the variation of repeated cognitive performances by sufferers of attention deficit and hyperactive disorder (Gilden and Hancock 2007). In each case, exponents close to brown noise reveal over-regular tendencies suggestive of exaggerated willful control.

Finally, the refined parameter (7) shows close analogies with the inertia/friction parameter (4) for the self-organized criticality of avalanche behavior. We end this essay by expanding this analogy as it relates to voluntary control. Note that inertia and friction differ in interesting ways. While inertia is a primary elementary characteristic of physical objects and cannot be reduced to more fundamental characteristics, friction emerges from the interaction of more elementary characteristics (i.e., the interactions among molecules). Analogously, the numerator of the new control parameter (involuntary control in affordances and effectivities) refers to irreducible units of behavior. And the denominator of the new control parameter (voluntary control as volition) may emerge from more elementary interactions.

Expanding on these ideas, the sources of involuntary control can be combined in irreducible cycles of perception-action (Gibson 1979, Järvi-

lehto 1998, Turvey 2004). Consistent with this move, the lack of linear interactions among cognitive factors implies that perception-action cycles cannot be reduced further to active cognitive components within a trial (Van Orden *et al.* 2003). In turn, the irreducible perception-action cycles constitute the elementary characteristics that sustain volition. Volition is sustained across iterative cycles of perception-action, as it constrains perception and action in the cycles that sustain it – the ultimate strange loop relation of voluntary control.

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