Evaluation of the effects of prescribing gait complexity using several fluctuating timing imperatives

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Abstract

Variability in the timing of walking patterns has a complex mathematical structure (fractality). Fractality of gait can reflect health, so practicing walking with specific temporal coordination could be helpful for various groups at high risk of falls. However, the degree to which gait fractality can be 'prescribed' using different auditory stimuli is yet to be elucidated. This study evaluated the use of several fluctuating timing imperatives on the consistency of 'prescribing' gait complexity in healthy individuals. 14 healthy young adults cued timing of heel contact to an fractal auditory stimuli across four conditions (uncued, white noise, pink noise, and red noise) administered across three sessions (session 1, session 2, and session 3), with each experimental trial repeated twice within each session. Fractality differed based on the walking condition while no effect of session was revealed. The results of this study suggest gait fractality adapts to various fractal stimuli and that fractality can be consistently prescribed in a desired direction within a group of healthy young individuals.

Key words: gait, complexity, fractals, adaptability.

1. Introduction

Independent walking requires appropriate control to remain stable and flexible while navigating complex and unpredictable environments (Shumway-Cook A, Woollacott, 2007). The motor control system regulates gait to continue progression, maintain equilibrium and remain adaptable. The gait pattern of healthy individuals characteristically reveals fractal-like fluctuations (Hausdorff et al., 1995). Fractal-like fluctuations in the gait pattern are due to the complexities of a highly composite nonlinear motor control system composed of mechanical, neural, and cognitive components, which cohesively operate nonlinearly over a range of temporal scales. Complexity is now understood to be a critical feature of healthy gait (Hausdorff, 2007).

Measures such as the fractal scaling index provide an indication of the temporal structure of a gait time series. By definition, the fractal scaling index provides an estimation of scale invariance. Previous reports have suggested that gait time series captured from healthy individuals approximate a scale-invariant process (Hausdorff, 2007; Terrier & Deriaz, 2011). More specifically, healthy stride behaviour is correlated across long and short temporal scales (i.e., long range correlations). Additionally, evidence from elderly and fall-risk individuals demonstrates that gait time series show a shift in the underlying fractal-like fluctuations behaviour towards randomness (Hausdorff et al., 1997). Hypotheses such as Loss of Complexity and Dynamical Disease propose that such changes from healthy levels of complexity (i.e., towards randomness), are related to decreased adaptive function of the movement system (Manor & Lipsitz, 2013; Rhea & Kiefer, 2014).

Utilizing fixed interval timing imperatives (i.e., a metronome with a fixed frequency) with healthy individuals, to cue stride timing, causes a shift towards randomness in scale-invariant gait behaviour as observed naturally with elderly and fall-risk individuals (Hausdorff, 2007). Terrier and Deriaz (2012) reported that gait fractality shifts towards anti-persistence (i.e., $\alpha < 0.5$) during tasks combining treadmill walking with a fixed-interval timing imperative. A fixed interval timing imperative is a highly predictable stimulus and does not contain complexity in the sequential timing of beeps. Hence, cueing steps to such stimuli, constrains the gait pattern to follow a fixed frequency. A fluctuating timing imperative (i.e., a metronome with a fluctuating frequency) when characterized in the frequency domain, are associated with different levels of fractality. For example, a white noise signal demonstrates equal power across the discrete range of frequencies which is associated with an $\alpha = 0.5$. The terms pink noise and red noise represent $\alpha > 0.5 – 1.5$ and $\alpha > 1.5$, respectively. More recent research has applied fluctuating timing imperatives, as a gait timing task, to assess whether gait complexity can be prescribed in a desired direction (Hunt et al., 2014; Marmelat et al., 2014; Rhea et al., 2014). Marmelat (2014) showed that young healthy participants can flexibly entrain their gait complexity to several different fluctuating auditory timing imperatives (i.e., various fractal levels). This finding has been mirrored with the use of visual cues (Rhea et al., 2014). More importantly, these studies highlight that gait complexity is flexible and can entrain with an external timing cue. The effect of entrainment observed in the previously mentioned studies can be viewed as method for 'prescribing' the gait patterns complexity. An established method for prescribing gait complexity would lend itself as a promising tool for assessing gait control. However, before such applications can be explored, an assessment of the 'prescription' reliability, is necessary.

We evaluated the efficacy of utilizing several distinct fluctuating timing imperatives as a paradigm to 'prescribe' gait complexity in a desired direction. The goals of the current study were two-fold: (1) to evaluate whether three different auditory stimuli characterized in the frequency domain as white, pink and red noise, can 'prescribe' gait complexity in a desired direction and; (2)

to assess the consistency of delivering three distinct fluctuating timing imperatives on ‘prescribing’ gait complexity. In this context, prescription is defined as the administration of an auditory stimulus, to induce a targeted shift in gait fractality. We hypothesized that gait fractality would shift towards the fractality of each timing imperative consistently across three sessions.

2. Methods and Protocol

2.1. Participants

Fourteen young, healthy, adult volunteers (10 males/4 females, mean; age: 26 ± 3 years, height: 1.73 ± 0.10m) were recruited to participate in the study. Participants were provided with the details of the study, and signed an informed consent form prior to engaging in the experiment. Approval to conduct the study was granted by the local university research ethics review board. Exclusion criteria included: younger than 18 and older than 35 years, a self-reported history of neurological injury or disorder, musculoskeletal injury or disorder, auditory impairment, and pain or discomfort in the past six months that might affect walking and listening to an audible sound simultaneously.

2.2. Equipment

A motorized, fixed-pace treadmill (Bodyguard Fitness, Quebec, Canada) was used to establish steady-state gait. Gait timing signals were acquired with a digital footswitch cell (FS-1, Bortex, Canada), placed directly underneath of the self-reported dominant heel of the participant. Two speakers (MLi 699, MidiLand, Germany) were used to elicit the auditory fluctuating timing imperatives. Simultaneous recording of the auditory stimulus and footswitch signals was completed with a custom-built cable. Both gait and auditory signals were synchronized in time at the initiation of each trial.

2.3. *Protocol*

2.3.1. *Preferred walking speed determination*

The determination of preferred walking speed (PWS) was a two-part protocol. The first part began with participants walking at a slow belt speed (~0.50 m/s); the speed of the treadmill belt was then systematically incremented (0.10 m/s steps) until the participant verbally communicated their "comfortable walking speed". The corresponding speed was noted as "preferred walking speed – lower" (PWS_L) and the number of increments was noted.

The second part of the protocol began at a speed above the participants previously noted as PWS_L, with approximately the same number of increments observed during the determination of PWS_L ($PWS_L + (PWS_L - 0.5)$). The speed of the belt was systematically decreased (0.10 m/s) until the participant verbally communicated their "comfortable walking speed". The corresponding speed was noted as "preferred walking speed – upper" (PWS_U). Each change in belt speed was performed by the participants for a total of 15 seconds. PWS was calculated as the average between PWS_U and PWS_L (Dingwell et al 2006). The range of tested treadmill speeds and the magnitude of each increment was partly guided by previous reports in the literature, which suggest that average treadmill PWS is 1.3m/s ± 0.13 m/s during treadmill gait (Terrier & Deriaz, 2011).

2.3.2. *Fluctuating timing imperative creation*

Each session included a baseline walking trial, which involved six minutes of walking on the treadmill at PWS. The initial baseline was trial was used to capture gait data in order to determine the average and standard deviation of the inter-stride interval for each participant. This trial was separate from experimental trials and not included in any statistical analysis. The average and standard deviation values obtained from the baseline trial were then used to create participant-specific timing imperatives used in the experimental trials.

White noise, pink noise, and red noise fluctuating timing imperatives were created in Matlab R2015b (The Mathworks, Natick, USA). First, a Guassian white noise vector of 256 data points (Marmelat et al., 2014; Delignieres et al., 2006) was created. The average and standard deviation of the white noise vector matched the individual participant's baseline walking.

Next, to generate the pink noise and red noise signals, the white noise signal was transformed into the frequency domain using the fast Fourier transform (FFT) algorithm. For the pink noise signal, the components of the power spectrum were multiplied by $1/\sqrt{f}$. For the red noise vector, the components of the power spectrum were multiplied by $1/f$ (Kasdin et al., 1995) (Figure 1). The subsequent pink noise and red noise signals were transformed back into the time domain using the inverse fast Fourier transform algorithm (Figure 2). The respective white noise, pink noise, and red noise vectors were used to define the inter-beat interval sound files for each fluctuating timing imperative. The beat duration was 10 ms.

2.3.3. Experimental trials

Participants were asked to attend three sessions, each separated by a minimum of 72 hours. During each session, participants completed two trials each of the four walking conditions (a total of eight trials) in a randomized order: uncued, white noise, pink noise, and red noise timing imperatives. For each participant, attempts were made to replicate the previous sessions metronome scaling exponents by running the noise generating process to achieve consistent scaling exponents for metronomes across session. The average and standard deviation of fractality of each timing imperative used in the study is presented in Table 1.

Each trial consisted of continuous walking for a total of 255 cued strides, which required approximately five to six minutes to complete. Limb dominance was self-reported; participants were asked to indicate which foot they would use to kick a ball. The heel switch was placed in the shoe of the dominant limb. Trial initiation began with the participant in steady-state walking. Initiation of the beat sequence began with a three-count countdown whereby the last count corresponded with the initiation of the first beat. Practice was provided prior to conducting experimental trials, in order for the participant to become familiar with the task of cueing their heel contact with the beat onset. Rest was provided following the completion of each trial to avoid fatigue. Participants verbally indicated to the research assistant when they felt comfortable to proceed to the next walking trial, which typically ranged between two to three minutes.

2.4. Data Processing and Analysis

The difference between successive heel contact across the entire trial defined the inter-stride interval time series (Hausdorff et al., 1995; Costa et al., 2003). Analog signals (i.e., the footswitch and timing imperative) were sampled at 1000 Hz. Heel contact and beat onsets were determined as the first instant at which the timing signals deviated from zero (i.e., baseline). Specifically, the footswitch produced a signal that was a step function, where the x-axis is "zero" when the switch is inactivated, but is "one" when it is activated (e.g., at heel contact).

2.4.1. Fractal Scaling Index

The fractality (i.e., fractal scaling index (α)) of inter-beat interval and inter-stride interval time series was calculated using a detrended fluctuation analysis (DFA) algorithm. Details of the algorithm have been outlined in several papers (Hausdorff et al., 1995; Rhea et al., 2014; Peng et al., 1992). The fractal scaling index (FSI) ranges between $0 \lesssim \alpha \lesssim 2$. An $\alpha \approx 0.5$ - 0.59

characterizes a white noise time series; $\alpha = 1.0$ is characteristically a purely scale invariant process (i.e., pink noise) time series; $\alpha > 1.5$ characterizes Brownian motion (i.e., red noise). The DFA algorithm is designed to have minimal sensitivity to non-stationary data (Terrier & Deriaz, 2012). The mean, standard deviation, and FSI of the inter-stride interval time series were estimated for each walking condition and session, across all participants. Entrainment error for each trial was quantified to assess the ability of participants to match their gait fractality to the elicited stimulus. Specifically, for each trial, entrainment error was calculated as the absolute difference between the fractal scaling index of the timing imperative and the fractal scaling index of the stride interval.

2.5. Statistical design and analysis

All statistical analysis was performed in JMP (v.9 product of SAS). A two-way repeated measures design [timing imperative (uncued/white noise/pink noise/red noise) x session (session 1 /session 2/session 3)] with mixed-effects was used to assess the differences of gait parameters and fractality across timing imperatives and sessions. A participants factor was included into the model as a random effect while timing imperative and session were fixed effects. Post-hoc comparisons were made with a Tukey-Kramer HSD test ($p < 0.05$).

3. Results

3.1. Inter-stride Interval gross parameters

All gait parameter data across timing imperative and session are presented in Table 2. A significant interaction effect of timing imperative and SES [$F (6,72) = 2.73$, $p = 0.02$] was found for mean inter-stride interval. Post-hoc analysis revealed that the mean inter-stride interval for white noise and pink noise were significantly greater than mean inter-stride interval for uncued, specifically at session 2. A main effect of timing imperative was found for mean inter-stride interval [$F(3, 37) = 36.93$, $p = 0.007$]. Post-hoc analysis revealed that the mean inter-stride interval for uncued was significantly less than white noise and pink noise; however, these differences were 1.1% and 1.3%, respectively. No main effect of session [$F(2,23) = 0.09$, $p = 0.914$] was detected.

No significant interaction effect of timing imperative and session [$F(6, 71) = 1.20$, $p = 0.315$] was found for SD inter-stride interval. A main effect of timing imperative was found for SD inter-stride interval [$F(3, 38) = 12.49$, $p < 0.0001$]. Post-hoc analysis revealed that the SD inter-stride interval for uncued was significantly lower than pink noise and red noise. Additionally, the SD inter-stride interval for pink noise was significantly lower than red noise. No other significant differences were revealed. No main effect of session was found [$F(2, 24) = 1.50$, $p = 0.244$].

3.2. Group entrainment effect and consistency

The results of FSI entrainment are presented in Figure 3. No significant interaction effect of timing imperative and session [$F(6, 74) = 0.88$, $p = 0.515$] was found for FSI. A main effect of timing imperative was found [$F(3, 39) = 34.33$, $p < 0.0001$] for FSI. Post-hoc analysis revealed that the mean FSI obtained for uncued and red noise were significantly greater than white noise and pink noise (uncued = 0.77 ±0.17; white noise = 0.50 ±0.13; pink noise PN = 0.58 ±0.14; red noise = 0.82 ±0.22). No other significant differences were found. No main effect of session [$F(2, 25) = 0.58$, $p = 0.565$] was revealed.

3.3. Entrainment Error

Table 2 displays the means and standard deviations across timing imperative and session. No significant interaction effect of timing imperative and session was found [$F(4,42) = 1.87$, $p = 0.13$] on the entrainment error feature. A main effect of timing imperative [$F(2,25) = 59.02$, $p <$

0.0001] was observed. Post-hoc comparisons revealed that entrainment error was different between all conditions white noise, pink noise, and red noise (Figure 3) No main effect of session [$F(2,25) = 2.33$, $p = 0.118$] was revealed.

4. Discussion

Complexity features are becoming accepted as an important indicator of the "healthy" walking pattern (Rhea and Kiefer, 2014). Approaches to restoring healthy gait are being explored by using methods such as auditory fluctuating timing imperatives that entrain "healthy" complexities (Hunt et al., 2014; Marmelat et al., 2014). However, the efficacy of such methods remains unclear. Furthermore, the meaning and function of complexity within the walking pattern is unknown, but it may have relation to adaptability and can potentially be revealed using fluctuating timing imperatives (Harbourne & Stergiou, 2009; van Emmerick et al., 2017). Therefore, the objective of this study was to assess whether the use of fluctuating timing imperatives could be used to consistently entrain the gait pattern. The results of the study suggest that stride interval fractality can be prescribed in a specified direction, with consistency across three sessions, in a group of healthy young individuals, suggesting that the method demonstrates repeatability. Furthermore, the results have revealed that the accuracy of the entrained fractality, or how closely the individual is able to match the fractality of the timing imperative, is dependent on the fractal characteristics of the timing imperative.

4.1. Group prescription and ceiling effect

The primary objective of this study was to examine the effect of entraining stride interval fractality to several different fluctuating timing imperatives. The results demonstrated a significant change in stride interval complexity with the use of a fluctuating timing imperative. Uncued walking complexity was consistent with previous literature, which demonstrated a fractality of ~ $\alpha = 0.75$ (Hausdorff, 2007). The fluctuating timing imperatives (white noise, pink noise, red noise) elicited a deviation from observed uncued fractality. This finding was consistent with previous literature, which has reported a prescription effect with the use of fluctuating timing imperatives (Hunt et al., 2014; Marmelat et al., 2014; Rhea et al., 2014; Rhea et al., 2014).

On average, participants were unable to achieve $\alpha \geq 1.0$ when entraining to the red noise imperative, though the FSI of the red noise timing imperative was on average $\alpha = 1.32$. Perhaps this result indicates a "ceiling" in the complexity observed in the healthy gait system. This ceiling is similar to findings presented in the literature, which have shown that participants have difficulty achieving a FSI above 1.0, despite entraining to a stimulus with an $\alpha \geq 1.0$ (Hunt et al., 2014). The underlying mechanism behind this effect is unknown but may indicate that the gait system is not a true scale invariant process ($\alpha = 1.0$), and is instead optimally composed of a mix of deterministic and random components in order to remain adaptable (Rhea & Kiefer, 2014; van Emmerick et al., 2017).

4.2. Prescription consistency and entrainment error

A second objective of the study was to assess the consistency of the entrainment effect. This study was the first to assess whether complexity can be consistently entrained across multiple sessions. No main effect of session was found, which suggests that white noise, pink noise and red noise demonstrated entrainment consistency across all three sessions, despite different fractal characteristics of each metronome. This finding is important for future investigations that aim to test gait control with the use of auditory fluctuating timing imperatives. Overall, it appears that the prescription effect of the auditory stimuli can consistently entrain gait complexity.

The absolute difference between the inter-stride interval fractality and inter-beat interval fractality was quantified to assess the error of entrainment. This was done to interpret how closely the participants' naturally matched gait complexity relative to the auditory stimulus. Interestingly, entrainment error scaled with the level of fractality of the metronome. More specifically, the entrainment error increased with greater fractality. The authors hypothesized that the pink noise would demonstrate the smallest error due to the similarity between pink noise fractality and the fractality observed in normal gait (Hausdorff, 2007). That hypothesis was based on the idea that information exchange between two complex systems is maximal when the two systems have a similar complexity (West et al., 2008).

Previous literature has demonstrated that the closer one can approximate the fractality of a timing stimulus is best observed with a stimulus that is approximating a pink noise signal (Hunt et al., 2014). Additionally, several studies have demonstrated that a pink noise signal with an $\alpha \cong 1.0$, will elicit an increase in the FSI away from typical baseline of $\alpha \cong 0.75$ towards a fractality closer to the stimuli (Rhea et al., 2014; Rhea et al., 2014). However, this was not observed in our study with the pink noise timing imperative. However, the methodology in our study was not entirely consistent with that of previous reports. Hunt (2014), implemented metronomes infused with a fractal stimulus approximating white noise, pink noise, and red noise into music, which was then used to entrain gait complexity. Whereas Rhea (2014), utilized a visual stimulus with an $\alpha \cong 1.0$. Differences in the methodology of entrainment between previous studies and the current study limit comparison and warrant further studies into the use of pink noise signals over a variety of fractalities. Additionally, further exploration into difference between stimulus modalities can reveal intriguing insights into how the gait responses entrain to fractal stimuli. A study of note by Marmelat and colleagues (Marmelat et al., 2014) had a similar mode of stimulus delivery (i.e., a simple beat not infused into music or visual) and showed results that were consistent with the current study's findings, in that participants were able to closely match their gait complexity with that of a timing imperative approximating white noise.

Perhaps the entrainment error observed with pink noise and red noise were due to the inability of participants to accurately time initial heel contact to the beat onset. However, the link between the local performance (i.e., lag time between heel contact to beat onset) and the entrainment error (i.e., the difference between metronome and gait fractalities) was out of the scope of the study. Rhea et al. (2014) did demonstrate that participants revealed a variety of strategies (e.g., reactive or proactive) when cueing a visual stimulus with FSI = 1.0, and participants were able to successfully match their gait complexity to the stimulus. Future investigations should assess the local performance (i.e., asynchrony between heel contact and beat onset) to discern whether the strategy adopted while cueing to the timing stimulus relates to entrainment.

5. Conclusions

The findings from the current study are the first to assess the use of auditory fluctuating timing imperatives in prescribing gait complexity over several sessions. Generally, the findings demonstrate the flexibility of the healthy gait system, albeit with an upper limit. This study specifically demonstrated that eliciting an auditory fluctuating stimulus can alter inter-stride interval complexity in a desired direction and consistently across three sessions. However, entrainment error appears to be a function of the fractal characteristics of the timing imperative.

A limitation in the study can be found in the duration between the sessions. As participation was voluntary, participants were asked to attend with a minimum time lapse of 72 hours between sessions. However, to truly test the consistency of the prescription effect, it would be important for all participants to strictly adhere to a fixed time between each session, to rule out any potential carry-over effects of timing gait to a stimulus. In addition, the ecological validity of the experiment is limited due to the use of treadmill in the current study, which imposed a fixed gait speed and constrained gait variability typically observed overground. Future studies replicating the current studies paradigm on overground will enhance the ecological validity of the results. Future studies should also assess the local performance (i.e., the lag between beat onset and heel contact) during entrainment to assess whether the coordination between gait complexity and stepping are linked. The results of this study are an initial step towards developing a paradigm aimed at prescribing complexity to assess gait control and potentially as a tool for gait rehabilitation. Additionally, future work will focus on the effects of complexity retention following entrainment.

Conflicts of Interests Statement

The authors confirm there are no conflicts of interest and that all authors have contributed to the production of the manuscript and have approved the final article.

References

Costa, M., Peng, C.K., Goldberger, A.L., & Hausdorff, J.M. (2003). Multiscale entropy analysis of human gait dynamics. *Physica A, 330*, 53-60.

Delignieres, D., Ramdani, S., Lemoine, L., Torre, K., Fortes, M., & Ninot, G. (2006). Fractal analyses for ‘short’ time-series: A re-assessment of classical methods. *Journal of Mathematical Psychology, 50*, 525-544.

Dingwell, J., & Marin, L.C. (2006). Kinematic variability and local dynamic stability of upper body motions when walking at different speeds. *Journal of Biomechanics, 39(3)*, 444-452.

Harbourne, R. T., and Stergiou, N. (2009). Movement variability and the use of nonlinear tools: principles to guide physical therapist practice. *Physical Therapy*, *89(3)*, 267–282.

Hausdorff, J. M., Peng, C. K., Ladin, Z., Wei, J. Y., & Goldberger, A. L. (1995). Is walking a random walk? Evidence for long-range correlations in stride interval of human gait. *Journal of Applied Physiology*, *78(1)*, 349–358.

Hausdorff, J. M., Mitchell, S. L., Firtion, R., Peng, C. K., Cudkowicz, M.E., Wei, J. Y., & Goldberger, A. L. (1997). Altered fractal dynamics of gait: reduced stride-interval correlations with aging and Huntington's disease. *J Appl. Physiol*, 82, 262–269.

Hausdorff, J. M. (2007). Gait dynamics, fractals and falls: Finding meaning in the stride-to-stride fluctuations of human walking. *Human Movement Science*, *26(4)*, 555–589.

Hunt, N., McGrath, D., and Stergiou, N. (2014). The influence of auditory-motor coupling on fractal dynamics in human gait, *Nature Science Reports, 4(5879)*, 1-8.

Kasdin, J. (1995). Discrete Simulation of Colored Noise and Stocashtic processes and 1/f Power Law Noise Generation. *Proceedings Of The IEEE, 83(5)*, 802-27.

Manor, B., and Lipsitz, L. A. (2013). Physiologic Complexity and Aging: Implications for Physical Function and Rehabilitation. *Prog Neuropsychopharmacol Biol Psychiatry, 45* 287-293.

Marmelat, V., Torre, K., Beek, P. J., and Daffertshofer, A. (2014). Persistent fluctuations in stride intervals under fractal auditory stimulation. *PLOS One, 9(3)*, 1-9.

Peng, C. K., Buldyrev, S. V., Goldberger, A.L., Havlin, S., Sciortino, F., Simons, M., & Stanley, H.E. (1992). Long-range correlations in nucleotide sequences. *Nature*, 356, 168-170

Rhea, C. K., Kiefer, A. W., Wittstein, M. W., Leonard, K. B., MacPherson, R. P., Wright, G., and Haran, J. (2014). Fractal Gait patterns are retrained after entrainment to a fractal stimulus. *PLOS ONE*, *9(9)*, 1-10.

Rhea, C. K., Kiefer, A. W., D'Andrea, S. E., Warren, H. K., Aaron, R. K. (2014). Entrainment to a real time fractal visual stimulus modulates fractal gait dynamics. *Human Movement Science*, *36*, 20-34.

Rhea, C. K., and Kiefer, A. W. (2014). Patterned variability in gait behaviour: How can it be measured and what does it mean?. In L. Li and M. Holmes (Eds.) Gait Biometrics: Basic Patterns, role of Neurological Disorders and Effects of Physical Activity (pp. 17-43). Hauppauge, NY: Nova Science Publishers

Shumway-Cook, A and Woollacott, M (2007). Fractals. In L. Horowitz (Eds.), Motor Control: translating research into practice. Philadelphia, PA: Lipincott Williams and Wilkins.

Terrier, P., & Dèriaz, O. (2011). Kinematic variability, fractal dynamics and local dynamic stability of treadmill walking. *Journal of Neureng and Rehab*., 8, 1-13.

Terrier, P., & Dèriaz, O. (2012). Persistent and anti-persistent pattern in stride-to-stride variability of treadmill walking: Influence of rhythmic auditory cueing. *Gait and Posture, 36(1)*, s40.

van Emmerick, R. E. A., Ducharme, S., Amado, A. C., and Hamil, J. (2017). Comparing dynamical systems concepts and techniques for biomechanical analysis. *Journal of Sport and Health Science*, *5*, 3–13.

West, B. J., Geneston, E. L., & Grigolini, P. (2008). Maximizing information exchange between complex networks. *Phys Rep, 468*, 1-99.

List of Tables

Table 1. Summary of fluctuating timing imperative fractality (mean ±SD) across timing imperative and session collapsed across all participants.

	Session 1	**Session 2**	**Session 3**
White noise	0.50 ±0.04	0.53 ±0.04	0.52 ±0.03
Pink noise	0.85 ±0.07	0.84 ±0.08	0.83 ±0.07
Red noise	1.30 ±0.09	1.33 ±0.11	1.33 ±0.15

Table 2. Summary of gait parameters (mean ±SD) across timing imperative and session.

Timing imperative	**Uncued**			**White noise**			**Pink noise**			**Red noise**		
Session	**Session 1**	**Session 2**	**Session 3**	**Session 1**	**Session 2**	**Session 3**	**Session 1**	**Session 2**	**Session 3**	**Session 1**	**Session 2**	**Session 3**
Mean inter-stride interval **(s)**	1.169 ±0.063	1.143 ±0.072	1.152 ±0.068	1.168 ±0.060	1.169 ±0.075	1.174 ±0.072	1.166 ±0.061	1.162 ±0.075	1.176 ±0.071	1.163 ±0.059	1.158 ±0.074	1.175 ±0.076
SD inter-stride interval **(s)**	0.017 ±0.005	0.017 ±0.006	0.016 ±0.005	0.018 ±0.003	0.017 ±0.005	0.019 ±0.005	0.019 ±0.006	0.018 ±0.005	0.022 ±0.006	0.024 ±0.008	0.022 ±0.007	0.024 ±0.005
Fractal Scaling Index (FSI)	0.76 ±0.14	0.81 ±0.17	0.75 ±0.19	0.52 ±0.13	0.48 ±0.13	0.51 ±0.14	0.56 ±0.15	0.58 ±0.12	0.61 ±0.15	0.89 ±0.11	0.84 ±0.18	0.96 ±0.13
Fractal Scaling Index (FSI) Error				0.10 ±0.06	0.11 ±0.10	0.12 ±0.08	0.30 ±0.14	0.27 ±0.11	0.22 ±0.11	0.50 ±0.27	0.56 ±0.25	0.45 ±0.17

Figure Legends

Figure 1: A representative plot of the frequency spectrum for three timing imperatives. Top: white noise shows approximately equal power in representative frequencies. Middle: pink noise demonstrates decay following multiplication by $1/\sqrt{\mathbf{f}}$. Bottom: red noise demonstrates sharper decay following multiplication by 1/f.

Figure 2: A representative plot of three fluctuating timing imperatives in the time domain, for a participant with a mean stride interval of 1.25 s and a standard deviation of 0.02s. CV = coefficient of variation and α = fractal scaling index. Top: white noise inter-beat intervals. Middle: pink noise inter-beat interval. Bottom: red noise inter-beat interval.

Figure 3: The mean ±SD of fractal scaling index (FSI) of each timing imperative condition separated across all sessions. Data is averaged across repeated trials and participants. Shade of bars represent different sessions: light grey bars represent means for session 1; dark grey bars represent means for session 2 and; black bars represent means for session 3. No differences were found across the main effect of session. Timing imperative demonstrated significant differences: uncued was different from white noiseand pink noise; red noise was different from white noise and pink noise; uncued and red noise were not different and; white noise and pink noise were not different. Error bars represent standard deviations. Asterisks represents significance at 0.05 level.

Figure 4: The mean ±SD entrainment error for each timing imperative condition. Each level of timing imperative was significantly different from each other; white noise different from pink noise and red noise and; pink noise different from red noise. Error bars represent standard deviations, Asterisks represent significance at 0.05 level.