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ABSTRACT

Typically, gait rehabilitation uses an invariant stimulus paradigm to improve gait related deficiencies. However, this approach may not be optimal as it does not incorporate gait complexity, or in more precise words, the variable fractal-like nature found in the gait fluctuations commonly observed in healthy populations. Aging which also affects gait complexity, resulting in a loss of adaptability to the surrounding environment, could benefit from gait rehabilitation that incorporates a variable fractal-like stimulus paradigm. Therefore, the present study aimed to investigate the effect of a variable fractal-like visual stimulus on the stride-to-stride fluctuations of older adults during over ground walking. Additionally, our study aimed to investigate potential retention effects by instructing the participants to continue walking after turning off the stimulus. Older adults walked 8 min with i) no stimulus (self-paced), ii) a variable fractal-like visual stimulus and iii) an invariant visual stimulus. In the two visual stimuli conditions, the participants walked 8 additional minutes after the stimulus was turned off. Gait complexity was evaluated with the widely used fractal scaling exponent calculated through the detrended fluctuation analysis of the stride time intervals. We found a significant ~20% increase in the scaling exponent from the no stimulus to the variable fractal-like stimulus condition. However, no differences were found when the older adults walked to the invariant stimulus. The observed increase was towards the values found in the past to characterize healthy young adults. We have also observed that these positive effects were retained even when the stimulus was turned off for the fractal condition, practically, acutely restoring gait complexity of older adults. These very promising

results should motivate researchers and clinicians to perform clinical trials in order to investigate the potential of visual variable fractal-like stimulus for gait rehabilitation.

1. Introduction

Numerous studies in the past two decades have shown that the dynamics of diverse biological signals examined over time (e.g. heart rate, blood pressure, gait parameters) reveal the presence of physiological complexity in healthy systems. Moreover, a loss of complexity due to aging and across a range of illnesses (Goldberger, 1996; Hausdorff, Peng, Ladin, Wei, & Goldberger, 1995; Hausdorff et al., 1996; Hausdorff, Rios, & Edelberg, 2001; Herman, Giladi, Gurevich, & Hausdorff, 2005; Lipsitz, 1992; Manor et al., 2010; Peng et al., 2002; Sosnoff & Newell, 2008; Vaillancourt & Newell, 2002). This complexity is defined as the temporal ordering of stride-to-stride fluctuations by the occurrence of scale invariant/fractal patterns. The classic definition of a fractal, first described by Mandlebrot, is a geometric object with “self-similarity” over multiple measurement scales (Mandlebrot, 1977). The outputs of the locomotor system measured over time also exhibit such fractal properties (Hausdorff et al., 1996; Hunt, McGrath, & Stergiou, 2014; Vaz, Groff, Rowen, Knarr, & Stergiou, 2019). Furthermore, they demonstrate power-law scaling where the smaller the frequency of oscillation (f) of these signals, the larger their amplitude (amplitude squared is power). This power-law relation can be expressed as 1/f, and is referred to as pink noise, where oscillations appear self-similar when observed over seconds, minutes, hours, or days.

It is widely suggested that fractal scaling confers enhanced connectivity between biological processes, while a breakdown in fractal scaling arises from a gradual deterioration in the number of “functioning elements of a given system and/or a decrease in the interactions between these components” (Goldberger, 2001; Goldberger et al., 2002). From this perspective, there is no particular component that causes fractal scaling to occur. Instead, it is an emergent property that stems from the interactions across the many spatiotemporal scales of organization instantiated within an organism (Orden, Holden, & Turvey, 2005), giving rise to a dexterous but coordinated biological system (Harrison & Stergiou, 2015). This complexity is thought to be biologically adaptive because it is flexible, allowing organisms to cope with stress and unpredictable environments (Stergiou, Harbourne, & Cavanaugh, 2006). The loss of complexity, on the other hand, is thought to reduce the adaptive capabilities of the individual, as in the case of aging (Lipsitz, 1992, 2002; Stergiou et al., 2006). Previous research has shown that highly active older adults exhibit more complex patterns of locomotor activity than less active older adults, despite the absence of differences between these groups in the variability of step counts (Cavanaugh, Kochi, & Stergiou, 2010). Furthermore, the natural locomotor activity patterns of older adults, particularly those with functional limitations, have been associated with a loss of complexity compared to a healthy, young group (Cavanaugh, Coleman, Gaines, Laing, & Morey, 2007). Interestingly, Hu and colleagues have shown that older adults and dementia patients have disrupted fractal activity patterns (Hu, Someren, Shea, & Scheer, 2009) and that the degree of disruption is positively related to the burden of amyloid plaques - a marker of Alzheimer's disease severity (Hu, Harper, Shea, Stopa, & Scheer, 2013). Also, a study of primates suggests a loss of complexity in locomotor behavior that is associated with illness and aging, reduces the efficiency with which an animal is able to cope with heterogeneity in its natural environment (MacIntosh, Alados, & Huffman, 2011). Additionally, fractal scaling has been observed in the locomotor activity of young, healthy small mammals, a feature that is less evident in aged animals (Anteneodo & Chialvo, 2009).

External cueing (visual or auditory) has emerged as a promising tool for rehabilitation of gait disorders (e.g. stroke (Hollands et al., 2015), Parkinson's disease (Baker, Rochester, & Nieuwboer, 2008), aging (van Ooijen et al., 2016) as it has been shown that walking to an invariant stimulus increased gait speed and stride length (Spaulding et al., 2013). Whilst these improvements in gait parameters are certainly important, we submit that this approach misses some important aspects. Practically, training patients towalk to external cues with no variability runs contrary to the natural stride-to-stride fluctuations that are known to exist in human gait (Hunt et al., 2014; Kaipust, McGrath, Mukherjee, & Stergiou, 2013). Support for this argument arises from studies that has found invariant rhythmic stimulus affecting the natural stride-to-stride fluctuations and breaking down the fractal properties of the locomotor system (Hunt et al., 2014; Kaipust et al., 2013; Marmelat, Torre, Beek, & Daffertshofer, 2014; Vaz et al., 2019). Specifically, it has been shown that healthy young adults exhibit a loss of complexity when walking to invariant cues, while the presence of a fractal-like stimulus did not affect the complexity of their gait patterns (Marmelat et al., 2014; Vaz et al., 2019; Vaz, Rand, Fujan-Hansen, Mukherjee, & Stergiou, 2020).

In terms of individuals with poor mobility, the elimination of variability from gait, as is the case when walking with an invariant external stimulus, will further impede their movement capabilities to navigate real-world, unpredictable environments. On the contrary, incorporating a fractal structure in the temporal presentation of an auditory or a visual stimulus, can restore healthy gait patterns of such individuals. Interestingly, a study by Hove and colleagues (Hove, Suzuki, Uchitomi, Orimo, & Miyake, 2012) showed that an “interactive” auditory stimulus, based on nonlinear oscillators restored the locomotor fractal properties in Parkinson's disease patients. Moreover, locomotor fractal properties persisted 5 min after the stimulus was removed, indicating stabilization of the internal rhythm generating system and reintegrated timing networks. Therefore, we believe that similar effects could be observed in older adults when a complex (rather than invariant) stimulus is utilized. In other words, providing a fractal-like stimulus to older adults may be more effective in the restoration of the fractal properties identified in walking patterns of the healthy young adults.

The present study aimed to investigate the immediate effects of how synchronizing to a visual external stimulus with different temporal structures could alter gait complexity during overground walking in older adults. We hypothesized that older adults that exhibit a loss of complexity in their gait patterns will exhibit patterns similar to those commonly observed in healthy young adults when they walk to a variable fractal-like visual stimulus. Additionally, we also aimed to investigate if such effects would persist after the removal of the stimulus. Based on the results from Rhea et al. (2014) in healthy young adults and from Hove et al. (2012) in Parkinson's Disease patients, we hypothesized that after the removal of the variable fractal-like visual stimulus, older adults will be able to maintain the above hypothesized positive effects.

In the present study we utilized visual stimuli because vision is the dominant sense during walking. Indeed, it has been shown that, compared to other sensory systems, vision uniquely provides positional information during walking (Chien, Eikema, Mukherjee, & Stergiou, 2014). Furthermore, we provided the visual stimuli through wearable glasses (Vaz et al., 2019). This novel aspect of our research solves concerns about clinical translation of visual stimuli as in previous studies authors have used virtual reality systems (e.g. head mounted displays) (Lantz, 1996; Mon-Williams, Warm, & Rushton, 1993; Santos et al., 2008). Another novelty of our research is that our experiment was performed overground and not on the treadmill, which reflects a more ecologically valid environment which more likely results in conclusions that translate to the real-world.

2. Methods

2.1. Participants

Sixteen older adults (10 females; age = 72 ± 5 yrs.; body mass = 73.2 ± 13.4 kg; height = 1.68 ± 0.10 m) participated in this study. The study was approved by the University of Nebraska Medical Center Institutional Review Board. Each participant provided informed consent prior to participation. Prior to any walking tests, the participants underwent a general health assessment for both inclusion criteria and demographic purposes. Participants younger than 65 yrs. of age were excluded. Those that had any musculoskeletal or neurological diagnoses that could affect gait and balance were excluded. Participants were also excluded if they reported any cardiovascular clinical diagnosis. Additionally, we only included participants that were able to walk independently, with no aids, up to 10 min. This was due to the type of analysis that we intended to use that requires longer time series.

After a brief health questionnaire to determine eligibility, the participants were assessed for cognitive function (Mini Mental State Examination, MMSE), confidence and balance (Activities-Specific Balance Confidence Scale, ABC), falls (Modified Falls Efficacy Scale, MFSE) quality of life (EQ-5D-5L and EQ-VAS). Those that had a score below 24 in the MMSE were also excluded from the study.

2.2. Experimental procedure

We asked the participants to complete two 16-min walking conditions synchronized to a visual stimulus, on a 1/8th-mile indoor track. Prior to this, the participants walked for 8 min with no stimulus (self-paced walking) and were instructed to walk at their self-selected pace while looking straight forward. For the two stimuli conditions, participants were instructed to synchronize their heel strikes to two different visual stimuli: invariant (INV) and variable fractal-like (FRC). Between conditions, rest periods lasted for a minimum of 15 min. The order of the stimuli conditions was randomized.

Fig. 1 illustrate the visual stimulus that consisted of a vertically moving bar displayed in front of a pair of glasses (Vufine+, Sunnyvale CA) as described in (Vaz et al., 2019). The participants were instructed to match the heel strikes of their right foot to the top of the moving bar's path. The moving indicator flashed red when reaching the top of the display. The participants wore the glasses in all three conditions, however for the self-selected pace there was no moving bar present. For the stimuli conditions, the stimulus was automatically turned off after 8mins and the participants kept walking for another 8mins. The participants were not instructed to try to reproduce the rhythms imposed by the stimulus during the last 8mins.

The FRC stimulus was generated using an approximation of a -10 dB/decade filter with a weighted sum of first order filters (pink noise). The signal results were validated using Detrended Fluctuation Analysis (DFA) and had a fractal exponent α equal with 1.0 (Peng, Havlin, Stanley, & Goldberger, 1995). Importantly, the FRC stimulus was scaled using the mean and standard deviation of each participant's self-paced stride-time. This scaling generated a set of subject-specific stimulus, but also maintained the consistency of stimulus patterns across subjects. The INV stimulus was generated using each participant's self-paced stride-time mean and a standard deviation of zero.

Participants wore footswitch sensors (Noraxon, Scottsdale, USA) sampled at 1500 Hz to precisely identify heel strike events. Using a custom MATLAB code, inter-stride intervals (ISIs) were determined by calculating the time between two consecutive heel strikes of the same foot.

2.3. Data analysis

The first 15 s of each condition were discarded to avoid any transient effect related to stimulus familiarization. Similarly, the first 15 s after the stimulus was turned off were discarded to avoid transient effects related to task changes. The mean and coefficient of variation was calculated for each ISIs time series: No Stimulus, INV-ON, INV-OFF, FRC-ON, FRC-OFF. “-ON” indicates walking with the stimulus turned on and “OFF” represents the walking after the stimulus turned off. The fractal-scaling exponent, α, was also calculated from the ISIs time series (α-ISIs) using DFA. Autoregressive fractionally integrated moving average (ARFIMA) modelling was conducted to assess the presence of long-range dependence of the time series and hence, justifying the use of DFA (see Supplementary materials for details).

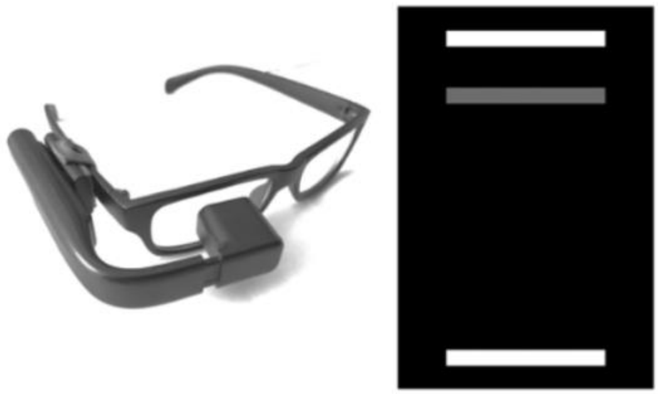

Fig. 1. The experimental apparatus (left) and the continuous visual stimulus (right) used. A miniaturized display was attached to a standard or participant's glasses. The visual stimulus consisted of a grey bar moving from top to bottom and the participants were instructed to match the heel strikes of their right foot to the top of the bar's path.

The DFA is a modified random-walk analysis that makes use of a long-range correlated time series. The long-range correlation can be mapped to self-similar calculations through simple integration. First, the time series is integrated and then divided into window sizes of length n. A least squares fit line is fitted to the data in each window, and data is detrended by subtracting the integrated time series from the least squares fit line. The root mean square is then calculated for each window and summed for the entire time series, F(n). The process is repeated with smaller and smaller n window sizes. Finally, the log F(n) is plotted against the log n (the root mean square versus the window sizes). The slope of this plot is the reported α-value. If the α-value is greater than 0.5, the long-range correlation is positively persistent. Meaning that increases are likely to be followed by increases and decreases are likely to be followed by decreases. Whereas if the α-value is smaller than 0.5, the long-range correlation is anti-persistent, meaning increases are likely to be followed by decreases and vice versa. If the α-value is greater than 1, the signal is regarded as brown (Jordan, Challis, & Newell, 2007). In the present study, the FRC stimulus was designed to present an α-value of 1, indicating pink noise and fractal like complexity in the signal. On the other hand, a lower value indicates loss of complexity. For example, a white-noise type of signal (i.e. highly variable and unstructured) typically present an α-value of 0.5. The range of window sizes of the DFA selected in the current study was from 16 to N/8, where N is the number of stride intervals.

We also calculated the asynchronies (ASYNC), i.e., the time difference between the heel strikes and the stimulus, to ensure that differences at the α of ISIs were not the result of different performance between condition. A negative value indicates that the heel strike occurred before the stimulus. A prior visual inspection of the data showed that participants altered the limb with which they synchronized to the stimulus a few times throughout the walking conditions. This, therefore, resulted in more strides than stimuli events. To overcome this issue, we calculated the time between all steps to the stimuli events and determined the ASYNC disregarding the limb with which the participants synchronized to the stimulus. Thus, the heel-strike that was closer to the stimulus events was considered for the calculation of the asynchrony. The ASYNC provide information regarding the strategies used and the performance of the synching processes. Thus, the ASYNC serves as a control parameter to reliably interpret our results in terms of gait complexity.

2.4. Statistical analysis

After a detailed exploration of the individual data, we have identified that four out of the sixteen older adults exhibited α-ISIs higher than 0.81, indicating a state of complexity similar to what is commonly observed in healthy young adults while walking overground (Terrier, Turner, & Schutz, 2005; Vaz et al., 2019). Thus, we have removed these four participants from the statistical analysis in order to have a more homogenous group of “true” older adults with a representative α-value for an aging population. This issue is further elaborated in the discussion section.

Normality was first assessed through Shapiro-Wilk test. To investigate the immediate effect of the stimuli, a one-way repeated measures ANOVA (No Stimulus, FRC-ON, INV-ON) was used for α-ISIs. A one-way repeated measures ANOVA was also used to investigate the retention effects of the stimuli compared to baseline (No Stimulus, FRC-OFF, INV-OFF). A two-way repeated measures ANOVA was performed to compare changes between ON and OFF states between the two stimuli condition. For this, we used the α-ISIs from the stimuli condition normalized to the α-ISIs obtained in the no stimulus condition. A positive value represents the percentage increase in α-ISIs relative to the no stimulus condition. Zero indicates no changes in α-ISIs. The Mauchly's test was implemented to test sphericity and Greenhouse-Geisser correction was used when not verified. Additional sample Student's t-tests with zero as a reference value was performed to assess if each condition and state (ON or OFF) was significantly different from zero to determine differences to baseline. Wilcoxon Signed-Rank Test was used to compare ASYNC from INV-ON and FRC-ON. The alpha level was set at 0.05. All statistical analyses were performed in SPSS software (SPSS Inc., Chicago, IL).

3. Results

3.1. Sample's characteristics

Twelve older adults (7 females and 5 males, 72 ± 6 yrs.; 1.71 ± 0.11 m; 74.9 ± 14.6 kg) were included in the statistical analysis (Table 1). The participants revealed normal levels of cognition assessed through the MMSE and overall high levels of perceived quality of life and health status as assessed through EQ-5D. Likewise, all the older adults reported high levels of balance confidence (ABC). Additionally, the fear of falling assessment revealed no concerns in all the participants. All together, these measures suggest a self-reported overall normal health status and quality of life.

Table 1
Demographics and sample's characteristics. Data are presented as group's Mean ± SD.

N = 12, 7 females	
Demographics	
Age (yrs)	72 ± 6
Height (m)	1.71 ± 0.11
Body Mass (kg)	74.9 ± 14.6
Health-related questionnaires	
MMSE	28.08 ± 2.07
EQ-5D-5L Index	0.97 ± 0.06
EQ-VAS	93.58 ± 6.64
ABC	95.98 ± 3.84
MFES	10.17 ± 0.39

MMSE – Mini Mental State Examination; **EQ-5D-5L Index** – EuroQol Group, 5 Dimensions Index of Health Status and Quality of Life; **EQ-VAS** – Overall self-rated health status; **ABC** – Activities-specific Balance Confidence Scale; **MFSE** – Modified Falls Efficacy Scale;

3.2. Inter-Stride-Intervals (ISIs)

3.2.1. Immediate effects

A significant main effect for condition was observed for α-ISIs ($F(2,22) = 5.454$, $p = 0.002$, $\eta p2=0.434$). Pairwise comparisons showed that the α-ISIs was significantly higher in the FRC-ON condition (0.85 ± 0.15) as compared to the INV-ON (0.61 ± 0.20, $p = 0.003$) and the No Stimulus (0.71 ± 0.09, $p = 0.015$) conditions. No differences were found between the No Stimulus and the INV-ON conditions ($p = 0.265$).

No main effect for condition was observed for mean ISIs ($F(1.326,14.583) = 1.556$, $p = 0.233$; Table 2).

Table 2
Summary results for all the studied gait variables in all conditions. Data are presented as group's Mean ± SD.

		Conditions			***p-value*** *(main effect)*
		No stimulus	Invariant	Fractal	
STIMULUS ON *(immediate effects)*	**Inter-Stride Intervals (ISIs)**				
	mean (seconds)	1.09 ± 0.09	1.11 ± 0.09	1.13 ± 0.09	0.233
	coefficient of variation (%)	1.87 ± 0.74	2.74 ± 0.67	2.26 ± 0.98	**0.006**
	α-scaling	0.71 ± 0.09	0.61 ± 0.21	0.85 ± 0.15	**0.002**
	Asynchronies (ASYNC)				
	mean (milliseconds)	–	209 ± 98	182 ± 83	0.643
STIMULUS OFF *(retention effects)*	**Inter-Stride Intervals (ISIs)**				
	mean (seconds)	1.09 ± 0.09	1.08 ± 0.08	1.08 ± 0.09	0.141
	coefficient of variation (%)	1.87 ± 0.74	3.27 ± 0.98	2.36 ± 1.36	< **0.001**
	α-scaling	0.71 ± 0.09	0.76 ± 0.16	0.86 ± 0.15	**0.016**

A significant main effect for condition was observed for CV-ISIs ($F(2,22) = 6.530$, $p = 0.006$, $\eta p2=0.373$). Pairwise comparisons showed that the CV-ISIs was significantly lower in the No Stimulus condition (1.87 ± 0.74%) as compared to the FRC-ON (2.26 ± 0.98%, $p = 0.029$) INV-ON (2.74 ± 0.67%, $p = 0.007$) conditions. No differences were found between the FRC-ON and INV-ON conditions ($p = 0.121$).

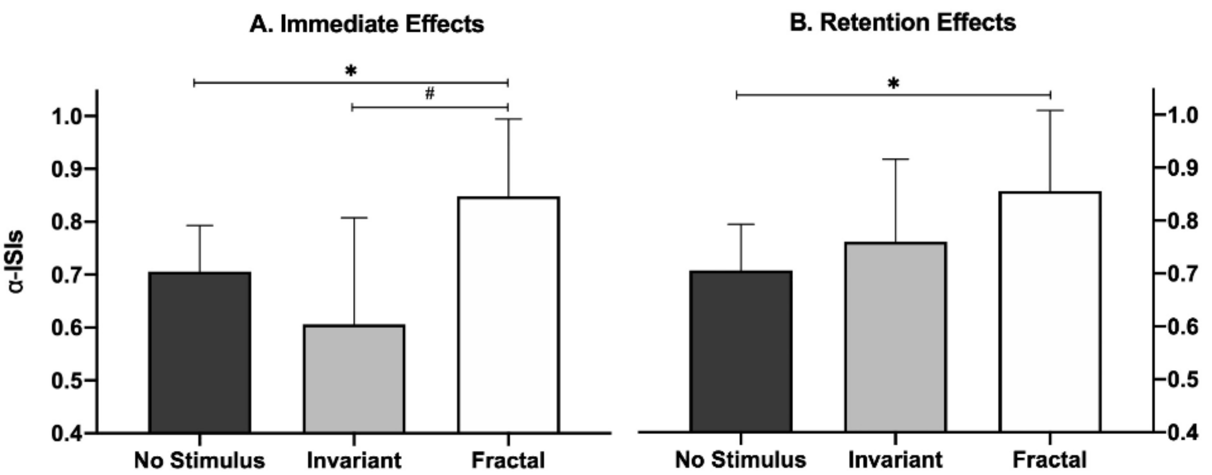

Fig. 2. The α-ISIs mean values listed for each condition. **A.** The immediate effects (ON state) of the two stimuli. Note that healthy young adults typically exhibit values between 0.8 and 1. The fractal-like stimulus revealed higher values as compared to the no stimulus and invariant condition and within such a "healthy" interval; the invariant condition showed no differences compared to no stimulus condition. **B.** Retention effects (OFF states). Note that after the removal of the fractal-like stimulus values remained elevated and were larger than the no stimulus condition; while the invariant condition showed no differences compared to no stimulus condition. * indicates $p < 0.05$; # indicates $p < 0.01$.

3.2.2. Retention effects

A significant main effect for condition was observed for α-ISIs ($F(2,22) = 5.050$, $p = 0.016$, $\eta p2=0.315$). Pairwise comparisons showed that the α-ISIs was significantly higher at the FRC-OFF condition (0.86 ± 0.15) compared to the No Stimulus (0.71 ± 0.09, $p = 0.009$; Fig. 2). No differences were found between the No Stimulus and the INV-OFF ($p = 0.764$) conditions.

No main effect of condition was observed for mean ISIs ($F(2,22) = 2.147$, $p = 0.141$; Table 2).

A significant main effect for condition was observed for CV-ISIs ($F(2,22) = 16.377$, $p < 0.001$, $\eta p2=0.598$). Pairwise comparisons showed that the CV-ISIs was significantly higher in the INV-OFF (3.27 ± 0.98%) as compared to the No Stimulus (1.87 ± 0.74%, $p < 0.001$) and the FRC-OFF (2.36 ± 1.36%, $p = 0.007$) conditions. No differences were found between the FRC-OFF and No Stimulus conditions ($p = 0.080$).

3.3. Normalized Inter-Stride-Intervals fractal scaling (α-ISIsnorm)

An interaction effect (stimuli condition x state) was observed for α-ISIsnorm ($F(1,11) = 12.572$,$p = 0.005$, $\eta p2=0.533$). A significant main effect was observed for stimuli condition ($F(1,11) = 10.526$,$p = 0.008$, $\eta p2=0.489$), but not for ON or OFF state ($F(1,11) = 2.169$,$p = 0.169$, $\eta p2=0.165$). A detailed analysis revealed that for the INV stimulus, there was a significant increase ($F(1,11) = 4.925$, $p = 0.048$, $\eta p2=0.309$) in the α-ISIsnorm from ON to OFF state (−11.90 ± 34.53% and 8.30 ± 21.49%, respectively). This was not the case for the FRC stimulus condition ($F(1,11) = 0.009$, $p = 0.925$, $\eta p2=0.001$). However, both ON and OFF states from the INV condition where not significantly different from zero ($p = 0.258$ and $p = 0.208$, for ON and OFF respectively), indicating that there were no changes in the α-ISIs relative to baseline. Conversely, both the ON and OFF states from the FRC condition revealed to be significantly higher than zero (p = 0.015 and p = 0.003), demonstrating an ~20% significant increase of α-ISIs relative to baseline. Fig. 3 illustrates these differences relative to baseline.

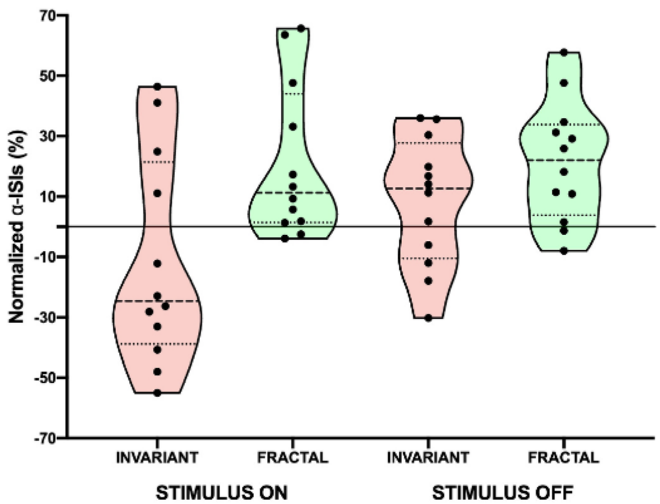

Fig. 3. Violin plots of the normalized α-ISIs for each stimulus (fractal, invariant) and state (ON, OFF) condition. Note that zero represents no changes relative to the no stimulus. Thus, positive values indicate a percentage increase in α-ISIs relative to the no stimulus and, therefore, a percentage increase in α-ISIs. Black dots indicate individual data. The thicker dashed line represents the median, and the thinner dashed lines represent quartiles.

3.4. Asynchronies (ASYNC)

Mean ASYNC were similar in all stimuli conditions (Table 2). There were no differences between ASYNC of the INV and FRC stimuli (p = 0.643). The mean values of ASYNC were positive in both stimuli conditions (209 ± 98 ms and 182 ± 83 ms for INV and FRC, respectively), meaning that the stepping generally occurred after the stimulus, indicating a reactive strategy from the older adults.

4. Discussion

The present study aimed to investigate the immediate effects of how synchronizing to a visual external stimulus with different

temporal structures could alter gait complexity during overground walking in older adults. Our hypothesis that older adults who exhibit a loss of complexity in their gait patterns would have an increase in gait complexity when walking to a fractal-like stimulus was verified. This was observed through the significant increase of the parameter under study, fractal scaling, from 0.71 to 0.85 in the fractal-like stimulus. We have also observed that walking to an invariant stimulus did not affect gait complexity of older adults. Additionally, we aimed to investigate potential retention effects after the stimulus was turned off. Our hypothesis that older adults would maintain their higher levels of gait complexity generated by the fractal-like stimulus even after this stimulus will be turned off, was also verified. These findings suggest that gait complexity can potentially be restored in older adults by means of a fractal-like visual stimulus.

As expected from older adults, we observed in this study a lower fractal scaling as compared to what is typically observed in healthy young adults during overground walking (Terrier et al., 2005; Vaz et al., 2019). A mean value of α=0.71 indicates that the older adults of the present study present fluctuations in their gait pattern that are more towards randomness (α=0.5 is typically observed in white-noise type of signals). This represents a breakdown in the fractal structure (α~1.0) of the gait patterns observed in healthy adults. This breakdown has previously been observed as an effect of aging and in the presence of neurological diseases (Buzzi, Stergiou, Kurz, Hageman, & Heidel, 2003; Hausdorff et al., 1997, Hausdorff, Cudkowicz, Firtion, Wei, & Goldberger, 1998, Hausdorff et al., 2001; Peng et al., 2002; Stergiou & Decker, 2011). Likewise, fallers older adults also exhbit a breakdown in fractal scaling compared to non-fallers (Herman et al., 2005). Therefore, restoring the fractal structure in older adults can possibly result in other health-related outcomes. In a previous study, we have recently shown that a visual fractal-like stimulus does not alter the fractal scaling of healthy young adults while walking overground (Vaz et al., 2019). On the other hand, an invariant stimulus exhibited a decrease in fractal scaling, towards values closer to what is observed in older populations. These and other similar findings (Hunt et al., 2014; Kaipust et al., 2013; Marmelat et al., 2014; Rhea et al., 2014), together with previous literature indicating that older adults present decreased gait complexity, motivated the investigation of how would sensorimotor synchronization would possibly improve gait complexity. In the present study, we found that synchronizing with a visual fractal-like stimulus altered gait complexity in older adults towards values typically observed in healthy young adults, and these values persisted after the removal of the stimulus. Interestingly, we have also observed the fractal-like stimulus resulted in a reduced stride time variability (i.e. coefficient of variation) after the stimulus was turned off. That resulted in values similar to those observed during uncued walking. On contrary, the stride time variability was higher during the invariant cueing and those values persisted after the stimulus was turned off.

4.1. Restoration of gait complexity by means of a fractal-like stimulus

This is the first time that gait complexity is found to be acutely restored in older adults while walking overground by means of a visual stimulus. Others have shown improvements in gait complexity of older adults while walking on a treadmill, either when exposed to an auditory (Kaipust et al., 2013) or a visual stimulus (Wittstein et al., 2019). Hove and colleagues have also reported improvements in gait complexity when Parkinson's Disease patients synchronized their steps to an auditory stimulus (Hove et al., 2012). Our results demonstrate a significant increase of ~20% in gait complexity relative to baseline (i.e. self-paced condition) while walking to the fractal-like stimulus. This increase is two to four times higher than those observed when an auditory stimulus was used during overground walking [~9%, (Hove et al., 2012)] and during treadmill walking [~5%, (Kaipust et al., 2013)], and when a visual stimulus was used during treadmill walking [~7%, (Wittstein et al., 2019)]. More importantly, this increase in gait complexity observed in our study was retained after the removal of the stimulus, indicating a positive retention effect. Hove and colleagues observed a similar effect in Parkinson's Disease patients. The authors further suggested that the stimulus may have fostered a stabilization of timing networks and basal ganglia functionality. Wittstein and colleagues, however, have not observed a retention effect when older adults walked to a fractal-like stimulus (Wittstein et al., 2019). The major difference in Wittstein et al.'s was the use of the treadmill. The treadmill can act as an external invariant pacemaker and, therefore, decrease gait complexity (Frenkel-Toledo et al., 2005). Getting back to the constant-speed state provided from the treadmill may have abolished any potential effect observed while the stimulus was on. It is also important to point out additional differences between the present study and others. Both Hove et al. and Wittstein et al. collected the “after-stimulus” data with a break in between. In our study, we have asked the participants to keep walking for 8 min after the stimulus was turned off. Although our ~20% increase after the stimulus was turned off is highly encouraging, using a different experimental design with a washout period in between the on and off states is a necessary next step to investigate the duration of the retention effects at the short term. Likewise, the implementation of a randomized control trial will also be required to establish the relationship between improvements in gait complexity with other health-related outcomes.

4.2. Synchronization performance is similar between invariant and fractal-like stimuli

The performance of the synchronization with the cues, commonly named ‘asynchronies’, are often not reported in the literature. This limits the interpretation of the results as one would question if the effects observed in gait complexity are affected or are the result of potential differences in the asynchronies. In the present study, we showed no differences between the invariant and fractal-like stimuli, supporting our interpretation of the fractal scaling values. These results also suggest that adding variability to the stimulus does not increase the task difficulty. It is likely, however, this is the case for our apparatus. Synchronizing to a continuous stimulus, that allows the anticipation of the stepping timing, can potentially increases performance compared to a discrete stimulus that does not allow anticipation of the events to syncrhonize with. Also interesting was the observation that the asynchronies were positive, indicating a reactive stepping strategy. In other words, the participants stepped after the stimulus events. We have recently shown that healthy young adults exhibit an anticipatory strategy, regardless of the type of stimuli (Vaz et al., 2019). This was observed with exactly the same apparatus and stimulus design used in this study. Marmelat et al. (2014) have also reported an anticipatory strategy while healthy young adults walked to discrete auditory stimuli. Considering that older adults tend to have a slower reaction time (Richer, Polskaia, Raymond, Desjardins, & Lajoie, 2019; Sun, Cui, & Shea, 2017), our results suggest that the pace set in the stimulus may need to be adjusted to improve synchronization (i.e. slower). Adjusting the stimulus may have resulted in greater increases when walking to a fractal-like stimulus and lower values when the participants walked to an invariant stimulus, as they would better follow the temporal structure of those. Regrettably, our data does not allow a more in depth understanding of the nature of synchronization, e.g. by means of windowed cross-correlation analysis (Roume et al., 2018). This is because some participants exhibited extra strides to follow the stimulus and others have changed the limb the use to synchronize to the stimulus several times across the cued trials, as we previously described. Future research should test the effects of stimulus's cadence on gait complexity and its correlation with asynchronies.

In addition, our results indicate that regardless of the temporal structure of the stimuli, the coefficient of variation from the inter-stride-intervals was similarly higher in both invariant and fractal-like cued conditions, compared to uncued walking. This further support our findings regarding gait complexity as both conditions were very similar from a task-constraint standpoint. More importantly, we found that this coefficient of variation decreased after the stimulus was removed (i.e. unconstrained walking), but only after the fractal-like stimulus. These values decreased towards the values observed in the uncued walking condition. No changes were observed after the invariant stimulus was turned off. These results strenghten our belief that the fractal-like stimulus likely modify internal regulatory processes that allow the restoration of these fractal-like, healthy, patterns of human walking.

4.3. Continuous visual stimulus as a more effective approach

There are several possible explanations for the greater improvement observed in the present study as compared to others. First, the apparatus and the type of stimulus was different from previous studies. Regardless of the modality of the stimulus (visual or auditory), our apparatus allows the presentation of the stimulus in a continuous fashion. Previous research has shown that a continuous visual stimulus increases the performance of matching with the cues, compared to a discrete stimulus (Repp & Su, 2013). Second, the design of the stimuli is not the same as in previous studies. While we and Wittstein et al. (2019) validated the fractal properties of the temporal structure of the stimulus provided, Hove et al. (2012) and Kaipust et al. (2013) did not report such information. Thus, it is possible that the fractal scaling from the stimuli was not what was really expected in those studies. Lastly, and perhaps more important, the characteristics of the participants under investigation are different compared to ours. Our sample's mean baseline values (no stimulus condition) are considerably lower (α=0.71) than those presented in other studies investigating acute effects of cueing intervention [α=0.92, α=0.85, α=0.80 in Hove et al., 2012, Kaipust et al., 2013 and Wittstein et al., 2019, respectively]. Compared to the pioneering studies from Hausdorff and colleagues (Hausdorff et al., 1997) that showed the breakdown of fractal scaling with aging, their results are similar to ours (α=0.68). These other studies possibly had a bias of assessing highly fit older adults, as actually some discussed within their limitations. To avoid the same type of bias, we have removed four older adults that exhibit a fractal scaling similar to what is typically observe in healthy young adults from the analysis. This resulted in a better representative sample of those older adults that are more likely to benefit from the proposed intervention. Conversely, one could also argue that our greater increase in gait complexity is also related to our lower baseline values and not uniquely the result of the apparatus itself. However, it remains to be determined if with similar baseline values, different approaches (e.g. visual vs auditory) would have resulted in the same increase. We believe that the apparatus used here would produce greater improvements as it provides continuous information that allow the user to anticipate when to step and to update the body segments relative to the phase of the moving bar. The commonly used auditory discrete stimulus, does not provide such rich information and may result in poorer synchronization (Vaz et al., 2020).

It is important to note that although our sample exhibited a lower fractal scaling in gait patterns, it is still a group of older adults considered at an overall good health and mobility, according to our health-related questionnaires. Although out of scope of the present study, this is an interesting finding to report as it can potentially suggest that an alteration in fractal scaling can emerge in earlier stages before behavioral manifestation. Indeed, this looks to be the case in the study of the complexity of activity patterns. Hu and colleagues found that older adults and individuals with dementia exhibit lower fractal scaling in their activity patterns (Hu et al., 2009) and that the degree of disruption is positively related to Alzheimer's disease severity (Hu et al., 2013). Additionally, these authors also showed that the decreased fractal scaling in activity patterns is strongly related to cognitive decline (Hu et al., 2016) and is a strong predictor of mortality (Li et al., 2019). Although speculative based on the present study's data, fractal scaling from gait data may also represent an important biomarker of health. This is worthy of investigation in future studies.

5. Conclusion

The present study showed that a continuous visual fractal-like stimulus can acutely restore gait complexity in older adults. Conversely, the commonly used invariant stimulus in clinical environment did not reveal such capabilities. We have also shown that regardless of the type of stimulus, there were no differences in terms of synchronization performance (i.e. asynchronies), despite older adults exhibiting a reactive strategy by stepping after the stimulus.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at Https://doi.org/10.1016/j.humov.2020.102677.

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