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The Role of Depth and $1/f$ Dynamics in Perceiving Reversible Figures

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When confronted with a reversible figure, such as the Necker Cube, viewers experience a spontaneously changing percept. We assess the dynamic of how the human visual system resolves perceptual ambiguity in stimuli that offer multiple interpretations. Subjects observed the Necker cube for one of three viewing durations during which they pressed a key each time they perceived a change in the orientation of the cube. Manipulations of binocular disparity served as a parameter to control perceptual stability. Low-depth conditions yielded more perceptual reversals than high-depth conditions. A Fourier analysis performed on the time series of reversals show $1/f$ (pink) noise was evident in their power spectra. These results together with theoretical models of complex systems (e.g., Bak, Tang, & Wiesenfeld, 1987) suggest that depth information may guide our perceptual system into a self-organized state to assist us in resolving ambiguous information. Moreover, slopes of the spectra were steeper in high-depth and brief viewing conditions, suggesting that the visual system relies more on previous perceptual states and filters more white noise in these conditions.

KEY WORDS: visual perception; Necker cube; $1/f$ Power laws; self-organization.

The problem of consciousness poses some of the greatest challenges to scientific understanding. One challenge pertains to the emergent property associated with our conscious state. When confronted with a reversible figure, such as the Necker Cube shown in Fig. 1, viewers experience spontaneous

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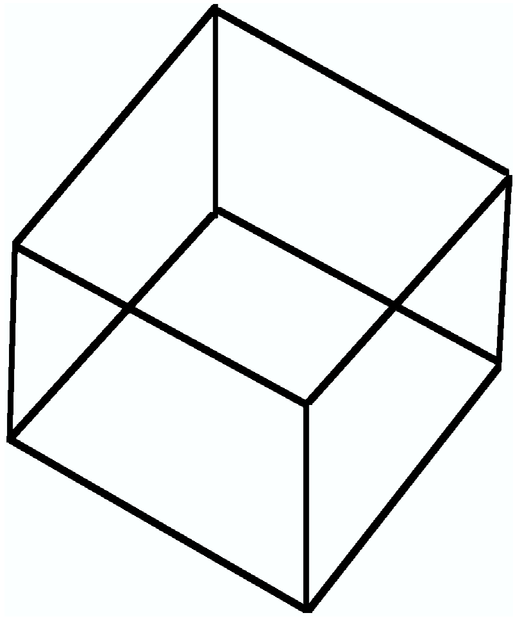

Fig. 1. Viewers perceive spontaneous changes in the perceived orientation of the Necker cube (1832).

changes in the orientation of the cube. This is a clear example of a dynamically emerging perceptual state—one that can easily be recorded by having observers press a key to indicate a shift in their percept.

Previous evidence, using such methodology, suggests that perceptual reversals are the consequence of a variety of factors (Long, Topping & Kostenbauder, 1983). Purported sources include satiation of neurons associated with a mental representation of the figure (Hochberg, 1950; Kohler, 1940; Howard, 1961; Orbach, Ehrlich, & Heath, 1963), and "priming" (Long, Topping, & Mondin, 1992), fixating (Peterson & Hochberg, 1983), or attending (Virsu, 1975) to a particular interpretation of the cube. In addition, a variety of stimulus manipulations such as binocular disparity can modulate the coherence and perceptual stability of the Necker cube (Ogle, 1962; Cormak & Arger, 1968). It is likely that many of these mechanisms operate concurrently to give rise to spontaneous changes in percepts with no obvious connection to their underlying sources.

The dynamical systems approach is well suited to describe emergent phenomena (e.g., percepts) that arise from the interaction of local constituents (e.g., neurons). Conventional approaches have been instrumental in our understanding of average perceptual behavior. But it is likely the

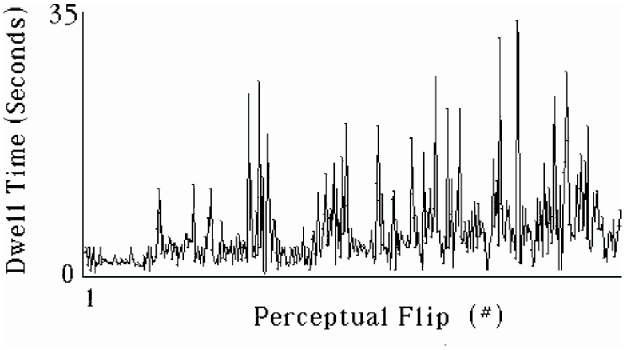

Fig. 2. This typical series of perceptual flips shows the erratic perceptual behavior that occurs while viewing the Necker cube. The data series consists of the intervals between key presses or equivalently the dwell times between flips.

typical focus on the cumulative record across conditions may overlook important aspects of perceptual processing. To ameliorate this potential gap, our approach entails recording over time the duration that a person dwells on a particular interpretation of the Necker Cube. Although the erratic flipping evoked by such a reversible figure (i.e., Fig. 2) is typically attributed to random or extraneous influences, and is ignored by most vision researchers (but see Gilden, 2001, Gilden, Thornton, & Mallon, 1995, Kelso, 1992 and Guastello, 1995 for a summary of Ash's 1914 work), we believe there may be a predictable, but subtle *dynamic* in perceptual changes that occur over time. Various applications of catastrophe theory has also examined the dynamic of perception and has shown us that gradual changes in a (bias) parameter produces a (nonlinear) effect on a perceptual state (e.g., Poston & Stewart, 1978; Ta'eed, Ta'eed & Wright, 1988). These studies have shown that an asymmetry in perceptual response depends on the direction of a parameter sequence.[4] While this topological approach provides a useful *description* of the change in response and illustrates one type of history dependence of the percept, we ask more broadly what produces complex perceptual behavior by looking at statistical regularities in these fluctuations: Are there clues of a subtle deterministic system that may drive perceptual change?

Borrowing from developments in fields such as Physics, Math and Biology we now reconsider the information content of complex and

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[4] Catastrophe theory and SOC are not competing models. The two theories are descriptions of different aspects of the same system. Catastrophe theory focuses on the shift in perception, whereas SOC focuses on the variability in perceiving the two stable states. SOC also provides a possible mechanism that can produce the erratic shifting inherent to our changing perceptual states.

seemingly random data. During the last decade, it has been established that a large number of natural systems containing several interacting individual components have statistically similar dynamical properties, independent of the particular details of the system. Examples include earthquakes (e.g., Bak & Tang, 1989), population dynamics (Miramontes & Rohani, 1998), DNA base sequence structure (Voss, 1992), epidemic outbreaks (Rhodes & Anderson, 1996, 1997), and various cognitive and reaction time behaviors (Gilden, 1996, 2001; Gilden, Thornton, & Mallon, 1995; see also Chen, Ding & Kelso, 1997; Clayton & Frey, 1997; Schmidt, Beek, Treffner & Turvey, 1991).

Examination of the statistical properties of these systems' fluctuations has revealed dynamics with well-defined generic scaling properties in the form of power laws (Bak, Tang, & Wiesenfeld, 1988). Since scaling reflects a system's changing properties, this suggests the system, by definition, has the ability to adjust to its surrounding context. Power exponents, the indicators of scaling, are obtained from decomposing a data series into sine waves through a Fourier transform procedure, and then plotting the amplitude squared (i.e., power) as a function of frequency. A linear function on a double-log plot indicates the presence of a power law. The regression slope of this function determines the power exponent, which as we will see, is also useful as a measure of memory or noise in the system (e.g., Peak & Frame, 1994).

Power law relations, obtained from the Fourier transform of fluctuations, have important *fractal* properties that can be a signature of a long-term dynamic. Moreover, a number of fractal properties implicate a concise and adaptive code underlie these systems: 1) their dynamic scaling characteristic noted above, 2) the infinite detail and self-similarity of their complex behavior, and 3) their underlying simplicity (e.g., Mandelbrot, 1967). We suggest that fractal structure may underlie and facilitate perception of a scene when viewing ambiguous items including those present in our natural environment.

The first property of dynamic scaling refers to the fact that the temporal evolution of a fractal system is not controlled by one time scale. This absence of a single characteristic scale is revealed through means and variances that depend on the size of the sampling resolution, which in the present case, is the amount of time available to perform the task. The system tends to use more time as it becomes available, and conversely, the system speeds up as less time is available. Thus, the mean performance changes over time, which as a result, contributes to the production of complicated behavior.

The second set of properties associated with fractal systems is the infinite detail and self-similarity that emerges in the resulting complicated output of these systems. The detail is a natural consequence of the irregular (i.e., noninteger) shape of fractals. Within the detail are self-similar fluctuations that occur in the same proportion at all scales suggesting that iterations of a simple underlying rule may be driving the behavior. Thus, behind the complex behavior an underlying simplicity may exist.

Thirdly, it is this very property of simplicity that provides the potential for unlimited coding of information through a compact representation of the fractal. The high degree of statistical redundancy in the environment reduces the amount of information needed to be stored to a unique pattern plus a simple iterative function (Barnsley, et al., 1988; Watson, 1987). Because of their compactness, fractals are currently used to store digital information, are used in automated identification systems (Daugman; 1991), and also appear to be a suitable candidate for coding in the human visual system.

In a particular form of power scaling, those dominated by low frequencies, the temporal phenomenon scales as the inverse of the frequency (f), or as $1/f^{\alpha}$ *noise*. Bak, Tang, and Wiesenfeld (1987) suggest that these systems, with a power spectral exponent of approximately $\alpha = 1.0$, consist of many interacting constituents, are found to be ubiquitous in nature (see examples above), and under many conditions, are dynamical systems which organize themselves into a state with a complex but rather general structure.

One proposed model of these systems is Self-Organized Criticality (SOC;[5] Bak et al., 1987). In the SOC model, dramatic change, or *criticality*, occurs from the local interaction of the system's component parts. The resulting complex behavior is produced by *simple* local rules with which neighbors interact, and *self-organize* so that structures and patterns develop in the absence of a controlling agent. Spontaneous emergence of a behavior (e.g., percept) could be one consequence of self-organization.

Bak et al. (1987) developed an avalanching sandpile model to demonstrate the simple set of rules underlying SOC. In this idealized model, grains of sand interact and may cause each other to topple. The rules are those of a cellular automata operating in a system that can be represented on a 2D grid (i.e., Wolfram, 1984). Each cell's activity is determined by its current state, as well as the states of its neighbors (Bak, 1996).

Figure 3 shows SOC generalized to a neural network that can evoke perceptual changes. Early conceptions of neural networks applied to cognitive phenomena can be found in Hebb's (1949) seminal work on associative learning in cell assemblies, and more recently in McClelland & Rummelhardt's (1986) *Parallel Distributed Processing (PDP) Models*. In the model presented

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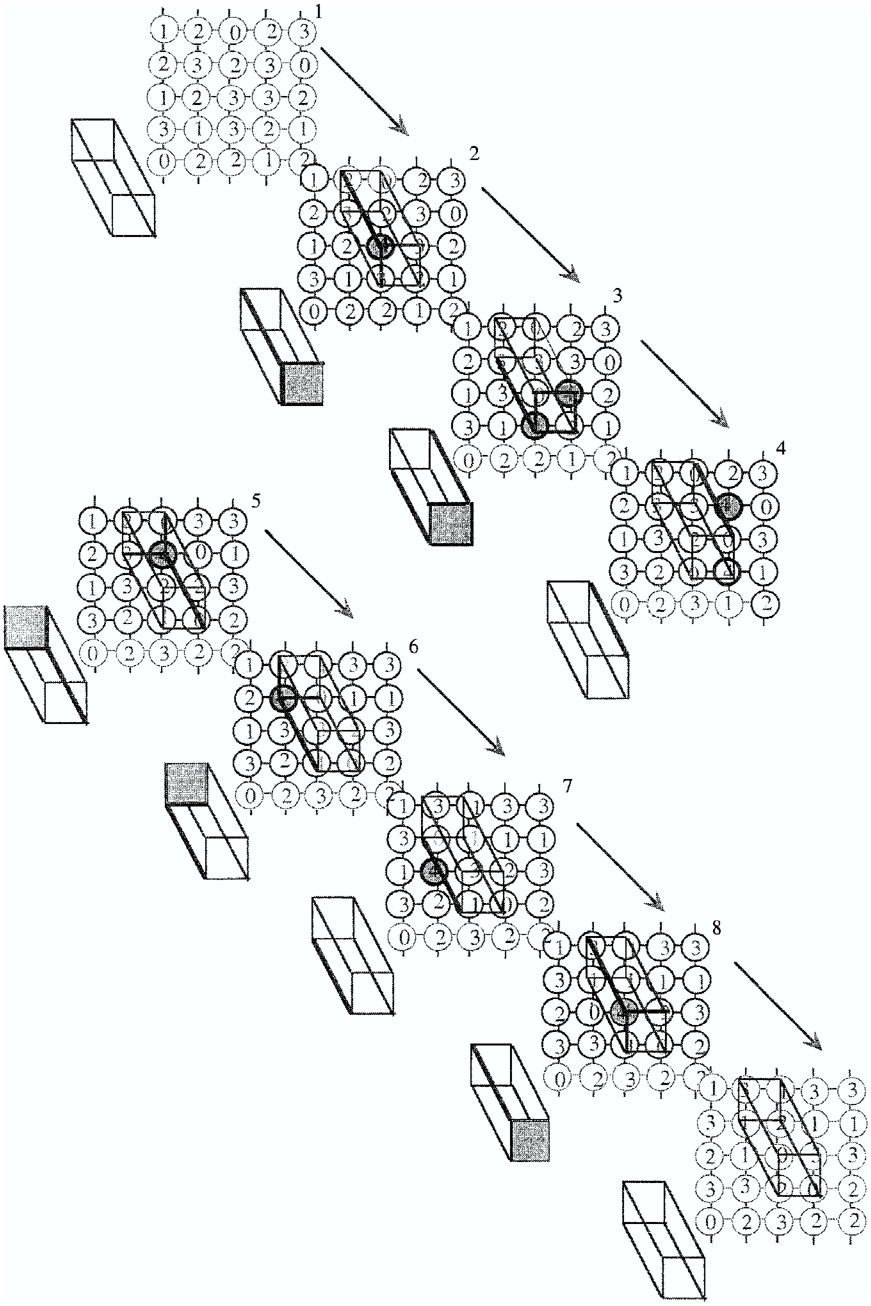
[5] Bak's SOC theory is currently under debate as to whether it is a reliable model of $1/f$ dynamics. Alternative models under investigation maintain many similar properties including simple rules producing complex behaviors and self-organization (e.g., De Los Rios & Zhang, 1999; Miller, Miller, & McWhorter; 1993). Thus SOC or similar alternatives could account for these data trends.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here, local interactions occur through lateral inhibitory and excitatory effects across neurons, and these can produce global perceptual changes via threshold mechanisms (i.e., Stassinopoulos & Bak, 1995).

The avalanching properties of SOC, and perhaps perceptual changes, can be described nicely as phase transitions from the field of thermodynamics. When the temperature of the system is equal to the transition temperature, there is a dramatic change for example from liquid to gas. For all other temperatures, one can disturb the system locally and the effect of the perturbation will influence only the local neighborhood. However, at the transition temperature, the local distortion will propagate throughout the system. Although only "nearest neighbor" members of the system interact directly, the interaction effectively reaches the entire system. The system becomes critical in the sense that all members of the system influence each other. Such properties are quite plausible in a system consisting of a network of neurons.

GOALS AND PREDICTIONS

We propose that the human visual system may be driven by a deterministic process with subtle but important self-organizing properties. While such a system can produce complex and emergent behavior, the underlying dynamic may be quite simple. In the present study, we examine the effect of *time* and *binocular disparity* on the dynamic of perceptual flips, and examine changes in the resulting data distributions and power spectra.

First, we look for scale-invariance in perceptual flipping by evaluating whether the means and variances of these data distributions change over time. Thus total time that viewers observe the Necker cube will be manipulated to assess for scale-invariance. The manipulation of time will also serve to assess the conventional theory of neural satiation. Kohler's (1940) theory of neural fatigue predicts that the alternating percept should speed up

Fig. 3. Bak's (1996) SOC model is applied to a neural network. The perceived orientation of the cube at any given step is shown by the cubes to the left of the network. The shifts in the cubes' orientation are the global effect of local neuronal interactions. Cells of the 2D grid represent receptive fields whose corresponding neurons have a random initial distribution of activity across the network. Activity is represented by numbers ranging from 0 to 4. A perceptual bias favoring a particular cube is represented by the greater weights in the cells and the corresponding bold edges of the cubes superimposed on the network. Activity is initiated by selecting one receptive field site and increasing the activity by one as illustrated here in the central site of the first network. This simple sequence is repeated many times. The interesting dynamic of spreading activation occurs when a simple rule is applied—when the activity in a single cell exceeds a critical value, in this case 3, activity from the site is distributed to four adjacent regions. After just seven update steps, a region of nine cells has been activated.

over time, since fatigue should build up with extended viewing of particular percepts. However, it is easy to conceive of fatigue occurring in the flips themselves rather than just the percept. Regardless of the impact of time, the critical finding will center on whether flipping behavior changes over time. Such changes will indicate the presences of scale invariance in the perceptual task of resolving such ambiguous information.

Additional analyses of the power spectra of the data series will further reveal whether flipping behavior can be modeled by a power law. A scale invariant perceptual system, characterized by a power law function, is important in a variety of ways. First, scaling suggests there is determinism in the system, even one that appears random. Second, as described earlier, this system is an efficient and compact means of coding information (Voss, 1992). And third, evidence of SOC in the perceptual system would help account for the flexibility of our visual system and the system's proficiency in adapting to novel environments.

The second main goal of this study is to evaluate the impact of binocular disparity on perceptual flipping. With disparity serving as a parameter to control the perceived reversibility of the Necker cube, we first assess whether an increase in disparity reduces the average frequency of flipping. We expect this result because disparity should encourage one interpretation of the cube.

Our second analysis focuses on the fourier transform of the flip series. Shifts in power spectra slopes may be the result of a mechanism that filters white noise in the system (i.e., Peak & Frame, 1994). Steepening power spectra slopes indicate a reduction of white noise; perhaps the filtering of the noise is a consequence of the processing of disparity information. Without disparity, we might expect shallower power spectra slopes, since without the filter, white noise is permitted into the system. The result would be to destabilize the system and allow for alternative perceptual states. Such increases in white noise, could facilitate the observer in seeking out appropriate perceptual states when the external information is too unstructured to lead to a reliable solution. Shallower slopes would further imply that disparity is not sufficient to guide the percept and the system is widening its scope of input.

Changes in power spectra slopes may alternatively reflect the extent to which the system is influenced by its preceding state. Presumably, a state containing reliable information is likely to be helpful as a guide to subsequent states. Long-term correlation in the data series, as reflected in relatively steeper regression slopes in the power spectra, may indicate that the system "knows" to sustain the unambiguous state. Since disparity assists the system in selecting reliable information it may too serve to modulate the memory of previous percepts.

METHOD

Subjects

A preliminary study consisted of ten subjects (6 female, age range = 18–24 years). Forty additional subjects (16 female, age range = 18–35 years) participated in the main study in one of three sessions. Twenty-five participants served in a brief viewing condition (target $M = 15$ min), ten in a moderate (target $M = 30$ min), and five in an extended viewing condition (target $M = 60$ min). All subjects were members of the University community, reported normal or corrected-to-normal vision, and an initial screening demonstrated an ability to perceive depth from binocular disparity at the levels tested in this study.

Stimuli & Apparatus

The facades of the Necker Cube observed by subjects measured 7.7 cm.[3] Cubes were rotated 80° from fronto-parallel and measured 7.65 mm × 7.40 mm along the vertical and horizontal dimensions. Cubes were generated on Gateway 2000 (P5-120) PC computers and displayed on 15″ Vivitron display monitors. Resolution was set to 800 × 600 pixels. Binocular disparity was depicted with red and blue 0.5 mm adjacent contours with offsets ranging from $0'$ to $4'$ of visual arc. To perceive depth from the offsets, subjects wore red-blue anaglyph glasses in all conditions. Subjects in the fifteen minute group received one of three sets of disparity conditions: $0'$, $1'$, $2'$ or $0'$, $2'$, $4'$. The thirty and sixty minute groups participated in the $0'$ and $2'$ disparity conditions.

Procedure

In the preliminary study, five subjects participated in three low ($0', 1', 2'$), and another five in three high ($0', 2', 4'$) disparity conditions. While viewing the Necker cube for a 15 minute period, subjects pressed a key each time they perceived a change in the cube's orientation (i.e., top-left vs. bottom-right). This experiment served to replicate earlier findings that flipping frequency decreases with increasing disparity (Ogle, 1962; Cormak & Arger, 1968). An additional goal was to select disparity conditions that would provide a sufficient number of data points to properly look for dynamical structure while permitting subjects to perform the task in a reasonable amount of time.

Once optimal binocular disparity conditions were found (i.e., $0'$ & $2'$), forty additional subjects observed the Necker cube in these conditions for a brief, moderate or extended viewing time. Targeted times were 15–, 30– or 60–minute viewing periods although mean deviations up to 6 minutes occurred.[6] Subjects in the brief and moderate viewing conditions performed the two disparity conditions separated by five minute break intervals. Subjects in the 60–minute condition performed two disparity conditions at the same time on separate days.

Inferential statistics were used to determine, in a conventional analysis, if a significant difference emerged across the different viewing-duration and disparity conditions. The primary reason for using these statistics is to provide a familiar point of comparison to previous findings. At the same time, we recognize the statistical assumption of independence across trials and caution the reader of the possible fallacy that may result from sole reliance on inferential statistics on data that may contain dependencies. To assess for such dependencies, and to evaluate our primary goal of learning about the overall dynamic of perception, the intervals between key presses were recorded and subjected to a variety of time-series analyses described below.

DYNAMICAL ANALYSIS

The dynamical systems approach makes use of a direct numerical analysis of data across a sequence of trials. We use the time intervals between key presses, or cube dwell-time, to map the trajectory of perception as it shifts from one state to another. A typical series of perceptual reversals is shown in Fig. 2. Key analyses[7] involve assessing for scale-invariance by looking for means and variance of data distributions that change as a function of the viewing duration. We also evaluate whether a $(1/f)$ power law characterizes this perceptual process.

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[6] Viewing time deviated from the 15, 30, and 60 minute target viewing times due to fatigue. Actual duration averaged across the two disparity conditions were brief: $M = 12$ min ($SD = 3$), moderate: $M = 27$ min ($SD = 6$), and extended viewing: $M = 49$ min ($SD = 13$).

[7] In multi-stable figures, each potential figure can be conceptualized as an attractor state whereby multistable perception may be a manifestation of the perceptual system switching between attractors (e.g., Kelso, 1992). To evaluate for the presence of an attractor, we tested various nonlinear analyses including assessments of return and phase space maps using Sprott and Rowland's (1995) CDA software. The dimension of all time series was unmeasurably high (at least 4.0) suggesting that the system has a large number of degrees of freedom. The high dimension of the system together with too little data (<1000 data points), prevent us from uncovering possible deterministic chaotic trends. This was the case even in the longest (60 minute) sessions. Acquiring additional data needed to detect chaotic processes was prohibitive given the present paradigm (i.e., collecting greater than 10^3 data points exceeds what a person can reasonably perform in one session of viewing the Necker cube). Thus, attempts to assess for chaos were thwarted by insufficient data relative to the excessive complexity of the system.

Spectral analysis[8] has been a popular technique used to probe noisy time series for hidden clues to underlying structure. Spectral analysis is sensitive to statistical correlations. We use a Fast Fourier transform (Press, Flannery, Teukolsky & Vetterling, 1986) on the data record, and display the power (mean square amplitude) as a function of frequency.

A power spectrum with a few dominant frequencies shows that the data can be well approximated by a Fourier series with just a few terms. Of greater interest to us is whether our data possess scaling behaviors characteristic of complex systems. Does the temporal phenomenon scale as the inverse of the frequency (f) or as "$1/f$ noise?" In this particular form of scaling, the dynamics can be very complicated, yet the underlying rules quite simple. We specifically are interested in whether perception of the Necker cube is dominated by low frequencies (i.e., long-term dynamics), and whether the dynamics are $1/f$.

Spectral analysis will be further used to measure the strength of memory and noise in the system. Contingencies will be quantified in terms of the slopes of the power law—steeper slopes suggest stronger contingencies and less white noise. Aks, Zelinsky & Sprott (2002) elaborate on how the spectra provide similar information to autocorrelation procedures, and how both indicate the dependence, or history in the signal.

RESULTS

Preliminary results, shown in Table 1, based on ten subjects participating in three of the four disparity conditions replicate earlier findings that increasing binocular disparity is associated with a decrease in the number of flips ($F(2, 16) = 12.3$, $p < .001$), and inversely, an increase in average dwell time ($F(2, 16) = 9.8$, $p < .01$). Variability of the dwell time (i.e., *SD*) also tended to increase with disparity ($F(2, 16) = 8.5$, $p < .01$).

Similar results emerged in the main experiment that examined the effect of $0'$ and $2'$ disparity across brief, moderate and extended viewing sessions

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[8] We note that our data is an ordered list (of time durations) rather than an event sampled at equal times as is usually the case in spectral analysis of standard time series. Nevertheless, our "duration" series does have ample precedent. For example Bassingthwaighte, Liebovitch, & West (1994) plot the power spectrum of the interval between heartbeats, and Musha, Sato, & Yamamoto (1991) show other biological examples.

Furthermore, a power-law spectrum of durations is also a power law for frequencies since the duration is the inverse of the frequency, although the slopes will differ. For example, a $1/f$ power law for durations will give a power law proportional to f for the corresponding frequencies. But differentiating a $1/f$ time series of durations (taking first-differences) will produce a $1/f$ power law in frequency. In general, if a quantity obeys a power law, any quantity proportional to any power of it will also be a power law.

Table 1. Summary of Mean Flips per Minute and Average Dwell Time (ms) from a Preliminary Test of 0′ to 4′ Disparity Influences on Flipping Frequency in the Necker Cube. Low and High Depth Groups Differed by a Factor of 2. Standard Deviations are in Parentheses

	Disparity		
Depth group:	0′	1′	2′
Low			
	16.8 (3.3)	12.5 (3.7)	10.5 (2.3)
	3694 (813)	5102 (1356)	6033 (1706)
	0′	2′	4′
High			
	16.3 (5.9)	10.9 (2.0)	10.5 (3.1)
	4060 (1386)	5656 (979)	6204 (2073)

(i.e., approximately 15, 30 and 60 minute sample times).[6] Total flipping frequency decreased with disparity ($F(1, 37) = 11.7$, $p < .01$), and increased with overall viewing duration ($F(2, 37) = 5.4$, $p < .01$). To remove the obvious confound of total flipping frequency and experimental duration, we assessed mean flipping frequency per minute. As shown in Fig. 4, average flipping frequency is inversely related to disparity ($F(1, 36) = 5.6$, $p < .05$), and overall viewing duration: greater disparity and longer viewing *reduced* flipping frequency ($F(2, 36) = 3.9$, $p < .05$).[9] Disparity and duration effects were additive ($F(2, 36) = 0.1$, *n.s.*).

A variety of analyses support these trends including the inverse finding that average dwell time increased with viewing duration—brief ($M = 8.4$ sec, $SD = 10.0$), moderate ($M = 9.7$ sec, $SD = 12.0$), and extended viewing ($M = 15.1$ sec, $SD = 17.0$; $F(2, 37) = 3.3$, $p < .05$). The clear influence of viewing time on flipping frequency and average dwell time is suggestive of a system that possesses scaling properties.

Analyses of the data distributions of the perceptual flip series were also consistent with a system that scales over time. A preponderance of brief intervals in the data produced probability distributions with a clear positive skew (M Skew $= 1.3$) and leptokurtic shape (M kurtosis $= 2.2$). Figure 5 shows typical probability distributions with skew and kurtosis tending to be larger in the 0′ disparity conditions (M Skew $= 1.4$; M Kurtosis $= 3.4$) relative to 2′ conditions (M Skew $= 1.1$; M Kurtosis $= 1.0$), but are similar across different viewing durations.

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[9] This trend was highly significant after removing one outlier that was 3 *SD*s above the mean. This case was included in all other analyses since no other outliers emerged and significance levels were not affected. Also, two of the 40 subjects participated only in the 0′ disparity condition. Therefore, the missing data in the 2′ condition was filled in with group means for statistical analyses, but the reported significance levels were not affected by this procedure.

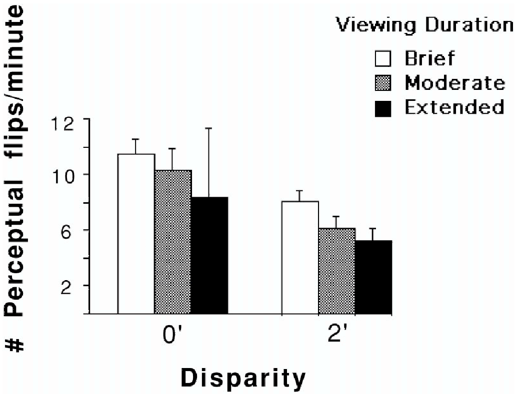

Fig. 4. Number of perceptual flips per minute in the 0′ and 2′ disparity conditions for brief, moderate, and extended viewing times. Increased disparity and viewing duration reduces flipping frequency.

An additional measure showing scaling properties is "relative dispersion" (*SD/M*; e.g., Liebovitch, 1998). This measure reflects system contingencies as function of sampling resolution, or in this case—viewing duration. As is shown in Fig. 6, relative dispersion (i.e., contingencies) tended to increase with average dwell time and decrease as the overall viewing duration increased. One final analysis of data distributions showed that

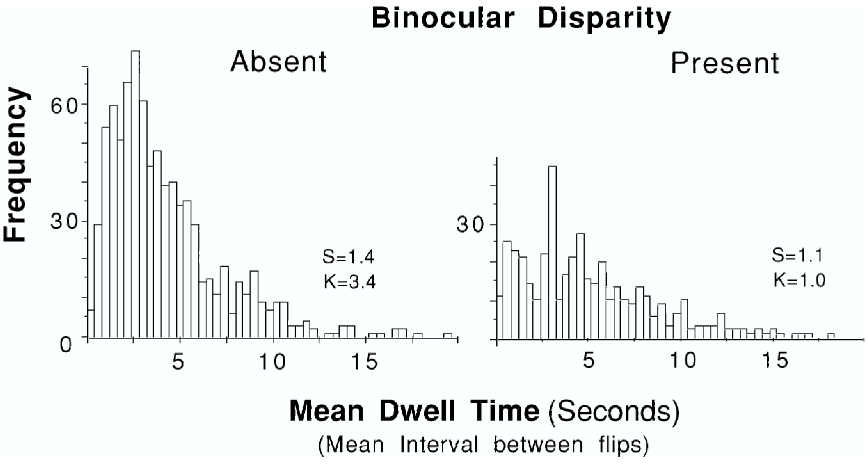

Fig. 5. Average probability distributions representing perceptual shifting that occurs while subjects view the Necker cube in the presence vs. absence of disparity.

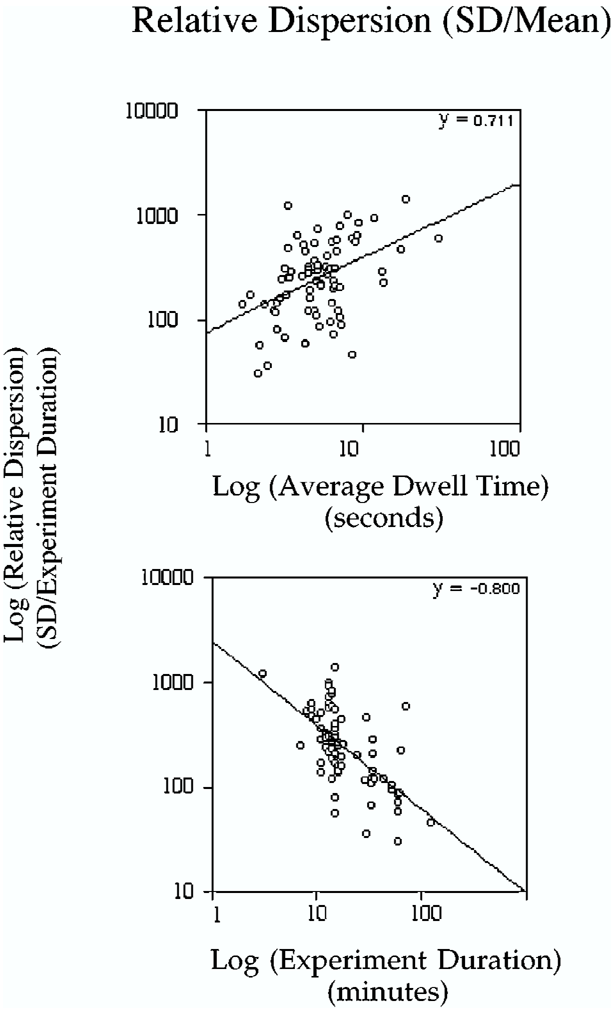

Fig. 6. Relative Dispersion (*SD*/*M*) increases with average dwell time and decreases with overall viewing duration.

variability (*SD*s) of the average dwell times tended to increase with viewing duration, although only reaching marginal significance ($F(2, 37) = 2.4$, $p = .10$).

Fourier analysis (FFT) revealed a consistent pattern of correlation or "coloring to the noise" that was reliably affected by the degree of disparity, and the duration of viewing the Necker cube. Fourier analyses produced

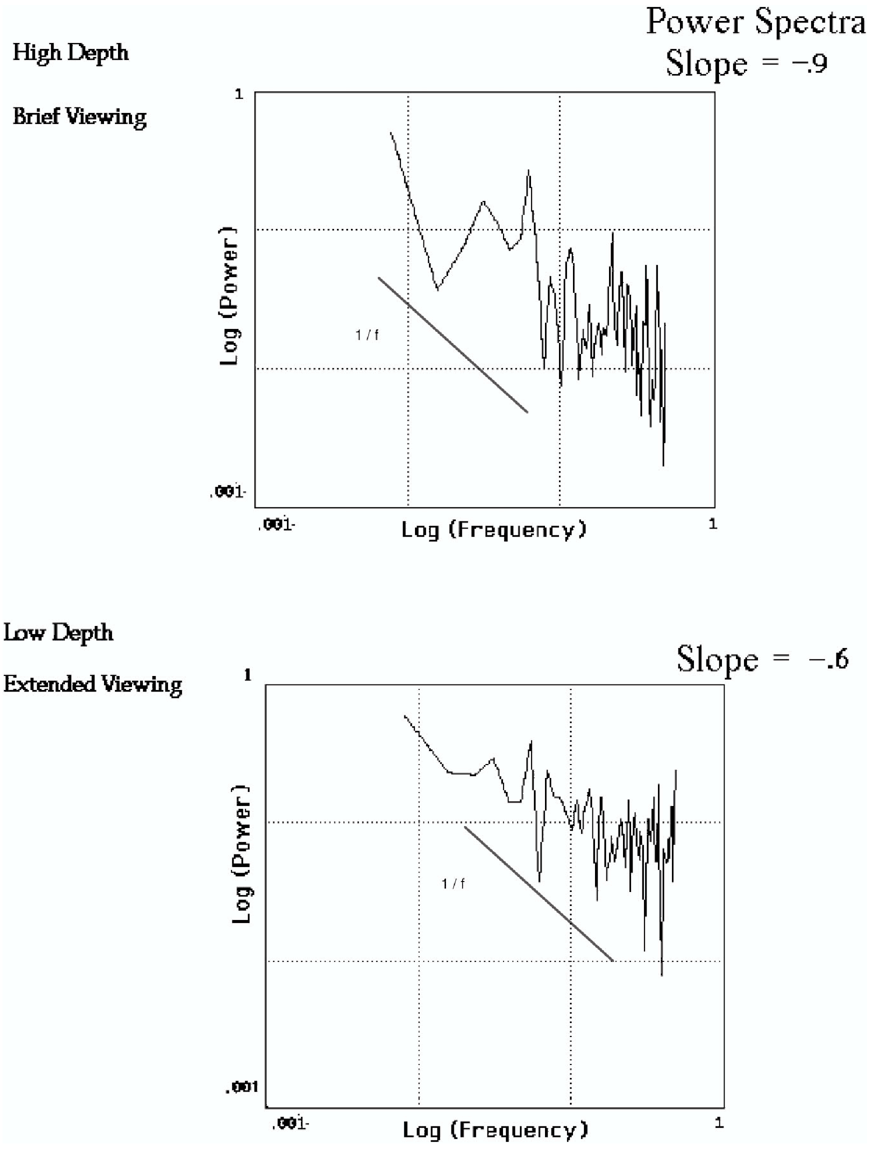

Fig. 7. Typical power spectra have 1/*f* trends. More disparity and brief viewing produce steeper slopes in the power spectra.

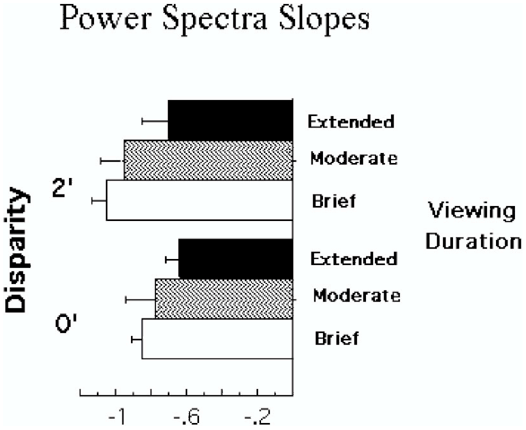

Fig. 8. Mean power spectra slopes are $1/f$. Slopes tended to increase with disparity and decrease with viewing time.

power spectra with $1/f$ pink noise in 80% of the 40 cases.[10] Typical power spectra are shown in Fig. 7 along with a demonstration of how increased disparity and reduced viewing time produce steeper slopes in the spectra (*M* slopes: $0' = -0.7$ vs. $2' = -0.9$, and brief $= -0.9$ vs. extended -0.7). Autocorrelations were consistent with these trends in $0'$ conditions showing a decrease in correlation from $r = .18$ in brief viewing, to $r = .05$ in extended viewing conditions.

Since all previous analyses are based on data from *alternating* percepts, instabilities might have been introduced into the data series. Therefore, we also performed power spectra analyses on alternate data points to assess the dynamic of the *same* percept obtained from the shifting perceptual series. Similar trends emerged for these analyses on alternate data points as shown in Fig. 8. In both cases, there were steeper power spectra slopes in brief viewing and $2'$ disparity conditions. The only change was the slightly steeper slopes in the alternate data point than the full data analysis. Additional analyses that assessed the reliability of the $1/f$ power spectra trends across individual power spectra confirmed these trends—reduced viewing duration and increased disparity produced spectra with a greater proportion of the spectra having $1/f$ trends.

[10] There is some ambiguity to the power spectra, and it is possible that these trends can also result from a combination of $1/f^0$ and $1/f^2$. Gilden (2001) describes this issue in interpreting the power spectra derived from inherently noisy human data, in which simple motor responses, for example, are known to introduce white noise into the data. Nevertheless, the reliability of the $1/f$ trend across the majority of subjects suggests this is likely a reflection of an underlying $(1/f)$ mechanism rather than superposition of noise.

DISCUSSION

Complex systems theory provides fresh insights into understanding complex behavioral systems. This perspective led us to predict that aspects of our visual system (e.g., perceptual-switching mechanism) may be modeled by simple cellular-automata type rules that produce self-organizing, emergent behavior. We started this investigation by looking at the effect of disparity and viewing duration on human perception of the Necker cube. Using Fourier, correlational and descriptive analyses of the data, we found an intrinsic dynamic to human perceptual shifting with clear signs of scaling and $1/f$ pink noise. Both properties suggest the system is highly adaptive and has self-organizing properties. Our additional finding of increased power spectra slopes across increasing disparity conditions suggests binocular disparity may serve to stabilize perception. We believe this may occur either by disparity acting to filter out extraneous information (i.e., white noise) or perhaps, it signals the system to rely more on previous percepts.

Scaling and $1/f$ Properties

Evidence for a scaling relation between perceptual reversals and time appeared in shifts in the means, variance and the shape of the probability distributions with different viewing durations. Such a relationship often appears in highly flexible and adaptive systems possessing a fractal structure. Unlike Gaussian distributions, with means and variance tending to converge to a constant value over time, flipping frequency tended to decrease over time. In addition to being a signature of a fractal, these time dependent changes suggest that priming from a prior state, or perhaps, fatigue to a changing state, may have mediated the dynamic of perception. Either way, we see clear evidence here for a fractal system with characteristic properties that change over time and circumstance.

Fractal properties are significant in that they can serve as an efficient and compact means of coding perceptual information, and may prove optimal for extracting information from the environment. Specifically, the presence of $1/f$ noise, such as in an SOC system, represents an optimal compromise between efficient transfer of information and tendency to err (Voss, 1992). Since biological systems must work on-line, computational complexity and data compression are critical to effective functioning in a dynamic environment. We believe that transitions in perceptual states may be well matched to the statistical redundancy of the visual environment (Field, 1993), and thus permit perceptual sampling and extraction of self-similar information with properties similar to those used in fractal image-compression (Daugman, 1988; Field, 1993; Watson, 1987).

The universal power relation that emerged in the Fourier analysis further confirmed the scaling and fractal properties of perceptual switching. The particular $1/f$ dynamic also suggests there is long-term determinism in a system that is often regarded as random. The long range effects are indicated by the preponderance of low frequency components in the power spectra. Moreover, these $1/f$ trends associated with perceptual flipping are consistent with the possibility that our perceptual system may be governed by a self-organizing system as described in Fig. 3. Particular models such as SOC may provide a straightforward account for the emerging behavior that typifies perception of the Necker cube. But note that finding $1/f$ patterns in our data does not mean that such a process necessarily generated it. These trends may be a consequence of any of a number of processes some of which are currently being investigated (e.g., Miller, Miller & McWhorter; 1993; De Los Rios & Zhang, 1999).

Depth as a Filter of Noise or a "Signal-to-Remember"

The cumulative effect of disparity and time on perceptual flipping suggests that scaling and the associated perceptual dynamic is mediated by depth. Relative to the $2'$ disparity conditions, the more ambiguous $0'$ conditions produced distributions with greater skew and leptokurtic shapes. These shifts in distribution shape with depth are due to the more frequent flipping (or greater preponderance of brief dwell times) in the absence of depth information. The higher frequency of flipping in the $0'$ disparity conditions also produced shallower slopes in power spectra. Shifts in the distribution shape and slope may be a manifestation of 1) filtering of white noise, or 2) memory in the system. In the first case, since the presence of white noise may increase the frequency of shifting perceptual states, depth information may act as a filter of white noise, and guide our perceptual system to coherent interpretations.

A mechanism based on memory is also plausible in light of the idea that coherent percepts may guide subsequent percepts. Since ambiguous states do not serve as a useful guide to subsequent percepts, the perceptual system may turn to the more reliable external source of disparity information. Thus, the steeper spectra that emerged in high disparity conditions could reflect greater filtering of white noise, or greater reliance on previous states in our self-organizing, yet malleable, perceptual system.

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