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Cognitive Workload and Fatigue Dynamics in a Chaotic Forecasting Task

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Abstract: *Many real-world tasks require people to forecast chaotic events in order to take adaptive action. This ability is considered rare, and less understood than other cognitive processes. The present study examined how the performance dynamics in a chaotic forecasting task would be affected by stressors such as cognitive workload and fatigue using two cusp catastrophe models. Participants were 147 undergraduates who were shown graphs and brief chaotic number series for which they needed to forecast the next four values. Performance data were complemented by variables known to represent cognitive elasticity versus rigidity, compensatory abilities for fatigue, and NASA TLX ratings of subjective workload.* R^2 *for the workload cusp was .56, which compared favorably to the next best linear alternative model (.12); it contained six bifurcation variables and three measures of workload (asymmetry).* R^2 *for the fatigue cusp was .54, which also compared favorably to the next best linear alternative (.07); it contained one bifurcation variable and two compensatory abilities. The role of field independence as an elasticity variable in the workload model and as a compensatory ability in fatigue was particularly noteworthy. Several elasticity-rigidity variables have now been identified over a series of studies. They appear to be operating in unison to produce a bifurcation effect, and different variables become salient depending on the task. Future research should consider how the ability to forecast chaos and its susceptibility to workload and fatigue carry over to dynamical decisions made while managing a complex system.*

Key Words: cognitive workload, fatigue, cusp catastrophe, forecasting, chaos, extrapolation

INTRODUCTION

There are many types of work in which chaotic patterns of events are the norm. The ability to forecast chaotic events is an important factor in maintaining a balance between a system's stability and its optimum level of variability to adapt to seemingly-random challenges from the environment. Examples could include

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managing a supply chain (Azghandi, Griffin, & Jalali, 2018; Sterman, 1988; Vera, Olivares-Benitez, Rivera, Lόpez-Campos, & Miranda, 2018), a manufacturing process (Guastello, 2002), medical surgery (Gonzales-Cava, Reboso, Casteleiro-Roca, Calvo-Rolle, & Pérez, 2018), fisheries (Hommes & Rosser, 2001) or a swarm of robots (Trianni, 2008). Therefore, effective control in-the-moment often requires the ability to anticipate a trajectory of events over time (Guastello, 2002). Although numerical prediction of chaotic numbers and events can be challenging enough (Guastello & Gregson, 2011), real-world demands often prevent stopping the system to build a data base and conduct numerous statistical analyses. This constraint is especially salient in emergency situations when volatile events transpire over very short amounts of time (Baber & McMaster, 2016). Forecasts and decisions must then be made on a heuristic basis. Some people are adept at making such forecasts, but many others are not, and the ability to do so is thought to be relatively rare (Guastello, 2002).

Cognitive processes for understanding probabilities and implementing them in forecasts have been steadily researched since at least the 1980s. The same is true for the ability to identify and extrapolate a numerical trend (DeLosh, Busemeyer, & McDaniel, 1997; Ritz, Nassar, Frank, & Shenhav, 2018; Schulz, Tennenbaum, Duvenaud, Speekenbrink, & Gershman, 2017). The limitations of that work are, however, that (a) the extrapolation experiments have been confined to simpler non-chaotic trends, and (b) chaos is a deterministic process and not a stochastic process. Comprehensive studies of the forecasting process in the context of weather (Hoffman, LaDue, Mogil, Roebber, & Trafton, 2017) and political-economic events (Mellers et al., 2015; Poore, Forlings, Miller, Regan, & Irvine, 2014) have only started to appear.

Meanwhile, a parallel line of research on the ability to forecast chaotic events specifically seems to have paused with Heath (2002), but has recently resumed (Guastello, Futch et al., 2019; Heath, 2019). The present study is a continuation of that effort to understand the cognitive processes. One direction for doing so is to observe what happens to performance under stress conditions, such as the changes in mental workload and fatigue that manifest with extended time on task. As with other cognitive operations studied so far, the effects of workload and fatigue can be substantial, which led to the development of the cusp catastrophe models for workload and fatigue.

A second objective of this study was to examine how workload and fatigue dynamics for forecasting tasks compare with the dynamics of other cognitive operations. As such it is part of an ongoing series of experiments was to establish the generalizability of the models across different types of cognitive work and to explore further the situational and psychological variables associated with the control parameters in each of the models. The next sections of this article explain what is currently known about the forecasting of chaotic events, the two cusp models, and an experiment that investigated relevant control variables.

FORECASTING CHAOTIC EVENTS

Chaotic Numbers

The available information about this ability is based on two research strategies: the prediction of chaotic numbers and dynamic decisions. In the former experimental paradigm, the research participants were presented with a brief series of numbers that were generated from the formula for either the logistic map or Hénon attractor. The participants were then asked to predict the next one to four numbers in the series. The correlation between participants' responses and the actual values comprised the measure of accuracy. Individuals' accuracies ranged from .45 to .99 in one study (Neuringer & Voss, 1993), and from -.31 to .76 in another (Metzger & Thiesz, 1996), both with sample sizes of less than ten adults. Ward and West (1998) reported an accuracy range similar to that of Neuringer and Voss. A fourth study (N = 40; Smithson, 1997) produced a mean accuracy of .71, which was substantially better than the participants' ability to forecast random numbers (mean r = .18).

A fifth study (Heath, 2002) examined accuracy of prediction up to four steps ahead. Unlike the experiments by Neuringer and Voss (1993) or Ward and West (1998), the participants were not given feedback as a means of examining ability rather than capacity to learn specific attractors. Accuracy results were best for forecasting one step ahead, roughly tied but lower for two and three steps ahead, and generally poor for predicting four steps ahead. The forecasting of chaotic number series was much better overall compared to the forecast of the randomized series. Based on the data shown in the graphs (Heath, 2002; p. 50-51), mean correlations for accuracy ranged from -.10 to +.15 (N = 12), depending on how many steps ahead the participants were forecasting.

Dynamic Decisions

A dynamic decision set is one in which the responses made by an agent impact the situation and decision options in the next situation presentation (Brehmer, 1987, 2005; Osman, 2010). There were two types of experiments with dynamical decisions in which the forecasting of chaotic trends was an object of the analysis. One involved supply and demand trends in a supply chain, and the second involved predicting economic dynamics when a known theory was in operation.

The supply chain problem was represented as a computer simulation of a beer distribution enterprise (Sterman, 1988, 1989, 1994). The dynamics of supply and demand, under conditions of perturbation were known to be chaotic in nature (Sterman, 1988), but not necessarily conforming to the deterministic dynamics of any of the specific attractors that have been studied in the mathematical literature. The participants were 49 individuals who were graduate students in business administration or professional economists. Their role was to maintain a supply of beer, place sufficient orders with the breweries and deliver proper quantities to final sales outlets. Participants needed to maintain an equilibrium between the two extremes of running out of beer and overflowing the warehouse. After a series of exposures that were intended to establish a (psychological) equilibrium in inventory, the program produced perturbations in supply and demand and induced an occasional chaotic regime in inventory levels. The net effect was that only six (12%) of the participants were successful in maintaining inventory between the two boundary conditions. Common errors were over-focus on the demand dynamics while overlooking the supply dynamics, misinterpretation of time lags in the supply, and misinterpretation of the consequences of their choices.

Real-world economic dynamics involve processes with multiple parameters. The forecasting errors can be characterized as distorted parameter settings, which agents mentally update, often incorrectly, to minimize their errors. Economic agents are not always able to distinguish a stochastic process from a chaotic process, however, and two types of outcomes could result (Hommes & Rosser, 2001; Sorger, 1998). The *perfect forecasting equilibrium* occurs when agents are aware of the actual dynamics, and their decisions produce smooth dynamics and a steady state. The *consistent expectations equilibrium* occurs when agents assume a stochastic process, and their decisions produce chaotic results as they try to compensate and adjust their decisions when using an autoregressive forecast strategy. Sorger (1998) examined these assumptions and results using a household finance model in which households adjust their spending in the face of income, taxes, expected interest rates, and need for savings. He used a mathematical analysis rather than observations of human subjects. Hommes and Rosser (2001) performed a similar type of mathematical analysis of fishing harvests, which have particularly complicated dynamics in the face of fluctuating market prices and competition with other agents for open access supplies of fish. They found that the stochastic thinkers make choices and act in a manner that unintentionally produces chaos in the economic environment, leading to a self-fulfilling prophesy that the process is chaotic, even though the dynamic system could have been a relatively tame if it were handled differently.

The plausible explanations for the self-fulfilling prophesy of chaos are both mathematical and psychological. Theiler and Eubank (1993) showed that the computational technique of removing autocorrelation from a time series before analyzing the residual for a fractal dimension or a Lyapunov exponent results in a higher level of dimension or turbulence compared to the original time series. Thus decisions that assume a stochastic process that would be optimized by an autocorrelation would produce the same impact on the system. The psychological aspect of the decision, as in the case of other dysfunctional beliefs, is traceable to a lack of information about the system (that it is a deterministic process) and bounded rationality for processing the available time series data (Stamovlasis & Vaiopoulou, 2017).

Chaotic Attractors and Heuristics

The most recent contribution to the forecasting of chaotic events (Guastello, Futch et al., 2019), from which the present study followed, examined conditions under which forecasting chaos could be better or worse, and what heuristics could have been used. The first result was that the type of attractor matters greatly when forecasting chaotic numbers. Contrary to the "folk hypothesis" that simpler attractors would be easier to forecast than computationally complex ones, simpler attractors (logistic map and Hénon) were more difficult to forecast than complex attractors (Sprott-B and Lorenz). This finding was partially attributed to the fact that the largest difference in between-attractor performance was whether the attractor was more persistent vs. anti-persistent (in the sense of the Hurst exponent), although there was some additional performance variance favoring better accuracy in the more complex attractors within the persistent and anti-persistent pairs. This additional difference in accuracy was not readily explained. Samples from the four attractors that were used in that study and in the present one appear in Fig. 1.

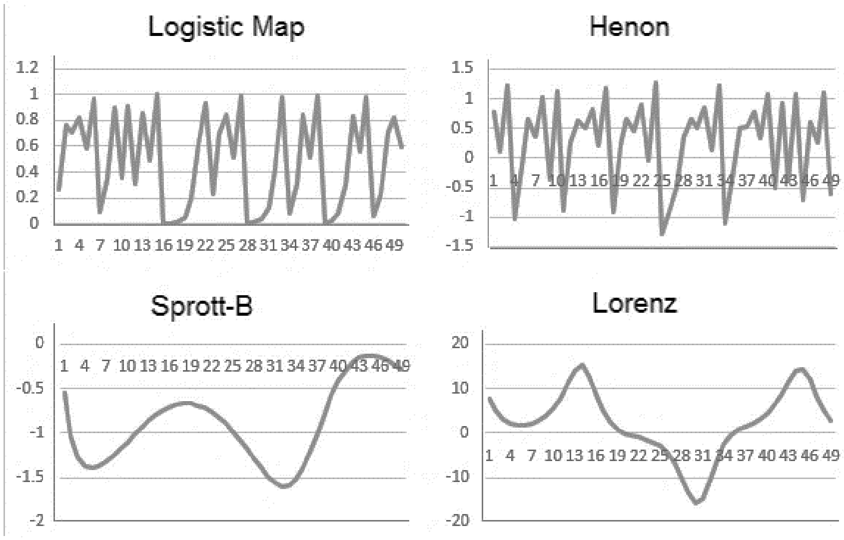


Fig. 1. Sample time series of the logistic map, Hénon, Sprott-B, and Lorenz attractors, 50 iterations each.

Participants in that study made four forecasts into the future for each stimulus. Accuracy declined over the first three forecasts as expected, but there was a rebound effect on the fourth forecast for reasons that are still unknown.

The same study also examined possible heuristics used by the participants for forecasting chaotic numbers. Prior research (Smithson, 1997) eliminated two possibilities such as gambler's fallacy or under-estimating dispersion. Metzger and Theisz (1996) suggested that participants in Neuringer and Voss (1993) could have been learning seed-feedback pairs instead of actual chaos, but that possibility was minimized in Guastello, Futch et al. (2019) because no feedback regarding correct forecasts was given to the participants. Instead, forecasts were compared for accuracy with regard to real numbers, 3-point moving averages, and 8-point moving averages. The 3-point moving average was more dominant for Sprott-B and Lorenz attractors, 8-point moving averages were dominant for the logistic map, and actual numbers were dominant for the Hénon attractor. When participants of low, medium, and high skill (with respect to actual numbers) were compared, results showed that low-skill participants relied on 8-point moving averages most often, medium-skill participants relied on 3-point moving averages most often, and high-skill participants match actual numbers more closely than either type of moving average.

CUSP CATASTROPHE MODELS FOR WORKLOAD AND FATIGUE

Cognitive work performance can fluctuate substantially over time as a result of changing levels of workload and fatigue (Ackerman, 2011; Guastello, 2014, 2016; Hancock & Desmond, 2001; Hancock & Warm, 1989; Matthews, Desmond, Neubaurer, & Hancock, 2012; Wickens & Tsang, 2015). Cognitive workload is the amount of information of a given type that a person can process in a given way in a fixed amount of time. Fatigue is the loss of work capacity as a function of the amount of time spent on a particular task; this source of fatigue is sometimes confounded with the type of fatigue that builds with time since the person last slept. There are also cross-over effects between workload and fatigue effects whereby the individual assumes less workload in an effort to combat fatigue while still maintaining performance quality. A person might also switch to a task requiring higher cognitive workload in an effort to counteract boredom and the performance deficits associated with too much time spent on an under-stimulating task (Hancock, 2007). Extended time on task can also have a positive effect on performance in the form of momentum, practice, or automaticity of the cognitive processes. The twin dynamics of workload and fatigue have been untangled successfully from time series data for work performance by modeling the performance dynamics as two cusp catastrophe models, one for workload and one for fatigue (Guastello, 2014, 2016; Guastello, Reiter et al., 2015; Guastello, Correro, & Marra, 2019; Guastello, Reiter, & Malon, 2016).

Workload

The cusp catastrophe model for cognitive workload invokes the concept of Euler buckling (Guastello, 1985; Zeeman, 1977). A piece of material that is subjected to sufficient amounts of stress in the form of repeated stretching will show deformity or strain. Rigid materials break; flexible materials rebound. Equation 1 defines the cusp catastrophe response surface that is shown in Fig. 2. For the workload applications, performance or response time would be the dependent variable, y:

$$dy/dt = y^3 - by - a \tag{1}$$

The amount of vertical weight is the asymmetry (*a*) parameter. The modulus of elasticity of the material is the bifurcation factor (*b*), with low elasticity located at the high end of the bifurcation axis that corresponds to the unfolded side of the response surface.

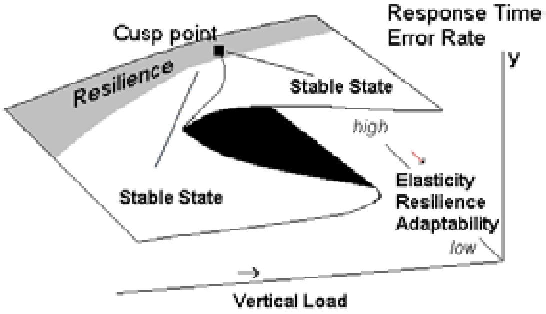


Fig. 2. Workload model.

Effects of Workload

The situational sources of workload would be analogous to the weight placed on the beam. Workload levels would also be related to the difficulty of a task, which is relative to a person's level of ability or skill. Task difficulty would be observed as the amount of cognitive work that a person could process in a fixed amount of time (Kantowitz, 1985). The effects of cognitive workload have been studied as changes in performance, subjective workload levels, and physiological indicators (Wickens & Tsang, 2015). The research with the cusp model is focused on performance as the dependent measure.

Differences in workload that arise from various task conditions are not always apparent in task performance data because individuals can employ coping strategies that buffer high and low workload levels (Hancock & Warm, 1989). As a result, subjective ratings of workload, such as the NASA Task Load Index (TLX; Hart & Staveland, 1988), have been valuable tools for research and system design evaluation. The TLX rating constructs are mental demands, physical demands, temporal demands, performance demands, effort required, and frustration.

Some subjective ratings of workload also play a role in the bifurcation process, while other ratings are more similar to the weight placed on the beam, as explained further on in this section. Although the TLX is responsive to differences in workload (Dey & Mann, 2010; Hart, 2008; Warm, Dember, & Hancock, 1996; Wierville & Eggemeier, 1993), additional variance in ratings has been traced to individual differences in personality or cognitive abilities (Guastello, Marra, Correro, Michels, & Schimmel, 2017; Guastello, Shircel, Malon, & Timm, 2015; Oron-Gilad, Szalma, Stafford, & Hancock, 2008).

Other recent work has drawn connections between subjective ratings and physiological events. Higher TLX ratings have been associated with higher levels of variability autonomic arousal, as measured by the Lyapunov exponent (Guastello, Marra et al., 2016). The TLX constructs have been extended to analogous ratings for group-level workload (GWL; Helton, Funke, & Knott, 2014; Sellers, Helton, Näswall, Funke, & Knott, 2014), and shown to be reflected in both team-level performance and the level of autonomic synchronization within a work group (Guastello, Correro, Marra & Peressini, 2019; Guastello, Mirabito, & Peressini, 2020).

Elasticity-Rigidity Constructs

Psychological analogues to elasticity-rigidity that have been discovered to date fall into several categories: affective constructs, coping constructs, fluid intelligence variables, and conscientiousness constructs. An early psychological question was whether the limits to human cognitive channel capacity are fixed and rigid, or flexible and variable. A review by Kantowitz (1985) showed that there was empirical support for both perspectives. Later research investigated several sources of flexibility associated with coping strategies (Hancock & Warm, 1989); minimizing conflict on visual, auditory, or other input channels and psychomotor, verbal, or other response modes (Wickens, 2002, 2008); the organization of brain resources that support working memory (Drag & Bieliauskas, 2010; Oberauer & Kliegl, 2006; Reuter-Lorenz & Cappell, 2008; Schneider-Garces et al., 2009); and the demand on the executive function arising from task switching (Remington & Loft, 2015).

Affective Constructs. Trait anxiety can slow response time, interfere with lucid decision making (Cox-Fuenzalida, Swickert, & Hittner, 2004) and increase frustration with a task (Rose, Murphy, Byard, & Nikzad, 2002), but it can also focus attention on threatening aspects of a situation that others might miss (Ein-Dor, Mikulincer, Doron, & Shaver, 2010; Guastello & Lynn, 2014). Participants in a vigilance task who scored higher on anxiety gave higher ratings of TLX temporal demands than participants with lower anxiety scores (Guastello, Shircel et al., 2015). In an emergency response experiment, anxiety was correlated with TLX frustration, and GWL communication demand, team support and team dissatisfaction (Guastello et al., 2017).

Emotional intelligence (EI) facilitates the understanding of one’s own emotions, the emotional messages from other people, and the forming appropriate actions in response to emotions (Mayer & Salovey, 1997). Low EI denotes rigidity in the form of indifference or unresponsiveness, which could be a buffer against low to moderate load stress. When stress becomes too high, however, the behavioral outcomes buckle and snap if the individual is not aware of his or her own emotional level or those of other people (Thompson, 2010). Participants in a vigilance task scored higher on EI rated TLX temporal demands, effort, and frustration than participants with lower EI scores if they were working alone (Guastello, Shircel et al., 2015). If they worked with another participant, however, EI had the opposite effect on the same three ratings. In an emergency response experiment, EI was correlated with TLX mental demand and GWL team efficacy (Guastello et al., 2017).

Coping Constructs. The construct of *coping flexibility* is centered on emotional adjustments in the sense of long-term life issues (Kato, 2012). People who have a broader repertoire of coping strategies are likely to be more resilient to stress and emotional hardship. Another construct of coping is oriented towards cognitive strategies such as planning, monitoring, decisiveness, and inflexible responses to changing work situations (Cantwell, & Moore, 1996). These aspects of coping all denote contributions from the executive function of working memory. The cognitive coping strategies functioned as bifurcation variables in an N-back task (Guastello, Reiter et al., 2015), and a vigilance task (Guastello, Reiter et al., 2016). Coping flexibility has not yet appeared as a variable directly related to bifurcation in a workload cusp, although it was correlated with GWL ratings of coordination demands in an emergency response simulation (Guastello et al., 2017).

Fluid Intelligence Constructs. The capacity and functionality of working memory are the limiting ingredients in workload tolerance, and they are also part of the broader mental operations of fluid intelligence (Kane & Engle, 2002). Field independence is a cognitive style that separates perceptions of a figure from a background. Although it appears to be a spatial perception phenomenon, it is actually a broader skill by which people can extract meaningful information from background distractions (Cantwell, 1986). People with high field independence are likely to use more of their working memory capacity according to Pascual-Leone (1970). As such, field independence worked well as a bifurcation variable in studies of problem solving in chemistry (Stamovlasis & Tsaparlis, 2012), financial decision making (Guastello, 2016), and a vigilance task (Guastello, Marra et al., 2016).

Anagrams are one of several cognitive measures of creativity and are a part of fluid intelligence (Hakstian & Cattell, 1976, 1978). The construct played a small but consistent role in performance changes in cognitive workload or fatigue in a financial decision making task (Guastello, 2016).

Algebra flexibility is based on the idea that, in addition to learning the rules of algebra, students should be flexible in their use of algebraic principles to solve problems (Rittle-Johnson, Star, & Durkin, 2009). It was an important bifurcation variable in the workload model for N-back tasks (Guastello, Reiter et al., 2015). In principal components analyses with other elasticity-rigidity variables, algebra flexibility formed a component with field independence and anagrams; the component was identified as fluid intelligence (Guastello & Marra, 2018; Guastello, Correro et al., 2019).

Conscientiousness Constructs. Conscientiousness is a personality trait that predisposes a person to pay close attention to details, rules, task orientation, and a broader proclivity to focus attention. It thus implies a type of rigidity (MacLean & Arnell, 2010). Conscientiousness has been measured as a broad trait

Table 1. Summary of Results for Cusp Models for Cognitive Workload.

R^2 *Cusp*	R^2 *Linear*	*Bifurcation*	*Asymmetry*
Episodic Memory[a]			
.44	.32	[Unknown]	Peak load
Pictorial Memory[b]			
.53	.13	Anxiety	Incentive condition
Multi-tasking [c]			
.49	.35	*Unknown*	Task difficulty
.75	.18	Self-determined task order	[Unknown]
Vigilance Dual Task, Night Scenario[d]			
.33	.29	TLX frustration	Load increase
Financial Decisions, Optimizing, All Time Periods Together and Separately[e]			
.39	.36	Conscientiousness, Impulsivity	Work speed
.46	.32	[Various]	[Various]
Financial Decisions, Risk Taking, All Time Periods Together and Separately[e]			
.25	.25	Work ethic	Load condition
.28	.23	[Various]	[Various]
N-Back[f]			
.98	.62	Algebra flexibility, TLX performance, TLX effort, TLX frustration, Inflexibility, Monitoring	2- to 3-back, TLX temporal demand
Vigilance dual task, day scenario, miss rates, false alarms[g]			
.39	.11	Field dependence, Anxiety, Irresolute	Workload direction
.44	.04	Anxiety, Inflexibility, Irresolute	[Unknown]
Emergency Response Simulation, Monsters Killed, Game Points[h]			
.51	.30	TLX performance, TLX effort, TLX frustration	TLX mental, TLX physical, TLX temporal
.00	.00	[None]	[None]
Unweighted Average			
.45	.25		

Sources: [a]Guastello, Boeh, Shumaker, et al., 2012; [b]Guastello, Boeh, Schimmels, et al., 2012. [c]Guastello et al., 2013. [d]Guastello et al., 2014. [e]Guastello 2016, [f]Guastello, Reiter et al., 2015. [g]Guastello, Reiter et al., 2016; [h]Guastello, Correro et al., 2019.

in the sense of the five factor model of personality (Costa & McCrae, 1992) in some of the workload experiments. In others, it was broken down into two narrower traits. One of the narrower traits measured conscientiousness in the sense of Factor G on the Sixteen Personality Factors Questionnaire (16PF; Cattell, Cattell, & Cattell, 1994; Conn & Rieke, 1994), which is a "primary factor" and defined as rule-conscious and dutiful, as opposed to expedient and noncomforming (H. Cattell, 1994). The other primary factor measured impulsivity versus self-control, which would be similar to Factor Q3 on the 16PF. In principle, it is possible for people to be rigid in the sense of Factor G and flexible in the sense of Q3 (Guastello, 2016).

Work ethic (Buchholz, 1977) was also considered as an elasticity-rigidity variable in the conscientiousness category because of an apparent conceptual similarity between the two constructs. Some counterintuitive correlations with other variables led to some concern that the questions or the construct of work ethic are no longer interpreted as they were originally intended (Guastello, Shircel et al., 2015).

Summary of Workload Models

Table 1 summarizes the workload models tested to date. The average R^2 associated with the cusp models was .45, compared to .25 for the next best linear models. The nonlinear features of the model thus represent more than one-third of the variance accounted for by the cusp model, which is a substantial improvement over conventional approaches to workload-performance assessment.

Ideally the R^2 for the cusp should meet or exceed the R^2 for the next best linear model. The cusp and bifurcation terms should be statistically significant components of the cusp model because those two terms compose the manifold that characterize the cusp response surface. There were some cases in Table 1 that were disappointing in that regard. These were retained in Table 1 because they were paired with fatigue models that met the usual criteria more clearly, or there were other dependent measures for workload in the same study that did so. As a general rule, one can expect some task and experimental manipulations to produce more of a workload effect than a fatigue effect or vice versa. The mean difference in R^2 coefficients was, nonetheless, .196 (95% CI: [.189, .202]).

The control variables that were identified in those studies are also listed in Table 1. Note that not all of the elasticity-rigidity constructs had been identified in the earlier studies. Also, because of the experimental participants' time constraints, only variables that seemed to have the greatest construct validity were included in some of the later studies.

The newest study (Guastello, Correro et al., 2019) involved a group task with a team-level performance measure, and team averages for the hypothesized control variables in a cusp model for team workload and performance. The results showed that the TLX ratings were clearly important control variables, but the other elasticity-rigidity variables did not add any further explanation to the performance trends. There were numerous correlations between the other elasticity-rigidity variables and the TLX and GWL ratings, however, at both the individual level of analysis (Guastello et al., 2017) and at the group level (Guastello, Correro et al., 2019).

Fatigue

Fatigue is defined as the loss of work capacity over time for both cognitive and physical labor (Dodge, 1917; Guastello & McGee, 1987). Depletion of work capacity is typically observed as a work curve that plots performance over time. Performance drops sharply when fatigue sets in and is coupled with a higher level of variability. Not everyone experiences a decline as result of the same expenditures, however. Some show an increase in physical strength akin to “just getting warmed up,” while others show consistently higher or lower performance levels for the duration of the work period. The cusp response surface (Fig. 2) accounts for the full range of possible work curves. Work capacity is denoted by the two stable states.

Change in work capacity is implied by change in performance, but with the understanding that psychological disengagement, or a drop in motivation, contribute to performance decrements in addition to changes in any physiological aspects of capacity. The drop in motivation for the task is also symptomatic of physical fatigue (Balagué, Hristovski, Agegones, & Tenebaum, 2012) or mental fatigue (Hockey, 1997, 2011). At some point the individual wants to stop working or switch to a different task (Guastello, Gorin et al., 2012). Motivation can still persist if capacity declines, however; the individual might then rearrange degrees of freedom inherent in the performance of a particular task (Hong, 2010) or switch tasks if possible.

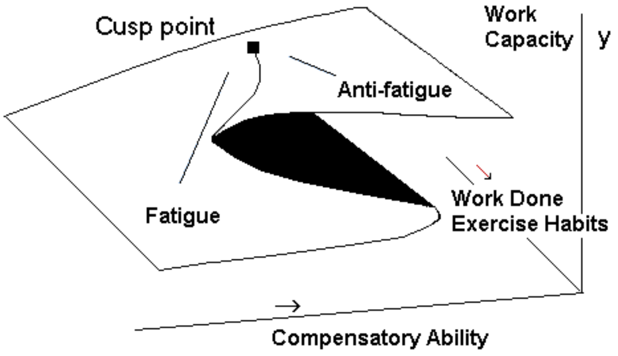


Fig 3. Fatigue model.

Work Accomplished

Several hours spent on a high workload task should produce more fatigue than the same amount of time on a lighter task. Thus some researchers have put,

Table 2. Summary of Results for Cusp Models for Fatigue.

R^2 Cusp	*R^2 Linear*	*Bifurcation*	*Asymmetry*
Episodic Memory[a]			
.53	.50	Intervening work done	Peak load
Episodic Memory, Memory Peak, Pictorial Memory[b]			
.30	.16	[Unknown]	[Unknown]
.39	.07	[Unknown]	[Unknown]
.52	.59	Intervening work done	Episodic memory peak
Multitasking: Accuracy Task, Memory Task, Perception Task[c]			
.47	.56	Fully alternating order, self-determined order	Spelling
.53	.33	Self-determined order, intervening work done	[Unknown]
.44	.20	Intervening work done	[Unknown]
Vigilance Dual Task, Night Scenario[d]			
.43	.17	Puzzle completed	Slow condition first
Financial Decisions, Optimizing, All Time Periods Together and Separately[e]			
.56	.24	Speed condition, Intervening work done	Field dependence
.24	.21	[Various]	[Various]
Financial Decisions, Risk Taking, All Time Periods Together Separately[e]			
.44	.27	Speed condition, Intervening work done	Field dependence, anagrams
.35	.19	[Various]	[Various]
N-Back [f]			
.47	.37	Intervening work done 2- to 3-back load shift	Algebra flexibility
Vigilance Dual Task, Day Scenario, Miss Rates, False Alarms[g]			
.26	.39	Puzzle completed, working in pairs, wearing GSR sensors	[Unknown]
.35	.02	working in pairs, wearing GSR sensors	[Unknown]
Emergency Response Simulation, Monsters Killed, Game Points[h]			
.49	.10	Group size, number of opponents, experimental session	Fluid intelligence
.59	.04	Group size, experimental session	Fluid intelligence
Unweighted Averages			
.40	.23		

Sources: [a]Guastello, Boeh, Shumaker, et al., 2012; [b]Guastello, Boeh, Schimmels, et al., 2012. [c]Guastello et al., 2013. [d]Guastello et al., 2014. [e]Guastello 2016, [f]Guastello, Reiter et al., 2015. [g]Guastello, Reiter et al., 2016; [h]Guastello, Correro et al., 2019.

some effort into determining where workload effects end and fatigue effects begin in particular practical situations such as railway operation (Fan & Smith, 2017; Smith & Smith, 2017). In the cusp model, the total quantity of work done between two measurement points would be the primary contributor to the bifurcation parameter: If the individual did not accomplish much in a fixed amount of time there would be comparably little positive or negative changes in work capacity (Guastello & McGee, 1987). The amount of work accomplished represents the end result of load demands, motivation issues, and flexibility with regard to the management of load. Experimental conditions that could affect workload could be considered as further contributions to individual differences in the amount of work done.

Compensatory Abilities

The asymmetry parameter would be a compensatory strength measure. For example, laborers displayed changes in arm strength as a result of about two hours of standard mill labor tasks, which primarily demanded arm strength. Leg strength, however, acted as a compensation factor for arm strength; those with greater leg strength experienced less fatigue in their arms (Guastello & McGee, 1987). A similar effect occurs in cognitive work, as the studies in Table 2 have shown. Experimental manipulations of the task such as changes in work speed can also affect fatigue (Guastello et al., 2014). The cognitive explanation for the compensatory effect is that the components of working memory are hierarchically organized (Conway, Kane, Bunting, Hambrick, & Engle, 2005; Oberauer & Kleigel, 2006) and part of fluid intelligence, as mentioned earlier. Fluid intelligence encompasses the processes that are involved in creative thinking, and could be responsible for adaptive responses. Fluid intelligence would thus be more proximally related to the fatigue process (demand on working memory) than crystallized intelligence.

Summary of Fatigue Models

Table 2 summarizes of the fatigue models tested to date. The average R^2 associated with the cusp models was .40, compared to .23 for the next best linear models. Once again the nonlinear features of the model represent more than one-third of the variance accounted for by the nonlinear properties of the cusp model. The mean difference in R^2 coefficients was, nonetheless, .174 (95% CI: [.095, .252]).

COGNITIVE WORKLOAD AND FATIGUE IN FORECASTING CHAOTIC NUMBERS

The present study examined cognitive workload and fatigue in the forecasting task with the cusp catastrophe models that were defined earlier. Following from Guastello, Futch et al. (2019), when presented with a new situation requiring forecasting, one does not know in advance which chaotic function is operating. Thus the stimuli for four types of attractors were presented without any announcement as to what function produced them or when the attractor switched during the experiment.

The contribution of workload (vertical load in Fig. 1) was assessed by comparing performance on attractors that are now known to have different levels of forecasting difficulty. The contributions of all six TLX ratings were assessed as asymmetry variables. Elasticity-rigidity was assessed by field independence, two measures of cognitive creativity, anxiety, conscientiousness (broad level), coping flexibility, and the four cognitive coping strategies.

The fatigue model evaluated performance changes between one of the four attractors and a final block of trials that was comprised on a randomized assortment of attractor structures. The number of stimuli between the two observation points and TLX mental demand ratings were used as measures of the amount of work performed. Three studies offered some suggestions for compensatory abilities. First, people in the movie industry that were particularly good at predicting whether new ideas would become successful had higher levels of cognitive creativity and personality traits associated with creative professions compared to others in the industry (Loye, 2000). Second, people from various careers who were particularly skilled at forecasting political-economic events scored higher than others on fluid intelligence, verbal ability, and openness to new information (Mellers et al., 2015). Guastello, Futch et al. (2019) found that, although there were also some connections among those variables to performance on forecasting chaotic numbers, field independence was the strongest correlate of performance. Thus field independence, general intelligence, and other cognitive creativity variables were tested as compensatory abilities in the fatigue model.

METHOD

Participants

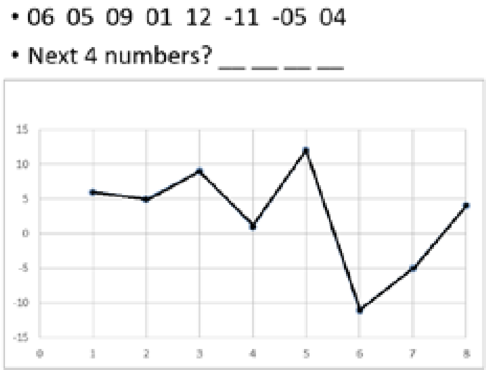
The participants were 147 undergraduates, aged 18-24 years, who were enrolled in psychology courses in a Midwestern U. S. University. There were 61 males and 84 females; two participants did not identify their gender. Participants were compensated with course credits.

Procedure

The experimental sessions accommodated small groups of participants according to the order and time at which they volunteered. Sessions were held in a standard classroom that was equipped with desks, chairs, a central computer and a projector screen. After signing the consent form, the participants completed three timed tests, an untimed survey, and the Sixteen Personality Factors Questionnaire (16PF), which was also untimed. The experimental task followed the testing. The TLX workload ratings followed the experimental task.

Experimental Task

The experimental stimuli consisted of 100 PowerPoint slides showing a sequence of eight chaotic number with a graph of those numbers. A sample slide appears in Fig. 4. Their task was to predict the next four numbers in the series using a paper and pencil form. The participants were given a practice item to start, but they were not given any specific context from which the numbers might have originated, nor were they told when the underlying chaotic attractor changed. Each slide was timed for 30 seconds. The participants were not given any feedback regarding the correct answers.



- 06 05 09 01 12 -11 -05 04
- Next 4 numbers? __ __ __ __

Fig. 4. Sample stimulus slide.

In one experimental condition, the sequence of stimuli was 20 examples each of the logistic map,

$$x_2 = cx_1(1 - x_1) \quad (2)$$

Hénon,

$$x_2 = 1 - ax_1^2 + y_1;\ y_2 = bx_1 \quad (3)$$

Sprott-B,

$$dy/dx = yz;\ dy/dt = x - y;\ dz/dt = 1 - xy \quad (4)$$

and Lorenz

$$dx/dt = a(y - z);\ dy/dt = -xz + rx - y;\ dz/dt = xy - bz \quad (5)$$

attractors, followed by another set of 20 stimuli drawn randomly from the four attractor types. In a second experimental condition the sequence was reversed: 20 each of Lorenz, Sprott-B, Hénon, and logistic map, again followed by a set of 20 stimuli from randomly chosen attractors. The random set was included in the fatigue analysis, but not in the workload analysis.

The logistic map series was generated with Eq. 2, a starting value of x = 0.26, and the control parameter = 4.0. The other three attractor series were drawn from a library of data file available with the *Chaos Data Analyzer* (Sprott & Rowlands, 1995). The numbers from the series were multiplied by 100 and trimmed to a maximum of three digits to eliminate the use of decimal points. Negative signs were retained. The properties of the data contained in the stimuli are given in Table 3. The participants' accuracy levels are summarized in Table 4.

Table 3. Descriptive Statistics for Properties of the Attractor Time Series Used to Prepare Stimuli.

Recoded Series	*Logistic*	*Hénon*	*Sprott-B*	*Lorenz*
Mean	47.60	2.86	-60.64	12.24
SD	35.96	7.13	102.45	75.79
Minimum	0	-13.00	-289.00	-159.00
Maximum	100.00	13.00	134.00	163.00
N	84	84	84	84

Table 4. Descriptive Statistics for Forecasting Accuracy for Four Attractors.

Attractor	*Mean*	*SD*	*Min.*	*95% CI-Lower*	*95% CI-Upper*	*Max.*
Logistic	0.00	0.13	-0.32	-0.02	0.02	0.65
Hénon	0.13	0.17	-0.44	0.10	0.16	0.67
Sprott	0.56	0.25	-0.61	0.52	0.60	0.98
Lorenz	0.65	0.27	-0.33	0.61	0.69	0.96
Random	0.56	0.32	-0.29	0.51	0.61	0.89

Measurements

Field independence. The Group Embedded Figures Test (GEFT; Witkin et al., 2002) presents a simple geometric form and a complex geometric form. The participants were instructed to locate and trace the simple form that was embedded in the complex form. The GEFT consists of a 2-min timed section of practice items that are not scored and two 5-min timed groups of 12 items that are scored. The split-half reliability values of the GEFT are .82 based on 177 adults and 0.85 based on 150 college students (Witkin et al., 2002). High scores indicate field independence.

Anagrams. The mixed anagram test was developed in our lab (Guastello, 2016). There were 15 items; each consisted of a five-letter word that was scrambled with five random digits mixed in. The random digits were introduced to place additional demand on working memory in studies of cognitive workload and fatigue. The participant was instructed to isolate the letters and rearrange them into a word. The vocabulary words for the anagrams were picked from words appearing on a test of commonly misspelled words used in previous experiments of cognitive fatigue. The anagram test was delivered in paper-and-pencil format. After giving the instructions and presenting a sample item, the participants were given 7.5 min to complete the 15 items. The alpha reliability for this test was .79 based on a laboratory sample of 299 research participants similar to the present sample (Guastello, 2016).

What If? What If (Guastello, 1994), which is a measure of one type of divergent thinking capability. What If consisted of five implausible scenarios to which the respondents gave suggestions about what would happen if the initial premise were true. An example item: “What would happen if pigs suddenly developed the ability to talk?” Although the initial cues tended to evoke humorous responses, the objective of the measurement was to assess how well the respondent could think through a complex situation with social implications. The score on What If was the number of suggestions given that were not redundant or illogically connected to the premise. The test construct was essentially the same as that of the *Consequences* test (Christensen et al., 1958; Guilford & Guilford, 1980), but with simpler scoring procedure. The inter-rater reliability of What If was .97 (N = 412; Guastello, Guastello, & Hanson, 2004). What If was also found to be significantly correlated with scores on other divergent thinking measures for ideational fluency (semipartial r = .37), originality (r_{sp} = .25, semantic fluency (r_{sp} = .25; Guastello et al., 2004).

Coping. The untimed survey contained measures of coping flexibility and self-regulatory control. Coping flexibility was measured by a 10-item questionnaire (Kato, 2012). An example item: “When a stressful situation has not improved, I try to think of other ways to cope with it.” Item responses used a 1-5 scale such that 1 = “never true of you,” and 5 = “nearly always true of you.” Kato reported alpha reliabilities ranging from .73 to .92 for different samples of adults. Alpha reliability based on the present sample was .72.

Self-regulatory control was measured by the Strategic Flexibility Questionnaire (Cantwell & Moore, 1996), which produced four scales – Monitoring (3 items, a = .66), Planning (4 items, a = .51), Inflexibility (7 items, a = .85), and Irresolute (7 items, a = .78). Planning and Monitoring items were part of an Adaptive scale in the original; Cantwell and Moore reported alpha reliabilities ranging from .79 to .87 for the three scales across different samples. Example item for Monitoring: “I believe that every problem has a particular way of being completed, and I adjust my methods of study when necessary” (p. 506). Example item for Planning: “Before starting work on a particular problem I like to play with a number of possible ways of attacking the problem” (p. 507). Example item for Inflexibility: “I rarely change the way I study, regardless of particular topic requirements” (p. 508). Example item for Irresolute: “I find that I’m easily distracted from my line of thought as I am working, and this often makes my work disjointed and uneven” (p. 509).

General Intelligence. One of the 16 primary personality factors on the 16PF (Cattell et al., 1994), Factor B, is actually measure of general intelligence. Factor B consists of 15 items. Its a reliability was reported as .80 for an adult sample, and its test-retest reliabilities ranged from .70 -.71 with adult and college samples (Conn & Rieke, 1994, p. 31).

Anxiety and Conscientiousness. The 16PF also produces global traits that are weighted combinations of primary trait scores. The 16PF measurements overall have high construct validities and strong test-retest reliabilities (Conn & Rieke, 1994). Two general population samples (N = 820 and 2500) and one sample of college undergraduates (N = 1340), yielded internal consistency reliability coefficients for the 16PF primary factors ranging from .68 to .87 (Conn, 1994, p. 81), and from .70 to .86 when all three samples were combined. In a sample of undergraduate students (*N* = 159), two-month test-retest reliability coefficients ranged from .64 to .79 (Conn, 1994).

The correspondence between the 16PF global factors and the Five Factor Model (FFM) was determined by a factor analysis of global traits and FFM facets (Conn & Rieke, 1994). There is a direct relationship between three of the 16PF global factors and three of the FFM traits. The global factor of anxiety corresponds to the FFM trait neuroticism (factor loading = .85). The global factor of self-control corresponds to the FFM trait of conscientiousness (factor loading = .72). The self-control scale is referred to as conscientiousness, however, in what follows here, but it should not be confused with the 16PF primary trait that is known as conscientiousness.

Performance. Forecasting performance was measured as a correlation between the forecasts given by the participants and the actual values from the mathematical time series. Performance measures were calculated for each attractors (20 items X 4 forecasts = 80 items) and for each step-ahead forecast (20 items each). The percentage of missing data was counted for each participant, and the accuracy correlation were reduced by the percentage of missing data to produce the accuracy metrics that were used in the statistical analysis.

Subjective Workload. After completing the forecasting task, participants completed the TLX ratings of workload. Responses were formatted as 20-point scales (1–21) anchored as 1="very low" and 21="very high." The six ratings were defined as follows: *Mental demand*: How mentally challenging (ex. thinking, searching, deciding) was the task? *Physical demand*: How physically challenging (ex. pushing, pulling) was the task? *Temporal demand*: How much pressure did you feel performing the task because of the pace of the task? *Performance*: How successful were you at achieving the goals of the task? *Effort*: How much energy was put forth to achieve your level of performance on the task? *Frustration:* How discouraged, bothered, irritated, and annoyed were you because of the task?

Difference Scores for Workload. Both catastrophe models required difference scores as dependent measures. The measurement strategy was that, in order to cover the whole cusp response surface, the data set should contain cases that reflect change from low to high, high to low, low to low, and high to high performance. In the case of the model for workload, each participant contributed five observations, which were observed in either ascending or descending levels of complexity and difficulty. All possible pairs of attractors were compared. The resulting *N* for this analysis was 735 total observations, and 715 after eliminating missing data. The comparisons are listed in Table 5 along with the resulting workload score.

Table 5. Definitions of Difference Scores and Workload for Attractor Comparisons in the Workload Cusp.

Dz *Type*	*Ascending series*			*Descending series*		
	z_1	z_2	*Load*	z_1	z_2	*Load*
1	Logistic	Hénon	7	Lorenz	Sprott-B	3
2	Logistic	Sprott-B	6	Lorenz	Hénon	4
3	Hénon	Sprott-B	5	Lorenz	Logistic	5
4	Logistic	Lorenz	5	Sprott-B	Hénon	5
5	Hénon	Lorenz	4	Sprott-B	Logistic	6

Table 6. Definitions of Difference Scores and Work Done for Attractor Comparisons in the Fatigue Cusp.

Dz *Type*	*Ascending series*			*Descending series*		
	z_1	z_2	*Work Done*	z_1	z_2	*Work Done*
1	Logistic	Random	3	Logistic	Random	0
2	Hénon	Random	2	Hénon	Random	1
3	Sprott-B	Random	1	Sprott-B	Random	2
4	Lorenz	Random	0	Lorenz	Random	3

For the workload score that was intended for use as an asymmetry variable, we made the assumption (based on Kantowitz, 1985) that high or low mean performance on an attractor (as shown in Table 4) reflected high or low difficulty, and thus high or low workload relative to the other attractors. The four difficulty levels were rank-ordered, and the workload measurement associated with a particular difference score was the sum of ranks for the pair of attractors.

Difference Scores for Fatigue. Each participant contributed four observations for different comparisons in performance between attractor sets and performance on the block of random attractor stimuli. The total *N* for this analysis was 588 observations, which reduced to 580 because of missing data.

Performance on the random attractor was figured as a correlation between forecasted and actual numbers, but the cases were weighted to compensate for the differential ranges on each type of attractor. Stimuli involving the Sprott-B attractor were weighted as 1.0. The other weights were 2.85, 14.37, and 1.35 for the logistic map, Hénon, and Lorenz stimuli, respectively. Performance on the random attractor set was the time-2 performance measure in all cases. Values of z_1 and work done are shown in Table 6. Each difference score represented different amounts of time elapsed (time of task) between the time-1 and time-2 observations.

Work done was measured as the number of attractor-stimulus sets in between the two performance observations. Work done did not reflect individual differences in performance on the intervening attractors, however. Therefore, two more bifurcation variables were introduced, which were TLX ratings for performance demand and mental demand.

Statistical Analyses

The cusp catastrophe models for workload and fatigue were tested using the polynomial difference equation:

$$Dz = b_0 + b_1 z_1^3 + b_2 z_1^2 + b_3 b z_1 + b_4 a. \qquad (6)$$

(Guastello & Gregson, 2011). In Eq. 6, *z* is the dependent variable (*y*) that was transformed by location and scale.

$$z = (y - l\ ) / s_{s.} \qquad (7)$$

Location (l) was the lowest value of *y* in the data set (not the mean). Scale (s_s) was the standard deviation. Similar transformations were made on all the control variables that were hypothesized to contribute to bifurcation (*b*) and asymmetry (*a*). Equation 6 can be expanded to include several possible bifurcation and asymmetry variables, each with its own regression weight (b_i).

The results from Eq. 6 were compared against two linear alternative models:

$$z_2 = b_0 + b_1 z_1 + b_i b + b_j a \qquad (8)$$

and

$$Dz = b_0 + b_i b + b_j a. \qquad (9)$$

RESULTS

Workload

Figure 5 shows the frequency distribution of difference scores for performance changes in the workload model. There are modes visible at -2.14 moments and +2.50. The middle section of the histogram ranging from $-1.79 < Dz < +1.79$ appears to represent a large number of observations that fell into the unimodal region closer to the cusp point.

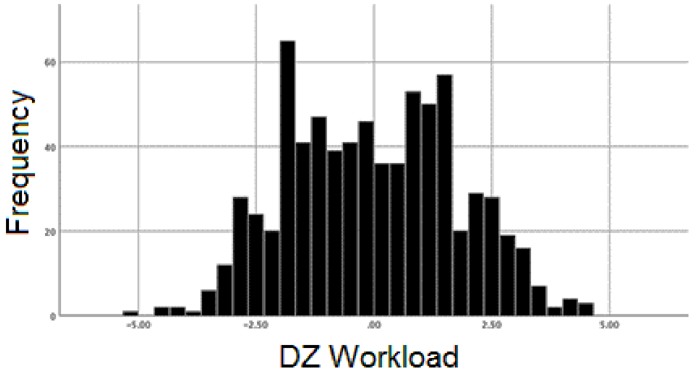


Fig. 5. Distribution of performance change scores in the workload analysis.

Table 7. Cusp and Linear Regression Results for the Workload Model.

Variable	*Std.* b	*t*
Cusp: $R^2 = .56$, adj. $R^2 = .56$, $F(11,703) = 82.21$, $p < .001$		
z_1^3	1.08	7.40****
z_1^2	-1.77	-10.39****
z_1*Field independence	0.10	3.06***
z_1*Anxiety	-0.07	-1.82*
z_1*Conscientiousness	0.07	2.33**
z_1*Coping flexibility	0.11	2.60***
z_1*Planning	-0.12	-3.46****
Workload	-.016	-5.84****
z_1*TLX Performance	-0.16	1.77*
TLX Mental demand	-0.11	-3.90****
TLX Performance	0.16	2.09**
Linear pre-post: $R^2 = .14$, adj. $R^2 = .13$, $F(7,707) = 15.94$, $p < .001$		
Field independence	0.13	3.65****
Anxiety	-0.08	-2.19**
Conscientiousness	0.08	2.13**
Coping flexibility	0.15	3.80****
Planning	-0.20	-4.84****
Workload	-0.21	-5.89****
TLX Mental demand	-0.14	3.88****
Linear difference: $R^2 = .07$, adj $R^2 = .06$, $F(7,707) = 9.54$, $p < .001$		
Field independence	0.07	1.96**
Anxiety	-0.12	-3.00***
Coping flexibility	0.18	4.40****
Planning	-0.17	-0.41****
TLX Mental demand	-0.13	-2.84**
TLX Temporal demand	0.10	2.39**
TLX Performance	-0.09	-2.40**

*$p < .10$, **$p < .05$, ***$p < .01$, ****$p < .001$

The regression model for workload was tested in two stages using the backward elimination method in both cases. The model containing all the control variables except TLX ratings was tested first. The model was then extended to include the TLX ratings. The goal was to give priority to the elasticity-rigidity and workload constructs before the TLX ratings. As it turned out, the TLX ratings accounted for a small (2%) additional amount of variance accounted for in the cusp model without any conflict with the other variables.

The results for the workload model appear in Table 7. All parts of the cusp model were clearly present. R^2 for the cusp (.56) was much larger than that of the next best linear alternative (.14) by more than a 3:1 margin. There were six bifurcation variables such that the discontinuous side of the surface was characterized by: field independence, low anxiety, conscientiousness, coping flexibility, less reliance on planning, and low ratings of TLX performance.

The linear pre-post model (R^2 = .14) was interesting because the time-1 performance measure was not part of the final model. The characteristics of people who performed better on the time-2 measure were field independent, low anxiety, conscientious, higher in coping flexibility, lower in planning orientation, were experiencing a decline in workload (attractor difficulty), and reported lower mental demand for the entire experiment.

The linear difference model (R^2 = .07) contained similar results. Participants whose performance improved over pairs of attractor exposures were more field independent, lower anxiety, reported greater coping flexibility and planning orientation, and rated the experimental task overall lower in mental demand, higher in temporal demand, and lower in performance demand.

Fatigue

Figure 6 shows the histogram of difference scores in the fatigue analysis. Modes are visible at 3.21 and 1.79. The middle section ranging from -2.50 to +1.43 appears to represent a large number of observations that fell into the unimodal region closer to the cusp point.

The results for the regression model for fatigue appear in Table 8. All parts of the cusp model were clearly present here as well once the quadratic term was removed. R^2 for the cusp (.54) was much larger than that of the next best linear alternative (.07) by more than a 7:1 margin. There was one bifurcation variable, such that the unfolded side of the surface was associated with lower ratings of mental demand. There were two compensatory abilities, field independence and lower general intelligence. The variable “work done,” which was defined as the number of blocks of attractor stimuli between the two comparison points, was not a significant contributor to the model.

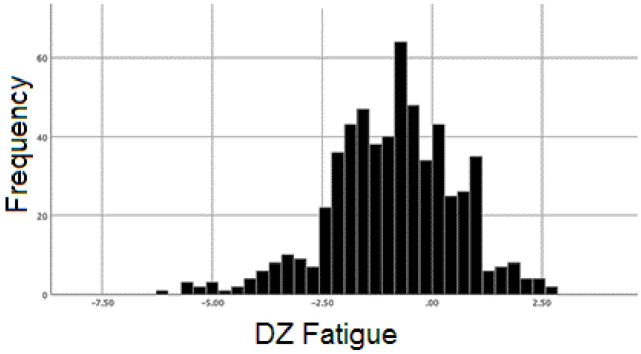


Fig. 6. Distribution of performance change scores in the fatigue analysis.

The linear pre-post model (R^2 = .07) contained four variables. Performance on the random attractor block of stimuli was positively correlated with performance on any one of the prior attractors, negatively correlated with ratings of mental demand, positively correlated with field independence, and negatively correlated with general intelligence.

The linear difference model (R^2 = .02) contained two variables. Work done was negatively correlated with performance change; this would be a straightforward fatigue effect showing that performance dropped to the extent that the individual executed more forecasts between the two comparison points.

Table 8. Cusp and Linear Regression Results for the Fatigue Model.

Variable	*Std.* b	*t*
Cusp: R^2 = .54, adj. R^2 = .54, $F(4, 575) = 169.51$, $p < .001$		
z_1^3	-0.66	-19.44****
z_1*TLX Mental demand	-0.12	-3.66****
Field independence	0.07	2.18**
General intelligence	-0.07	-2.16**
Linear pre-post: R^2 = .07, adj. R^2 = .06 $F(4, 575) = 10.81$, $p < .001$		
z_1	0.20	4.78****
TLX Mental demand	-0.11	-2.66***
Field independence	0.09	2.00**
General intelligence	-0.12	-2.70***
Linear difference: R^2 = .02, adj. R^2 = .01, $F(2, 577) = 5.24$, $p < .01$		
Work done	-0.10	-2.40**
General intelligence	-0.09	-2.17**

*$p < .10$, **$p < .05$, ***$p < .01$, ****$p < .001$

DISCUSSION

The objective of the present experiment was to gain some further knowledge about a mental operation, forecasting chaotic events, that is not well understood in the current cognition literature. The research stream in this area seems to have made a strong start, but it languished for the better part of the last twenty years. It is now possible to say, however, that (a) some chaotic structures are more difficult to forecast than others, (b) decision makers use a combination of statistical and deterministic heuristics, and (c) the use of those heuristics varies by skill level (Guastello, Futch et al., 2019). The point of attack for the present study was to examine how the dynamics of forecasting performance would be affected by cognitive workload and figure. Two cusp catastrophe models were used for this purpose.

The cusp models for cognitive workload and fatigue were developed to resolve some conflicting or confounding stress-performance relationships in the human factors and ergonomics literature, and to represent some nonlinearities that were also known in that literature. One goal of the experiments summarized in Tables 1 and 2 was to explore the generalizability of the cusp models across different types of cognitive operations that were otherwise well-known in the psychological literature. Another goal was to expand the exploration of psychological variables that contributed to the control parameter constructs of elasticity-rigidity, measurements of cognitive load, and compensatory abilities. Thus, a collateral goal of the present study was to examine how the forecasting task compared with the other tasks on record. The cusp results were particularly strong in both cases, in comparison with previous experiments; the cumulative average R^2 for the cusp workload model increased to .46 for the cusp, compared to .25 for the next best linear alternative, and .41 for the cusp fatigue model, compared to .22 for the next best linear alternative. The specific elements of the models are discussed next.

Workload

There were six separate bifurcation effects that expressed elasticity versus rigidity. It would be useful to consider how the bimodality was expressed in performance patterns.

Field independence is the ability to detect a target image (figure) from background (ground). It is associated with better use of one's working memory capacity (Pascual-Leone, 1970), and although it is not a basic cognitive ability, it facilitates quicker development of the more basic abilities (Cantwell, 1986). Better use of working memory capacity would actually move a person closer to the limits of true underlying memory capacity. When the limit is reached, then the discontinuities associated with the cusp would become more apparent. Not every field independent person would have the same underlying limit of course, but a strong enough workload demand would put some people over the critical threshold. In the present application, field independence was associated with the bimodal portion of the cusp surface. Focused attention to target information is an advantage so long as it is the correct information.

Higher levels of trait anxiety are thought to be indicative of rigidity, as opposed to the flexible or adaptive region of the cusp surface. The current theory about anxiety, workload and performance indicates that anxious people could have either an advantage or disadvantage, hence the bimodality in performance. It appears that this bimodal pattern only occurs when the participant is working with one or more other people, or some type of threat is present. The forecasting task did not require interaction or suggest danger. In the present application, lower anxiety was associated with better performance in the linear model and the bimodal region of the surface in the cusp model. The effect size was relatively small, however.

Conscientiousness denotes a tendency to adhere to best, prescribed, or required practices without deviation. The trait conveys rigidity in that regard. Conscientious individuals would be slow to adapt spontaneously to conditions that fall outside the prescribed rules of situation-response combinations, unless other traits were present that suggest otherwise. In this application, higher levels of conscientiousness were associated with the bimodal region of the cusp surface.

The results for coping flexibility were curious. One would think that the construct would place high flexibility on the low-bifurcation side of the surface and low flexibility on the high-bifurcation side, but the opposite result was obtained. A plausible explanation was that coping flexibility functioned more like a gradient that connects the cusp point with the attractors and had a net positive effect on performance. Another possible interpretation is that the more flexible people could make adaptations, but not every adaptation would have a positive effect on performance; in other words some trial and error was underway. A third possibility was that it was a gradient that interacted with planning orientation. One would think that planning orientation would be rigid, and lack of planning not so, but hesitance to plan and the maintenance of spontaneity could be adaptive also.

The TLX ratings for performance demands contributed to both the bifurcation and asymmetry control parameters. Some writers have expressed concern that ratings of TLX performance demands do not behave the same way as the other ratings, as evidenced by component analyses (Guastello & Marra, 2018; Sellers et al., 2014). Further analyses of traits associated with TLX performance ratings indicated that low ratings could have two different meanings: The obvious meaning is that the demand on the individual to produce a good result was not particularly high. The less obvious meaning is that some people give lower ratings because they are not aware of the nature of the performance requirements (Guastello et al., 2017).

In light of the cluster of variables appearing as bifurcation variables, it would be possible to speculate that the set of variables is working together in some fashion to produce overall elasticity and rigidity. Different combinations of contributing elements (personality, fluid intelligence, coping strategies) become salient depending on specific task demands. As bifurcation variables they interact with the current state of the system (performance level) to produce diverging effects on the subsequent state.

The regression weights in the linear model showed that some elasticity-rigidity variables had a net positive effect on performance changes and others had a net negative effect. It is possible that the two subgroups of variables operate along the two gradients of the cusp surface. The gradients are trajectories along the cusp surface that connect the cusp point to the stable states. In this case the gradient leading toward performance improvement consisted of field independence, conscientiousness, and coping flexibility. The gradients leading toward performance decline consisted of anxiety, planning orientation, and perceived performance demands.

TLX mental demand also contributed to the asymmetry control parameter. Lower ratings of demand were associated with positive changes in performance. The ratings were capturing individual differences in response to workload, whereas the variable Workload was calibrated in terms of normative task difficulty.

Fatigue

The block of random attractor stimuli that was placed at the end of the experiment was the primary means of inducing fatigue. It was thought to have three effects: First, it produced more time on task and allowed for comparisons with the other attractor-specific stimulus blocks. Second, the final block required a lot of regime switching, which could tax executive functioning. Third, the extended time on task could produce a practice or momentum effect for some participants. They did acquire exposure to the four attractors, albeit without explanations of chaos or feedback regarding accuracy, and thus whatever mental processes they preferred to use would have consolidated to some extent.

Two bifurcation variables were tested: the amount of work done and TLX ratings of mental demand. The amount of work done is partially a measure of time on task. When it was used in previous studies, however, the measurement was defined to reflect correct answers or quantities of production between the two observation points in order to make a distinction between people who worked harder and those who worked indifferently for the same amount of time. Because of the difficulty of the forecasting task with at least two of the attractors, it did not seem advisable to measure work done as an accuracy correlations for the stimuli in between the time 1 and time 2 measurements. Instead, ratings of mental demand were used to capture the cognitive engagement aspect of work done. The linear pre-post results confirmed that participants who performed better on the random block rated the task less demanding mentally.

Two compensatory abilities emerged from the analysis. Field independence was positively associated with performance changes, and general intelligence was negatively associated with performance changes. Although field independence is not a primary mental ability, its connection to fluid intelligence made it a logical compensatory ability for working memory. As mentioned previously, field independence facilitates the development of other more basic abilities (Cantwell, 1986).

Limitations and Future Directions

The present study had several limitations to consider in future research. At the most granular level, a few discrepancies were already noted regarding the direction of a couple variables with regard to their bifurcating effect in the workload model. Further research should explore conditions under which those contrary results could occur. The tentative conclusion remains, however, that the elasticity-rigidity variables all contribute to the underlying control parameters and gradients of the cusp response surface and function more or less in unison. The elasticity-rigidity characteristics or traits might not be equally developed among all participants. However, many seem to be important, and there could be some complimentarity effects operating among them.

Furthermore, it would be an odd conclusion that the more intelligent forecasters do not perform well under conditions of fatigue compared to others. The paradox probably resides in the nature of general intelligence, which contains both fluid and crystallized intelligence. The relationship suggests that a suppressor effect could be operating such that the best performers have a profile of skills in which their fluid intelligence is much stronger than their crystallized intelligence, even though both types of ability could be high. An alternative explanation is that the more intelligent participants became bored with the task sooner than others, thus their motivation to perform dropped significantly.

One could reasonably question whether the cognitive and personality tests that were given at the outset of the experimental session might have contributed to the overall levels of fatigue during the experiment. One perspective could agree because the measurements extended the time on task if one were to imagine the entire experimental session as the task. A second perspective would disagree because the task shift between the tests and questionnaires and the actual experiment could have alleviated fatigue to some extent. A third perspective would say it would be more realistic to present the central task after the non-central tests and questionnaires, as we did here, because the central tasks would occur after the work shift had started, and any number of prior non-central tasks could have occurred before the central one. A fourth perspective would be that it has become standard practice to present the tests and questionnaires before the central experimental task to enhance the interpretation of any cause-and-effect relationships that might be associated with abilities and predispositions, and to prevent contamination of the test and questionnaire measurement from exposure or priming from the central experimental task. In addition, the segments of performance that were compared to determine fatigue all occurred within the experiment itself; thus, all participants and all pairs of conditions were equally exposed to any effect that the tests and questionnaires might have had.

At the intermediate level, some improvements are possible for the theories of cognitive workload and fatigue and the forecasting of chaotic events. In the former case, elasticity-rigidity variables and their links to fluid intelligence were not fully explored in the earliest experiments. Some of the early experiments could benefit from a repetition in which the current range of known variables can be assessed. For some of the early experiments, a more challenging task with regard to workload or fatigue could be devised.

As new tasks undergo assessment with the cusp models, one should bear in mind that, in the broader literature, workload and performance are not linearly related. The relationship is curvilinear such that very low workload produces sub-optimal arousal and performance, and excessively high workload produces overstimulation and sub-optimal performance again. Coping strategies, which were vaguely defined initially, were thought to buffer the performance declines (Hancock & Warm, 1989). A good number of them have now come to the surface, however, but there is no reason to think that all the relevant psychological characteristics have been identified.

There is still much to be learned about forecasting ability, particularly when chaotic events are involved. Future research should investigate personality and cognitive variables that could be associated with success in making those forecasts. Such research could explain how forecasting ability draws on those basic characteristics and could assist with the identification of talented individuals.

At a more global level of theoretical development, the prediction of chaotic numbers is only one feature underlying the effective management of a complex system. Although chaos is dynamic over time, the experimental task was not a dynamic decision task in which the participants' forecasts resulted in actions that produces responses from the system. Dynamic decision studies might adopt a small world simulation as an experimental task. The performance objective would then include forecasting events and the results of possible actions, and the efficacy of those actions for keeping the system stable versus unraveling into chaos. From there, future research could then consider the special requirements for complex systems such as supply chains, fisheries, or complex systems with a substantial human social component, and complex systems that are operated by a team rather than a single individual.

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