

## Entrainment to a real time fractal visual stimulus modulates fractal gait dynamics

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### **Abstract:**

Fractal patterns characterize healthy biological systems and are considered to reflect the ability of the system to adapt to varying environmental conditions. Previous research has shown that fractal patterns in gait are altered following natural aging or disease, and this has potential negative consequences for gait adaptability that can lead to increased risk of injury. However, the flexibility of a healthy neurological system to exhibit different fractal patterns in gait has yet to be explored, and this is a necessary step toward understanding human locomotor control. Fifteen participants walked for 15 min on a treadmill, either in the absence of a visual stimulus or while they attempted to couple the timing of their gait with a visual metronome that exhibited a persistent fractal pattern (contained long-range correlations) or a random pattern (contained no long-range correlations). The stride-to-stride intervals of the participants were recorded via analog foot pressure switches and submitted to detrended fluctuation analysis (DFA) to determine if the fractal patterns during the visual metronome conditions differed from the baseline (no metronome) condition. DFA  $\alpha$  in the baseline condition was  $0.77 \pm 0.09$ . The fractal patterns in the stride-to-stride intervals were significantly altered when walking to the fractal metronome (DFA  $\alpha = 0.87 \pm 0.06$ ) and to the random metronome (DFA  $\alpha = 0.61 \pm 0.10$ ) (both  $p < .05$  when compared to the baseline condition), indicating that a global change in gait dynamics was observed. A variety of strategies were identified at the local level with a cross-correlation analysis, indicating that local behavior did not account for the

consistent global changes. Collectively, the results show that a gait dynamics can be shifted in a prescribed manner using a visual stimulus and the shift appears to be a global phenomenon.

**Keywords:** Gait | Fractals | Persistence | Global entrainment

**Article:**

## 1. Introduction

Healthy individuals produce temporal gait patterns, or rhythms, that are not consistent from stride to stride. Rather, each stride interval varies slightly due to the complex nature of locomotor control. These patterns not only reflect the coordination of many neuro-musculo-skeletal components to generate a fluid walking motion, but also reflect sensorimotor modulation by proprioceptive and visual information (Glass, 2001). Together they lead to variability in the stride-to-stride rhythm. The magnitude of the variability was once used as a marker of locomotor dysfunction. Specifically, greater variability was believed to be caused by imprecise locomotor control. However, further examination of the structure of the stride-to-stride variability has revealed that patterns emerge that exhibit self-similarity—termed a fractal pattern—at many different temporal scales (Hausdorff, 2007 and Hausdorff et al., 1995): a characteristic that is shared by living systems at many levels, including cardiac and respiratory rhythms as well as neural firing patterns (Glass, 2001 and West, 2006). Many names have been used to describe this structure, including persistence, long-range correlations,  $1/f$  scaling and pink noise. For consistency in this paper, we will use the term fractal when talking about self-similarity in general and the terms persistence (structured temporal fluctuations) and randomness (unstructured temporal fluctuations) to describe the nature of gait variability.

Fractal patterns in biological rhythms may reflect the underlying control processes that govern the system. For example, a change in the structure of physiological rhythms has been observed in disease and aging, suggesting that persistence in the variability patterns may reflect healthy functioning in biological systems (Van Orden, 2007 and West, 2006). This is true of the stride-to-stride variability in gait as well (Bartsch et al., 2007, Choi et al., 2011, Hausdorff et al., 1999, Hausdorff et al., 1997 and Lamothe et al., 2011). For example, Hausdorff and his colleagues have demonstrated a systematic shift from persistence toward randomness in the stride intervals of patients suffering from Huntington’s disease—a neurodegenerative disease affecting the central nervous system—as well as in aging gait (Hausdorff et al., 1997). Conversely, persistence is preserved in patients suffering from peripheral neuropathy (Gates & Dingwell, 2007)—a disease affecting the peripheral nervous system—and also in patients known to exhibit neuromuscular and proprioceptive deficits following an anterior-cruciate ligament injury (Rhea, Kiefer, D’ Andrea, Warren, & Aaron, 2010).

A breakdown in the temporal structure of stride intervals has also been shown to occur when individuals synchronize their strides with a standard auditory metronome (Hausdorff et al.,

1996), and this result has been replicated during the synchronization of finger taps to a metronome (Chen, Ding, & Kelso, 1997). It has been suggested that the metronome constrains the locomotor system by overriding the normal control processes that produce the gait rhythm, and that this ultimately leads to a breakdown in the temporal structure of stride intervals (Hausdorff et al., 1996). However, it should be noted that there is a lack of consensus about the nature of the observed changes in the temporal structure (Delignières & Torre, 2009).

The results of Hausdorff et al. (1996), and to a lesser degree those of Chen et al. (1997), demonstrate the utility of rhythmic stimuli as tools to probe the flexibility of the locomotor control system, in an effort to uncover the underlying control processes. In the context of this paper we define flexibility as the ability of the locomotor system to exhibit a range of behaviors. Since task and environmental constraints typically require different gait behaviors in order to be compliant with the demands, the ability of the individual to exhibit flexible locomotor behavior is a desirable characteristic for the emergence of adaptive, functional behavior. Previous research has shown that stimuli can be developed that influences the temporal structure of movement timing intervals in specific ways (Hove et al., 2012, Kaipust et al., 2012 and Stephen et al., 2008), and we utilize a similar method here to probe the flexible nature of the healthy locomotor system.

In the present experiment, we elected to test locomotor flexibility by employing a visual metronome, with specific timing patterns not typically observed in the gait of young, healthy adults, to determine if gait dynamics could be reliability shifted in a particular direction. While previous research has employed auditory stimuli to alter locomotor timing behavior (Hove et al., 2012 and Kaipust et al., 2012), however we elected to use a visual stimulus for two reasons. First, the impetus for our study was the observation made by Stephen et al. (2008) that long-range correlations in finger tapping inter-stimulus intervals could be reliably shifted in a particular direction when synchronizing to a visual metronome with a variety of fractal patterns. Thus, we elected to adopt their methodology to determine if a similar shift in dynamics would be observed in a more complex task (treadmill walking). Second, our research interests ultimately focus on how changes in gait dynamics could be retained following training. Visual stimuli may be useful in this context not only for their ability to alter gait dynamics, but could potentially lead to retention due to the perceptual or motivational effects. While Stephen et al. (2008) used a variety of fractal patterns to drive their visual metronome, and thus were better positioned to examine motor control flexibility, we elected to focus on dynamic patterns at the two extremes observed in human walking (random and persistent timing patterns). Thus the notion of flexibility was tested in our study by determining if gait timing could be bi-directionally shifted.

This approach could prove beneficial in rehabilitation because stride intervals that exhibit persistence may reflect more adaptive gait, due to the combination of a consistent yet flexible pattern of movement (Hausdorff, 2007 and Stergiou and Decker, 2011). Such locomotor behavior presumably enables the patient to walk safely throughout the environment by appropriately responding to threats to stability. Since a primary goal of locomotor rehabilitation

is to restore mobility in activities of daily living without risk of injury, incorporating training programs designed to redevelop persistence in stride intervals could lead to the re-emergence of adaptive gait, allowing the patient to more safely navigate the environment. However, a necessary first step is to establish the degree of flexibility in the stride intervals of healthy participants prior to attempting to change the gait of clinical populations. Thus, the goal of the current experiment was to determine whether locomotor control in healthy participants is flexible enough to be shifted bi-directionally, toward stronger persistence *or* randomness. The present experiment tested whether a metronome could be used to alter the fractal structure of stride intervals during walking in healthy adults. Specifically, we employed two different visual metronomes with beat intervals exhibiting either persistence or randomness (see Section 2 for details) in order to investigate stride intervals across a spectrum. We hypothesized that synchronizing the gait to a stimulus exhibiting greater persistence than normal gait would lead to an increase in the strength of the long-range correlations in stride intervals. Conversely, we hypothesized that synchronizing gait to a stimulus exhibiting randomness would lead to weaker long-range correlations in stride intervals. Since the inter-stimulus intervals were variable, we did not expect the participants to perfectly match the local temporal structure. However, the global temporal structure was prescribed in a specified manner, which is information that participants have been shown to attune to in order to drive their visual-motor timing dynamics (Stephen et al., 2008). Thus, we expected the overall (global) fractal structure of participants' stride intervals to shift toward the fractal structure of the metronome when considered across the entire trial, rather than a reliance on consistent local coupling strategy to drive the stride interval dynamics.

## 2. Methods

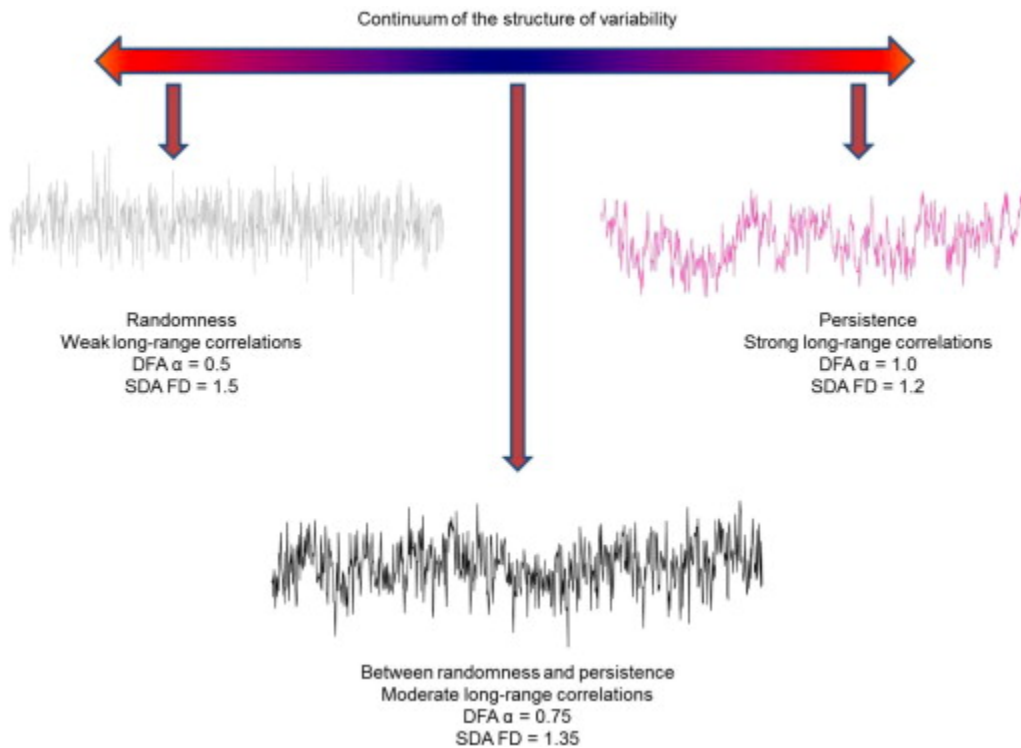
### 2.1. Participants

Fifteen young, healthy adults (8 males and 7 females; age:  $27.8 \pm 4.4$  yrs; height:  $1.70 \pm 0.09$  m; weight:  $66.9 \pm 12.6$  kg) participated. All procedures were approved by the Institutional Review Board at the Providence VA Medical Center and conformed to the principles expressed in the Declaration of Helsinki. All participants signed a written informed consent form. All participants were screened to ensure they did not have any neurological disorders or injuries that would preclude them from walking normally, and had normal or corrected-to-normal vision.

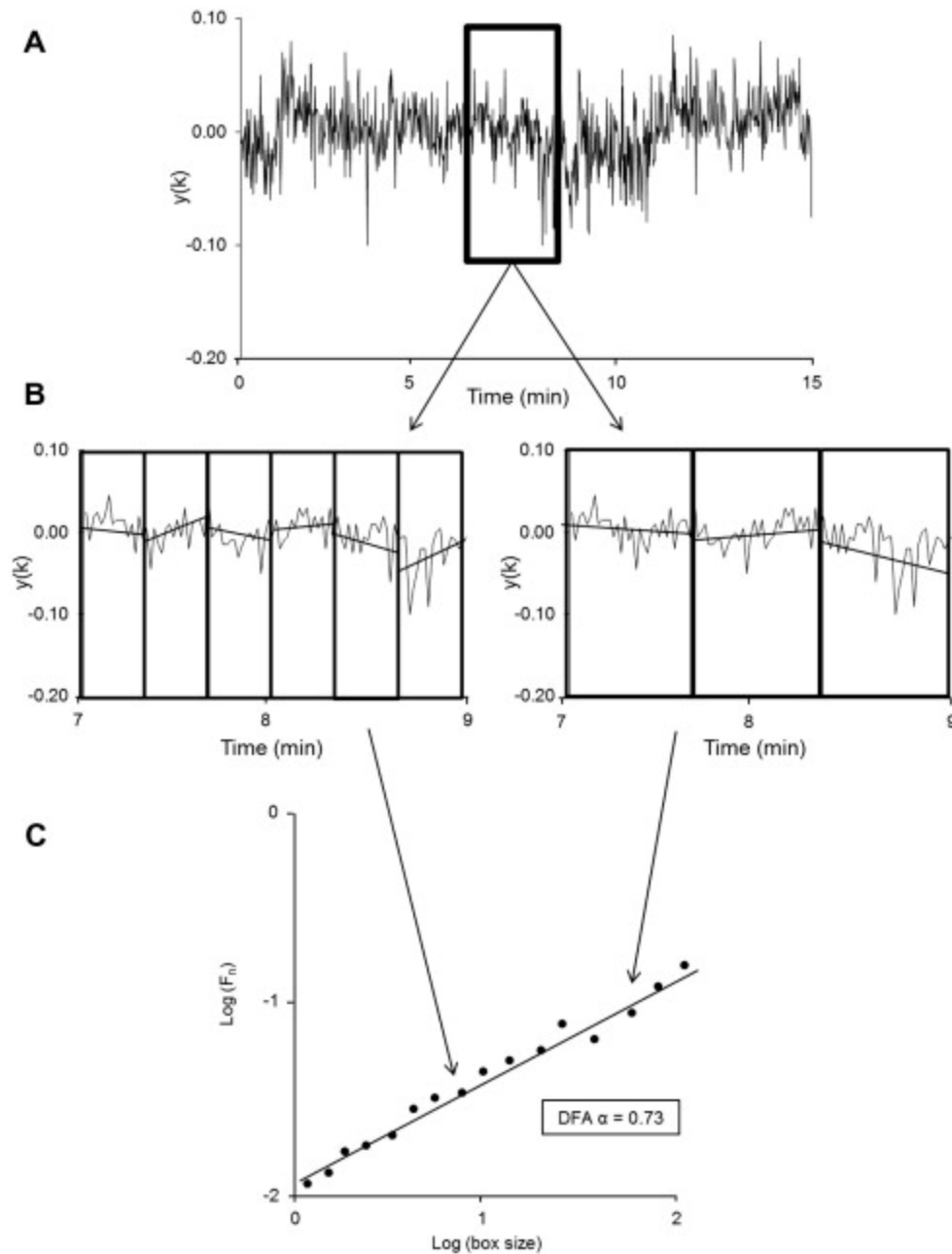
### 2.2. Procedure

The visual metronome was created by generating two time series, each consisting of 750 data points, using a previously published algorithm designed to prescribe fractal properties to a data set (Little, McSharry, Roberts, Costello, & Moroz, 2007). Both time series were bounded from 1.10 to 1.40 s and had a mean of  $1.25 \pm 0.07$  s, which is approximately the mean time of a healthy adult's stride interval (Hausdorff et al., 1995 and Hausdorff et al., 1996). One time series

exhibited persistence and one exhibited randomness (Fig. 1), as quantified through detrended fluctuation analysis (DFA) (Peng et al., 1995 and Peng et al., 1994). The details of DFA are outlined in Fig. 2. In short, DFA is a modified root mean square analysis of a random walk. First, the time series is integrated. Next, the integrated time series is divided into intervals of equal size (i.e., boxes of equal size). A least-squares linear fit is then applied to the data in each box (i.e., the data are detrended) and the average deviation about the line within each box is calculated, with only the variability of the detrended data considered. This process is repeated for all boxes of a given size ( $n$ ), and the log of the average deviation for size  $n$  is plotted on a log (box size) by log (variability) plot. This process is repeated for a range of box sizes ( $n = 4$  to  $n = 1/4 \times$  number of data points), and the slope of the best-fit line in the log-log plot corresponds to the scaling exponent ( $\alpha$ ). The goodness-of-fit of the best-fit line is denoted by  $r^2$ . DFA  $\alpha$  near 0.5 are tending toward randomness in the time series, whereas values near 1.0 are tending toward persistence. The random time series used in this experiment had a DFA  $\alpha = 0.49$  and the persistent time series had a DFA  $\alpha = 0.98$ .



**Fig. 1.** A schema representing the continuum of the structure of variability within a time series. Three time series with varying structure are shown, along with their corresponding detrended fluctuation analysis alpha (DFA  $\alpha$ ) and standardized dispersion analysis fractal dimension (SDA FD) values.



**Fig. 2.** Visualization of a portion of the detrended fluctuation analysis (DFA). Part A shows an integrated stride-to-stride interval time series. Part B shows two sizes of the boxes in which the data are separated and a linear trend within each box has been fitted. Part C is the log-log plot of the variability across different box sizes. The slope of the line (0.73) corresponds to the DFA  $\alpha$  value.

Participants walked on a treadmill while viewing the visual metronome, which consisted of a red square flashing on a laptop computer screen (0.44 m diagonal) placed at eye height in front of the treadmill. The two time series were used to drive the metronome separately, such that every

successive number in a time series prescribed the number of seconds between each flash. Thus, the beat intervals of the two metronomes varied and exhibited either randomness or persistence. Participants walked 1.3 m/s on a treadmill, which was selected as the testing speed because that was the mean walking speed of four pilot subjects. Each trial lasted for approximately 15 min (duration of each time series) in each of three randomly ordered conditions: (1) random metronome, (2) persistent metronome, and (3) no metronome. The 15 min trial duration was selected to ensure that at least 600 strides would be recorded so that DFA  $\alpha$  could be reliably indexed, in accordance with the recommendation of Damouras, Chang, Sejdić, and Chau (2010). In the metronome conditions, participants were explicitly instructed to be at right heel contact when they anticipated each square to flash. There was no visual stimulus for the left limb so both limbs were analyzed separately.

Heel-strike data for each leg were collected at 100 Hz via force sensors (Delsys, Boston, MA) placed directly on the heel of each participant. A customized Matlab (Mathworks, Inc., Natick, MA) algorithm identified the initiation of heel contact for a given leg. The time between each subsequent heel-strike for the same leg was then calculated as the stride interval. For each condition the stride time series for each limb was submitted to DFA to determine if the stride intervals and beat intervals of the metronomes exhibited similar patterns.

To obtain converging evidence of the altered fractal structure of the stride intervals in the metronome conditions, standardized dispersion analysis (SDA) was also used (Bassingthwaigthe et al., 1994, Caccia et al., 1997, Eke et al., 2002 and Holden, 2005). SDA characterizes the relative coherence of the variations in the data via a computation of the fractal dimension (FD) of a time series. The FD is computed by resampling the same data repeatedly over different box sizes and a dispersion statistic (i.e., standard deviation of the sample mean) is calculated for each box size. All resulting pairs of dispersion statistics are graphed as a function of box size in log-log coordinates, similar to plotting the detrended fluctuation versus box size in DFA. The slope of a linear fit to that function is then subtracted from 1 and this yields the FD of the time series—a value of 1.2 is indicative of statistical persistence and a value of 1.5 is indicative of randomness.

Lastly, a cross-correlation analysis was employed. This analysis has previously been used to examine the local coupling between two systems (Marmelat & Delignieres, 2012). The cross-correlation analysis quantified the correlation of the two time series (metronome and stride intervals) at a variety of time-lags ( $\pm 20$  intervals) to determine if consistent local behavior emerged across the metronome conditions. Because the stimulus presentation and stride interval measurements took place on separate computers that were not time-synchronized, we cannot assume the first time interval stride interval time series corresponds to the first time interval in the metronome time series. Both programs were initiated at nearly the same time, potentially accounting for a 3-4 interval difference between the two time series. Thus, we extended the cross-correlation analysis to  $\pm 20$  time intervals (approximately 200 ms), which allowed us to determine if a consistent time-lag occurred within each participant's trial. Collectively, the cross-

correlation analysis provided a coarse estimate of the local effects of the metronome on stride behavior; while the DFA analysis provided insight into the metronome's global effect on stride behavior.

### 2.3. Statistics

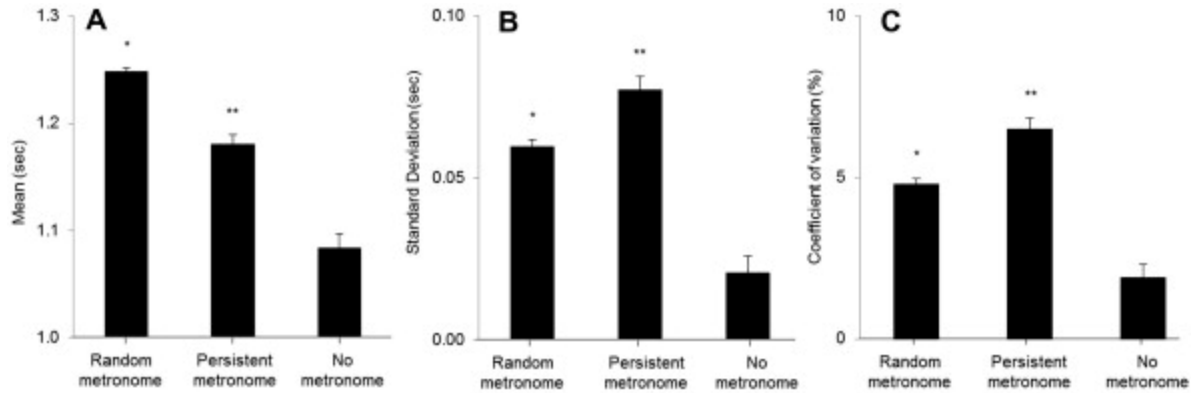
Summary statistics (mean, standard deviation, coefficient of variation and total number of strides) and the fractal structure (DFA and SDA) of the stride intervals were examined for each of the three conditions (random metronome, persistent metronome, no metronome). Since no difference between limbs was observed for any of the variables (all  $p > .05$ ), all results are reported with respect to only the right limb performance (the limb the participants were instructed to synchronize with the metronome). A repeated measures ANOVA was used for each metric separately to determine whether conditions differed ( $p < .05$ ). Follow-up paired  $t$ -tests with Bonferroni corrections were used when appropriate. For the cross-correlation analysis, the time-lag at which the peak correlation was observed was noted for qualitative analysis to identify different strategies adopted in each condition.

## 3. Results

### 3.1. Summary statistics

An effect of metronome condition was observed for the mean ( $F(2, 28) = 58.27, p < .001, \eta^2 = 0.81$ ), standard deviation ( $F(2, 28) = 37.35, p < .001, \eta^2 = 0.73$ ), and coefficient of variation ( $F(2, 28) = 36.62, p < .001, \eta^2 = 0.72$ ) of stride intervals. Follow-up tests indicated that, for each measure, the three metronome conditions were significantly different from each other (all  $p < .005$ ; see Fig. 3). The number of strides taken in each condition was also different ( $F(2, 28) = 127.33, p < .01, \eta^2 = 0.90$ ), with more strides taken in the no metronome condition ( $838 \pm 37$ ), followed by the persistent metronome condition ( $740 \pm 12$ ) and the random metronome condition ( $693 \pm 14$ ). To account for these differences, all of the time series were cropped to a length equal to the shortest time series ( $n = 649$  strides) and all analyses were repeated. The cropped and non-cropped data sets did not differ with regard to any of the summary statistics or fractal structure metrics ( $p > .05$ ), so we have elected to control for time rather than data points and present the results from the analyses of the non-cropped time series throughout the rest of the paper.

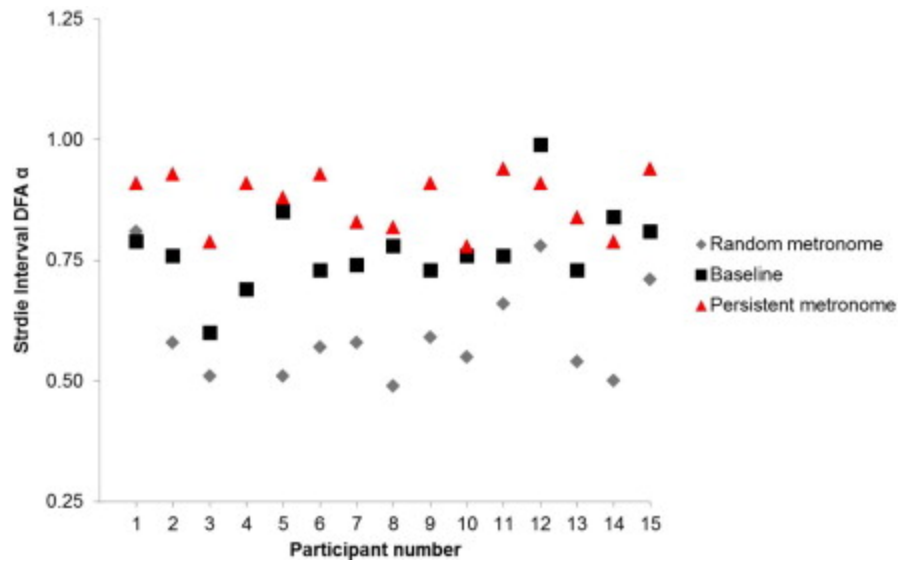




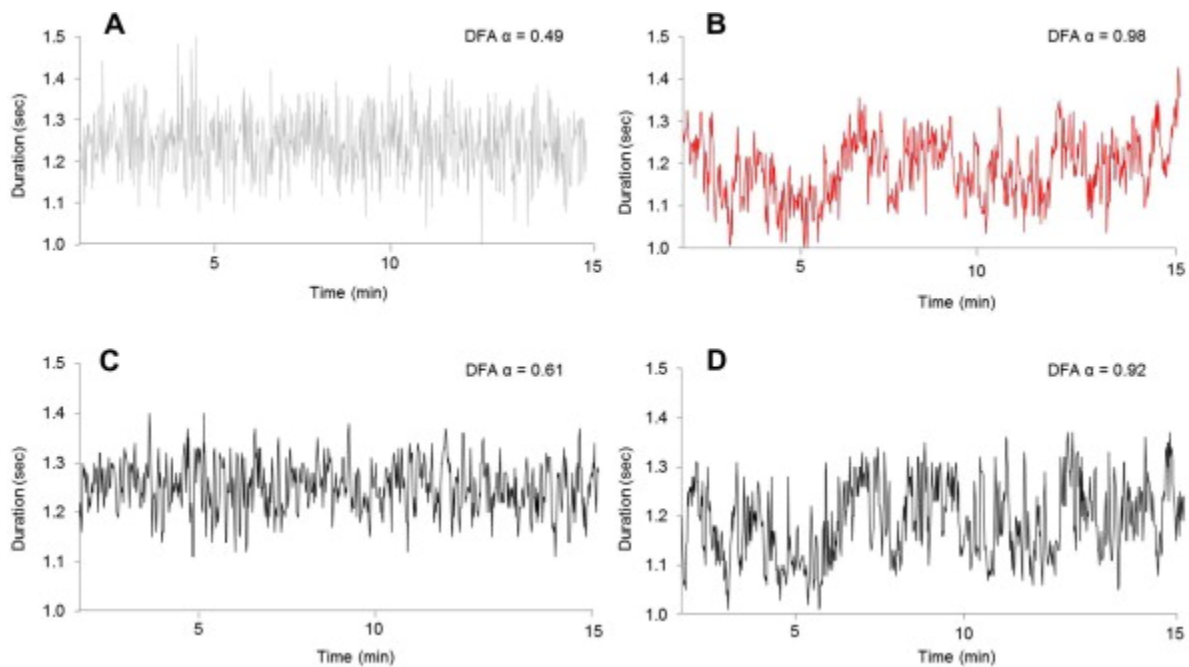
**Fig. 3.** Summary statistics of the stride interval time series. Mean (A), standard deviation (B), and coefficient of variation (C) are shown for in each condition. Asterisks represent significant differences between conditions ( $p < .01$ ).

### 3.2. Fractal structure

An effect of metronome condition was also observed for the DFA  $\alpha$  of stride intervals ( $F(2, 28) = 63.56, p < .001, \eta^2 = 0.82$ ). The follow-up tests indicated that DFA  $\alpha$  significantly decreased from the persistent metronome ( $\alpha = 0.87 \pm 0.06, r^2 = 1.00 \pm 0.00$ ) to the no metronome ( $\alpha = 0.77 \pm 0.09, r^2 = 0.99 \pm 0.01$ ), and to the random metronome ( $\alpha = 0.61 \pm 0.10, r^2 = 0.98 \pm 0.01$ ; see Fig. 4). To illustrate the similarity in dynamics between the stimulus and participants' gait behavior, Fig. 5 presents the time series of the persistent and random metronomes, followed by the stride interval time series of one participant for each metronome condition. The fractal dimension derived from the SDA of stride intervals provided converging evidence that the metronome affected the fractal structure, with a significant effect of metronome condition ( $F(2, 28) = 58.24, p < .001, \eta^2 = 0.81$ ). The random metronome (FD =  $1.42 \pm 0.02$ ) was significantly different from the baseline (FD =  $1.25 \pm 0.01$ ) and persistent metronome (FD =  $1.23 \pm 0.02$ ) conditions (all  $p < .001$ ). However, no difference was observed between the baseline and persistent conditions ( $p = .18$ ).



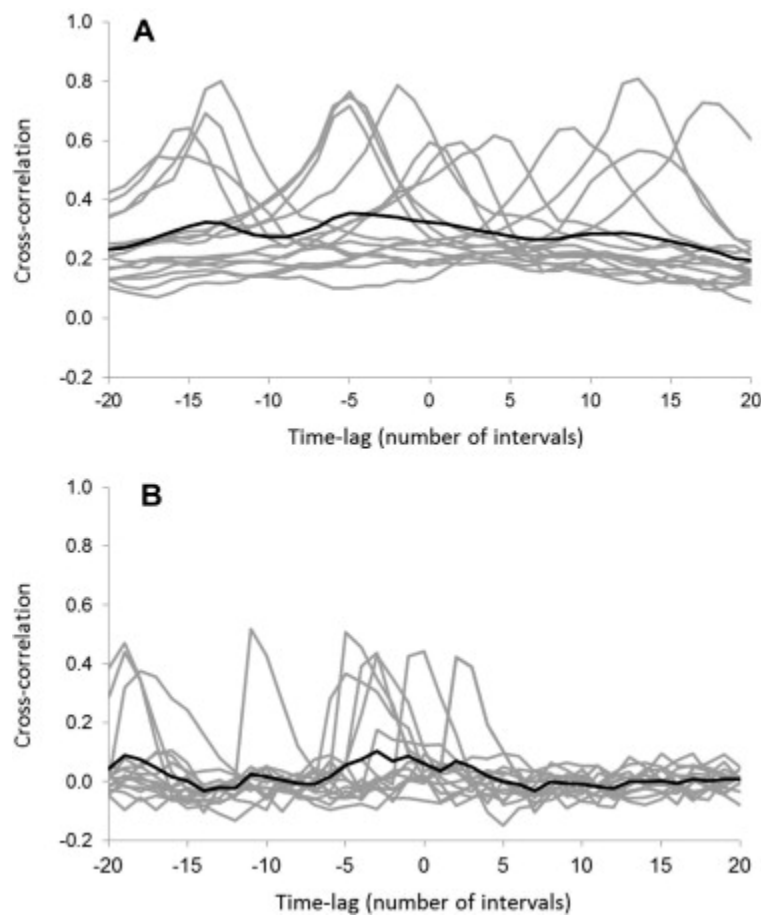
**Fig. 4.** Fractal structure of the stride interval time series. Detrended fluctuation analysis alpha (DFA  $\alpha$ ) values for each participant in each condition. The overall means for each condition were different ( $p < .01$ ), with the persistent metronome condition having the highest DFA  $\alpha$  ( $0.87 \pm 0.06$ ), followed by the no metronome condition ( $0.77 \pm 0.09$ ) and the random metronome condition ( $0.61 \pm 0.10$ ).



**Fig. 5.** Stride interval time series for one participant. Time series for the random (A) and persistent (B) metronomes, along with a subject's stride-to-stride interval time series when synchronizing to the random (C) and persistent (D) metronomes. This subject's baseline DFA  $\alpha$  was 0.76.

### 3.3. Cross-correlation analysis

Fig. 6 shows the cross-correlation analysis for each participant during the two metronome conditions, including the mean correlation across the range of time-lags. For the persistent metronome condition, each participant appeared to adopt a different dominant time-lag, indicated by the location of the peak cross-correlation value on the  $x$ -axis. The peak correlation ranged from 0.57 to 0.81 and was observed at a time-lag ranging between  $-15$  and  $17$  time intervals, indicating the adoption of a variety of reactive and predictive strategies. In the random metronome condition, the strength of the peak correlation for each participant was weaker ( $0.07$ - $0.52$ ) and most were observed at a negative time-lag, indicating a predominant reactive strategy in this condition.



**Fig. 6.** Cross-correlation analysis. The correlation coefficients across  $\pm 20$  time interval time delays for the persistent metronome condition (A) and the random metronome condition (B). The gray lines indicate each participant's correlation coefficient at each time-lag and the black line is the mean correlation coefficient for all participants at each time-lag.

## 4. Discussion

The present study examined the flexibility of the locomotor control system. Flexibility in the context of this paper was defined as the ability of the locomotor system to exhibit a range of behaviors. This was accomplished by requiring participants to synchronize to a visual stimulus that exhibited either persistence or random patterns. Our goal was to determine whether the fractal scaling in stride intervals could be shifted in a desired direction using variably paced stimuli. The findings provide three unique contributions to the literature: (1) gait dynamics can be moved in a prescribed direction, (2) a visual stimulus can shift gait dynamics, and (3) shift in gait dynamics appears to be an emergent phenomenon due to global entrainment. Each contribution is further discussed below, with the third contribution addressing the proposed mechanisms to describe our findings.

#### 4.1. Gait dynamics can be moved in a prescribed direction

Fractal scaling in stride intervals emerges from the complex interaction between system components at multiple observational scales (Hausdorff, 2007). This includes the muscular and skeletal anatomy, the neural physiology, and the environmental and task constraints that influence the locomotor system. It is believed that young healthy adults exhibit the most adaptive behavior due to their mature neuromuscular and skeletal systems, which support a form of locomotion that is functional across contexts (Hausdorff, 2007, Lipsitz, 2002 and Stergiou and Decker, 2011). To probe the flexibility of the system, researchers have used stimuli with various timing patterns to determine if movement timing can be reliably changed. For example, Stephen et al. (2008) showed that fractal patterns in movement timing can be shifted toward either more random or persistent behavior using a visual stimulus exhibiting a fractal timing structure. The authors used a relatively simple task (finger tapping), so our goal was to determine if similar timing behavior could be prescribed during a more complex task (treadmill walking). While Stephen et al. (2008) tested participants' ability to synchronize with a variety of different fractal patterns, we selected two fractal patterns that represented what we considered the limit of gait behavior in young healthy adults (DFA  $\alpha = 0.49$  and  $0.98$ ). Our data supports the findings of Stephen et al. (2008) and contributes uniquely to the literature in that the fractal timing of stride intervals can be moved in a prescribed direction (i.e., toward either more random or persistent behavior).

#### 4.2. A visual stimulus can be used to shift gait dynamics

Previous research has shown that an auditory stimulus can be used to shift the fractal characteristics of gait (Hove et al., 2012 and Kaipust et al., 2012). However, Hove et al. (2012) only attempted to shift their participants in one direction (toward more persistent behavior). Conversely, Kaipust et al. (2012) attempted to shift participants' gait dynamics bi-directionally (toward more random or persistent behavior) using an auditory stimulus. While they did show a bi-directional shift in elderly participants, no change in the gait dynamics of the young participants was observed. To our knowledge, with the exception of humans synchronizing to each other (Nessler et al., 2013), this is the first paper to report that a visual

fractal stimulus can also cause a shift in gait dynamics. Visual stimuli may be useful in this context not only for their ability to alter gait dynamics, but could potentially lead to retention due to the perceptual or motivational effects. Moreover, this shift was observed bi-directionally. Differences between an auditory and visual stimulus when examining sensorimotor synchronization have been shown (Hove et al., 2010 and Varlet et al., 2012), so our data contributes to the literature by showing that a visual metronome can also be used to shift gait dynamics in a prescribed direction. This opens up the possibility of uni- and cross-modality manipulations to address the issue of motor control flexibility and may be of particular interest to clinical researchers interacting with a population exhibiting degraded sensitivity in one or more sensory systems.

#### 4.3. The shift in the gait dynamics appears to be a global phenomenon

Previous literature has suggested that fractal patterns observed in movement dynamics may be due to the coordination of nested sub-systems (see Diniz et al. (2011) for a review). This postulate has been investigated in the movement coordination literature by examining the behavior of two systems when operating in isolation and together. Each system can have its own unique dynamics (e.g., two interacting humans) or one system can act as a master (e.g., a metronome) and one as a slave (e.g., a human attempting to coordinate with the metronome's timing).

A proposed theory behind the synchronization of fractal behavior is the concept of strong anticipation (Dubois, 2003). When anticipating an event prescribed by a non-fractal, predictable stimulus, the behavior might be driven by an internal model of timing that (1) predicts when the event will occur and (2) makes a series of short-term corrections based on error feedback. That explanation assumes synchronization is a local process and has been termed weak anticipation (Dubois, 2003). Alternatively, strong anticipation proposes that synchronized behavior emerges without an internal model and can occur at the local or global level (Stephen and Dixon, 2011 and Stepp and Turvey, 2010). Locally, synchronization is an emergent property of the interaction between the agent and the environment, with the degree of synchronization dependent on the coupling strength in the agent-environment system. It has been hypothesized that an agent's behavior is constrained by the overall dynamic structure of the stimulus, rather than predicting the timing of local events. Supportive evidence for this theory was provided by Stephen et al. (2008), who asked participants to synchronize finger taps to a fractal visual metronome. The authors observed a variety of responses that included proaction (ahead of the stimulus), reaction (behind the stimulus), and synchronization (in time with the stimulus), even though consistent changes at the global level were observed. In the current study, we aimed to determine if the change in global structure of the stride interval time series could be accounted for by coupling at the local level by employing a cross-correlation analysis, consistent with previous research addressing similar questions (Marmelat & Delignieres, 2012). In the persistent metronome condition, the participants appeared to adopt a variety of different strategies (Fig.

6A). This is highlighted by the observation that some participants peak cross-correlation value occurred at a negative time-lag, while other's occurred at a positive time-lag. Thus, while each participant appear to adopt a fairly consistent strategy within their trail (highlighted by the 0.6-0.8 peak correlations), the strategies seemed to range from reaction (negative time-lag at peak correlation) to prediction (positive time-lag at peak correlation) among the participants. The random metronome cross-correlation analysis showed different results, with the majority of peak correlations occurring at a negative time-lag, indicating that most of the participants adopted a reactive strategy in this condition (Fig. 6B). Interestingly, despite the variety of strategies that were adopted locally, similar global dynamics were observed for each participant within each condition. Thus, the consistent global changes do not appear to be a function of the local strategy that was adopted.

#### 4.4. Gait entrainment to a fractal visual metronome

Note that participants did not precisely match the global dynamics of the fractal metronome. The random and persistent metronomes corresponded to a DFA  $\alpha$  of 0.48 and 0.98, respectively. The DFA  $\alpha$  of participants in the baseline (no metronome) condition was  $0.77 \pm 0.09$ , similar to previously reported data (Chang et al., 2009, Echeverria et al., 2010, Hausdorff, 2007, Hausdorff et al., 1996, Hausdorff et al., 1997, Hausdorff et al., 1999, Jordan et al., 2009, Jordan et al., 2007 and Kiefer et al., 2009). The participants DFA  $\alpha$  shifted to  $0.60 \pm 0.10$  and  $0.87 \pm 0.06$  when synchronizing to the random and persistent fractal metronomes, respectively - each mid-way between the baseline and the prescribed dynamic structure. This lack of congruence could be due to a number of factors. First, the synchronization task may have been relatively difficult. Participants reported some difficulty in synchronizing to a variable visual stimulus, echoing previous work that found a combination of proaction and reaction when attempting to synchronize to a fractal visual metronome (Stephen et al., 2008). This was qualitatively confirmed by observing participants occasionally miss a "beat" and then shuffle their steps to get back in sync with the metronome. Second, the visual information may not have been optimal to elicit synchronized locomotor behavior. The stimulus was a flashing red square that presented discrete information about the desired timing of heel-strike. Previous research has shown that a continuous oscillatory visual signal enhances synchronization behavior and allows for online corrections throughout the movement cycle (Hove et al., 2010 and Varlet et al., 2012).

Synchronizing to the fractal metronomes also produced differences in locomotor behavior as indexed by the summary statistics (i.e., mean, standard deviation, coefficient of variation and number of strides). Even though both metronomes had the same mean and standard deviation ( $1.25 \pm 0.07$  s), these measures of the stride interval differed between conditions ( $1.25 \pm 0.06$  s and  $1.18 \pm 0.08$  s for the random and persistent metronome, respectively). This indicates participants adopted different strategies in the two conditions, a finding that was reflected in the results from the analysis of stride number and cross-correlation analysis as well. This is an

interesting finding and speaks to the nature of the task when asked to couple to a random vs. structured visual stimulus. It also speaks to the issue of equifinality as a characteristic of a complex system. Specifically, both the metronome and the individual can exhibit different paths to the same (or in this case similar) fractal dynamics. These results demonstrate that local synchronization may not be as important to the emergence of new locomotor dynamics.

#### 4.5. Potential clinical utility

Several theoretical models have been formulated to describe how a shift in fractal behavior reflects the adaptive or maladaptive nature of the behavior (Harbourne and Stergiou, 2009, Hausdorff et al., 2001, Lipsitz and Goldberger, 1992, Stergiou et al., 2006 and Vaillancourt and Newell, 2002), and a shift away from fractal locomotor behavior could lead to an increased risk of collisions, trips, or falls (Herman, Giladi, Gurevich, & Hausdorff, 2005). Consequently, the potential for using fractal stimuli to shift or retrain gait patterns in clinical populations appears promising. To effectively utilize fractal stimuli in a clinical framework, it is imperative to determine whether the shifted fractal patterns are retained once the stimulus is removed. To begin to address these questions, Hove and colleagues (2012) asked patients with Parkinson's disease to synchronize their walking to a fractal auditory metronome for approximately three minutes. They found that the patients' fractal gait pattern not only shifted in the desired direction, but the shifted patterns remained elevated in a retention trial that occurred five minutes after the training trial. This demonstrated that the altered locomotor dynamics were not simply due to concurrent synchronization with the metronome, but implies a reorganization of locomotor control may have occurred. While these results are interesting, it should be noted that fractal patterns in stride intervals have been shown to be inconsistent in short time series (Damouras et al., 2010), so it will be important to measure retention over longer trial durations in the future to ensure the findings are reliable. Furthermore, long-term retention across days, weeks, and even months will need to be tested to determine the influence a single session or multiple training sessions has on gait behavior. Lastly, it is important to note that our observed change in the fractal gait pattern was accompanied by an increase in the coefficient of variation in the stride-to-stride interval time series. While the shift toward stronger persistence in gait behavior in clinical populations may be ideal to enhance functional mobility, the corresponding increase in the coefficient of variation may be an undesired effect. Alternatively, an increase in the coefficient of variation may only be a by-product of the task constraints, which actually facilitate the reemergence of adaptive behavior.

#### 4.6. Suggestions for future research

To further probe the influence a variably paced metronome has on gait, it will be important for future research to test the extent to which the shifted fractal gait pattern is retained after removal of the visual stimulus. The continuation of timing behavior after synchronizing to a stimulus has been an area of interest in the timing literature (Ivry and Hazeltine, 1995, Kiefer et al., 2009, Kiefer et al., 2014, Repp and Steinman, 2010, Robertson et al., 1999, Spencer et al.,

2003, Studenka and Zelaznik, 2008 and Zelaznik et al., 2002). The continuation paradigm generally primes the response (finger tapping or circle drawing tasks) by presenting a metronome with the desired frequency for a short synchronization period (~30 s) and measuring the timing behavior after the metronome is turned off. The findings suggest that fractal behavior patterns emerge following the removal of a fixed-interval metronome (Diniz et al., 2011, Kiefer et al., 2009, Kiefer et al., 2014, Lemoine et al., 2006 and Torre et al., 2011). In this paradigm the priming metronome is antithetical to the dynamic properties normally observed in healthy, freely-behaving participants. Indeed, in the locomotor domain, the normal fractal pattern shifts toward randomness when healthy participants synchronize to a fixed-interval external cue (Frenkel-Toledo et al., 2005 and Hausdorff et al., 1996), although the mechanisms that underlie those findings are under debate (Delignières & Torre, 2009). Future research should focus on the duration of retention of the fractal patterns, how different stimuli influence the development of fractal patterns, and if transferability is observed between training modalities (treadmill vs. overground walking). Such questions will need to be addressed in order to determine whether this framework can be applied to clinical settings. However, the present results and those of past studies show promise for the development of a therapeutic modality that targets the retraining of functional and adaptive locomotor ability.

#### 4.7. Limitations

There are several aspects of our study that limit certain analyses or interpretation of our data. The data collection computer was not time-synchronized to the computer providing the visual metronome, allowing for the potential of a 3-4 time interval offset between the metronome and stride interval time series. If the computers had been time-synchronized, other analyses such as discrete relative phase or a correlation between the dominant time-lag between conditions could have been employed to further investigate the synchronization between the participants' behavior and the metronome. Also, all participants were required to walk at the same speed (1.3 m/s) in all conditions, which was determined by pilot testing four subjects. It could be argued that having the participants walk at a non-preferred speed (however slight it may be) could influence their gait dynamics, as has been observed in larger walking speed manipulations (Jordan et al., 2007).

### 5. Conclusions

In sum, the present research showed that locomotor control in healthy participants is flexible enough to respond to a fractal visual metronome that exhibits either persistent or random temporal dynamics. By altering the dynamic properties of the stimulus and asking participants to synchronize their locomotor behavior, we found that participants could shift their gait pattern toward randomness *or* persistence. Thus, the fractal dynamics of gait may be moved in a specified direction by an external stimulus. To the extent that these fractal dynamics index adaptive locomotor behavior, and can be retained over time, the results are suggestive for the development of clinical rehabilitation programs for retraining functional locomotor ability.



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