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Fractal Structure of the Nested Actions in Keeping the Beat

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Abstract

The current experiments investigated the fractal structure in the nested actions of tapping behavior. The results revealed that task constraints (e.g., tapping to a metronome) alter the fractal structure of a given aspect of the behavior (e.g., inter-tap interval) and decouple its long-term interactions with other aspects of the behavior (e.g., key-press duration). These results support the idea that fractal structure reflects the dynamical organization of complex systems.

Keywords: complex systems, fractal scaling, finger tapping

Introduction

There is certainly no shortage of complexity for the student of human mind and behavior. The human system is at once physical, chemical, biological, psychological, and social. We cognitive scientists carefully design experimental tasks and manipulations to gain an empirical purchase on the many forces that shape human behavior. Traditionally, the field has relied on classical techniques of linear statistics. We take different averages or degrees of variability in reaction time to be indicative of the cognitive processes underlying performance in our experimental tasks. Recently, however, researchers have turned to examining more subtle and complex statistical facets of data to understand the processes involved in the organization of human behavior; namely, fractal structure.

Comprehensive review of this statistical property, the available mathematical techniques for its assessment, and the potential implications for theories of cognitive science is not possible in the limited space provided here (see Brown & Liebovitch, 2010; Delignieres & Marmelat, 2013; Holden, 2005; Van Orden Kloos, & Wallot, 2010). Nonetheless, a brief introduction to the topic is warranted. The term "fractal structure" is here being used loosely to refer to patterns of variability in repeated measurements of human behavior. Most traditional, linear statistical techniques operate on the assumptions that deviations from mean performance will obey a Gaussian distribution and that these "errors" will be uncorrelated with one another. Data displaying fractal structure violates these assumptions. That is, fluctuations in repeated performances exhibit "long-term dependencies" such that errors in early observations are correlated with errors in much later observations. Fractal data obey power-law scaling such that size of a given error is inversely proportional to how often errors of that size occur. Thus, like geometric fractals, these data are said to be "self-similar" and "scale-invariant". Fractal data entail nested patterns of variability wherein small variations in measurement have the same structure as large variations. Such structure in repeated measurements is often referred to as "pink noise", as contrasted against the random variation entailed in "white noise" (Holden, 2005).

In part, these patterns are important to researchers in cognitive science as they have been discovered in a plethora of human data from the simplest of reaction time tasks taking place over the course of minutes (Van Orden, Holden, & Turvey, 2003) to measurements of self-esteem over a many months (Delignieres, Fortes, Ninot, 2004). More importantly, experimental manipulations of the type typically employed by cognitive scientists have been shown to affect fractal structure. For instance, Kello et al., (2007) demonstrated that reaction times to unpredictable cues were not only slower, but also closer to white noise (i.e., random) variation, than reaction times to predictable cues.

Despite their widespread occurrence, there is not yet a unified account of how these fractal patterns get into the data or what they imply for theories of cognitive science (e.g., Van Orden, Holden, & Turvey, 2005; Wagenmakers, Farrell, & Ratcliff, 2005). The current experiments are intended to contribute to the on-going discussion by examining the fractal structure in the nested actions in a tapping task, their dynamical interaction with one another, and the impact of employing different task constraints.

Experiment 1

Most statistical techniques used to assess fractal structure require very many observations made under relatively constant task conditions. As such, research revealing these structures in human behavior has typically preferred very simple tasks. One frequently studied task is finger tapping (e.g., Chen, Ding, & Kelso, 2001; Chen, Repp, & Patel, 2002; Gilden, Thorton, & Mallon, 1995; Lemoine, Torre, & Delignieres, 2006; Madison, 2001; Musha, Katsurai, & Teramachi, 1985; Ogden & Collier, 1999; Yamada, 1995).

Generally, studies have found evidence of fractal structure in continuation tapping, wherein participants attempt to keep a steady beat briefly demonstrated to them by a metronome stimulus at the beginning of a trial. In this case, the intervals between taps take on a "persistent" structure (i.e., longer taps tend to be followed longer taps). Interestingly, the fractal structure is different during synchronization tapping, wherein participants synchronize their taps to a constant metronome stimulus. In this case, the intervals between taps take on an "anti-persistent" structure, (i.e., longer taps tend to be followed by shorter taps) whereas the asynchronies between the participant's taps and the metronome show a persistent fractal structure. These findings have been interpreted and modeled as the result of the metronome serving as a corrective feedback mechanism for the maintenance of a given tapping interval (Torre & Delignieres, 2008).

While these results are reasonably well-understood, to date there have been no investigations of the nested actions comprising finger tapping. That is, most tasks require a behavior that consists of many "sub-actions", all of which may not be measured or examined. In tapping, the task requires striking the key, holding it down for some period of time, releasing the key, and waiting some period of time before striking the key once more. Our first experiment was designed to investigate the fractal structure in these nested actions during continuation tapping, how these nested behaviors might interact with one another across the measured span of behavior, and what differences might be evident during synchronization tapping.

Method

Participants

Sixteen undergraduate students from the University of Cincinnati participated in the study for partial course credit. All participants were over 18 years of age and right-handed.

Apparatus

The participants' tapping behavior was recorded using a USB midi keyboard. The keyboard was connected to a PC computer running Ableton Live (Ableton, Berlin Germany). This software was used to simultaneously record the time-series of the participants' taps (with a ±5 ms error) and present the auditory metronome stimulus to the participant through a pair of headphones.

Procedure and Design

After informed consent, participants were instructed that they would complete two trials of tapping behavior while being presented different auditory stimuli. They were then shown how to produce the desired tapping behavior; namely, by resting their right hand on the table and producing taps with their index finger on a key marked with a small piece of tape, being sure to depress and release the key entirely on each tap. Each participant first completed the continuation tapping condition. The stimulus consisted of 10 seconds of a 2 Hz metronome (500 ms between beats) followed by 10 minutes of silence. Participants were instructed to synchronize their taps to the metronome for the first 10 seconds, and then to maintain that same beat without the metronome for the remainder of the trial. Each participant then completed the synchronization condition. In this trial, the stimulus simply consisted of 10 minutes and 10 seconds of a 2 Hz metronome. Participants were instructed to synchronize their taps to the metronome for the duration of the trial. At the conclusion of the experiment participants were thanked and debriefed.

Data Analysis

The data output by the recording software were collated to yield three different time-series for each trial. The first series contained inter-tap intervals (ITI) where data signified the time elapsed between each tap and the following tap. The second series consisted of key-press durations (KPD) where data signified the time the key was depressed on each tap. The third series consisted of key-release intervals (KRI) where data signified the time between the release of the key of each tap and the following tap. The relationship between these three measures of tapping behavior is depicted in Figure 1. Note that these variables are not independent. For any given tap, determining any two of the variables completely determines the third as well. Thus, we consider this data set to properly consist of only two pieces of information. Nonetheless, we will use all three variables for reasons that will become apparent.

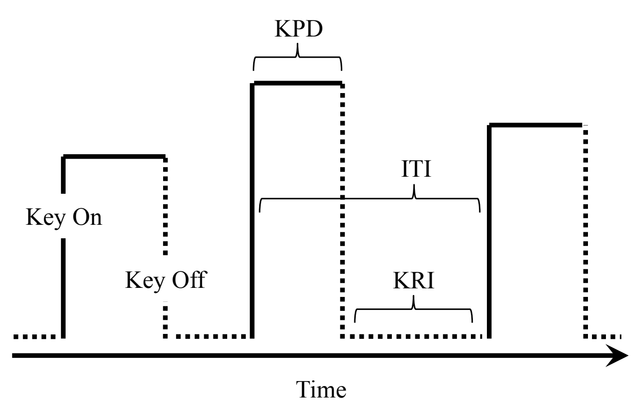

Figure 1: The figure portrays a sequence of three taps and the three measurements collected for each tap.

Prior to fractal analysis, each time-series was subjected to several pre-processing steps to eliminate outliers and linear trends that might otherwise affect the outcome of the test (see Eke et al., 2000; Delignieres et al., 2006). Specifically, individual taps were removed from the data set when either the corresponding ITI was outside the range of 300-700 ms, or the corresponding KPD was greater than 500 ms. These values were chosen to reflect instances in which the participant failed to either depress or release the key entirely or failed to keep their taps close to the prescribed tempo. When a tap met either of these exclusion criteria, it was removed from each of the three measurement series. Following outlier removal, each time-series was trimmed to 1024 taps as the fractal analysis employed requires series of a length equal to a power of two. Finally, a linear bridge detrending was applied to each series.

The pre-processed series were submitted to a power spectral density (PSD) analysis to assess fractal structure. First, each series is standardized by Z-scoring each value. Then each series is approximated by a set of sinusoids with variable power and frequency by a Fourier transformation. As described above, fractal data obey power-law scaling wherein the size of each deviation is inversely proportional to how often deviations of that size occur. This relationship can be expressed mathematically between the power (P) and the frequency (f) of the sinusoids generated by Fourier transformation, where $P = 1/f^{\alpha}$. The "scaling exponent" (α) summarizes the nature of the fractal structure evident in the series with persistent fractal structure indicated by $\alpha \approx 1$, with random, white noise structure indicated by $\alpha \approx 0$, and anti-persistent structure indicated by $\alpha \approx -1$. An estimation of α can be obtained by plotting power against frequency on double-logarithmic axes, and finding the slope (S) of the regression line that best fits this "spectral plot", with $\alpha = -S$. In accordance with past research, we estimated α from only the lowest portion (25%) of the power spectrum (Eke et al., 2000; Delignieres et al., 2006).

We also sought to investigate the dynamical interaction of the three measures (ITI, KPD, KRI). To this end, we used cross-correlation analyses. Similar to auto-correlation, cross-correlation computes the correlation between two series across a range of time-lags. The cross-correlation function therefore can capture dependencies between the different tapping variables that exist across several taps.

Results and Discussion

Participants generally had no trouble completing the task and there were on average only 5.5 outlier taps per trial. Generally, there were no significant differences in either the means or standard deviations for any of the three variables as a function of experimental condition (all *p*'s > 05). The sole exception was that the standard deviation for ITI was smaller during synchronization (M = 26.5 ms, SD = 4.58) than during continuation tapping (M = 31.4 ms, SD = 8.12), $t(15) = 2.57$, $p = .021$.

PSD Analysis

The change in the fractal structure in ITI across experimental conditions was consistent with the findings of past research (e.g., Chen et al., 2001; Gilden et al., 1995). Specifically, there was a significant decrease in α from persistent structure during continuation tapping (M = .60, SD = .20) to anti-persistent structure during synchronization tapping (M = -.48, SD = .58), $t(15) = 7.79$, $p < .001$. Both KPD and KRI showed different patterns of results. There was a small but significant increase in α for KPD from continuation (M = .71, SD = .23) to synchronization tapping (M = .88, SD = .22), $t(15) = -2.41$, $p = .03$. Conversely, there was no difference in α for KRI between continuation (M = .66, SD = .18) and synchronization tapping (M = .60, SD = .30). This pattern of effects is depicted in Figure 2.

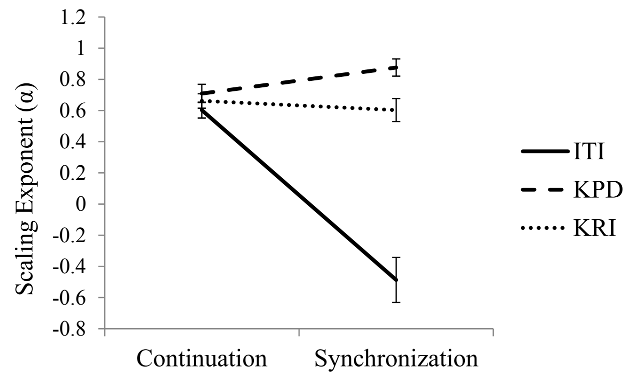

Figure 2: Change in α for ITI, KPD, and KRI from the continuation to synchronization tapping conditions.

Although the observed difference in the fractal structure in ITI is in line with the results of the past tapping research, the effects for KPD and KRI are new findings without established theoretical interpretations. One proposal endorsed by several researchers is that the fractal structure evident in ITI during continuation tapping, and in the asynchronies to the metronome during synchronization tapping, is the empirical signature of the emergent behavior of complex systems (e.g., Chen et al., 2001; Gilden, 2001; Lemoine et al., 2006; Yamada, 1995). Briefly, this account asserts that the structures present in the data are reflective of the dynamical organization of the behavioral system that produced them. The implication is thus that the observed fractal structure does not issue from one particular cognitive or physiological component. Rather, the variation in behavior is the collective result of the interaction of many interdependent processes (Holden, Van Orden, Turvey, 2009). To attempt to extend this account to the results of KPD and KRI, we examined the cross-correlations between the three measures of tapping behavior in hopes of revealing the nature of their dynamical interaction.

Cross-Correlation Analysis

The cross-correlation functions for ITI-KRI and for KPD-KRI are depicted in Figure 3. As these functions were found to be roughly symmetrical across negative and positive lags, only the positive half of the function is shown here.

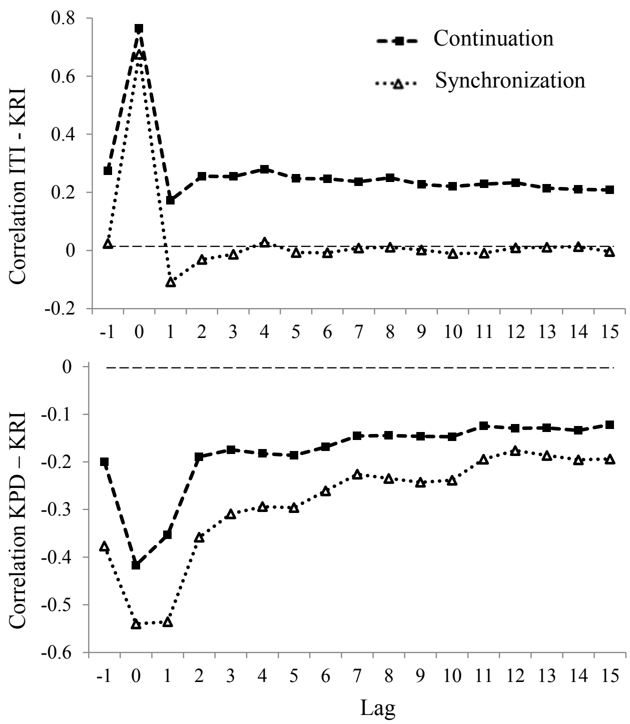

Figure 3: Cross-correlations for ITI-KRI and KPD-KRI.

As discussed above, "long-term dependencies" are entailed in fractal variation within a single behavioral measure. The upper panel of Figure 3 suggests that similar long-term dependencies exist between the nested actions involved in continuation tapping behavior. Specifically, the full interval between taps (i.e., ITI) is moderately correlated with the sub-interval (i.e., KRI) out to 15 taps and later. Interestingly, all of this long-term structure is absent during synchronization tapping. This suggests that the constraint of the metronome effectively "decouples" these two dynamics of the tapping behavior. The same basic pattern was evident in the cross-correlation function for ITI and KPD, although it was less pronounced.

In contrast, the cross-correlation function for the two sub-intervals (KPD and KRI) reveals a fundamentally different pattern across task conditions (lower panel Figure 3). During continuation tapping these variables reveal a moderate negative long-term correlation with one another. Most interestingly, this long-term structure is not damped out by the advent of the metronome in synchronization tapping, but rather grows stronger (i.e., more negative).

It is important to note that the measurement variables analyzed in this experiment are just one window into the processes underlying the tapping behavior. Recall, these variables are not strictly independent. As such, one might contest that the cross-correlation between KPD and KRI does not reflect the relationship of two separate variables, but simply variation in the times when the key was released. This is essentially correct. As revealed by PSD, and explicated by cross-correlation, the persistent structure in these sub-intervals is unaffected, or is actually stronger, when the metronome constrains the interval between taps (i.e., ITI). Interestingly, this structure in key release times cannot simply be accessed by taking the difference of the key release times (IRI). Submitting IRI to PSD reveals the exact same pattern of effects found for the ITI variable; persistent structure during continuation tapping (α = .55), and slightly anti-persistent structure during synchronization tapping (α = -.33). As such, this variable accesses the same structure in the time between taps as does ITI. Thus, the two independent (sub)behaviors entailed in this task might be best construed as the "tap-to-tap" behavior and the "between-taps" behavior, with our measurement variables being only convenient windows into these dynamics.

Experiment 2

Experiment 2 was designed to further investigate the interplay of these nested actions and how task constraints affected their fractal structure. To our knowledge, only one other study has investigated the fractal structure in multiple, nested actions. Kello et al., (2007) conducted a series of reaction time experiments in which they recorded not only the time taken to respond to a stimulus, but also the length of time the participants depressed the key on each response. Taken together, these experiments suggested that reaction times and key contact times were not correlated with one another, and that the fractal structure in reaction times could be affected independently of the structure in key contact times. They did not, however, actually attempt to alter the fractal structure of the key contact times directly. The purpose of Experiment 2 was thus to attempt a manipulation that might constrain the between-taps behavior (i.e., KPD) in our tapping task and thereby investigate the relationship between task constraints and fractal structure generally.

Method

Participants

Twenty-two undergraduate students from the University of Cincinnati participated in the study for partial course credit. All participants were over 18 years of age and right-handed.

Procedure and Design

The design was nearly identical to that of Experiment 1. The primary difference was that half of the participants were instructed not only to synchronize their taps to the metronome during the synchronization condition, but also to attempt to keep the key depressed for the length of the metronome tone. So that the length of the tone would be salient to the participants, the metronome stimulus consisted of alternating 400 ms tones and 400 ms periods of silence.

Prior to this additional manipulation, each participant first completed the continuation tapping condition. In this trial, participants were played the metronome for 10 seconds, and then attempted to maintain the same beat for 8 minutes. Each participant was then given task instructions according to their experimental group and completed the synchronization condition. Participants in the "hold" group both synchronized their taps with the metronome and held the key down for the length of the tone, while participants in the "tap" group simply synchronized with the metronome.

Due to the change in the prescribed tempo of the tapping behavior, the criteria for outlier taps changed. Here, taps were discarded from the data set when either the corresponding ITI was outside the range of 600-1000 ms, or the corresponding KPD was greater than 800 ms. Also, as this frequency of tapping yielded approximately 600 taps within each trial, the time-series were trimmed to 512 points rather than 1024. The final, pre-processed time-series were submitted to PSD and cross-correlation analyses as before.

Results and Discussion

As in Experiment 1, participants had little difficulty with the task and there were on average only 9.8 outlier taps per trial. There were, however, several effects in the linear statistics of the tapping variables. Most importantly, there was a significant interaction effect for mean KPD, $F(1,20) = 8.84$, $p = .008$. Mean KPD for the hold group increased strongly from continuation tapping ($M \approx 270$ ms) to synchronization tapping ($M \approx 440$). In contrast, the tap group KPD only slightly increased from continuation ($M \approx 250$) to synchronization tapping ($M \approx 300$). This finding is important in that it indicates that the manipulation between groups was successful in altering their tapping behavior. There were other significant effects in the linear statistics, but as their theoretical import is less germane to the discussion at hand they are not reported.

PSD Analysis

As depicted in Figure 4, both groups showed a significant decrease across condition for ITI, and no significant change across condition for KRI. The groups differed, however, in the change in α for KPD. As in Experiment 1, the tap group showed a (marginally) significant increase in α from continuation ($M = .59$, $SD = .23$) to synchronization tapping ($M = .75$, $SD = .24$), $t(10) = -2.08$, $p = .064$. Remarkably, this effect was reversed for the hold group, showing a significant decrease from continuation ($M = .93$, $SD = .33$) to synchronization tapping ($M = .78$, $SD = .27$), $t(10) = 2.25$, $p = .05$. This effect buttresses the results of Experiment 1. The fractal structure of KPD changes in the same direction as that of ITI when both of these aspects of tapping are constrained by the metronome (i.e., for the hold group).

Cross-Correlation Analysis

The results of the cross-correlation analysis compliment the findings of the PSD analysis. As in Experiment 1, the long-term dependencies between ITI and KPD or KRI evident during continuation tapping are absent during synchronization tapping. Recall, in Experiment 1 this pattern was reversed for the KPD-KRI cross-correlation. That is, the long-term correlations were stronger during synchronization tapping. This same effect is evident in the cross-correlations for the tap group (upper panel Figure 5). For the hold group, however, this effect is largely absent (lower panel Figure 5). As suggested by the PSD analysis, the KPD of the hold group was constrained by the metronome stimulus. As with ITI, this task constraint appears to have lessened the long-term dependency between these two aspects of the tapping dynamics.

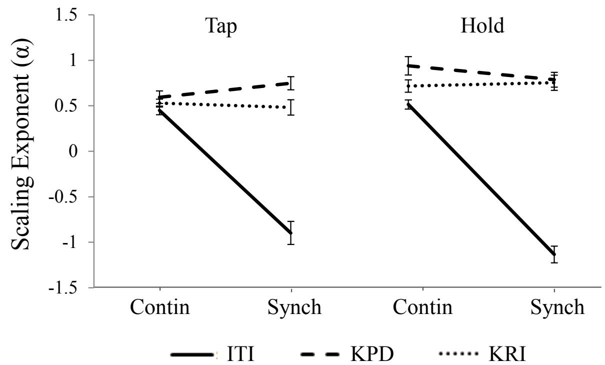

Figure 4: Change in α for ITI, KPD, and KRI across tapping conditions by experimental group.

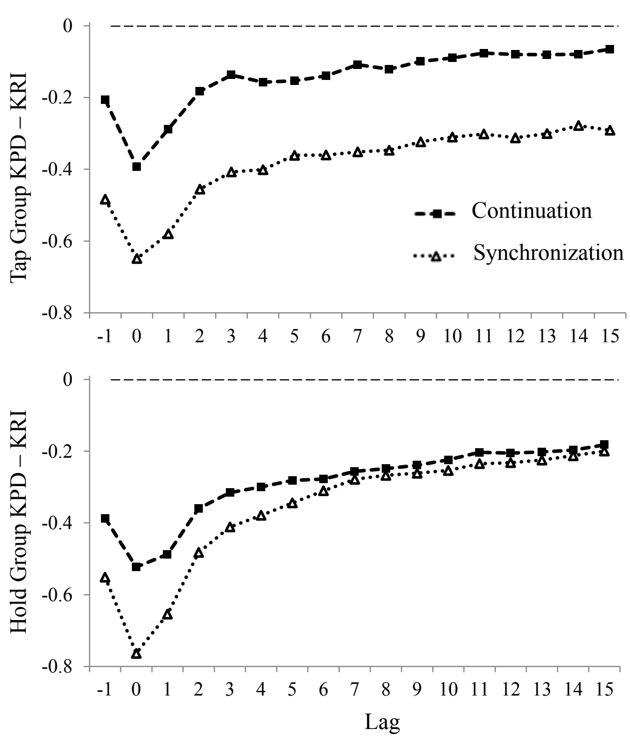

Figure 5: KPD-KRI cross-correlation function by experimental group.

General Discussion

The current experiments support and extend the previous findings on the fractal structure of finger tapping behavior. Although the measurement variables used in these analyses (i.e., outputs of the MIDI keyboard) might prove only a convenient window into the dynamics of finger tapping behavior, the results do reveal a consistent relationship between the long-term interplay between the different parts of the tapping behavior and how changes in task constraints affected this long-term structure. Specifically, these experiments suggest that when control of any (sub)behavior can be sustained with the aid of task constraints that behavior is effectively decoupled from other parts of the action and shows a reliable shift in its fractal structure.

Though superficially finger tapping may not seem to bear weightily on the issues of interest to the cognitive sciences, these findings do speak to larger theoretical questions about the organization of human mind and behavior. In particular, several researchers have proposed that fractal structure in human behavior reveals the "interaction-dominant" nature of the human system (see Van Orden et al., 2010). That is, these findings suggest that the behavioral in question is not the result of one dominant process (e.g., an internal timer), but instead is organized by many interdependent processes. Whereas more traditional views promote a modular, disembodied impression of the cognitive process, these findings suggest that a behavior as simple as keeping the beat is the product of non-linear interactions across the participant-task system. In short, these ideas invite reconsideration of the nature of the cognitive process and hold promise for addressing the vast complexity inherent in the complete human system.

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