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Original Research

Effects of Cueing Training on Gait Variability

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Abstract

International Journal of Exercise Science 19(1): 1006, 2026. Self-generated cueing is considered a promising approach to improve gait stability. This study examines whether rhythm training enhances cueing performance by influencing rhythm perception and gait variability in young healthy participants as a preliminary step before applying it to patients with Parkinson's disease (PD). Fifteen healthy participants (7 males, 8 females; age 22.0 ± 2.6 years, height 163.1 ± 9.6 cm, weight 55.9 ± 8.3 kg) completed the 10-minute rhythm training, synchronizing button taps with a metronome at their individual cadence-based beats per minute (BPM) while receiving visual feedback. Rhythm and gait were assessed pre- and post-training to evaluate changes in each parameter and variability. No significant changes were observed in BPM or rhythm variability. However, the cadence-BPM difference significantly decreased ($p = 0.006$) with a moderate effect size ($g = 0.592$). In gait evaluation, cadence significantly decreased, and right step time significantly increased, both with small effect sizes. No significant changes were found in gait variability. A significant negative correlation was observed between the cadence-BPM difference and variability in right step time ($p = 0.001$, $r = -0.749$) and left stance time ($p = 0.006$, $r = -0.676$). Rhythm training improved synchronization between internal rhythm and walking cadence but did not reduce gait variability. The negative correlation between cadence-BPM difference and gait variability suggests enhanced rhythm synchronization may increase cognitive load, potentially worsening certain gait variability factors. Future research should explore these effects in patients with PD and determine optimal timing for self-generated cueing to maintain stable gait.

Keywords: Rhythm training, rhythm perception,cueing, Parkinson's disease

Introduction

Gait is a complex motor function requiring precise time-and-rhythm coordination between neural and musculoskeletal systems, which is essential for maintaining stable and adaptive walking patterns.[1] Disruptions in rhythm abilities—including the ability to perceive rhythmic regularities (rhythm perception) and to anticipate the timing of movements (predictive timing)—have been linked to gait impairments in various neurological disorders, suggesting that rhythm

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plays a central role in locomotor control.[2,3] Taken together, interventions that enhance rhythm perception and internal timing may provide a foundation for improving gait stability.
Insights on the above may facilitate the design of strategies for disorders such as Parkinson's disease (PD).[4] In PD, rhythm perception and predictive timing derangements are common and contribute to gait-related disturbances. One such disturbance is freezing of gait (FoG),[5,6] a transient inability to initiate or continue walking. In PD, proprioception sensory processing deficits impair sensations of movement and planning, thereby contributing to FoG.[7] Additionally, deficits in complex rhythm discrimination support the hypothesis that impaired predictive timing contributes to FoG.[8–10] Therefore, elucidating the mechanisms underlying motor planning in gait and developing rhythm-based interventions are critical. However, given the considerable variability among individuals with PD due to disease progression, it is imperative to initially investigate the fundamental effects in healthy individuals.

Pharmacological and surgical treatments provide limited relief from gait disturbances such as FoG, prompting exploration of cueing-based interventions.[11] Cueing involves external stimuli that assist gait initiation and is classified into two categories: spatial cues, which provide visual guidance (e.g., horizontal floor lines)[12,13] and temporal cues, which provide timing signals for movement execution (e.g., metronomes or vibratory stimuli).[14] These cues help patients predict and initiate steps, thereby facilitating unhindered smoother walking. Previous studies have reported that cueing reduced the frequency of FoG[12,14] and significantly improved step length, walking speed, as well as ankle and hip kinematics.[13]

Although various devices have been proposed for PD motor symptom management,[15–20] simple cueing devices can be developed as compact, cost-effective, and non-invasive solutions to support gait performance. Research suggests that the beneficial effects of cueing can be observed even in the early stages of PD and may become more pronounced as the disease progresses.[21] Furthermore, recent research has focused on the implementation of rhythmic auditory cueing as a home-based rehabilitation setting. In context, studies have shown that incorporating rhythmic cueing into self-managed walking programs may improve gait outcomes in individuals with PD.[17,18,22] Recent studies have also highlighted that individual rhythmic abilities may influence an individual's synchronization to external cues. Bella et al. has demonstrated that participants with better rhythm perception showed greater improvements in gait parameters when exposed to rhythmic auditory stimulation.[22] Similarly, Cochen De Cock et al. reported considerable interindividual variability in response to rhythmic cueing among patients with PD, and suggested that individual differences in rhythm-related abilities might influence cueing efficacy.[23] These findings underscore the importance of assessing and possibly training rhythm abilities as part of individualized gait interventions. However, cueing also has drawbacks, such as dependency, which may impair movement when discontinued.[24] Additionally, external cueing requires gait synchronization, potentially increasing cognitive load and gait variability.[25] Gait variability, referring to fluctuations in step-to-step consistency, is a critical factor linked to falls.[26]

Given these concerns, self-generated cueing has gained widespread interest. Unlike external cues, self-generated cueing involves conscious maintenance of an internal rhythm. Studies suggest that singing, rather than externally presented cues, can serve as a self-generated cue to improve gait and reduce gait variability.[26–28] One study comparing self-generated cues (singing) with external cues (listening to music) found that self-generated cues significantly improved step cadence, whereas external cues increased gait variability.[29] These results suggest that active music production, such as singing, may activate reward and motor networks—including the basal ganglia, thalamus, and cerebellum—more effectively than passive listening, thereby enhancing motivation and motor drive. This finding suggests that self-generated cueing may promote a more stable gait.

As noted earlier, FoG is linked to a general rhythm processing deficit in PD.[2] Previous studies have demonstrated that interventions involving rhythmic cueing can improve gait performance.[21,30,31] Additionally, studies investigating the effects of rhythm training has shown that it can influence motor functions, including gait, as well as rhythm abilities.[19,20] However, no studies have examined whether rhythm training enhance the effects of self-generated cueing. This study hypothesized that rhythm training would improve the synchronization between internal rhythm and walking cadence, thereby reducing gait variability. Such improvement may be mediated by enhanced rhythm perception and predictive timing ability, as suggested in previous studies. To explore this concept, we conducted a preliminary study on healthy young individuals before applying the approach to patients with PD.

Methods

Participants

Assuming a large effect size (Hedges' g = 0.80), with a significance level of $\alpha = 0.05$ and power $(1-\beta) = 0.80$, a priori power analysis using G*Power 3.1 indicated that a sample size of 15 was required for this study. To account for potential dropout or data exclusion, 16 healthy young individuals aged 20–29 years were recruited. This study was approved by the Ethics Committee of Tokushima University Hospital (approval number, 4554; July 29, 2024) and was performed in accordance with the principles outlined in the Declaration of Helsinki. All participants provided written informed consent to participate in this study. All procedures were performed in accordance with the relevant guidelines and regulations.

Protocol

Parameters on body composition, including weight, total muscle mass, and body fat percentage, were measured using a bioelectrical impedance analyzer (model RD-803L; Tanita Corp., Japan). The experiment was conducted according to the following procedure.

Target Tempo Determination.

To establish the target tempo for cueing, participants were instructed to walk in place naturally for several steps while their gait cadence was measured using a tap tempo application. This application determined the beats per minute (BPM) by recording the interval between consecutive key presses on a PC. Although this method does not rely on a strict step count or fixed time, it allowed for a quick approximation of each participant's general walking cadence for use as a target tempo. During the measurement, the evaluator visually observed the participant's foot contact and pressed the key accordingly. The BPM obtained was set as the participant's target BPM.

Rhythm Synchronization Assessment.

Before rhythm training, participants underwent an assessment of rhythm synchronization. Rhythm synchronization was assessed using a standard synchronization tapping task. While listening to a metronome set at their target tempo, participants instructed to synchronize their key presses with the rhythm of the beats. This test lasted for one minute and was conducted twice. A stopwatch application was used solely to log the timestamp of each key press (recorded as lap times), which allowed us to calculate the tap-to-tap intervals. These intervals were then used to compute rhythm variability, defined as the coefficient of variation of key-press intervals. The first 10 beats were excluded from analysis to account for rhythm stabilization. Although the rhythm synchronizationtask was developed specifically for this study, its structure is based on the principle of sensorimotor synchronization, in which participants attempt to match their motor output (key presses) to auditory stimuli (metronome beats).[32]

Gait Assessment.

Before rhythm training, gait was evaluated under a self-generated cue condition. To implement this, participants were first exposed to a metronome set at their target BPM for 15 seconds. Immediately afterward, they walked back and forth along a 10-meter straight path while internally recalling the tempo of the previously presented metronome beats. Therefore, despite the rhythm being externally presented initially, the ongoing cue during walking was self-generated internally by the participant. Gait assessment was conducted using the G-WALK wireless inertial sensor gait measurement device (BTS Bioengineering S.p.A., Italy). This procedure was developed with reference to previous studies that introduced auditory cues before gait tasks.[26,33] The 10-meter walking distance was chosen based on practical considerations and general compatibility with typical gait assessments performed using the G-WALK system.

Rhythm SynchronizationTraining.

Participants were presented with the target tempo and instructed to press a PC key continuously in sync with a metronome. The target tempo was determined as described in Target Tempo Determination, The BPM of their key presses was displayed on the PC screen as feedback, allowing them to recognize any deviations from the target tempo. The BPM of each tap was calculated based on the time interval between the most recent tap and the immediately preceding tap. To prevent over-reliance on visual feedback, the BPM display alternated between visible and hidden every 30 seconds. Training lasted five minutes, followed by a break, and was then repeated for another five minutes. The training protocol was designed based on the concept of sensorimotor synchronization, where individuals practice aligning their motor output with a rhythmic auditory stimulus.[32]

Post-Training Evaluation.

To assess changes following training, the evaluations from steps 2 and 3 were repeated immediately after the training session.

Evaluation Methods.

From the rhythm synchronization assessment, BPM (mean key press interval) was obtained, and the average of the two trials was used for analysis. Rhythm variability was calculated as the coefficient of variation of key press intervals, obtained by dividing the standard deviation by the mean value.

From the gait assessment, the following parameters were measured: total walking time, cadence (steps per minute), walking speed, stride length, step duration for the left and right legs, stance time (duration of foot contact with the ground), and swing time (duration of foot off the ground). The coefficient of variation was calculated for stride length, step duration, stance time, and swing time to assess gait variability. Additionally, the difference between cadence during gait assessment and BPM during rhythm synchronization assessment was calculated as the cadence-BPM difference. Pre- and post-training comparisons were made, and correlations between the cadence-BPM difference and gait variability were analyzed. The cadence-BPM difference represents the gap between cadence, the gait cycle during walking, and BPM measured during rhythm synchronization assessment. A smaller cadence–BPM difference indicates that participants were better able to internalize the target rhythm and translate it into their walking performance, whereas a larger difference reflects difficulty in maintaining the intended rhythm. Therefore, this metric serves as an index of the participant's ability to implement rhythm perception and synchronization skills in actual gait.

Statistical Analysis

In a comparison of pre- and post-intervention, the paired *t*-test was used to analyze the two groups when the normality of distribution was verified by Shapiro–Wilk's test. If normality was not confirmed, Wilcoxon's signed-rank test was employed. Significance and effect size were determined using Hedges' g when normality was observed or Cliff's delta when it was not. Due to the small sample size, Hedges' g was used as an unbiased estimator of effect size in place of Cohen's d. Correlations between cadence-BPM difference and gait variability were determined using Pearson's correlation coefficient. In the correlation analysis for this research, cadence-BPM difference and gait variability values were taken as the differences between the values before and after the interventions. The Bonferroni correction was applied only to correlation analyses, as multiple gait variability parameters were tested against a single outcome (cadence-BPM difference). All statistical analyses in this study were performed using R version 4.2.1,[34] and the significance level was set at $P < 0.05$.

Results

Sixteen healthy participants (eight males, eight females) were initially recruited, but one male participant was excluded due to technical issues, resulting in a final sample size of 15 participants. The average age was 22.0 ± 2.6 years, and all participants were right-foot dominant, with an average height of 163.1 ± 9.6 cm, weight of 55.9 ± 8.3 kg, and body mass index of 21.0 ± 2.1, muscle mass of 41.0 ± 8.3 kg, and body fat percentage of 22.8 ± 8.0%.

Pre–Post Changes in Rhythm Performance

Comparing pre- and post-training results, no significant changes were observed in BPM or rhythm variability (Figures 1 and 2). However, the cadence-BPM difference significantly decreased (Figure 3) with a moderate effect size.

Pre–Post Changes in Gait

In the gait evaluation, cadence significantly decreased (Table 1), while right step time significantly increased (Table 1), both with small effect sizes. No significant changes were found in gait variability before and after training (Table 2).

Correlation Analyses

A significant negative correlation was observed between the cadence-BPM difference and the coefficient of variation for right step time and left stance time (Table 3).

Table 1. Change in gait measurements.

Item	Before intervention (Mean±SE)			After intervention (Mean±SE)			p-value		Effect size	
Time required (s)	51.373	±	4.976	43.793	±	3.672	0.129		g =	0.435
Cadence (steps/min)	111.471	±	2.392	109.412	±	2.261	0.007	*	g =	0.222
Velocity (m/s)	1.127	±	0.058	1.105	±	0.056	0.298		g =	0.094
Step length (body ratio)	74.264	±	2.776	74.051	±	2.540	0.871		g =	0.020
Left step time (s)	1.111	±	0.039	1.108	±	0.022	0.164		δ =	-0.129
Right step time (s)	1.083	±	0.022	1.109	±	0.023	0.006	*	g =	-0.300
Left stance time (s)	60.243	±	0.503	59.815	±	0.504	0.414		g =	0.214
Right stance time (s)	59.109	±	0.495	58.560	±	0.485	0.191		δ =	0.111
Left swing time (s)	39.757	±	0.503	40.185	±	0.504	0.414		g =	-0.214
Right swing time (s)	40.891	±	0.495	41.440	±	0.485	0.191		δ =	-0.111

SE, standard error; P < 0.05 indicates statistical significance. Asterisks indicate statistically significant results.

Table 2. Change in gait variability.

Gait variability	Before intervention (Mean±SE)			After intervention (Mean±SE)			p-value	Effect size	
Step length (body ratio)	0.063	±	0.016	0.048	±	0.007	0.679	δ =	0.040
Left step time	0.085	±	0.047	0.039	±	0.010	0.300	δ =	0.267
Right step time	0.031	±	0.004	0.042	±	0.011	1.000	δ =	0.000
Left stance time	0.026	±	0.002	0.029	±	0.005	0.679	δ =	0.084
Right stance time	0.031	±	0.005	0.035	±	0.004	0.804	δ =	-0.209
Left swing time	0.040	±	0.003	0.042	±	0.006	0.599	δ =	0.076
Right swing time	0.046	±	0.008	0.050	±	0.006	0.847	δ =	-0.173

SE, standard error; P < 0.05 indicates statistical significance.

Table 3. Correlation between cadence-BPM difference and gait variability.

Gait variability	p-value		Correlation coefficient
Step length (body ratio)	0.035		-0.546
Left step time	0.423		-0.224
Right step time	0.001	*	-0.749
Left stance time	0.006	*	-0.676
Right stance time	0.043		-0.527
Left swing time	0.008		-0.654
Right swing time	0.034		-0.548

P < 0.05 indicates statistical significance. Asterisks indicate statistically significant results.

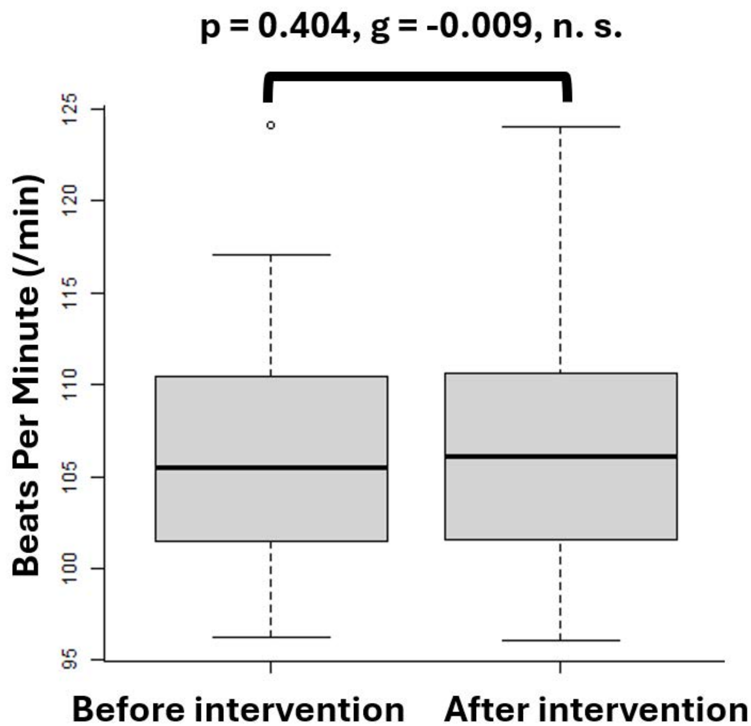

Figure 1. Change in the beats per minute. This figure shows the change in beats per minute in rhythm synchronization assessment comparing pre- and post-training. Circles indicate outliers.

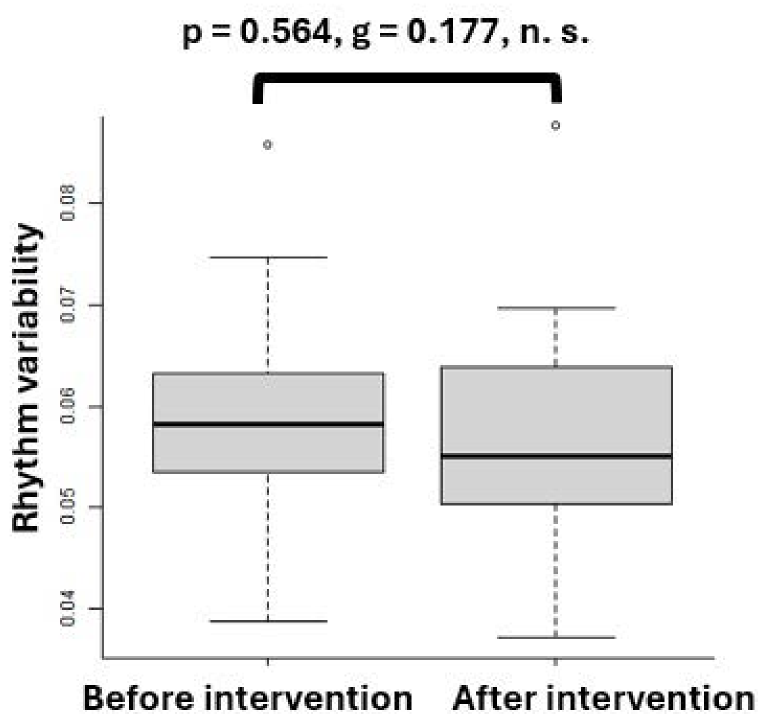

Figure 2. Change in rhythm variability. This figure shows the change in rhythm variability in rhythm synchronization assessment comparing pre- and post-training. Circles indicate outliers.

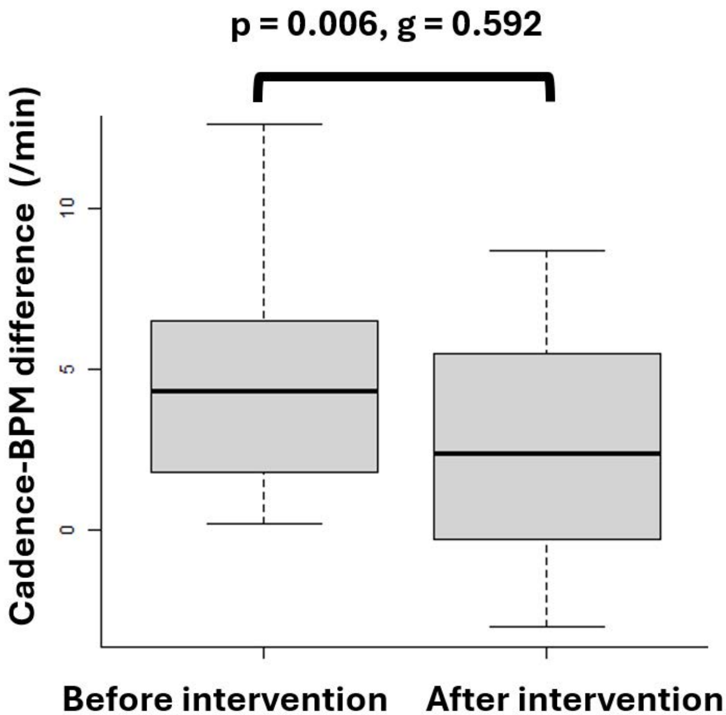

Figure 3. Change in the cadence-BPM difference. This figure shows the change in cadence-BPM difference between pre- and post-training.

Discussion

The rhythm evaluation results indicated that although rhythm variability remained unchanged with training, the cadence-BPM difference significantly decreased. This difference represents the gap between cadence, the gait cycle during walking, and BPM measured during rhythm evaluation. These findings suggest that training may have improved the ability to synchronize internal rhythm with walking cadence. This improvement may be attributed to enhanced temporal prediction and strengthened sensorimotor coupling through repeated synchronization tasks during training. Such mechanisms are consistent with previous findings showing that rhythm training can improve both rhythm ability and motor performance by reinforcing the interaction between auditory and motor system.[19,20]

Accompanying these changes, cadence decreased, and right step time increased in the gait evaluation, suggesting that rhythm perception changes may have influenced gait performance. However, gait variability did not significantly differ before and after training, implying that while rhythm perception and gait characteristics changed, these effects were insufficient to alter gait variability. Additionally, the significant negative correlation between the cadence-BPM difference and the coefficient of variation for right step time and left stance time suggests that reducing the cadence-BPM difference might inadvertently worsen certain gait variability indices. All participants were right-foot dominant, yet the observed correlations were limited to one leg for both step time and stance time variability, implying that foot dominance may influence susceptibility to these changes.

While our study did not find a significant change in gait variability, this does not directly contradict previous studies demonstrating reductions in gait variability through self-generated cueing during gait in individuals with PD.[26-28] The previous studies involved clinical populations with distinct motor impairments and used cueing during walking. In contrast, our study included healthy young adults and focused on the isolated effect of rhythm training without concurrent gait practice. In addition, prior studies on rhythm training have investigated multi-week rhythm-based interventions using serious games to improve motor function in PD.[19,20] While these studies demonstrate the feasibility and potential of rhythm training in home settings, they did not specifically assess its effect on self-generated cueing or gait variability under internally guided rhythmic conditions. The present study differs in its scope and population, aiming to evaluate whether short-term rhythm training alone can influence gait performed under self-generated cue conditions. This approach addresses an early-stage research question regarding how rhythm perception training may modulate internally driven gait control in the absence of external feedback, potentially laying the foundation for future applications in clinical populations. In external cueing, gait variability typically increases due to the adjustments required for synchronizing walking with the cue and the associated cognitive load. Similarly, self-generated cueing necessitates synchronization with an internal rhythm, which, though less pronounced than external cueing, may contribute to increased gait variability. Furthermore, rhythm training might heighten cueing awareness, leading to stronger gait adjustments and an increased cognitive load, potentially exacerbating gait variability.

Regarding the application of these findings to FoG in PD, FoG often occurs at gait initiation and during turns. Selectively applying cueing only when necessary may therefore be beneficial. Using cueing only during FoG episodes while otherwise walking without cues could help maintain gait stability without increasing variability.

In external cueing, devices have been developed to detect FoG and provide cues accordingly;[35] however, similar strategies have not been explored for self-generated cueing. The relationship between rhythm perception and gait variability identified in this study could facilitate future research in this area.

Future studies should determine whether similar trends occur in patients with PD by replicating these experiments in this population. Additionally, investigating more effective rhythm training methods and optimizing the timing of cue application in self-generated cueing to maintain low gait variability are important considerations.

A notable limitation of this study is the relatively short walking distance (10 m out-and-back), which may have resulted in an insufficient number of steps for precise assessment of gait variability. Despite this constraint being partly attributable to space and time limitations during testing, we acknowledge that longer walking trials or repeated measures would improve the reliability of variability metrics. Although the sample size was determined based on a large, expected effect, the observed effect was smaller than anticipated, suggesting that continued research with larger samples may be required to confirm subtle training effects. Additionally, the lack of a control group limited the ability to distinguish training effects from potential test–retest influences. Subsequent investigations should incorporate a randomized controlled design to ascertain the causal impact of rhythm training. Precision indicators such as the phase coordination index may offer additional insights into gait coordination. Future studies using instrumented walkways or dual foot sensors may enable such analyses.[36]

This study hypothesized that rhythm training in self-generated cueing would improve the synchronization between internal rhythm and walking cadence, thereby reducing gait variability. As a preliminary investigation before testing this hypothesis in patients with PD, we conducted experiments with young healthy participants.

The results indicated that although training improved the cadence-BPM difference, it did not enhance gait variability. Moreover, a significant negative correlation was observed between the cadence-BPM difference and gait variability indices such as right step time and left stance time, suggesting that training might have worsened certain gait variability factors. This effect may be attributed to increased cueing awareness and the cognitive load induced by rhythm training.

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