

Research article

Synchronization dynamics modulates stride-to-stride fluctuations when walking to an invariant but not to a fractal-like stimulus

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ARTICLE INFO

Keywords:

Gait dynamics

Sensorimotor synchronization

Cueing

Metronomes

Fractals

Asynchronies

ABSTRACT

Walking with different types of cueing/stimulus (i.e. auditory, visual) has been shown to alter gait variability, thus emerging as an innovative therapeutical tool to restore abnormal gait variability in clinical populations. However, the majority of the research in this area has focused on auditory stimuli while visual stimuli are an understudied alternative that needs more attention, particularly due to the natural dependence on vision during walking. Furthermore, the time differences between the occurrences of the walking steps and the sensory cues, also known as asynchronies, have also received minimal attention, even though the ability to synchronize with different stimuli is of great importance. This study investigated how synchronizing to visual stimuli with different temporal structures could affect gait variability and the respective asynchronies. Participants performed four 15-min walking trials around an indoor track while wearing insole footswitches for the following conditions: a) self-paced walking, and b) walking with glasses that instructed the subjects to step in sync with a virtual moving bar. The stepping occurrences of the moving bar were presented in three different ways b1) non-variable, b2) variable and b3) random. Stride times and asynchronies were determined, and the mean values along with the fractal scaling (an indicator of the complexity) in their time series, were calculated. The fractal scaling of the stride times was unaltered when participants walked with the variable stimulus as compared to the self-paced walking condition; while fractal scaling was significantly decreased during the non-variable and random conditions, indicating a loss of complexity for these two conditions. No differences were observed in the means or the fractal scaling of the asynchronies. The correlation analysis between stride times and asynchronies revealed a strong relationship for the non-variable condition but a weak relationship for both variable and random conditions. Taken together, the present study results supports the idea of an existing internal timekeeper that exhibits complexity. We have shown that this complex pattern is similar regardless of the stimulus condition, suggesting that the system's complexity is likely to be expressed at the task performance level – asynchronies – when walking to a stimulus. Thus, future research in sensorimotor gait synchronization should focus and further explore the role of the asynchronies, as it may be of clinical significance.

1. Introduction

Sensorimotor synchronization is the coordination of a movement with an external rhythm [1], and it has become popular in gait rehabilitation. Specifically, external auditory or visual cues have been implemented with several gait impairments related to Stroke [2], Parkinson's Disease [3–6], Multiple Sclerosis [7] and Aging [8]. Typically, patients are instructed to synchronize their walking to a non-variable stimulus that lacks any temporal variability in its presentation. This approach has been shown to have positive effects on gait characteristics (e.g., cadence and stride length) in clinical populations [9–11].

However, there is recent evidence indicating that such stimuli may not be optimal, as they do not incorporate the natural variability that is observed in gait [12,13]. Gait variability, the natural stride-to-stride fluctuations that are present in walking, is essential for humans to adaptively and safely interact with the ever-changing environment and, therefore, it has been recommended that variability should be incorporated in external cueing interventions [12–14].

Interestingly, multiple studies have shown that gait variability exhibits fractal-like fluctuations with power-law scaling extending over hundreds of steps, demonstrating complexity in healthy gait [12,13,15,16]. The classic definition of a fractal is a geometric object

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Received 9 August 2018; Received in revised form 24 December 2018; Accepted 23 March 2019

Available online 25 March 2019

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with self-similarity over multiple measurement scales [17], and the outputs of the locomotor system measured over time exhibit such fractal properties [13,15,16]. Furthermore, they demonstrate power-law scaling such that 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. However, pathology breaks down this complexity, and as a result, gait variability can become either too periodic or too random [13,18,19]. A similar result is also observed when healthy adults walk with a non-variable auditory stimulus or an auditory stimulus that has a completely random temporal order in its presentation [12,13,20–22]. However, the use of a variable auditory stimulus that exhibits a pink-noise type of temporal order does not affect the gait variability of healthy adults [12,22]. Therefore, a plausible hypothesis is that for clinical populations that rehab their gait using an auditory stimulus, much better results could be achieved if the auditory stimulus is carefully structured to incorporate the pink-noise type of temporal order that is present in healthy gait.

However, in addition to the issue of how an auditory stimulus should be temporally structured, another problem is that an external cueing intervention cannot be used by individuals with declining hearing. This necessitates the exploration of other methods. One alternative is using visual stimuli which is understudied in the context of sensorimotor synchronization, though limited research has suggested that visual stimuli could provide gait improvements (e.g. gait speed, step length, gait symmetry) in neurological patients [23–25]. It has been shown that rhythms portrayed solely by visual input receive encoding in the auditory domain that is not arbitrary but is, instead, isomorphic [26] (i.e. similar in its structure). Thus, entrainment to external rhythms occurs regardless if they are presented visually or auditorily [26]. A visual stimulus also seems to aid walking performance by allocating attention to task-relevant information [27], which reflects the natural dependence of gait on visual information [28,29]. Recently, Terrier [20] has shown that both visual and auditory non-variable stimuli could decrease complexity in the same fashion in the gait variability of young adults [20]. This result suggests that a non-variable visual stimulus could produce similar results as an auditory regarding gait variability. However, it is important to note that Terrier [20] used spatial cues in the visual cueing condition. Visual cues can target different levels of gait regulation: stride time (e.g. flashing light) or stride length (e.g. markers on the floor). It is thus evident that our knowledge and understanding of how a variable visual stimulus can affect gait variability is very limited.

Another important problem regarding sensorimotor synchronization in gait is the lack of understanding regarding how asynchronies (the lag between steps and the stimulus) change due to different sensory systems used (i.e. auditory, visual). Although it has already been shown that subjects exhibit similar mean asynchronies (± 50 ms) when auditory stimuli are used [22], this topic requires further investigation so we can understand how changes in gait variability are related to changes in asynchronies. For example, Delignières and Torre [30] and Torre and Delignières [31] have studied the fluctuations present in the asynchronies while subjects walked to a non-variable auditory stimulus. The authors observed the presence of statistical persistence in the asynchronies generated, supporting the existence of an internal fractal-like timekeeper that affects gait variability [30,31]. Therefore, such information may be able to assist in establishing a connection between the temporal structure of the stimulus and its effect on gait variability in order to get a better understanding of how a variable stimulus actually works.

Based on the above, the study aims to address several knowledge gaps, by investigating 1) how synchronizing to a visual stimulus with different temporal structures could affect gait variability during over-ground walking; 2) how visual stimuli with different temporal structures could affect asynchronies, and 3) how asynchronies and gait

variability relate while walking with visual stimuli of different temporal structures. We hypothesized that 1) compared to non-variable and highly variable randomly structured stimuli, walking to a variable visual stimulus that exhibit fractal-like fluctuations, would result in gait variability that will be similar to what is observed in self-paced walking; 2) asynchronies will be similar across stimuli conditions; and 3) gait variability will have a weaker relationship with the asynchronies observed in the variable stimulus as compared to non-variable or random. This is because the variable stimulus will mimic the natural healthy gait variability and continuous potential adjustments or corrections during walking will be less dependent on the stimulus.

2. Methods

2.1. Participants

Eleven healthy young adults (5 females, 6 males; age = 24.3 ± 5.8 yrs.; body mass = 70.9 ± 14.1 kg; height = 1.75 ± 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.

2.2. Experimental procedures

For this experiment, participants were asked to complete four 15-minute walking trials on a ~200 m indoor track. The first trial consisted of self-paced walking, where the participants were instructed to walk at their self-selected pace while looking straight ahead. For the other three trials, participants were instructed to synchronize their heel strikes to three different visual stimuli: non-variable (NVAR), random (RAND) and variable (VAR). A minimum of 5 min of rest was taken between each trial. The order of the stimuli was randomized.

The visual stimulus consisted of a vertically moving bar displayed in front of a pair of glasses (Vufine +, Sunnyvale CA) (Fig. 1). The participants were instructed to match the heel strikes of their right foot to the top of the moving bar's path and the heel-strikes of their left foot to the bottom of the bar's path. The moving indicator turned red when reaching the top of the display. The participants wore the glasses in all four conditions, however for the self-selected pace there was not a moving bar present.

The RAND stimulus was generated using a normal distribution of random numbers. The VAR stimulus was generated using an approximation of a -10 dB/decade filter with a weighted sum of first order filters. The two stimuli were validated using Detrended Fluctuation Analysis [32] (DFA; RAND: $\alpha = 0.5$, white noise, VAR: $\alpha = 1$, pink noise). Both stimuli were scaled using the mean and standard deviation of each participant's self-paced stride-time. This scaling generated a set of subject-specific stimuli, but also maintained the consistency of stimulus patterns across subjects. The NVAR stimulus was generated using



Fig. 1. Experimental apparatus (left) and the continuous visual stimulus (right) used. A miniaturized display was attached to a standard or participant's glasses, as illustrated. Note that the miniaturized display does not cover the whole lenses and was placed only on one side, allowing the subject to explore the surrounding environment while viewing the continuous stimulus. The visual stimulus (right) 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 and left heel-strikes with the bottom of the bar's path. The white arrows present on the figure are only illustrative of the bar's movement direction.

each participant's mean self-paced stride-time 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 30 s of each trial were discarded prior to the analysis to avoid any transient effect related to stimulus familiarization. The mean and standard deviation were calculated for each ISIs time series. The fractal-scaling exponent, α , was also calculated from the ISIs time series using DFA.

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 fit 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 followed by increases and decreases are followed by decreases. Whereas if the α -value is smaller than 0.5, the long-range correlation is anti-persistent, meaning increases are followed by decreases and vice versa. If the α -value is greater than 1, the signal is regarded as Brown [33]. The range of window sizes of the DFA selected in the current study was from 16 to $N/9$ [34], 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 occurrence of the stimulus. A negative value indicates that the heel strike occurred before the stimulus. The α -scaling of ASYNC time series was also determined. Additionally, we calculated the time difference between the matched ISI and inter-stimulus-interval, i.e., the difference between the temporal distance between strides and the temporal distance between stimulus (SSDyn, Stride-Stimulus Dynamics). This variable represents the dynamics of the interaction between changes in the inter-stimulus intervals and ISIs. While ASYNC represents the absolute time lag between stimulus and stride over time, SSDyn represents how the changes in inter-stimulus-interval modulates the ISIs, indicating the ability of the subject to adapt and compensate to sudden changes from the stimulus. The standard deviation and α -scaling were determined for SSDyn time series. In addition, and to further understand the nature of the synchronization, we have determined the Windowed Detrended Cross Correlation function (WDCC) according to Roume et al. [35]. WDCC was calculated from lag -10 to lag +10, between ASYNC and ISIs time series for each stimuli condition. WDCC were computed over non-overlapping windows of 15 data points, and data were linearly detrended within each window before the computation of cross-correlation. WDCC functions were then point-by-point averaged.

2.4. Statistical analysis

Normality was first assessed through the Shapiro-Wilk test. A one-way repeated measures ANOVA on the visual stimulus factor was used for all the variables studied: mean and α -scaling from ISIs, ASYNC and SSDyn. Mauchly's test was implemented to test sphericity and Greenhouse-Geisser correction was used when not verified. Omega squared (ω^2) was used to assess ANOVA effect sizes. *Post-hoc* analyses with Tukey's tests were used to highlight specific differences between

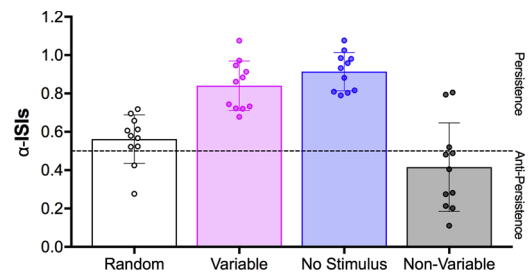


Fig. 2. The α -ISIs mean values listed for each condition. Note that values above 0.5 indicate statistical persistence and below 0.5 statistical anti-persistence. The variable condition revealed to be similar to the no stimulus condition by exhibiting statistical persistence; while the random and non-variable conditions shown a significant decrease in statistical persistence, moving towards the anti-persistence range. Each bullet represents individual value.

conditions. Friedman's Test was used when normality was not verified. The correlation analysis between α -ISIs with α -ASYNC and α -SSDyn was performed through Pearson's R correlations for each stimuli condition. The alpha level was set at 0.05. All statistical analyses other than Fisher's z were performed in SPSS software (SPSS Inc., Chicago, IL).

3. Results

3.1. Inter-Stride-Intervals (ISIs)

We observed similar values of α -ISIs when subjects walked to a variable stimulus or with no stimulus (Fig. 2). Conversely, we observed a significant decrease in α -ISIs in both RAND and NVAR, compared to VAR and no stimulus conditions. This indicates that the variable visual stimulus characteristics did not alter the temporal structure of walking compared to both random and non-variable stimuli.

A significant main effect for condition was observed for α -ISIs ($F(3,30) = 27.632$, $p < 0.001$, $\omega^2 = 0.734$). Pairwise comparisons showed that the α -ISIs was significantly higher in the no-stimulus condition (0.91 ± 0.10) compared to NVAR (0.42 ± 0.23 , $p < 0.001$) and RAND (0.56 ± 0.13 , $p < 0.001$) conditions. Likewise, the α -ISIs for VAR (0.84 ± 0.13) was significantly higher than NVAR (0.42 ± 0.23 , $p = 0.003$) and RAND (0.56 ± 0.13 , $p < 0.001$) conditions. No differences were found between VAR and no-stimulus conditions. Contrary to random and non-variable stimuli, the variable visual stimulus preserved the statistical persistence of ISIs observed in healthy normal gait (no stimulus condition). The random and non-variable conditions showed a significant decrease towards the anti-persistence range ($\alpha < 0.5$), corresponding to values typically observed in older adults or neurological patients.

A significant main effect of condition was observed for mean ISIs ($F(1.216, 12.162) = 12.273$, $p < 0.001$, $\omega^2 = 0.551$; Table 1). Pairwise comparisons showed that the mean ISIs was significantly higher in the VAR condition compared to the no-stimulus ($p = 0.008$), NVAR ($p < 0.001$), and RND ($p = 0.003$) conditions. The differences observed are, however, marginal as they represent differences in stride times lower than 50 ms (Table 1).

3.2. Asynchronies (ASYNC)

Mean and α -scaling from ASYNC were similar in all stimuli conditions (Table 1). Interestingly, α -ASYNC revealed statistical persistence ($\alpha > 0.5$) in all the conditions.

No main effect was observed in α -ASYNC ($F(2,20) = 1.182$, $p = 0.327$, $\omega^2 = 0.106$). Likewise, no main effect for stimuli was observed in mean ASYNC ($F(2,20) = 0.224$, $p = 0.802$, $\omega^2 = 0.022$), indicating that the lags between the strides and the stimuli were, on average, similar throughout conditions. The mean values of ASYNC were negative in all the conditions (Table 1), meaning that the stepping

Table 1Summary results for all the studied variables in all conditions. Data are presented as Mean \pm SD.3.

	Conditions				<i>p</i> -value (main effect)
	No stimulus	Variable	Random	Non-Variable	
Inter-Stride-Intervals (ISIs)					
Mean (seconds)	1.09 ± 0.05	1.13 ± 0.06	1.11 ± 0.06	1.11 ± 0.05	< 0.001
α-scaling	0.91 ± 0.10	0.84 ± 0.13	0.56 ± 0.13	0.42 ± 0.23	< 0.001
Asynchronies (ASYNC)					
Mean (milliseconds)	–	–156 ± 52	–141 ± 48	–153 ± 71	0.802
α-scaling	–	0.94 ± 0.13	0.89 ± 0.22	0.99 ± 0.25	0.327
Stride-Stimulus Dynamics (SSDyn)					
Standard deviation (milliseconds)	–	34 ± 8	35 ± 12	23 ± 6	< 0.001
α-scaling	–	0.36 ± 0.20	0.30 ± 0.15	0.35 ± 0.16	0.608

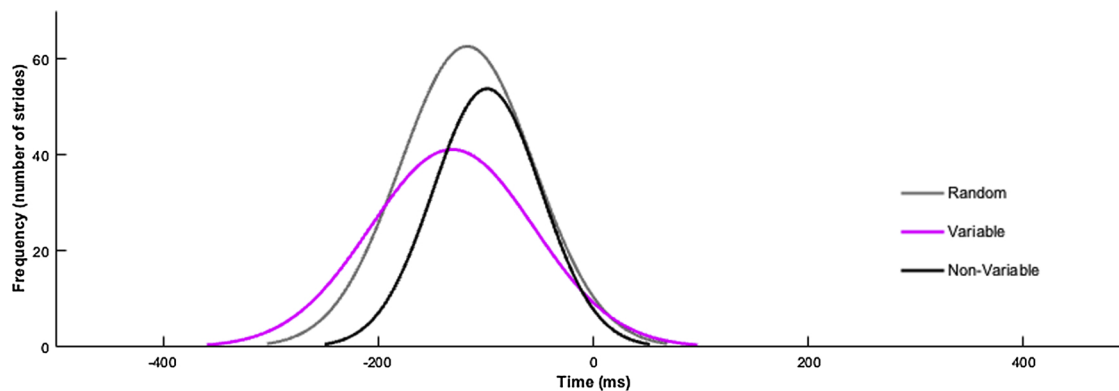


Fig. 3. Illustration of one participant's asynchronies (ms) distribution in all the conditions. Negative values represent stepping before the stimulus (anticipation) and positive stepping after the stimulus (reaction). This example shows a clear anticipatory strategy (i.e. stride occurred before the stimulus) regardless of the condition. Note that the plotted lines represent the fitting of the original distribution.

generally occurred before the stimulus, indicating an anticipatory strategy. Fig. 3 illustrates an example of the distribution of the asynchronies in the three stimuli conditions.

3.3. Stride-Stimulus Dynamics (SSDyn)

We have observed the temporal structure of SSDyn to be anti-persistent in all the three stimuli conditions (Table 1). We have also observed that the NVAR stimulus provided lower variability (SD) compared to VAR and RAND.

No main effect of stimuli condition was observed for α -SSDyn ($F(2,20) = 0.608$, $p = 0.554$, $\omega^2 = 0.057$). A significant main effect was observed for SSDyn's standard deviation ($\chi^2(2) = 13.636$, $p < 0.001$). Pairwise comparisons showed NVAR to be significantly lower than RAND ($p = 0.004$) and VAR ($p = 0.004$).

3.4. Linear correlation analysis

Correlation analysis between α -ISIs and α -ASYNC in the three stimuli conditions are shown in Fig. 4 (left panel). We observed a strong significant correlation for the NVAR stimulus ($r = 0.861$, $r^2 = 0.741$, $p < 0.001$), and a moderate, though not significant, for RAND ($r = 0.451$, $r^2 = 0.204$, $p = 0.163$) and VAR ($r = 0.434$, $r^2 = 0.188$, $p = 0.182$) stimuli.

The correlations between α -ISIs with α -SSDyn are shown in Fig. 4B. RAND ($r = 0.341$, $r^2 = 0.116$, $p = 0.305$) and NVAR ($r = 0.494$, $r^2 = 0.245$, $p = 0.122$) stimuli showed a moderate positive correlation, while VAR showed a very weak negative correlation ($r = -0.215$, $r^2 = 0.046$, $p = 0.525$).

3.5. Windowed Detrended Cross-Correlation Analysis (WDCC)

The averaged cross-correlation function in the three stimuli condition is presented in Fig. 5. Overall, all the stimuli present a similar pattern. An average lag 0 coefficient of about -0.53, -0.55 and -0.41 for the VAR, RND and NVAR was observed. In the VAR condition, however, this was not the local minima. An average lag -1 coefficient of about -0.60 was observed. At lag +1, the NVAR condition revealed a unique characteristic compared to VAR and RND, by exhibiting its local maximum with a coefficient about 0.41. VAR and RND, on the other hand, exhibited the local maximum at lag +2 and lag +3 with a coefficient of about 0.37 and 0.38, respectively.

4. Discussion

The study aimed to address several knowledge gaps by investigating 1) how synchronizing to a visual stimulus with different temporal structures could affect gait variability during overground walking; 2) how visual stimuli with different temporal structures could affect asynchronies, and 3) how asynchronies and gait variability relate while walking with visual stimuli with different temporal structures. Regarding our first aim, we found that, contrary to random and non-variable stimuli, gait variability is not affected when walking to a variable visual stimulus. We showed here that a variable visual stimulus enables the presence of higher persistence fluctuations (i.e. increased complexity) in inter-stride-intervals ($\alpha = 0.84$), while random ($\alpha = 0.56$) and non-variable ($\alpha = 0.42$) visual stimuli showed evidence of lower persistence fluctuations (i.e. decreased complexity). For the second aim, our results showed that asynchronies are not affected by the structure of the stimulus and exhibited fractal-like fluctuations. Finally, for the third aim, we have observed that asynchronies and gait

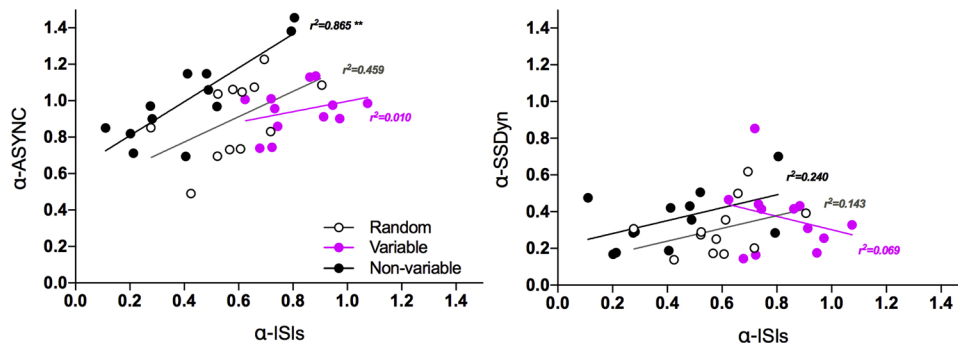


Fig. 4. Correlation results between α -ISIs and α -ASYN (left panel); α -ISIs and α -SSDyn (right panel). The lines represent the trendline for each condition. (A) Left panel's plot shows that the non-variable condition exhibited a strong positive correlation; while a moderate positive correlation was observed for the random and variable conditions. This seems to represent that gait variability is more affected by the asynchronies when walking to a non-variable stimulus. (B) Right panel's plot shows that both random and non-variable stimuli exhibited a moderate positive correlation between SSDyn and ISIs; while a negative weak correlation was observed in the variable condition. Although these correlations were moderate to weak, it is interesting to note how the variable stimulus showed an inverted trend, particularly compared to non-variable.

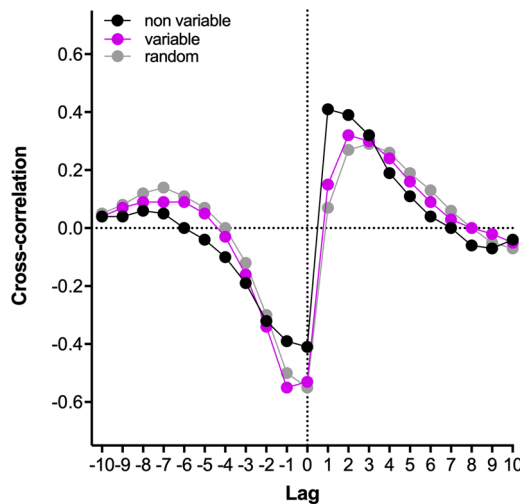


Fig. 5. Windowed detrended cross-correlation functions (from lag -10 to lag +10) between asynchronies and inter-stride intervals for each stimuli condition.

variability are strongly correlated when subjects walked to a non-variable stimulus, and moderately correlated for the two other conditions.

4.1. Synchronizing to a visual stimulus with different temporal structures could affect gait variability during overground walking

Our findings demonstrate that a variable visual stimulus does not affect the natural healthy gait variability during overground walking. Conversely, random and non-variable stimuli affect gait by exhibiting a breakdown in the complexity of gait variability. While other studies have conducted experiments with similar research questions [12,13,20–22,36,37], this is the first study to compare the effects of visual stimuli with different temporal structures during overground walking. We observed higher complexity while walking with a variable visual stimulus and lower statistical persistence or anti-persistence while walking with non-variable or random visual stimuli. Our group has also previously shown similar results with auditory stimuli during overground walking [12]. This, therefore, suggests that our apparatus is a trustworthy alternative to auditory stimuli during overground walking. The use of an auditory stimulus in overground walking can expose the subjects (e.g. older adults) to a risky environment by limiting the auditory system to the stimulus. Our proposed apparatus, on the other hand, enables vision to explore the surrounding environment

as it does not block your entire field of view (Fig. 1).

Thus, we also addressed the issue recently discussed by Terrier [20], such that there is a pressing need to examine the effects of visual cueing in the context of stride-to-stride fluctuations during overground walking. While auditory stimulus has been examined in both overground and treadmill walking, visual stimulus has only been reported in treadmill walking [36]. However, it is important to note that the present study used a temporal based stimulus with no spatial component. As discussed by Terrier [20], it would be challenging to design a device that allows for the manipulation of visual-spatial information during overground walking. Although we believe it is achievable through virtual reality glasses, the potential disadvantages may not worth the effort. First, both stride-time and stride-length statistical persistence were found to be similarly altered whether a temporal (auditory) or a spatial (visual) stimulus is used [20]. Second, the use of a spatial stimulus – either tape lines fixed on the floor (commonly observed in a clinical environment) or virtual horizontal bars projected on the floor or treadmill – requires the individual to look down and to step on the cues. Previous studies have shown that looking down while walking affects energy expenditure [38] and attentional cost [27]. A visual temporal stimulus has been shown to be less attentionally demanding than a visual spatial stimulus [27] (i.e., less constrained). Third, it has also been observed that there is larger body motion while walking and looking down compared to walking and looking ahead [39]. Other than causing potential changes in energy expenditure, looking down can also affect the vestibular system through changes in head orientation. Lastly, looking down at spatial visual cues may reduce peripheral visual information, which is essential for humans to explore the environment and to avoid obstacles while walking. In the present study, we used a highly portable device with great clinical translational capabilities that enables the individuals to explore the surrounding environment.

Our results are in line with previous findings showing that either an auditory or a visual stimulus with statistical persistence (variable) can preserve the complexity and the fractal characteristics of natural stride-to-stride fluctuations; while anti-persistence stimuli (non-variable or random) break down the fractal nature of gait variability [12,13,22,36,37]. Compared to Marmelat et al.'s study [22], our previous [12] and present studies showed that α -ISIs time series is higher for all conditions, including the no stimulus walking condition. The differences may be due to the usage of the treadmill in Marmelat et al.'s study [22], which has been shown to reduce the fractal persistence of stride-time intervals compared to overground walking [40]. This indicates that treadmill walking may enhance the potential adverse effect of a non-variable metronome, which is one of the most commonly used approaches in clinical settings [5,11,25]. Rhea et al. [36,37], however, have also used treadmill walking and reported similar values to ours

when using a discrete [36] and a quasi-continuous [37] visual stimuli. More interestingly, Rhea et al.'s [36] no stimulus condition revealed similar results to Marmelat et al.'s [22], which were lower than ours. One may think that the visual stimulus used in Rhea et al.'s studies [36,37] compensates the treadmill anti-persistence effects compared to Marmelat et al.'s [22] auditory stimulus, by showing a significant increase in α -scaling when walking to a persistent stimulus. This was possibly due to a variety of methodological characteristics in Rhea et al. studies. First, in the Rhea et al studies, the treadmill walking speed was set to be the same for all participants and did not account for the natural self-selected walking speed. However, gait speed on the treadmill has previously been shown to affect inter-stride-intervals fluctuations [33,40]. Second, Rhea et al. [36,37] used a stimulus with a fixed mean and standard deviation for all the subjects, not taking into consideration individual-specific preference cadence, as others have been doing [12,13,22]. This may explain why Rhea et al. [36] reported higher α -ISIs when walking with a persistent visual stimulus compared to the no-stimulus condition. The presentation of the visual stimulus is also a relevant feature of cueing interventions. While Rhea et al. [36] showed decreases in α -scaling when walking synchronized to a flashing light presented in a non-variable fashion, Sejdic et al. [41] observed no changes in the α -scaling. The potential explanation for such contradictory results is the use of the treadmill in the Rhea et al. [36] study compared to overground walking in Sejdic et al. [41]. However, our results are closer to what Rhea et al. observed, though our participants walked overground. We believe that the use of a discrete visual stimulus increases the likelihood of not synchronizing in time with the cues. Thus, the decreased α -scaling observed by Rhea et al. is likely a result of the treadmill acting as an external pacemaker [42]. This idea is further supported by the results observed in the Sedjic et al study in terms of the asynchronies (named residuals in their study). The authors observed increased standard errors in asynchronies during visual cues compared to auditory cues, suggesting that the matching with the cues was poorer when walking to visual cues. In our study, our stimulus is presented in a continuous fashion, which increases the task performance. Previous research has shown that a continuous visual stimulus increases the performance of matching with the cues, compared to a discrete stimulus [1]. Additionally, when synchronizing to an auditory discrete stimulus, humans perform better compared to a visual stimulus [1].

4.2. Asynchronies exhibit fractal-like fluctuations regardless the structure of the stimulus

Our results also showed that walking synchronized to a continuous visual stimulus promotes an anticipation strategy, regardless of the stimulus's structure. Fig. 3 shows an example of the step-to-stimulus synchronization distribution in each condition. Although some reactive steps took place, the distribution is clearly shifted to the negative values, which represent an anticipatory strategy dominance. These results are in line with previous findings where all conditions showed an average of 50 ms anticipation, regardless of the stimuli [22]. Our results, however, showed a greater anticipatory behavior (± 150 ms). This is likely to be due to the nature of the sensory source of stimulus input – vision. Several works in sensorimotor coordination, especially in finger tapping, support the improved performance (i.e., decreased time lag between taps and the stimulus) in auditory compared to a visual stimulus (see Repp and Su [1] for a detailed review).

We further analyzed the temporal structure of the time series of the asynchronies (i.e., ASYNC). We have observed statistical persistence regardless of the structure of the stimuli. This has previously been found in tapping [31,43–45] and walking [30] to a non-variable stimulus. The new findings from the present study are the observed statistical persistence in ASYNC regardless of the temporal structure of the stimuli. These results further support the idea of an existing internal timekeeper that contains fractal-like fluctuations [30,31]. In particular, Delignières and Torre [30] have previously suggested that the loss of complexity

observed when walking to a non-variable metronome does not necessarily indicate a less complex system. In such case, the intrinsic complexity of the system is still at work but is expressed in the task performance, i.e., asynchronies. Our results further support these findings as we observed no differences between stimuli conditions in the structure of ASYNC. Moreover, the fractal scaling of ASYNC revealed statistical persistence similar to that observed in ISIs during walking with no stimulus.

Also, it may mean that in healthy young adults, the asynchronies are not driven by the structure of the stimulus. This interpretation is also in line with the extensive work from Repp and colleagues [1] that suggested synchronization phase correction to be independent of interval-based processes. Another interesting result we had was the presence of a strong and significant positive correlation between the temporal structure of ISIs and ASYNC in the non-variable condition, while a moderate and not significant correlation was observed in both variable and random conditions. Therefore, we found that when subjects had statistical persistence in their gait variability while walking to a non-variable stimulus, the ASYNC linearly increased towards levels of persistence known to exist in Brownian noise. This is an interesting finding that might have an important clinical significance as the non-variable stimulus is commonly used in gait. These results suggest that when the subjects do not follow the structure of the non-variable stimulus, the structure of their ASYNC were also increased. This might be the case in clinical populations, as we believe that patients will struggle to follow a non-variable stimulus while walking. In such case, the structure of the ASYNC will be altered and an increase in gait complexity will be observed. Therefore, finding a way to manipulate the ASYNC may be another solution to restore gait variability when walking to a non-variable stimulus. While the role of the ASYNC dynamics is not fully understood, this suggests it plays an important role when walking to a non-variable stimulus. Future research should focus on the role of the ASYNC in gait variability.

4.3. Compensatory strategies are not driven by the structure of the stimuli

From a performance and learning perspective, a greater difference should ideally be followed by smaller and smaller differences, suggesting an efficient feedback control mechanism. In the present study, we did not find differences between stimuli in the temporal structure of SSDyn time series (α -SSDyn). The α -SSDyn mean values revealed anti-persistence for all the stimuli. This is likely to represent the effect of the task (sensorimotor synchronization) as a constraint. However, this stimulus-constraint phenomenon did not seem to affect the temporal structure of gait variability (i.e., α -ISIs) for the variable stimulus and showed a greater impact on the non-variable than on the random stimuli. This interpretation is based on the observed stronger correlation between α -ISIs and α -SSDyn for the non-variable and random stimuli as compared to variable stimulus. This may indicate a control strategy of gait when walking synchronized to a stimulus. As the α -ISIs decreases towards anti-persistence, it means that a large stride interval is more likely to be followed by a small one and vice versa. In SSDyn, anti-persistence means that a larger difference between inter stride intervals and inter stimulus intervals is more likely to be followed by a smaller, and a smaller difference between those are likely to be followed by a larger difference, reflecting step-to-step adjustments to the changes within the stimulus. Our interpretation here is that with both random and non-variable stimuli, gait variability is affected by how subjects adjusted their strides to the stimulus changes. This was not the case for the variable stimulus, possibly by mimicking the natural fluctuations of healthy gait (note that no differences in α -ISIs were observed between no stimulus and variable stimulus).

To further understand the nature of the synchronization we computed the windowed cross correlation analysis (WDCC) that provides information about the local dynamics, i.e. the short-term processes. As recently proposed [35] the WDCC function should be considered as a

pattern. Here we observed an overall identical pattern between conditions suggesting similar local dynamics regardless of the stimulus temporal structure. However, we would like to stress that the non-variable stimulus exhibited a slight, but possibly relevant, feature compared to the other two stimuli. Its correlation coefficient was higher at lag + 1 compared to variable and random conditions. This could indicate that the synchronization with a non-variable stimulus could partly be driven by cycle-to-cycle corrections. This is likely the case for the other two conditions, but at a different extent as revealed by the lower coefficient at positive lags. More important is the higher negative correlation coefficient at lag-1 in the variable condition compared to the other two. This, together with the negative coefficients at lag-0, is suggestive that synchronization was also modulated by an anticipation and not driven by cycle-to-cycle corrections. Delignières and Marmelat [46] has shown a clear negative peak with a coefficient around -0.6 at lag-2 and a coefficient around 0 at lag-0, during synchronized walking with a fractal stimulus. The authors suggest that the synchronization was then modulated by cycle-to-cycle corrections, i.e. asynchrony-based coordination. Our results do not arrive at the same conclusions. We believe that these differences might be due to the type of the stimulus provided. Because Delignières and Marmelat [46] used an auditory discrete metronome, the possibility of anticipation was reduced and the subjects relied on feedback mechanisms. It is then very plausible that the subjects relied on cycle-to-cycle corrections to maintain coordination with the stimulus. However, in our study, the subject had continuous visual information on *when* to step. This provided the participant with information to successfully anticipate the step, to step in sync with the stimulus. Therefore, the local synchronization process is hardly the result of cycle-to-cycle corrections only. This is evidenced by the pattern of the WDCC graph in which the correlation coefficient is very similar at lag-1, lag-0 and lag+1 (or lag+2) compared to the clearly higher peak at lag-2 observed from Delignières and Marmelat [46]. However, in either study, this analysis revealed that coordination dynamics seems to be modulated by localized processes and not be driven by the structure of the stimulus itself.

Taken together, our results indicate that localized synchronization processes are fundamental to the overall coordination understanding. The anti-persistent results in all the conditions for SSDyn suggest that the participants were also relying on feedback mechanisms. This was further supported by the results observed from the WCCD. This is an interesting finding as it may provide further insights into the nature of synchronization. In particular, these findings in the dynamics between stride and stimulus intervals suggest that subjects ignored or were unable to predict the changes in the stimulus. It means that rather than predicting the tempo of the stimuli, the subjects relied on real-time feedforward mechanisms provided from the moving bar and feedback mechanisms from their performance (note that the subjects could understand how well synchronized were with the stimulus). Our results further support the idea there is a distinction between the perception and production of rhythmic sequences [47]. This plays against the notion that anticipation results from prediction from an internal model, i.e., weak anticipation. However, one should note that the subjects were not instructed to try to identify or predict the temporal structure. In fact, our apparatus provided a continuous stimulus, so a less predictive dependency was required. We interpret these results as the subjects focused on the task (i.e., synchronizing the steps), and ignored the prediction of future changes within the stimulus.

In summary, our major conclusions were that a continuous visual stimulus with a variable temporal structure keeps the natural and healthy stride-to-stride fluctuations during overground walking, while random and non-variable stimuli break down these natural fluctuations. Furthermore, we have shown that, although the mean asynchronies (time between the strides and the stimulus) were not different between the different stimulus, the random and the non-variable stimulus are likely to constrain the natural fluctuations. This is because we observed a strong correlation between stride time and asynchronies temporal

structure for non-variable, compared to a weak correlation in the variable condition. Future experiments that could challenge our findings should focus on the exploration of the role of the asynchronies in terms of modulating or being modulated by gait complexity. For example, exploring the temporal structure of the asynchronies in older adults or clinical populations which are known to have a decrease in gait complexity, can provide a better understanding on the idea of the existence of an internal fractal-like timekeeper. Furthermore, a possible next step is the investigation of the potential relationship with attentional demands to better understand the underlying control mechanisms when exposed to stimulus with different temporal structures. Moreover, the effect of the proposed apparatus in stride length and walking speed during overground walking should be analyzed in future studies. It has previously been observed that stride length and walking speed are not affected during overground walking with auditory cues, compared to stride time [48]. Also, as external cueing is a conventional approach used in gait rehabilitation, understanding this control mechanism in older adults or neurological patients would bring new insights to gait control and rehabilitation. It is likely that, since gait variability is known to be altered (towards anti-persistence) in older adults and neurological patients, the attentional demand would be higher when walking with a stimulus with higher persistent fluctuations. However, training with a variable, persistent stimulus would possibly improve gait dynamics and decrease attentional demands through time. Lastly, the present study results show that visual cueing with a variable and fractal-like structure could have great potential as a clinical tool for gait rehabilitation. The specific experimental apparatus used here still allows the individual to explore the surrounding environment while visualizing the continuous stimulus, emerging as a reliable and safe alternative.

Acknowledgments

This study was supported by the Center for Research in Human Movement Variability, the National Institutes of Health (P20GM109090 and R15HD086828) and the Office of Research and Creative Activity at the University of Nebraska at Omaha.

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