論文 / 著書情報
Article / Book Information

題目(和文)	
Title(English)	Spatiotemporal Gait Guidance Using Audiovisual Cueing with a Synchronized Walking Avatar in Augmented Reality
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出典(和文)	学位:博士(学術), 学位授与機関:東京科学大学, 報告番号:甲第397号, 授与年月日:2025年3月26日, 学位の種別:課程博士, 審査員:三宅 美博,山村 雅幸,小野 功,瀧ノ上 正浩,吉村 奈津江
Citation(English)	Degree:Doctor (Academic), Conferring organization: Institute of Science Tokyo, Report number:甲第397号, Conferred date:2025/3/26, Degree Type:Course doctor, Examiner:,,,,
学位種別(和文)	博士論文
Type(English)	Doctoral Thesis

INSTITUTE OF SCIENCE TOKYO

DOCTORAL THESIS

Spatiotemporal Gait Guidance Using Audiovisual Cueing with a Synchronized Walking Avatar in Augmented Reality

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February 16, 2025

Abstract

The use of augmented reality (AR) for gait guidance has shown promise as an approach for rehabilitation. This thesis presents an AR system for gait guidance that provides spatial and temporal cues through a synchronized avatar. The first study developed a system to present a synchronized walking avatar and provided visual spatial cues through distance changes from the user and auditory temporal cues via phase difference changes. Evaluations with young, healthy participants demonstrated that the system could effectively guide gait spatially and temporally. The second study improved the phase estimation module and evaluated using elderly participants which showed similar spatial and temporal guidance. The results from both studies highlight the system's effectiveness for gait guidance and potential for rehabilitation.

Acknowledgements

First and foremost, I wish to express my deepest gratitude to God. His blessings through knowledge, strength, opportunities, and unwavering grace have guided me throughout this journey, enabling me to complete this thesis successfully.

The research and writing of this thesis were made possible through the incredible support and assistance of many individuals and organizations, to whom I owe my heartfelt thanks.

I extend my sincere gratitude to the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) for their financial support, which allowed me to pursue my studies and conduct this research.

I am immensely thankful to my academic supervisor, Professor Yoshihiro Miyake, for his exceptional guidance, encouragement, and unwavering support. His acceptance of me into his laboratory and his efforts in fostering an environment conducive to learning, discovery, and growth have been invaluable to my academic and personal development.

A special note of appreciation goes to Professor Hirotaka Uchitomi for his valuable assistance in the development and evaluation of the system, which was a critical component of this thesis. I would also like to express my gratitude to Professor Taiki Ogata for his insightful guidance and feedback, which played a pivotal role in shaping my research questions and methodology.

I am deeply grateful to the participants of my experiments, whose contributions were integral to the success of this research.

My heartfelt thanks go to the secretaries of Miyake Lab, Ms. Tominaga and Ms. Hayashi, for their kind and efficient assistance. As an international student, I greatly appreciated their help with applications, procedures, and day-to-day tasks, which eased my journey in many ways.

To my parents, Grace and Patrick Miller, I owe the deepest gratitude. Your unconditional love, encouragement, and faith in me have been my greatest source of strength and perseverance. Your unwavering belief in my abilities has been my anchor throughout this journey.

To my sister, Ruth-Ann Miller, your constant support, belief in me, and words of encouragement have been a source of inspiration. Your faith in my abilities and your pride in my achievements have motivated me to push forward, even during the toughest moments.

To Semiha Karaoğlu, your patience, understanding, and unwavering support have been a cornerstone of my strength. Your encouragement and belief in my potential have lifted me during challenging times and driven me to succeed. For this and so much more, I am profoundly grateful.

Finally, I once again thank God for His guidance, blessings, and grace, which have made this achievement possible.

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List of Abbreviations

AR	**A**ugmented **R**eality
CPG	**C**entral **P**attern **G**enerator
DD (Condition)	**D**istance **D**ecreasing
$D_D P_D$	**D**istance **D**ecreasing and **P**hase Difference **D**ecreasing
$D_D P_I$	**D**istance **D**ecreasing and **P**hase Difference **I**ncreasing
DI (Condition)	**D**istance **I**ncreasing
$D_I P_D$	**D**istance **I**ncreasing and **P**hase Difference **D**ecreasing
$D_I P_I$	**D**istance **I**ncreasing and **P**hase Difference **I**ncreasing
HMD	**H**ead **M**ount **D**isplay
IMU	**I**nertial **M**easurement **U**nit
PD (Condition)	**P**hase Difference **D**ecreasing
PI (Condition)	**P**hase Difference **I**ncreasing

Chapter 1

Introduction

1.1 Gait and Elderly Gait Impairments

Gait is an important aspect of human life. Gait impairments are a common experience as people age[1]. Reduced stride length, increased cycle time and reductions in gait speed are common characteristics of elderly gait [2–6]. Individuals over 70 years of age have been shown to have these noticeable gait changes[7–9]. These impairments can drastically reduce independence and Quality of Life [10] The elderly population is expected to increase with the current worldwide aging population issue. This increase in age will also increase the risk of gait disorders and neurological gait disorders such as Parkinson's Disease become more common [3, 11, 12]. High habitual activity levels and early gait training can help improve gait and reduce gait impairments associated with age [12, 13].

To understand elderly gait training we have to first understand gait and why it is so difficult to guide. Gait is a complex process and features many spatial (e.g. stride length), temporal (e.g. cycle time) and spatiotemporal (e.g. gait speed) parameters[14]. These parameters are all related and a change in one parameter might have unexpected changes in another parameter[15]. This relation of the gait parameters makes gait guidance difficult, as simultaneous guidance of parameters would be required[16].

1.2 Augmented Reality Gait Guidance

Gait guidance using augmented reality(AR) has been the focus of many studies in recent years[17–20]. When applied to gait training of the elderly , AR interventions have shown significant improvements in balance, gait speed, and overall mobility [21–24]. Additionally, AR can provide additional gait coordination assistance in the elderly[23, 25]. AR allows for multi-modal approaches using a combination of visual, auditory or haptic feedback to provide guidance[26]. The effects of AR with real-time feedback on gait function in gait-impaired individuals, highlight the versatility of AR technologies in addressing various mobility challenges[27]. Lim et al., used projected line cues and audio cues to guide gait and found significant improvements to stride length as a result[17]. Similarly, Sekhavat et al., used projected footprint cues on a treadmill to help guide gait and successfully improved stride length[19].

1.2.1 AR Avatar Guidance

One emerging approach to gait guidance is the integration of virtual avatars to enhance rehabilitation outcomes[28–30]. Using synchronized walking avatars that mimic natural human movement, spatial and temporal cues can be provided and healthy gait patterns can be promoted. Booth et al. (2019) showcased the feasibility and usability of an avatar-based biofeedback system for gait training. The study revealed using avatars can enhance gait training with minimal additional setup time[31]. This highlights the practical applications of avatar-based feedback in gait rehabilitation. Alyami and Nesser(2021) also reported the benefits of human-avatar synchronization in gait training, suggesting improvements to gait asymmetries and enhancements to motor function in individuals[32].

A study by Shan et al., explored the effects of a synchronized walking avatar on human gait[33]. For the study they used a walking avatar and audio cues, both synchronized to the step timings of the participant. It was revealed that changes to the phase difference between the participant and avatar there was also a change in participant cycle time. Although, there was significant temporal guidance the application was limited and improvements to spatial guidance can be made. Meerhoff et al. showed the use of projected avatars and distance regulation and their effects on gait Using synchronized avatars allows for gait training to be customized to individual needs,thereby improving the effectiveness of rehabilitation programs.

1.3 Temporal Guidance

Temporal guidance of gait has been the focus of many studies. Commonly rhythmical sensory stimuli has been used to provide sensory cues to help regulate temporal aspects of gait (cadence, cycle time etc). In particular auditory cues in the form of rhythmical auditory stimuli (RAS)have shown dominance over other modalities in the temporal guidance of gait [34].

Metronomes have long been explored as a form of RAS for gait guidance [35, 36]. Baker et al. demonstrated the use of metronomes to guide cadence and reduce cognitive demand of attentional cues [37]. Muto et al. used synchronized audio cues to help reduce temporal gait asymmetries in patients[38].

External rhythmical cueing helps compensate for central pattern generator(CPG) dysfunctions in the body[39]. The CPG is a network of spinal neurons responsible for locomotion in the body [40]. Dysfunctions in the CPG could be the cause of locomotor and gait challenges. Rutz et al., showed external auditory cues can aid in CPG dysfunctions and improve gait timing and coordination[41]. Other studies like Hove et al. used interactive audio cues and showed that it could reinstate natural walking frequency in the gait of persons with Parkinson's disease [42].

1.4 Spatial Guidance

While auditory cues have been shown to have temporal dominance, for spatial guidance visual cues show enhanced effects[43, 44]. One common approach is the use of rhythmical visual stimuli, in the form of visual cues placed at fixed intervals for the user to interact with. Bank et al., demonstrated the use of stepping stones places at fixed intervals to aid in gait guidance and found it had a greater effect on the stride length than metronome cues[43]. Hoogendoorn et al., used AR to project various visual cues (footprints, lines, boxes) and found significant changes to stride length and step height both spatial attributes of gait[45]. Although these types visual cues show significant effects on gait guidance, they also impose higher attentional demand on participants[46].

An alternative to the rhythmical visual cues is the observation of healthy walking patterns whether virtual or actual person. Observing and walking with a healthy partner improves gait in impaired individuals[47]. The use of action observation has been used in studies such as one by Walter et al in 2017[48]. The study had participants watch a video of various actions standing from a chair and walking and then perform the same action afterwards. The results showed significant improvements to gait in the impaired individuals. The mechanism behind this is the activation of the mirror neuron system. This system consists of neurons in the brain that activate not only when performing an action, but also when performing the same action[49]. This has been applied to rehabilitative studies and shows improvements to motor functions as a result of the visual observations[50]. The same activation and effects can be seen when observing and following a person as when we are observing and following a virtual avatar[51].

1.5 Remaining Problems

Due to the complex nature of gait, previous studies focused primarily on one modality of gait (spatial or temporal). However, gait is a spatiotemporal process and should be guided both spatially and temporally. Previous studies have been limited by the use of constant time metronomes and choice of spatial cues. Additionally, fixed rhythmical cueing (both visual and auditory) common in previous research, has an impact on the effectiveness of the cues through the increased attentional demand required by the participant to synchronize with the cues. Perhaps, cues that illicit subconscious responses such as activation of the mirror neuron system and CPG might be effective in achieving the goal of spatial and temporal guidance. Therefore, in this thesis, we designed a system to utilize these subconscious mechanisms of the body for gait guidance. Utilizing synchronized audio cues instead of constant-tempo metronomes for temporal guidance through use of the CPG. An avatar walking with healthy gait and distance changes to activate the mirror neuron system for spatial guidance.

In addition, if a system can be developed to guide gait both spatially and temporally we would be able to help speed up recovery and gait rehabilitation, increasing independence and quality of life. As such, for use in impaired individuals, the system should be easy to use and not physically demanding for solo application.

1.6 Purpose

The purpose of this thesis was to develop synchronized walking avatar system using AR to guide gait both spatially and temporally. A walking avatar synchronized to the foot contact timings of the user is used in AR to provide spatial and temporal guidance to stride length and cycle time respectively. Additional audio cues are played, synchronized using the Walk-Mate model to the avatar’s steps, to provide improved temporal guidance to the participant. The first study developed the system and evaluated using healthy young participants as the first step in developing the system for gait impaired individuals. The second study improved on the limitations of the first study and evaluated its effectiveness on elderly gait. We hypothesized that the combined cues provided by the avatar system in AR will provide both spatial and temporal guidance to elderly gait.

1.7 Structure

This thesis consists of four chapters. This chapter provides a background to the problem, introduction to the previous studies as well as the overall purpose of this study.

The second chapter reflects the research conducted in our first paper entitled "Spatiotemporal Gait Guidance Using Audiovisual Cues of Synchronized Walking Avatar in Augmented Reality"[52]. In the chapter we presented the development and evaluation of a synchronized walking avatar system that would provide simultaneous spatial and temporal guidance. We hypothesized that the system would be effective in guiding gait both spatially and temporally and evaluated using healthy young participants.

The third chapter presents the research conducted in the second paper "Effects of Gradual Spatial and Temporal Cues Provided by Synchronized Walking Avatar on Elderly Gait" [53]. In the chapter, based on the results of Chapter 2, we improved the AR guidance system to allow for better synchronization with elderly gait which is known to have higher variability and harder to guide. We evaluated the improved system in a behavioral experiment with elderly participants and observed both immediate and carry-over effects.

The final chapter, discuses the implications of the studies as well as summarize the results. Finally, conclusions and future applications

Chapter 2

Spatiotemporal Gait Guidance Using Audiovisual Cues of Synchronized Walking Avatar in Augmented Reality

2.1 Aim

In this study we aimed to develop a synchronized walking avatar system that is able to guide gait both spatially and temporally simultaneously. To evaluate the developed system we designed an evaluation experiment using young healthy participants using the system and analyzed their gait before and after the presentation of the cues using ankle attached IMU sensors. Stride length and cycle time were chosen gait parameters to be evaluated as they provided the most common spatial and temporal gait parameter respectively. We hypothesized that using a virtual avatar with healthy walking animation will allow for gait to be guided spatially through changes in distance between the user and avatar. Additionally we hypothesized that by providing audio cues, synchronized to the avatar step timings, gait can be guided temporally through changes in the phase difference between the avatar and participant.

2.2 Method

2.2.1 Participants

The experiment was conducted with eight young and healthy participants aged 23.75 ± 1.47 years and consisting of three females and five males. The participants heights averaged 1.65 ± 0.09 m, with weights 60.0 ± 10.45kg. The participants self reported no visual, auditory, or locomotive impairments that could impact their performance prior to the trials. The experiment was conducted with the approval of the Research Ethics Review Committee of the Tokyo Institute of Technology, and written informed consent was obtained from all participants. A summary of participant information can be seen in Table 2.1.

2.2.2 AR Avatar Gait Guidance System

For this study we developed an AR synchronized walking avatar system and used distance and phase difference changes to provide spatio-temporal cues to human participants for gait guidance. The flow of the system was implemented as shown

TABLE 2.1: Study 1 Participant Characteristics

Characteristic	**Value**
Number of Participants	8
Gender Distribution	3 Females, 5 Males
Age (years)	23.75 ± 1.47
Height (m)	1.65 ± 0.09
Weight (kg)	60.0 ± 10.45
Impairments	None reported (visual, auditory, or locomotive)

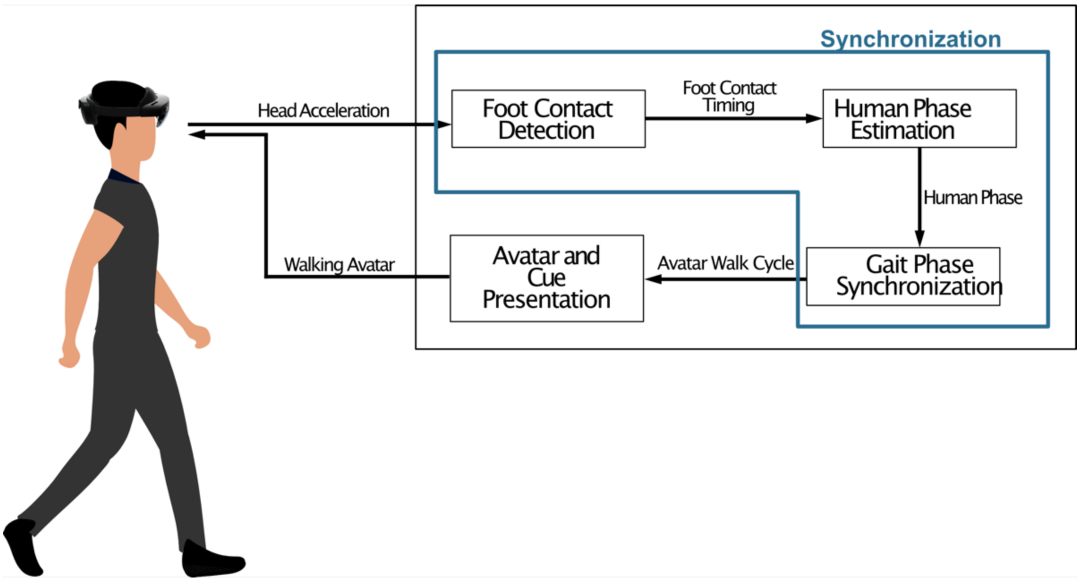

FIGURE 2.1: Information flow throughout the AR Avatar Gait Guidance System. Input to the system is provided through head acceleration data from the HMD. This is used as input for foot contact detection module. Foot contact timings are then used to estimate human phase. The estimated human phase is used to synchronize the avatar's phase and audio cues. The synchronized avatar and auditory cues are presented back to the user using the HMD.

in Figure 2.1. Head acceleration readings from the HMD was used as input and the synchronized walking avatar and audio cues were presented as output. The system featured 4 modules for foot contact detection, human phase estimation, gait synchronization and avatar and cue presentation. The first 3 modules worked towards synchronization of the participant and avatar and the final module presented the synchronized cues.

Foot Contact Detection

The first module is responsible for foot contact detection. Accelerometer readings from the HMD are used to estimate head trajectory as shown in Figure 2.2. Using the head trajectory we can estimate foot contact timings using the minimas of the trajectory. Minimas in the trajectory are used to indicate respective foot contacts while the maximas are used to indicate swinging foot as demonstrated in Figure 2.3.

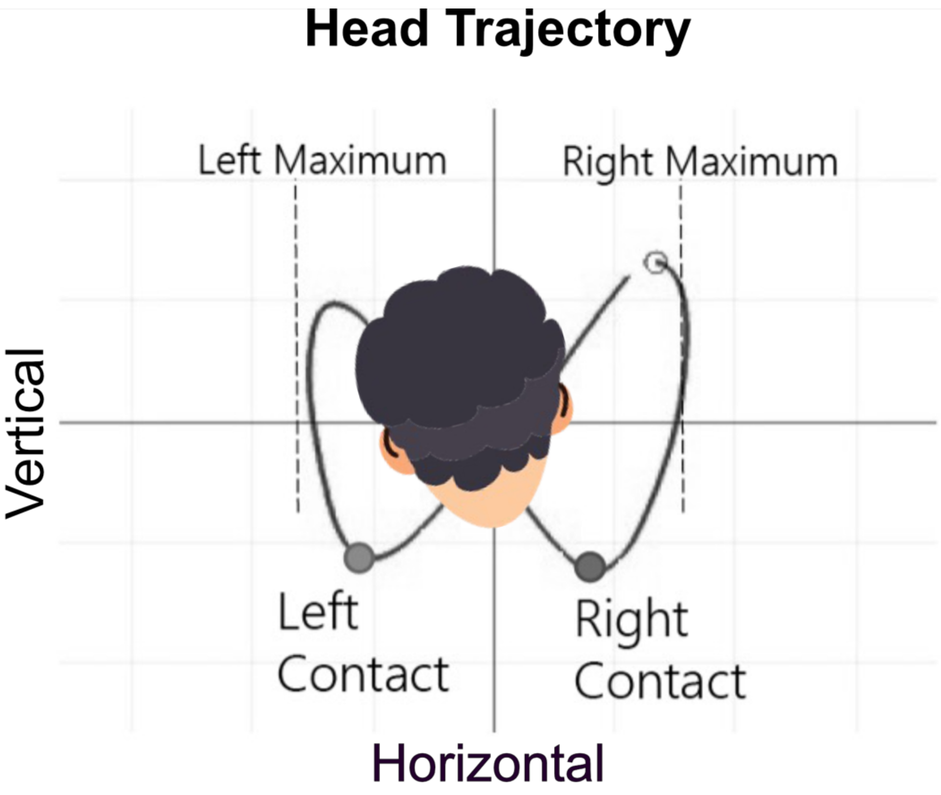

FIGURE 2.2: Estimated Head trajectory on vertical and horizontal planes during one gait cycle. From the head trajectory, data of the left and right maxima are used to determine the next foot contact, which occurs at the minima.

Human Phase Estimation

The second module uses the foot contact timings from the previous sub-module to estimate human phase. Gait phase is cyclic and thus can be represented numerically in the range $[0, 2\pi]$. Human phase, $\dot{\theta}_h$, of 0 *rad* was used to represent left foot contact while π *rad* was used to represent right foot contact. Intermediate phases were estimated using Equation 2.1.

$$\dot{\theta}_h = \frac{\pi}{\Delta t} \tag{2.1}$$

Δt represents the time between consecutive foot contact timings.

Gait Synchronization

The next sub-module uses the WalkMate Model proposed by Miyake et al. to synchronize the system to the human phase [54]. Figure 2.4 shows an overview of the model.

The module accepts the human phase, θ_h, as input and outputs the system phase of the avatar, θ_m. The module is further broken down to two sub-modules for synchronization and phase difference control.

The first sub-module for synchronization calculates the system phase using Equation 2.2.

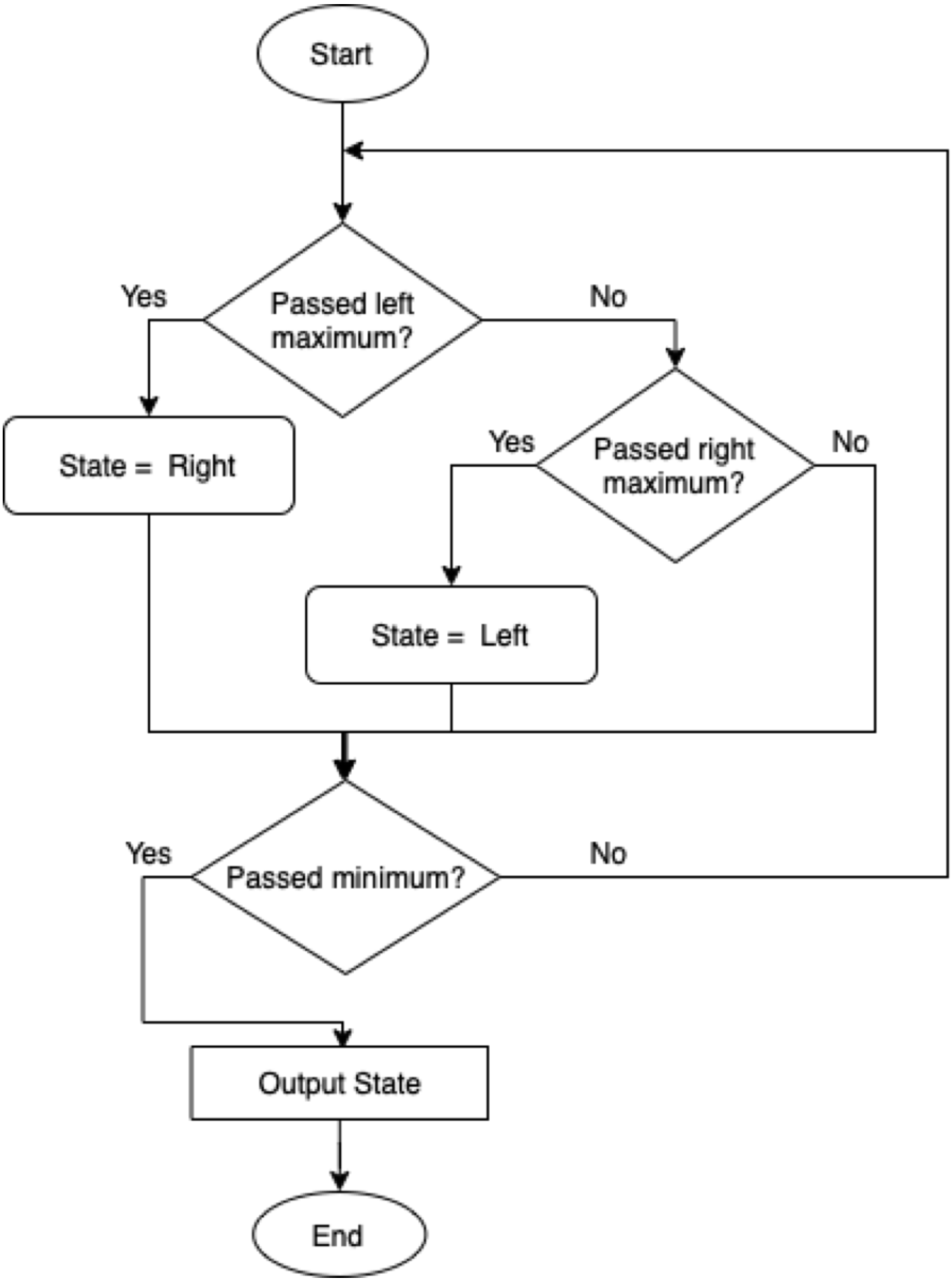

FIGURE 2.3: Flowchart for foot contact timings from head trajectory. Maximas are used to determine which foot will make next contact and minimas are used for foot contact detection.

$$\dot{\theta_m} = \omega_m + K_m \sin(\theta_h - \theta_m) \tag{2.2}$$

θ_m represents the avatar walking rhythm phase andω_m, its natural frequency. K_m refers to the coupling constant which is assumed to be symmetrical for simplicity. θ_m can be closely matched to the human phase, θ_h, to achieve synchrony.

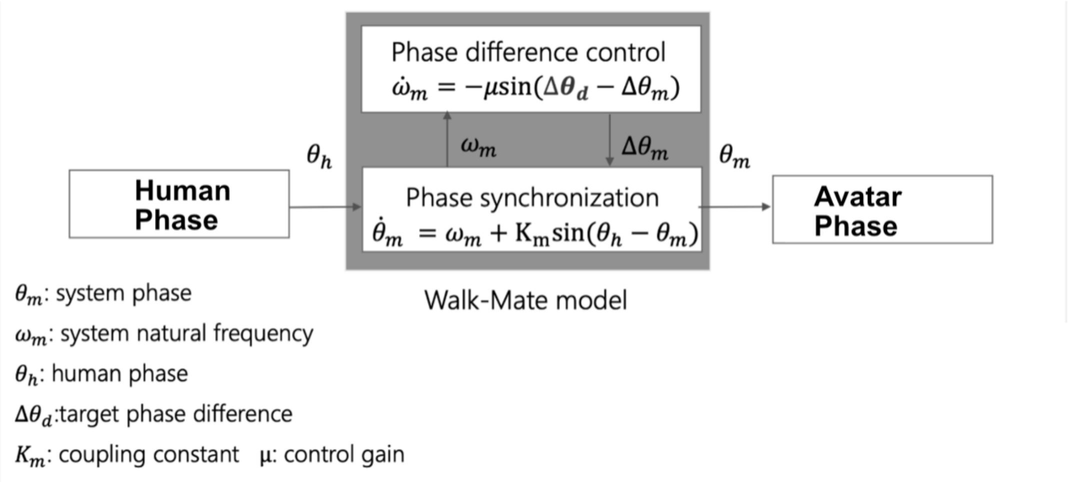

FIGURE 2.4: Walk-Mate model proposed by Miyake *et al.* [54]. The model accepts the participant phase as input. Using the two submodules for phase synchronization and phase difference controls, the system synchronizes its phase to that of the participant. Finally, the module applies the system phase to the avatar and delivers auditory cues.

The second sub module is responsible for phase difference control and shown in Equation 2.3 below.

$$\dot{\omega_m} = -\mu \sin\left(\Delta\theta_d - \Delta\theta_m\right) \tag{2.3}$$

μ represents the control gain of the system while $\Delta\theta_m$ between the sensory input, θ_h, and the motor output, θ_m.

$$\Delta\theta_m = \theta_h - \theta_m \tag{2.4}$$

$\Delta\theta_d$ represents the target phase difference. A zero value indicates perfect synchrony, while a positive value indicates the system is slightly behind in phase and similarly a negative value indicates the system is slightly ahead in phase. Temporal feedback and guidance can be provided by controlling the target phase difference of the system [33].

Avatar and Audio Cue Presentation

The final module in the system is the cue presentation. An avatar, whose gait phase matches the system phase from the previous module, is presented to the participant as shown in Figure 2.5. Synchronized to the foot contact timings of the avatar, audio cues are also presented to the participant. Spatial feedback is provided through visual cues of distance changes between the participant and avatar. We hypothesize that changes in stride length will be proportional to the changes in distance. Temporal feedback is simultaneously provided through changes to the target phase difference, $\Delta\theta_d$ more easily noticed through the audio signals. Similarly, changes in cycle time are expected proportional to the changes in phase difference.

FIGURE 2.5: View of avatar from the head-mounted display. The back of the avatar is observed as the participant walks down the corridor. A translucent white screen is used to make the avatar more visible under bright lighting conditions.

2.2.3 Task and Procedure

The participants were tasked to walk down an approximately 55m straight corridor while observing the walking avatar in the front. Initially, the avatar is walking synchronized to the participant's steps (phase difference = 0) and the distance is fixed at 5m. After the 30^{th} stride, there was an instantaneous and simultaneous change to both the distance and phase difference between the participant and avatar to provide spatial and temporal feedback respectively.

- Distance changes were used to provide spatial feedback to the participant. This consisted of increases or decreases of 2m between the participant and avatar. This $\pm$2m change led to a final distance of 3m or 7m compared to the initial 5m at the beginning of the trial. Participants were also instructed *"For the following trials, while wearing the headset, try to maintain the same initial distance by modifying your stride length. If the distance increases, increase the length of your stride. Likewise, if it reduces, reduce your stride length."*
- Phase difference changes were used to provide temporal feedback to the participant. This consisted of increases or decreases of $\frac{\pi}{4}$ between the participant and avatar. These changes led to the avatar being slightly ahead or behind in gait cycle. The participants were also instructed *"Try to maintain synchronization with the avatar."*

Combinations of increases and decreases of the two changing parameters led to four distinct conditions shown in Table 2.2.

Each condition was conducted twice for a total of eight trials whose order was randomized. The order was counterbalanced between the participants. Eight practice trials of each condition twice were conducted to get the participants accustomed to the system. Following the practice trials, the eight real trials were conducted.

Condition	Distance Change (m)	Phase Difference Change (rad)
$D_D P_D$	-2	$-\pi/4$
$D_D P_I$	-2	$+\pi/4$
$D_I P_D$	+2	$-\pi/4$
$D_I P_I$	+2	$+\pi/4$

TABLE 2.2: Summary of Conditions

Participants were not informed of the condition that was analyzed in each trial. In between each trial, there was a 1-2 minute break for the participant to rest and prepare for the next trial. Following every 4 trials, there was a longer 5-minute break. The total experiment lasted around 1.5 hours with a combined total of 40 minutes of rest on all trials.

2.2.4 Setup and configuration

Based on preliminary experiments, the values for K_m and μ in 2.2.2 were set to 0.5 and 0.32 respectively. Initial values of 0 and 6 were set for θ_m and ω_m.

The participants were required to wear the HMD prior to the start of the trial to aid in avatar positioning and scaling based on height. The initial distance and phase difference were set to 5m and $0rad$ respectively.

2.2.5 Data Analysis

Using a method proposed by Mao et al., ankle accelerometer and gyroscopic readings were used to estimate the gait parameters for evaluation and analysis [55]. Gait parameters of stride length and cycle time were estimated to evaluate gait spatially and temporally respectively. Time series data of stride length and cycle time revealed changes caused by the cueing and avatar during the trials. Simultaneous spatial and temporal cues occurred at the 30^{th} stride in each trial for each of the four conditions. The averaged normalized stride length and cycle time of the strides 20-29 were later compared to those of strides 36-45. The intervening strides allowed for gait adjustments.

Normalized values were used to decrease the impact of participant height on the trends [56] and were calculated using:

$$Norm_x = X_i/(h_i/\bar{H}) \tag{2.5}$$

X represents either cycle time or stride length. $Norm_x$ represents the normalized value of X. X_i represents the average value for participant i, while h_i represents the height. $\bar{H}$ represents the average height of all participants.

Following the calculation of the averages of each trial, the values were grouped into the four conditions and averaged to provide their respective values for comparison. To eliminate IMU noise, which would otherwise lead to incorrect readings, 3-Sigma standard deviation threshold was used to eliminate outliers.

To compare the effects of the different conditions, the change ratio was calculated using the averages of the trails grouped by condition and were calculated using :

$$CR_X = \frac{X_{AFTER} - X_{BEFORE}}{X_{BEFORE}} \tag{2.6}$$

X represents either cycle time or stride length. CR_X represents the change ratio of parameter x. X_{AFTER} represents the average value after the cue and X_{BEFORE} represents the average before the cueing.

Repeated analyses of variance (ANOVAs) measures were conducted using 0.05 as the significance factor. Python and its statsmodels library were applied to analyze differences before and after the changes. Three independent factors were tested: before/after, distance increase/decrease, and phase increase/decrease. Multiple comparison analyses were conducted using the Benjamini-Hochberg correction method with a significance level of 0.05.

2.2.6 Hardware

The experimental system featured three components: the AR HMD (Microsoft HoloLens 2 Mixed Reality HMD with WiFi-5, Microsoft, USA), ankle-mounted IMUs (TSND121, ATR-Promotions, Japan), and a controller (Android, ASUS Zen Pad Tablet). The IMU and HMD configurations are shown in Fig. 2.6, and the controller was carried by the experimenter, who followed the participant at a safe distance.

The HMD weighed 566 g and featured its own built-in IMU and spatial surround-sound speakers. The IMU readings were used as the input for the synchronization of the avatar to the participant. The speakers allowed for audio cues to be played with the the step timings of the avatar.

The ankle attached IMU were used to provide the readings for analysis. The IMU were sensitive to six degrees of freedom (three acceleration-three angular velocity) using a 100-Hz sampling rate. Using a method proposed by Mao *et al.*, the ankle accelerometer and gyroscopic readings were used to estimate the gait parameters for evaluation and analysis [55].

The controller was used to monitor participant gaits and cues while viewing live IMU data delivered via Bluetooth. The controller communicated with the HMD via a transport control protocol server running on the controller tablet, transferring batch data at each footstep.

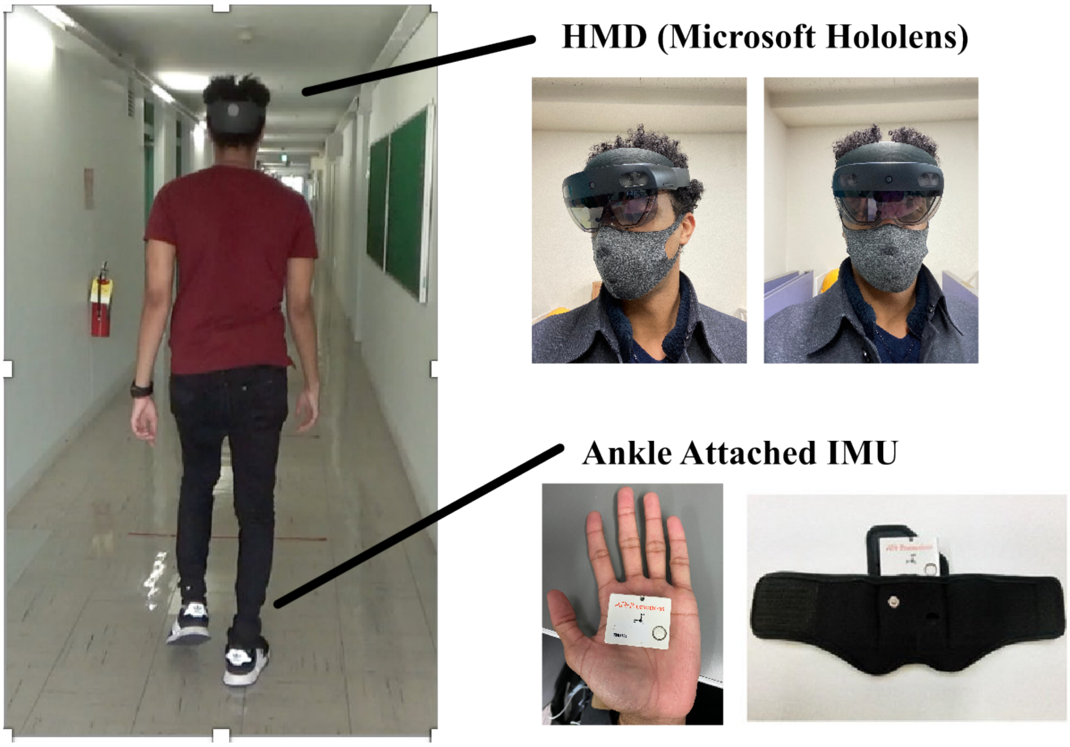

FIGURE 2.6: Participant walking while wearing the head-mounted display (HMD) and ankle-attached inertial measurement units (IMUs).

2.3 Results

2.3.1 Raw Time-series data

The raw time series data allows us to visualize the response of the participant based on the instantaneous cueing.

Stride Length

Figures 2.7 and 2.8, shows the raw time-series stride length data for each condition. The first highlighted region (steps 20-29) shows the range of values used as the average before the change, and the second highlighted area (steps 36-45) shows the values after the change.

From the image we can see that conditions with increased distance, Figure 2.8, showed an increased stride length regardless of changes in phase difference. Similarly conditions with decreased distance, Figure 2.7, showed decreased stride length regardless of changes in phase difference.

Cycle Time

The raw time-series cycle time data samples are shown in Figures 2.9 and 2.10. Figure 2.10 has conditions with increased phase difference and Figure 2.9, decreased target phase difference.

The first highlighted region (steps 20-29) shows the range of values used as the average before the change, and the second highlighted area (steps 36-45) shows the values after the change. In these figure we see the cycle time and the phase difference changes.

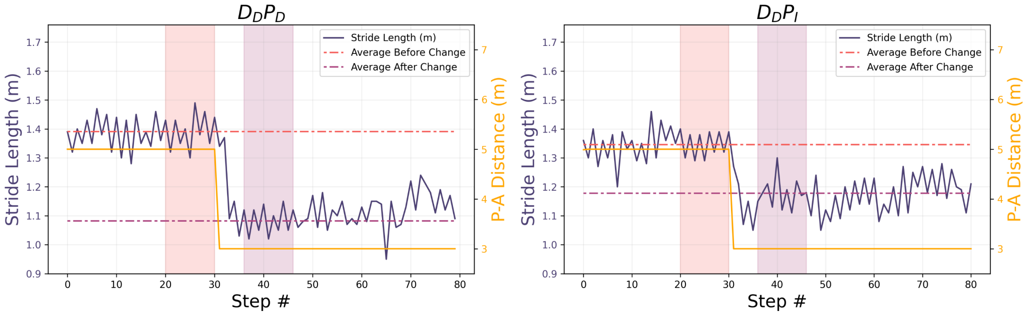

FIGURE 2.7: Graphs showing the time-series stride length samples for conditions with decreased distance.**Left**: D_DP_D - Distance Decrease & Phase difference Decrease, **Right:** D_DP_I - Distance Decrease & Phase difference Increase.

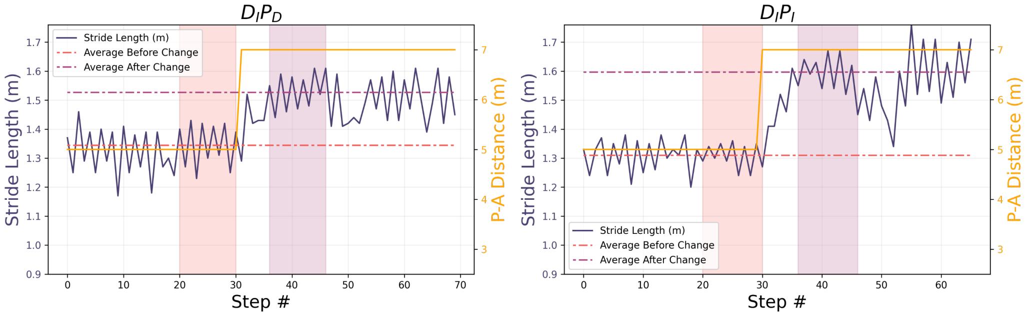

FIGURE 2.8: Graphs showing the time-series stride length samples for conditions with increased distance.**Left**: D_IP_D - Distance Increase & Phase difference Decrease, **Right:** D_IP_I - Distance Increase & Phase difference increase.

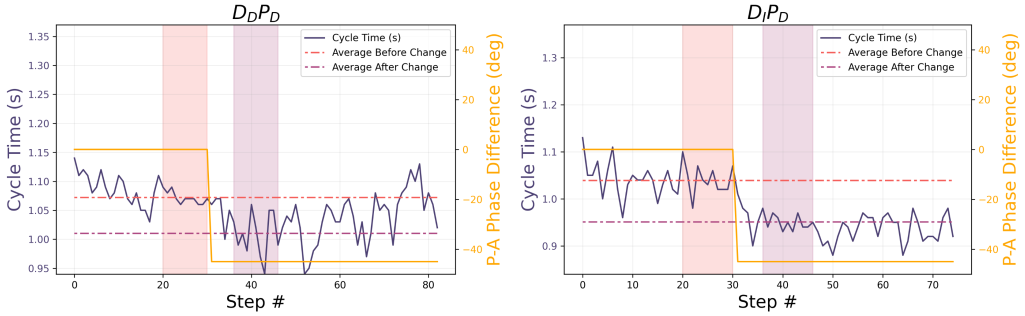

FIGURE 2.9: Graphs showing the time-series cycle time samples for conditions with decreasing target phase difference. **Left**: D_DP_D - Distance Decrease & Phase difference Decrease, **Right:** D_IP_D - Distance Increase & Phase difference Decrease.

From Figure 2.10, we can see that the conditions with phase difference > 0, the cycle time also increased irrespective of changes in distance. Decreases in phase difference, shown in Figure 2.9, also showed similar decreases in cycle time regardless of distance changes.

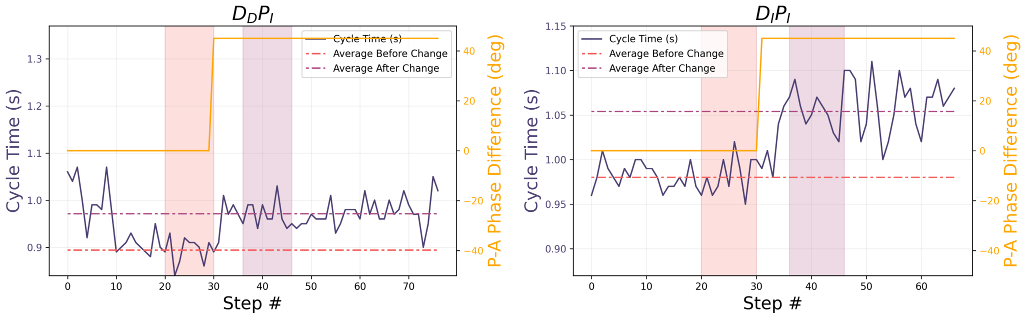

FIGURE 2.10: Graphs showing the time-series cycle time samples for conditions with increasing target phase difference. **Left**: D_DP_I - Distance Decrease & Phase difference Increase, **Right:** D_IP_I - Distance Increase & Phase difference Increase.

2.3.2 Normalized Values Before and After Cues

Comparison of the values before and after the cueing can highlight the effect of the cues (distance and phase difference changes) on the different gait parameters. Average values from strides 20-29 are used to calculate the average before the change, and strides 36-45 are used after the change.

Stride Length

Figure 2.11 displays the average normalized stride length (m) between conditions before and after cueing. Repeated measures ANOVAs revealed significant main effect of distance on the stride length ($F = 30.84$; $p = 0.0009$). The analysis also revealed interaction effects between before and after cueing and distance changes ($F = 25.7$; $p = 0.001$).

Multiple comparison analysis with Benjamini-Hochberg correction revealed significant differences between all pairs of before/after cueing and increases/decreases to distance except for the pair of before cueing for increasing and decreasing distance ($p = 0.06$).

Conditions with increased distance, D_IP_I and D_IP_D, showed significant increases to stride length after the cue compared to before ($p < 0.0001$). Conversely, conditions with decreased distance, D_DP_I and D_DP_D, had stride lengths significantly lower after the cueing compared to before ($p = 0.0001$). The after values in the increased distance conditions, D_IP_I and D_IP_D, were significantly larger than the after values in the decreased distance conditions, D_DP_I and D_DP_D ($p < 0.0001$).

Cycle Time

Figure 2.12 displays the average normalized cycle time (s) between conditions before and after cueing. Repeated measures ANOVAs revealed significant interaction effect of phase difference changes and before and after cueing on the cycle time ($F = 13.47$; $p = 0.008$). However, there was no main effect of phase difference on cycle time ($F = 2.22$; $p = 0.18$)

Multiple comparison analysis with Benjamini-Hochberg correction again showed no differences between the before values in any of the conditions ($p = 0.8$).

Conditions with increased phase difference, D_IP_I and D_DP_I, showed significant increases to cycle time after the cue compared to before ($p = 0.013$).

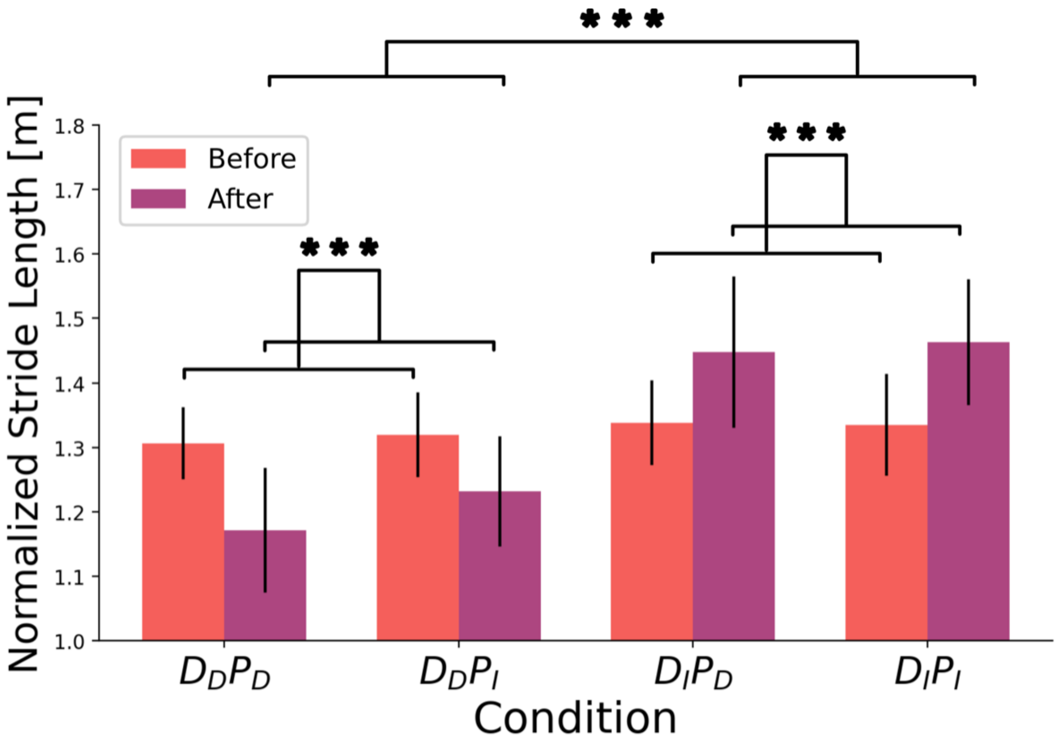

FIGURE 2.11: Normalized stride length before and after cueing. Pink values show the normalized average stride length before the change in spatiotemporal cues (strides 20–29). Purple values indicate the normalized average stride length after changes (strides 36-45). There were no significant differences between the results before the change based on distance. $D_I P_I$: Distance Increase & Phase difference increase; $D_I P_D$: Distance Increase & Phase difference Decrease; $D_D P_I$: Distance Decrease & Phase difference Increase; $D_D P_D$: Distance Decrease & Phase difference Decrease. *** denotes a significant difference of $p < 0.001$ between conditions.

Though conditions with decreased phase difference, $D_I P_D$ and $D_D P_D$, showed decreases in cycle time after the cue compared to before the change was not significant ($p = 0.28$).

The after values of conditions with increased phase difference, $D_I P_I$ and $D_D P_I$, were significantly larger than decreased phase difference conditions, $D_I P_D$ and $D_D P_D$ ($p = 0.04$).

2.3.3 Change Ratio

The change ratio analysis is used to observe the differences in effects between conditions. The change ratios were calculated using Equation 2.6.

Stride Length

The stride length change ratio, CR_S, can be seen in Figure 2.13. Here we can see the conditions with increased distance, $D_I P_I$ and $D_I P_D$, have $CR_S > 0$ indicating a larger after value than before the cues. Alternatively the conditions with decreased distance, $D_D P_I$ and $D_D P_D$, have $CR_S < 0$ indicating a smaller after value than before the cues.

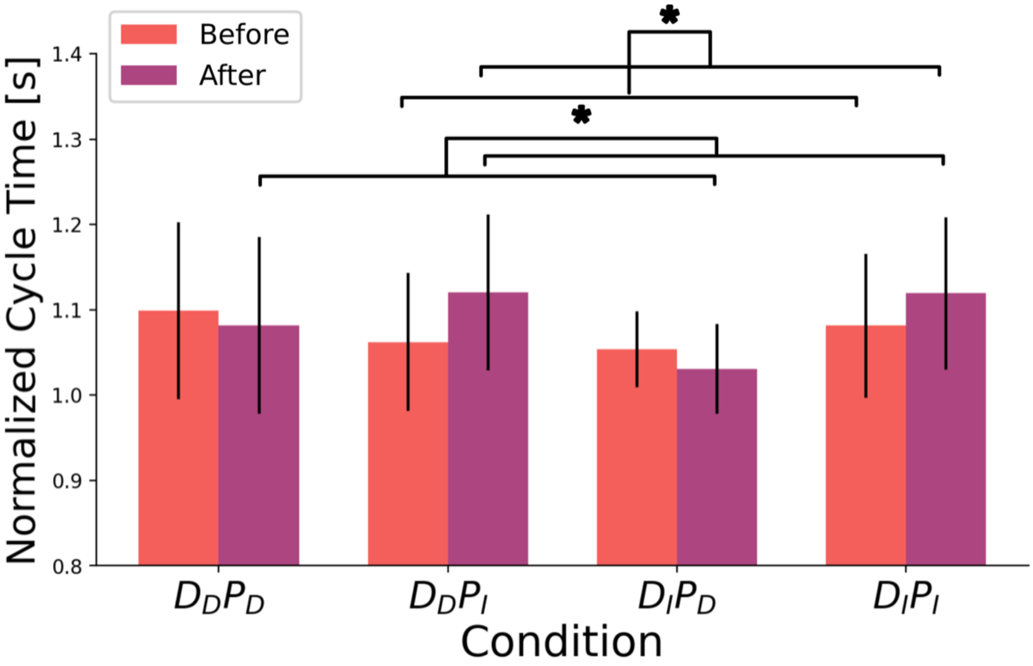

FIGURE 2.12: Normalized cycle time before and after cueing. Pink values demonstrate the normalized average cycle time before the change in spatial and temporal cues (strides 20–29). Purple values indicate the normalized average cycle time after changes (strides 36-45). There were no significant differences between the results before the change based on cycle time. D_IP_I: Distance Increase & Phase difference increase; D_IP_D: Distance Increase & Phase difference Decrease; D_DP_I: Distance Decrease & Phase difference Increase; D_DP_D: Distance Decrease & Phase difference Decrease. * denotes a significant difference of $p < 0.05$ between conditions.

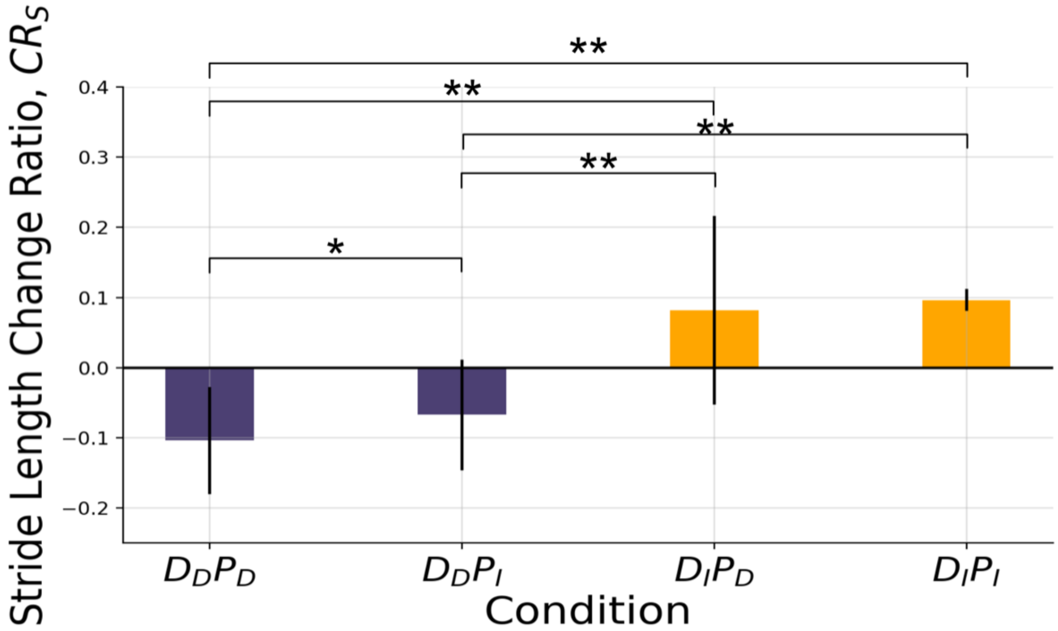

FIGURE 2.13: Change ratios of stride length per condition. Yellow values indicate conditions with increased distance and purple values, conditions with decreased distance. D_IP_I: Distance Increase & Phase difference increase; D_IP_D: Distance Increase & Phase difference Decrease; D_DP_I: Distance Decrease & Phase difference Increase; D_DP_D: Distance Decrease & Phase difference Decrease. * denotes a significant difference of $p < 0.05$ between conditions. ** denotes a significant difference of $p < 0.01$ between conditions.

Multiple comparison tests revealed significant differences between the conditions, apart from those with similar increases in distance (D_IP_I and D_IP_D) ($p = 0.34$). Conditions with similar decreases in distance (D_DP_I and D_DP_D) showed a significant difference between the two ($p = 0.03$). All other comparisons showed significant differences with $p < 0.01$.

Cycle Time

The cycle time change ratio, CR_C, can be seen in Figure 2.14. The increased phase difference conditions, D_IP_I and D_DP_I, have $CR_C > 0$ indicating a larger cycle time after the cue versus before the cues. Alternatively the conditions with decreased phase difference, D_IP_D and D_DP_D, have $CR_S < 0$ indicating a reduced cycle time after the cues compared to before.

Multiple comparison tests revealed significant differences between the conditions, in particular with the D_DP_I condition. D_DP_I condition was significantly larger change than the conditions with decreased phase difference, D_IP_D and D_DP_D, with p-values of $p = 0.017$ for both comparisons.

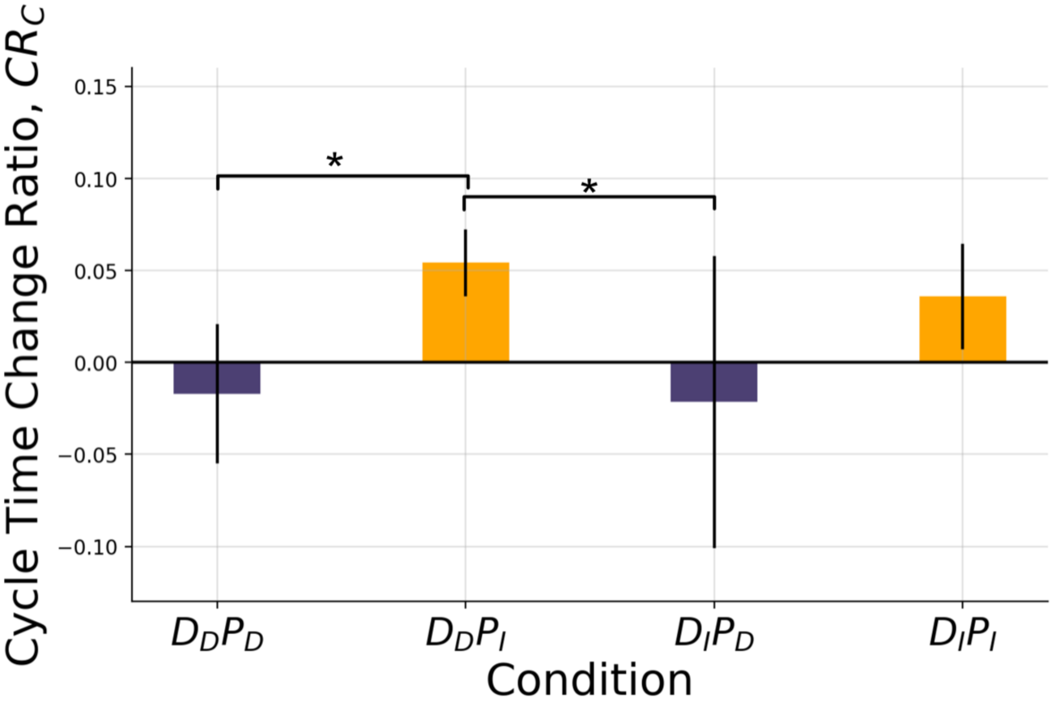

FIGURE 2.14: Change ratios of cycle time per condition. Yellow values indicate conditions with increased phase difference and purple values, conditions with decreased phase difference. D_IP_I: Distance Increase & Phase difference increase; D_IP_D: Distance Increase & Phase difference Decrease; D_DP_I: Distance Decrease & Phase difference Increase; D_DP_D: Distance Decrease & Phase difference Decrease. * denotes a significant difference of $p < 0.05$ between conditions. ** denotes a significant difference of $p < 0.01$ between conditions.

2.4 Discussion

The results of this study highlight the efficacy of combining audiovisual cues through a synchronized walking avatar on gait guidance.

The results support the dominance effects of different audiovisual and spatiotemporal modalities on gait parameters [14, 57]. Despite simultaneous cueing both spatially and temporally, this study showed that the gait parameters could be driven somewhat independently with minimal interference from the other cues.

2.4.1 Stride length guidance

The results of this study showed that the visual avatar distance change cues were effective in guiding stride length. The changes in distance between the avatar and participant exhibited a significant effect on the participant's stride length. Increases to distance led to a similar increase in stride length. Similarly decreases in distance led to decreases in stride length. Meerhoff *et al.* also used apparent distance changes of an avatar and found changes to stride length, however cycle time effects were not targeted or observed[58].

Suteerawattananon *et al.*, reported significant changes in stride length using visual cues. However, no additional improvements were found when visual cues were combined with auditory cues [14]. This study was able to achieve significant changes with both audio and visual cues perhaps because the cues having reduced attentional demand of the visual cue allowing for simultaneous guidance[59]. The audio (temporal) cues in this study, phase difference changes which advances/delays the timing of the audio cues, showed a noticeable but insignificant effect on the stride length. This interference between the cues reflected higher magnitude of the change ratios in constructive conditions (both increasing or both decreasing), $D_I P_I$ and $D_D P_D$, compared to destructive conditions (one increasing and one decreasing), $D_I P_D$ and $D_D P_I$, shown in Figure 2.13. Those constructive conditions also showed lower variability than the destructive conditions, perhaps due to the relation of the gait parameters[15].

2.4.2 Cycle time guidance

The temporal cue in the form of phase difference changes, was shown to have an influence the cycle time of the participant. Phase difference increases led to the cycle time also being increased. Similarly, reductions in the target phase difference showed the cycle time was also reduced. These results were similar to that of Shan *et al.*, who reported similar cycle time changes with avatar phase difference changes[33]. However, this study showed cycle time guidance despite simultaneous distance changes which weren't present in the study by Shan et al. This demonstrates we were able to guide cycle time despite the influence of the changing stride length.

Conditions with increased phase difference, $D_I P_I$ and $D_D P_I$, showed greater changes to cycle time than conditions with reduced phase difference, $D_I P_D$ and $D_D P_D$. Rochester *et al.*, reported larger cycle times when external rhythmical cues were provided[60]. Additionally the participants being young and healthy, their cycle times would be close to optimal and so improvements in reductions were more difficult.

Although the stride length showed greater changes in the constructive conditions, the cycle time appeared to show a larger effect in the conditions with one cue increasing and the other decreasing, $D_I P_D$ and $D_D P_I$, as seen in Figure 2.14. This needs to be investigated further, however, this may have been to maintain stability in walking. Reduced stability has been shown at larger stride lengths and slower speeds ($D_I P_I$ Condition) [61]. Verbal feedback from the participants indicated the $D_D P_D$ condition was difficult to maintain faster cycle times without losing balance.

2.4.3 Simultaneous Guidance

This study showed that gait could be guided both spatially and temporally, simultaneously. Previous studies indicated larger cycle times with external cueing [60]. This could result in lower stability and a greater risk of falling [61]. Other studies indicated the combinatorial cues were as effective as strictly temporal guidance on cadence (cycle time), however, it was not effective in stride-length guidance [14]. Baker *et al.*, also reported significant increases to walking speed when using a combination of auditory (temporal) and attentional (spatial) cues[37]. Although the auditory cues helped reduced the cognitive demand of the attentional cues in the study by Baker *et al.*, the added visual cues in this study further helped improve the effects[62].

2.5 Limitations

Though the synchronized walking avatar system was able to guide gait in healthy young participants, the study presented some limitations. Firstly, the study evaluated the system with healthy young participants with no gait impairments and almost peak gait. This made gait changes and guidance more difficult. Secondly, the system assumed linear gait phase change which is appropriate for this study with healthy young gait with little variability it might be insufficient for impaired or elderly gait with higher variability. Lastly, the cues presented in this study were instantaneous and thus elicited an impulse reaction to the cues which shortly returned to normal gait values.

2.6 Chapter Conclusions

The present study found that gait could be guided both spatially and temporally using the developed AR synchronized walking avatar system. Spatial cues, in the form of distance changes with the avatar, had a significant effect on stride length and temporal cues, in the form of phase difference changes with the avatar, had significant effects on the cycle time.

Chapter 3

Effects of Gradual Spatial and Temporal Cues Using Synchronized Walking Avatar on Elderly Gait.

3.1 Aim

In this chapter, we aimed to improve on the synchronized walking avatar system developed in the previous study. While the previous study was evaluated with healthy young participants, this study will be evaluated using elderly participants (over 70 years old). Elderly gait is known to have higher variability and experience some level of impairment making it more difficult to estimate and guide[63, 64]. As a result, we improved the phase estimation module to increase stability of synchronization and robustness of the system. We then evaluated both the immediate and carry-over effects of the cueing via the system on the participant gait. Stride length, cycle time and gait speed before and after the cueing and served as the basis for analysis. We hypothesized that spatial cueing in the form of distance changes would have a significant effect on stride length and temporal cueing in the form of phase difference would have a significant effect on cycle time.

3.2 Method

3.2.1 Participants

The experiment was conducted with 19 elderly participants aged 74.16 ± 2.90 years and consisting of 13 males and 6 females. The participants had an average height of 1.64 ± 0.06 m, with weights 61.15 ± 8.26kg. The criteria for inclusion were :

1. Over 70 years old
2. Could walk 200m without assistance
3. No impairments (auditory, visual , pain or other) that could affect their performance in the trials.

The participants self reported no visual, auditory, or locomotive impairments that could impact their performance prior to the trials. The experiment was conducted with the approval of the Research Ethics Review Committee of the Tokyo Institute of Technology, and written informed consent was obtained from all participants. A summary of participant information can be seen in Table 3.1.

TABLE 3.1: Study 2 Participant Information

Category	**Details**
Number of Participants	19
Sex	13 males, 6 females
Age (years)	74.16 ± 2.90
Height (m)	1.64 ± 0.06
Weight (kg)	61.15 ± 8.26
Inclusion Criteria	(1) Over 70 years old (2) Can walk 200m without assistance (3) No uncorrected visual, auditory, or other impairments that could affect avatar perception or walking

3.2.2 AR Avatar Gait Guidance System

In this study, in order to accommodate for the increased variation or impairments in elderly gait, improvements were made to the phase estimation in the previous system. Improvements were made in 3 points: motion detection, phase estimation and real-time synchronization. For this study we developed an AR synchronized walking avatar system and used distance and phase difference changes to provide spatio-temporal cues to human participants for gait guidance. The flow of the system was implemented as shown in Figure 3.1. Head acceleration readings from the HMD was used as input and the synchronized walking avatar and audio cues were presented as output. The system featured 3 modules for real-time human phase estimation, gait synchronization and avatar and cue presentation.

Real-Time Human Phase Estimation

A new real-time human phase estimation module was developed to more accurately estimate elderly gait phase, which has higher variability than healthy young gait. Head acceleration from the HMD is used as the input to the module.

From these head acceleration readings we can estimate neck position and trajectory as shown in Figure 3.2. The neck trajectory is used instead of head trajectory as it has a similar trajectory but with less noise and more stable leading to more stable synchronization. This change from head to neck trajectory led to improvements in the motion detection with more stable foot contact detection. The center of rotation of the neck, p_{NECK} was calculated using the following equation:

$$p_{NECK} = p_{CAM} + R_{CAM} \times b_{NECK} \tag{3.1}$$

p_{NECK} was calculated from the camera position, p_{CAM}, and the camera orientation, R_{CAM}. Note that the distance from the head to the neck, b_{NECK}, is a constant.

From the trajectory we can see that foot contact occurs at the local minima. If we consider the vertical displacement, Y, and calculate the derivative, $\dot{Y}$, such that

$$\dot{Y} = \frac{\Delta Y}{\Delta t} \tag{3.2}$$

we can see foot contact occurs when $\dot{Y}$ is 0 and Y is at a minimum.

To keep Y and $\dot{Y}$ on the same scale [-1, 1] we normalized using:

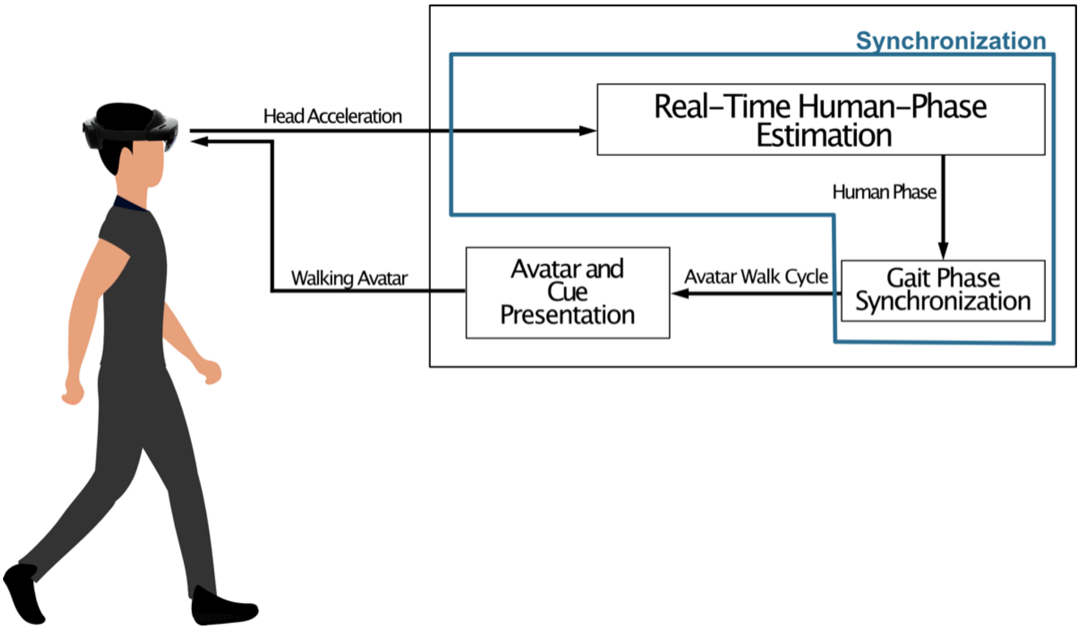

FIGURE 3.1: Information flow throughout the AR Avatar Gait Guidance System. Head acceleration data is used for foot-contact detection and human phase estimation. The avatar's phase is then synchronized with the estimated human phase, and finally the synchronized avatar and auditory cues are presented.

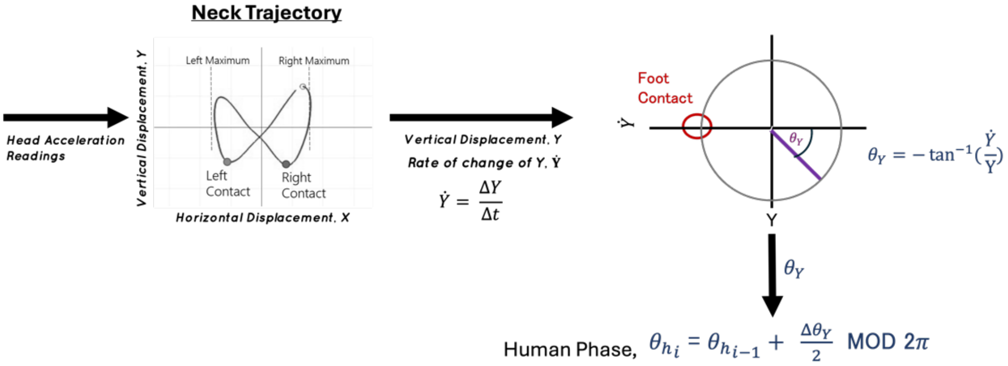

FIGURE 3.2: Phase estimation and foot contact timing from neck trajectory vertical displacement and its derivative.

$$X_{NORM} = -1 + 2\frac{X_i - X_{MIN}}{X_{MAX} - X_{MIN}}, \tag{3.3}$$

Where X represents the parameter we are normalizing.

Plotting the normalized values of Y and $\dot{Y}$, as seen in Figure 3.2) we can see foot contact when Y is at minimum, -1, and $\dot{Y}$ is at 0.

The step phase, θ_Y, can then be calculated in real-time using the negation of the arctan of Y and $\dot{Y}$ since our vertical displacement first decreases at the start of a stride.

$$\theta_{y_i} = -\tan^{-1}\frac{\dot{Y}_i}{Y_i} \tag{3.4}$$

Finally, human phase, θ_h, can then be calculated real-time using the following equation:

$$\theta_{h_i} = \theta_{h_{i-1}} + \frac{\Delta\theta_y}{2} mod 2\pi \tag{3.5}$$

Note, $\Delta\theta_y$ is halved to keep the phase in $[0, 2\pi]$.

The real-time calculation of θ_h allows for continuous synchronization of the system. This improved on the previous system which only performed human-system synchronization at foot contact, with intermediate values estimated using a linear model.

Estimations and foot contact timings were validated using hip and ankle-attached IMUs (WALK-MATE Viewer®, WALK-MATE LAB., Tokyo, Japan) [65].

Gait Synchronization

The WalkMate model [54] is used to synchronize the avatar's walking cycle,θ_m, to that of the participant,θ_h. The module features two sub-modules for synchronization and phase difference control.

The first sub-module obtains the system phase based on the following equation:

$$\dot{\theta}_m = \omega_m + K_m \sin(\theta_h - \theta_m), \tag{3.6}$$

where θ_m represents the avatar walking rhythm phase, and ω_m denotes its natural frequency. K_m refers to the coupling constant, . θ_m can then be closely matched to the human phase, θ_h, to achieve synchrony.

The second sub-module is used for phase difference control:

$$\dot{\omega}_m = -\mu \sin(\Delta\theta_d - \Delta\theta_m). \tag{3.7}$$

where μ is the control gain of the module.

Avatar and Audio Cue Presentation

The avatar phase and audio cues are set to match the system phase provided by the Walk-Mate model in the previous module. Finally, the synchronized avatar is presented as shown in Figure 3.3 along with audio cues. Spatial cueing was provided by gradual increases and decreases to the distance between the avatar and participant. The default starting distance is set at 5m as shown in Figure 3.3-*Middle*. The final distance after the distance decrease condition is 2m in front of the user as shown in Figure 3.3-*Left*. Finally the avatar is presented at 8m after the increase of 3m in the distance increase condition, as shown in Figure 3.3-*Right*.

Audio cues are also provided, synchronized to the foot-contact timing of the avatar. By increasing or decreasing the phase-difference between the participant and the avatar, temporal cueing guidance was provided. Phase difference changes between the user and avatar are reflected by advances or delays to the steps of the avatar (and auditory cues). Based on previous studies, we assumed that changes in the stride length are directly proportional to changes in distance and that changes in the cycle-time of the user are proportional to changes in the phase difference.

The avatar model and motion were created using Mixamo(Adobe). The model and motion data were imported into Unity 3D where the system flow was implemented and used to control the synchronization with the user.

FIGURE 3.3: View of the avatar at different distances from the head-mounted display. **Left**: Avatar 2m away from the user as shown after the gradual decrease in distance in the D_D condition. **Middle**: Avatar is shown 5m away from the user. This is the default distance before any changes. **Right**: Avatar is shown 8m away from the user as would be seen after the gradual increase in distance in the D_I condition.

3.2.3 Task and Procedure

The participants were tasked to walk 1.5 laps of an approximately 65m × 2.5m straight corridor while observing the walking avatar in the front. Each trial were split into 5 sections in 3 phases separated by the turns at the ends of the corridor as illustrated in Figure 3.4.

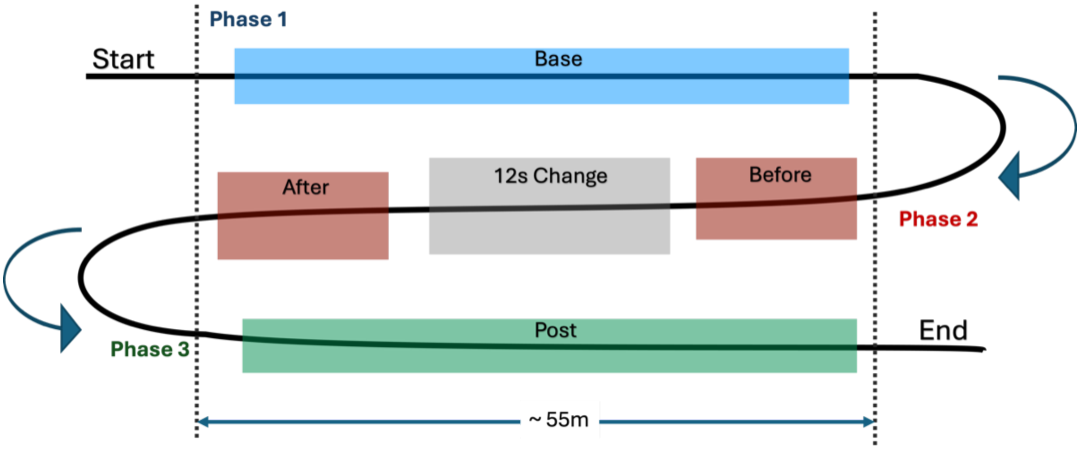

FIGURE 3.4: Figure showing the sections and phases of each trial conducted by the participant. The phases are separated by turns at the ends of the corridor. Phase 1 consists of the the base section and is shown before the first turn and no avatar is shown. Phase 2 is split into before, change and after sections in relation to the gradual change. Finally phase 3 consists of the post section and is after the final turn with again no avatar shown.

1. Phase 1: Base Section - No avatar or auditory cue is presented to the participant as they walk down the corridor wearing the HMD.

2. Phase 2: Conditioned - Avatar appears after the first turn and synchronizes its steps with the participant playing auditory cues in-sync with the foot contacts of the avatar. In the middle of this phase there will be a gradual 12s change to either the distance or phase difference between the participant and avatar. This phase can be further split into 3 sections:
   (a) Before - The time between the first turn and the beginning of the gradual change.
   (b) Change - gradual 12s change to either the distance or phase difference between the participant and avatar.
   (c) After - The time following the end of the gradual change and the beginning of the second turn.
3. Phase 3: Post Section - Following the second turn, similar to base, participant will walk with no avatar or auditory cue presented while wearing the headset until the end of the corridor.

Initially, the avatar is walking synchronized to the participant's steps (phase difference = 0 rad) and the distance is fixed at 5m. Gradual changes to distance or phase difference served as the spatial and temporal cues respectively. In conditions with distance changes, the distance was gradually increased(decreased) over 12s by 3m to 8m(2m) as shown in Figure 3.3.

Conditions with temporal cueing had phase difference changes of $\frac{\pi}{4} rad$ to values of $\frac{\pi}{4} rad$ and $-\frac{\pi}{4} rad$ for increases and decreases respectively.

Increases and decreases of distance and phase difference led to four conditions as shown in Table 3.2.

Condition	**Description**
D_D	Distance Decreasing
D_I	Distance Increasing
P_D	Phase Difference Decreasing
P_I	Phase Difference Increasing

TABLE 3.2: Study 2: Summary of Conditions

Each condition was conducted twice for a total of eight trials split into two sets. Each set contained all four conditions and the order was randomized in the first set then reversed in the second. Two practice trials were conducted to get the participants accustomed to using the system. Following the practice trials, the eight real trials were conducted. Participants were not informed of the condition that was analyzed in each trial. In between each trial, there was a 2-3 minute break for the participant to rest and prepare for the next trial. Following every 4 trials, there was a longer 5-minute break. The experiment lasted 2 hours including practice time and breaks. A total of 40 minutes was taken for breaks.

3.2.4 Hardware

The system utilized four hardware components divided into two sub-systems as shown in Figure 3.5 : sensing and actuating sub-systems.

The sensing performed gait measurement and tracking using hip and ankle-attached IMUs(WALK-MATE Viewer®, WALK-MATE LAB., Tokyo, Japan) [65].

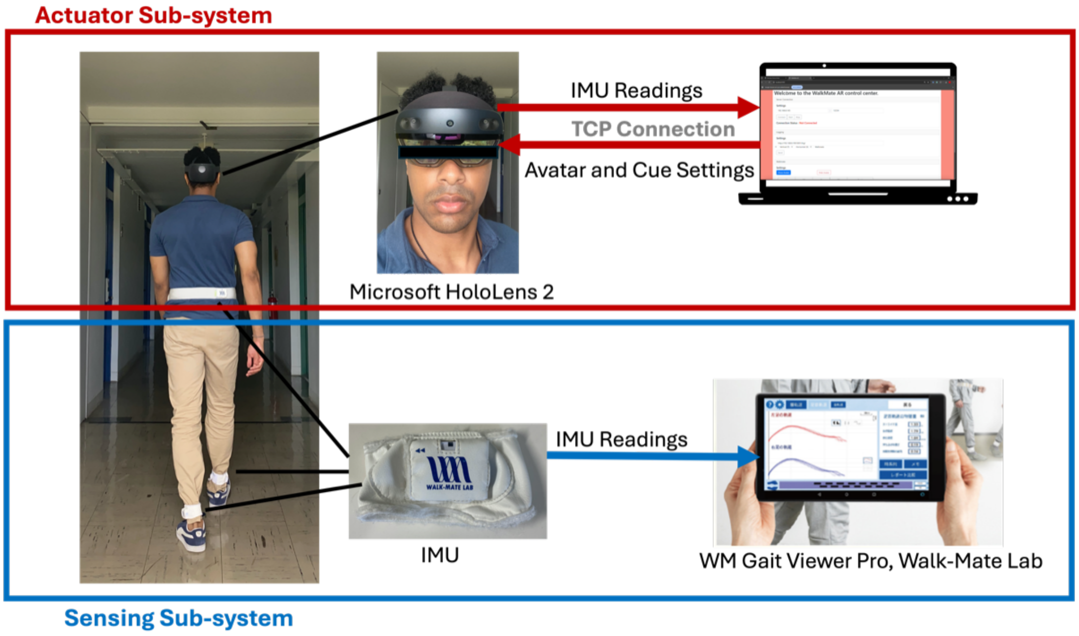

FIGURE 3.5: Hardware components and sub-systems. Participant walking while wearing the head-mounted display (HMD) and ankle-attached inertial measurement units (IMUs).

Ankle accelerometer and gyroscopic readings were used to estimate the gait parameters for evaluation and analysis [55]. An Android Tablet (LAVIE Tab T11, NEC, Tokyo, Japan), running the Walk-Mate Viewer Pro application, facilitated the real time monitoring of the gait parameters were facilitated by the controller, . The controller was actively being monitored and carried by the experimenter to ensure the safety of the participants.

The actuating sub-system included the AR HMD (Microsoft HoloLens 2 Mixed Reality HMD with WiFi-5, Microsoft, USA) and a laptop controller (Latitude 7280, Dell Inc., USA) connected via TCP server running on the HMD and client running on the laptop. The HMD, weighing 566 g, featured its own built-in IMU and spatial surround-sound speakers. The laptop was running a custom TCP client and an interface using Flask library written in Python to send commands to the HMD for changing conditions and starting and ending the trials. The complete information flow presented in Figure 3.1 was run on the HMD, and commands for cueing conditions were sent via TCP by the experimenter.

3.2.5 Setup and configuration

Based on the results of preliminary experiments we set the length of time of the gradual change to be 12 s. This period of change allowed enough time and strides before and after the change for analysis and comparison. Additionally, the distance change was increased to ±3m and the phase difference change remained the same . The values for K_m and μ in 2.2.2 were set to 0.5 and 0.32 respectively. Initial values of 0 and 6 were set for θ_m and ω_m.

The participants were required to wear the HMD prior to the start of the trial to aid in avatar positioning and scaling based on height. The initial distance and phase difference were set to 5m and $0 rad$ respectively.

3.2.6 Data Analysis

The ankle accelerometer and gyroscopic readings were used to estimate the gait parameters(stride length, cycle time and gait speed) for evaluation and analysis [55]. Each trial was split into sections as shown in Figure 3.4. The gait readings (stride length, cycle time and gait speed) for each trial were split into these sections (Base, Before, After and Post) and grouped by condition(DI, DD, PI, PD). The sections represent the average of the values as shown in Figure 3.4 and the description are as follows:

- Base - refers to the average of the values in the first phase of the trial before the first turn and with no avatar showing. 10 strides at the start and end of the phase were omitted to eliminate the readings during acceleration and deceleration. This is used as the baseline and control value for comparison for the learning/carry-over effect.
- Before - refers to the average values before the gradual change. This corresponds to 10 strides after the first turn but before the gradual cue. 10 strides immediately after the turn were omitted to not include acceleration values. This is used as the baseline and control value for comparison for the immediate effect.
- After - refers to the average values after the gradual cue, corresponding to 10 strides before the second turn but after the gradual cue. The last 10 strides before the turn are omitted to eliminate deceleration readings. This is used as the other value for comparison for the immediate effect.
- Post - refers to the average of the values in the final section of the trial after the second turn and with no avatar showing. 10 strides at the start and end of the phase were omitted to eliminate acceleration and deceleration readings. This is compared to the Base value to observe the carry-over effect.

Gradual change lasting 12s to either the distance or phase difference between the participant and avatar occurred at approximately 20m after the first turn for each of the four conditions. The first 10 and last 10 strides in each trial were removed from analysis as it featured unstable and high variability gait readings caused by the acceleration and deceleration at the start and end of the trial.

To decrease the impact of participant height on the trends normalized values were applied [56] and were calculated using the following equation:

$$Norm_X = X_i/(h_i/\bar{H}), \tag{3.8}$$

where $Norm_X$ represents the normalized value of X, which represents cycle time, speed or stride length. X_i represents the average value for participant i, h_i represents the height of participant i, and $\bar{H}$ represents the average height of all participants. After the averages were calculated for each trial, they were grouped into the four conditions and averaged to provide their respective values for comparison. Immediate effects of the cueing were revealed through the comparison between the before and after values. Additionally, the base and post comparison shows the carry-over effect of the cue.

Change ratio values were used to observe the differences in changes between the conditions. Change ratio values were calculated using the following equation:

$$ChangeRatio = \frac{After\ Value - Before\ Value}{Before\ Value} \tag{3.9}$$

The change ratio were used for comparisons between base and post sections (Base-Post) and comparisons between before and after sections (Before-After).

Repeated analyses of variance (ANOVAs) measures were conducted using a significance factor of 0.05. Python and its statsmodels library were applied to analyze differences before and after the changes. Two independent factors were tested: conditions (SI, SD, PI, PD) and section (base, before, after, post). Multiple comparison analyses were conducted using the Benjamini-Hochberg correction method with a significance level of 0.05.

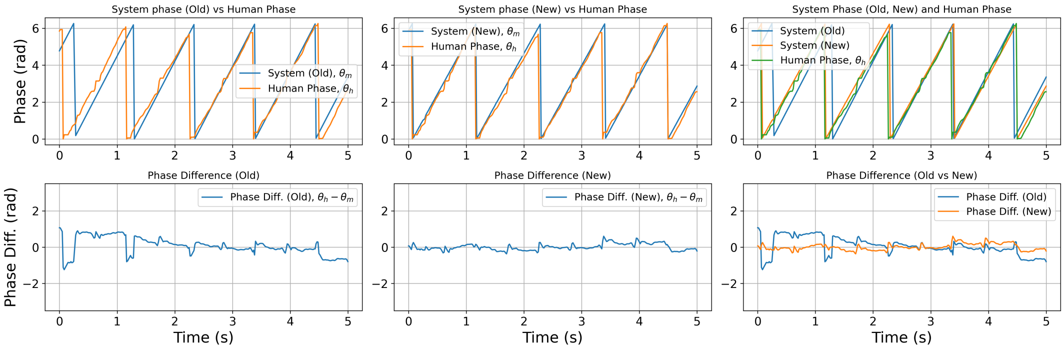

FIGURE 3.6: System synchronization comparison of old system and current system on healthy young gait. Top Row: Comparison between human phase, θ_h, and the system phase, θ_m. Bottom Row: Comparison of Phase Difference between θ_h and θ_m for the old and new system.

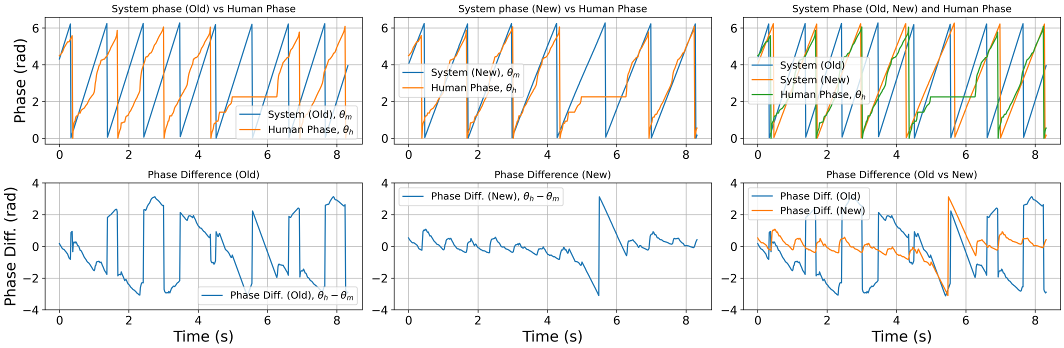

FIGURE 3.7: System synchronization comparison of old system and current system on healthy young gait. Top Row: Comparison between human phase, θ_h, and the system phase, θ_m. Bottom Row: Comparison of Phase Difference between θ_h and θ_m for the old and new system.

3.3 Results

3.3.1 Comparison with Previous Study

To observe the improvements in the system over the previous study we looked at the comparison between the system phases and the human phase.

Healthy Young Gait

Figure 3.6 shows the synchronization comparison between the old and new system on healthy gait. From the graphs we can see the human gait, θ_h, remains stable and both the old and new system are able to synchronize well. Both the old and new systems showed phase differences oscillating around 0, with low amplitude. The new system is more stable and has less noise than the previous system.

Asymmetric Gait

Although the previous system performed similarly well in healthy gait synchronization, as shown in Figure 3.6, in asymmetric gait, shown in Figure 3.7, the new system

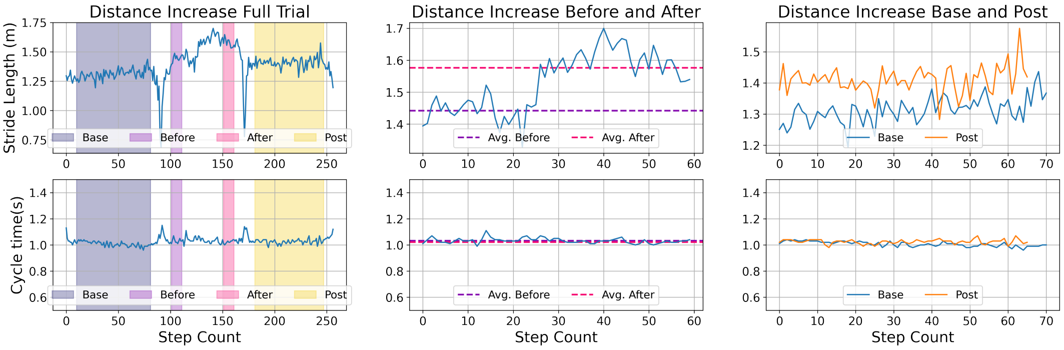

FIGURE 3.8: Raw Data sample for DI condition. Top Row: Stride length, Bottom Row: Cycle time. Left column: Full trial data, Center column: before and after sections, Right column: base and post comparison. DI - Distance Increase; DD - Distance Decrease; PI - Phase Increase; PD - Phase Decrease

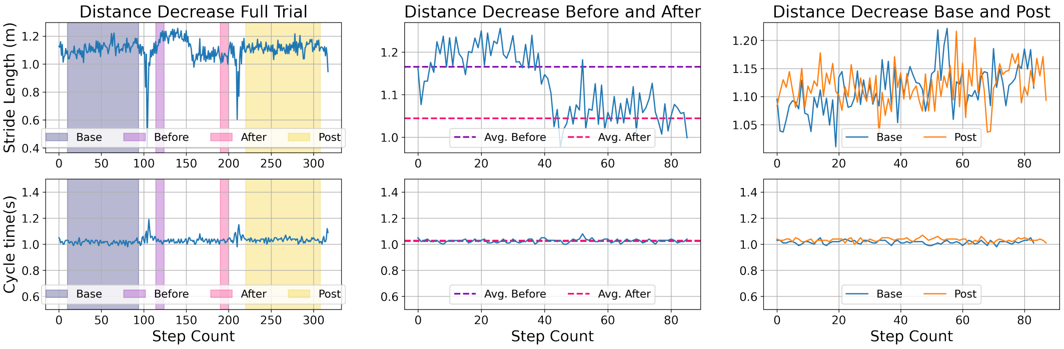

FIGURE 3.9: Raw Data sample for DD condition. Top Row: Stride length, Bottom Row: Cycle time. Left column: Full trial data, Center column: before and after sections, Right column: base and post comparison. DI - Distance Increase; DD - Distance Decrease; PI - Phase Increase; PD - Phase Decrease

outperforms. In asymmetric gait which has higher variability and less stability, the previous method often goes out of sync (Top Left). The newly designed system remains stable despite the high variability of the human gait. Though both systems have phase differences oscillating around 0, the new system is a lot less noisier and much lower amplitude.

3.3.2 Raw Data Samples

Figure 3.8 shows a raw data sample of the distance increase condition from participant 7. From the full trial graphs we can see that there was an increase in the stride length in the middle of the trial where the gradual change in distance occurred. This can be further seen in the Before and After comparison Top-Center graph, the before section (first half) is less than the after-section (second half). The base post comparison showed a noticeable increase in the stride length in the post compared to the base. These changes were not seen in cycle time (bottom row). Despite the increase in distance the cycle time had no noticeable change.

Figures 3.8 and 3.9 show the effects of distance changes, Figure 3.10 however, shows the effect of increasing phase difference. The raw data sample, taken from the

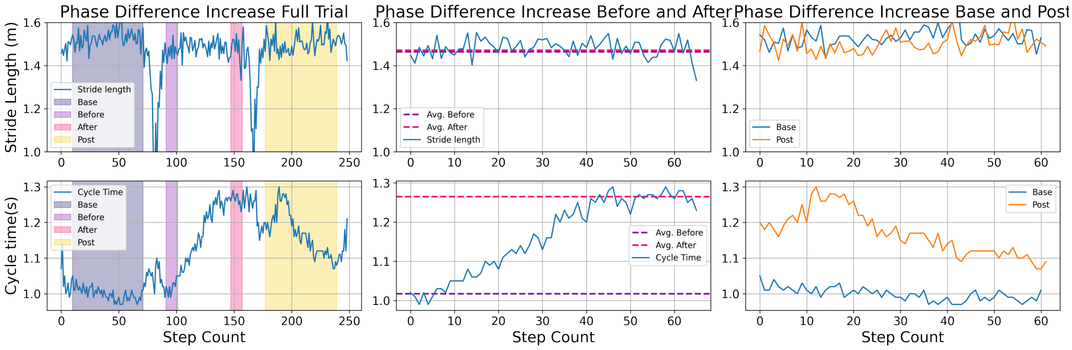

FIGURE 3.10: Raw Data sample for PI condition. Top Row: Stride length, Bottom Row: Cycle time. Left column: Full trial data, Center column: before and after sections, Right column: base and post comparison. DI - Distance Increase; DD - Distance Decrease; PI - Phase Increase; PD - Phase Decrease

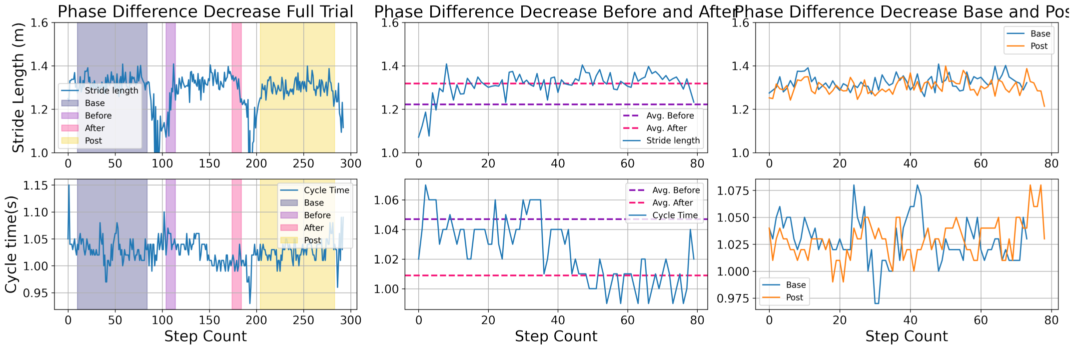

FIGURE 3.11: Raw Data sample for PD condition. Top Row: Stride length, Bottom Row: Cycle time. Left column: Full trial data, Center column: before and after sections, Right column: base and post comparison. DI - Distance Increase; DD - Distance Decrease; PI - Phase Increase; PD - Phase Decrease

PI condition trial of participant 1, shows the changes of stride length and cycle time throughout the difference sections. We can see the phase difference increase had no noticeable effects on the stride length (Top row). The cycle time, however, showed increases following the increased target phase difference shown in the latter half of the full trial(Bottom-Left graph). The gradual increases can also be seen in the before after section graph as well as the comparison between base and post.

Finally, Figure 3.11 shows the PD condition raw sample data from participant 10. No noticeable changes were seen in the stride length (Top row) throughout the trial. In the cycle time, however, showed reduced cycle time with the reduced target phase difference however returns to initial value after the turn.

3.3.3 Normalized Values Before and After Cues

Normalized values were used to analyze the effects of the cues (distance or phase difference changes) on different gait parameters. Each trial was split into 5 sections: Before, Base, Change, After and Post as shown in Figure 3.4. Of these, the values of Before, Base, After and Post are used for analysis. The comparison between Before

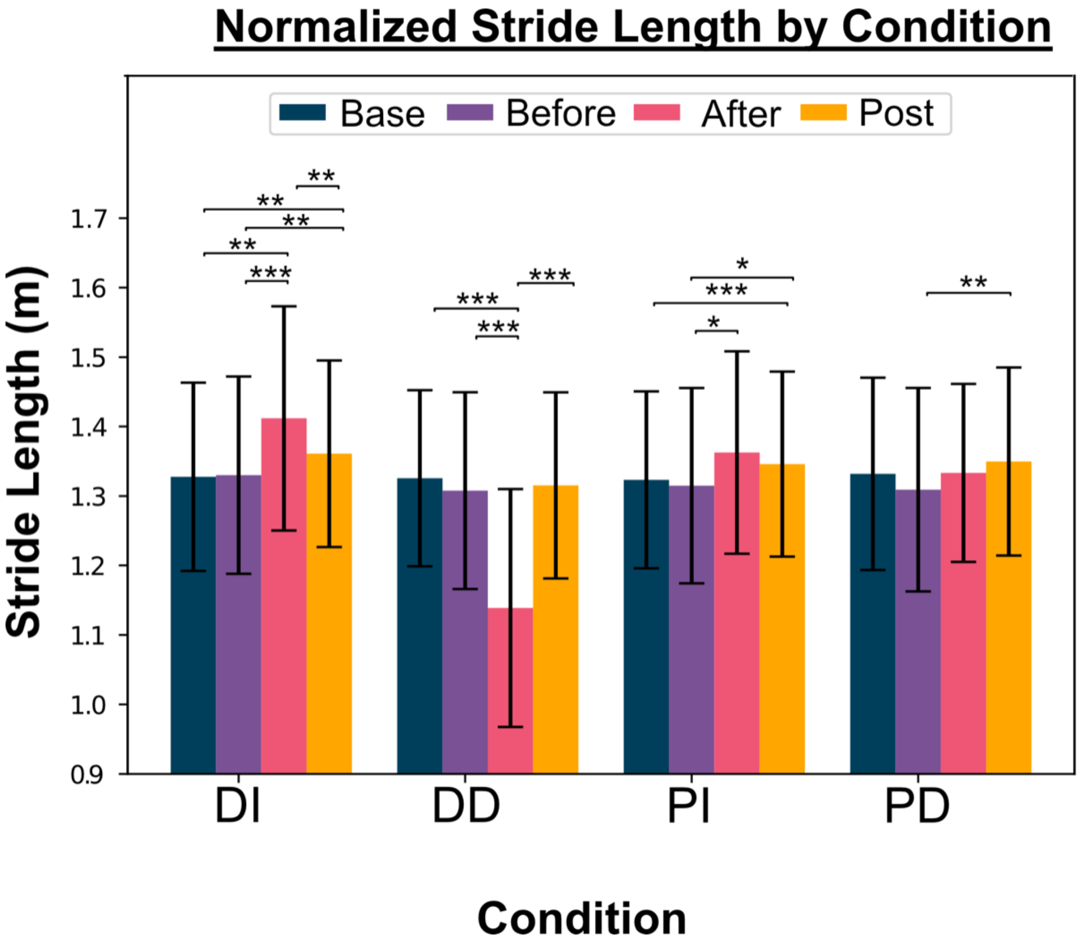

FIGURE 3.12: Normalized average stride length values and standard deviation of each section and grouped by condition. DI - Distance Increase; DD - Distance Decrease; PI - Phase Increase; PD - Phase Decrease * - $p < 0.05$; ** - $p < 0.01$; *** - $p < 0.001$

and After, will highlight a learning or carry-over effect of the cue. The Before-After comparison reveal immediate effects of the cue.

Stride Length

The normalized stride length values for each condition is shown in Figure 3.12. Repeated measures ANOVA revealed a significant main effect of the condition ($F = 28.6$; $p < 0.0001$) as well as the Section($F = 3.6$; $p = 0.02$) on the stride length. An additional interaction effects with the sections was found($F = 25.6$; $p < 0.0001$).

The DI condition showed increases to stride length in the sections after the gradual cue (After and Post) compared to before (Base and Before). Multiple comparison analysis revealed significant increases in the After compared to the Before ($p = 0.0009$) and in the Post compared to the Base ($p = 0.0012$). This indicates an immediate and carry-over effect respectively. All comparisons of sections in the DI condition showed significant differences except the Base and Before comparison($p = 0.89$).

There was a significant stride length decrease in the After section compared to the Before section in the DD condition ($p = 0.0008$). This reveals a potential immediate effect of the distance decreased condition on the stride length. There was also a noticeable but insignificant reduction in the stride length in the Post section compared to the Base section ($p = 0.25$).

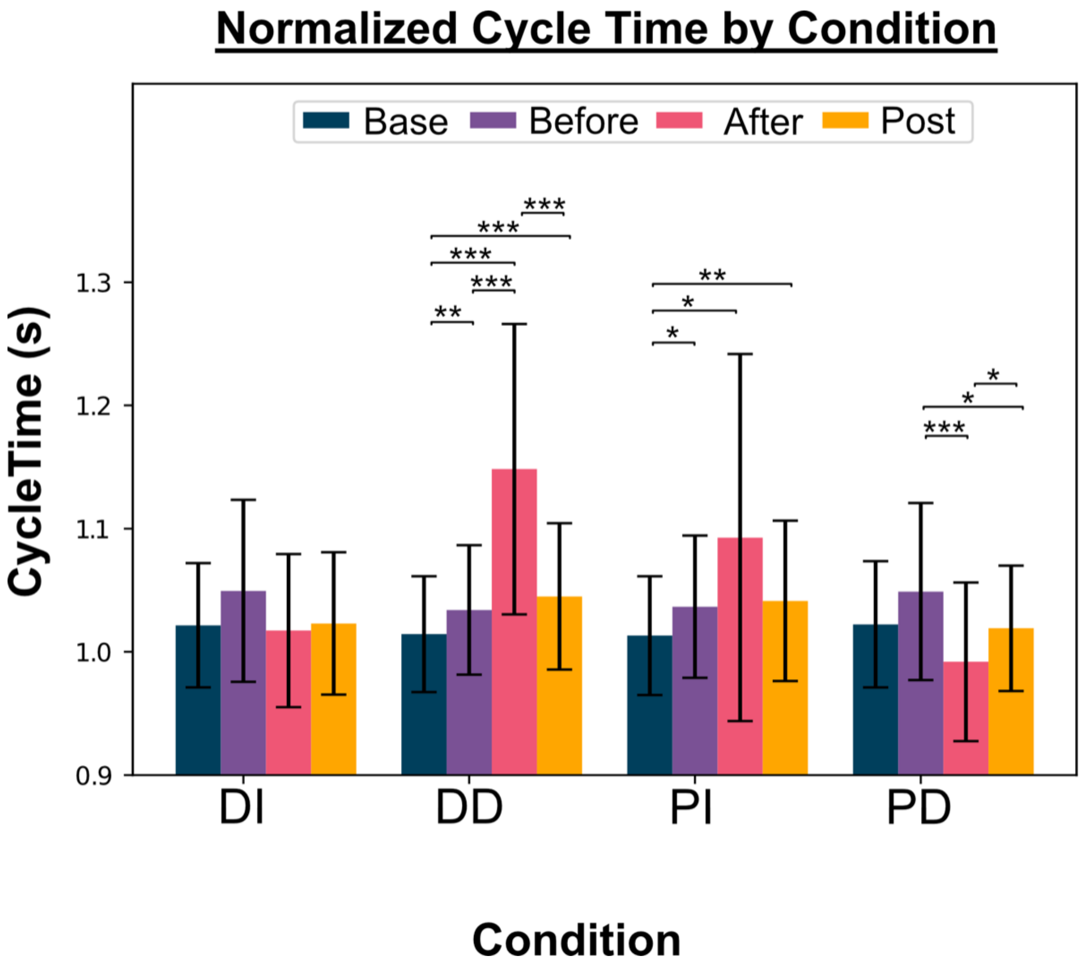

FIGURE 3.13: Normalized average cycle time values and standard deviation of each section and grouped by condition. DI - Distance Increase; DD - Distance Decrease; PI - Phase Increase; PD - Phase Decrease * - $p < 0.05$; ** - $p < 0.01$; *** - $p < 0.001$

Similar increases to stride length were seen in the Post compared to the base sections in the phase difference change conditions, PI and PD. An additional significant increase between the before and after cue values was seen in the PI condition ($t(36) = 2.47; p = 0.047$).

Cycle Time

Figure 3.13 shows the normalized cycle time grouped by condition and split by Section. Repeated measures ANOVA revealed a significant effect of the Condition ($F = 12.3; p < 0.0001$) and an additional interaction effect with the sections ($F = 17.1; p < 0.0001$).

The PD condition was the only condition with significant decreases to cycle time in the After section compared to Before ($t(36) = 6.56; p = 0.0002$). There was also insignificant decreases between the base and post($t(36) = 0.62; p = 0.609$). These results could indicate an immediate effect but no carry-over effect.

The PI condition showed a noticeable but insignificant cycle time increase in the After section compared to Before ($p = 0.099$). There was however, a significant increase in cycle time in the Base compared to Post section($p = 0.009$). These results could indicate a carry-over effect but no immediate effect.

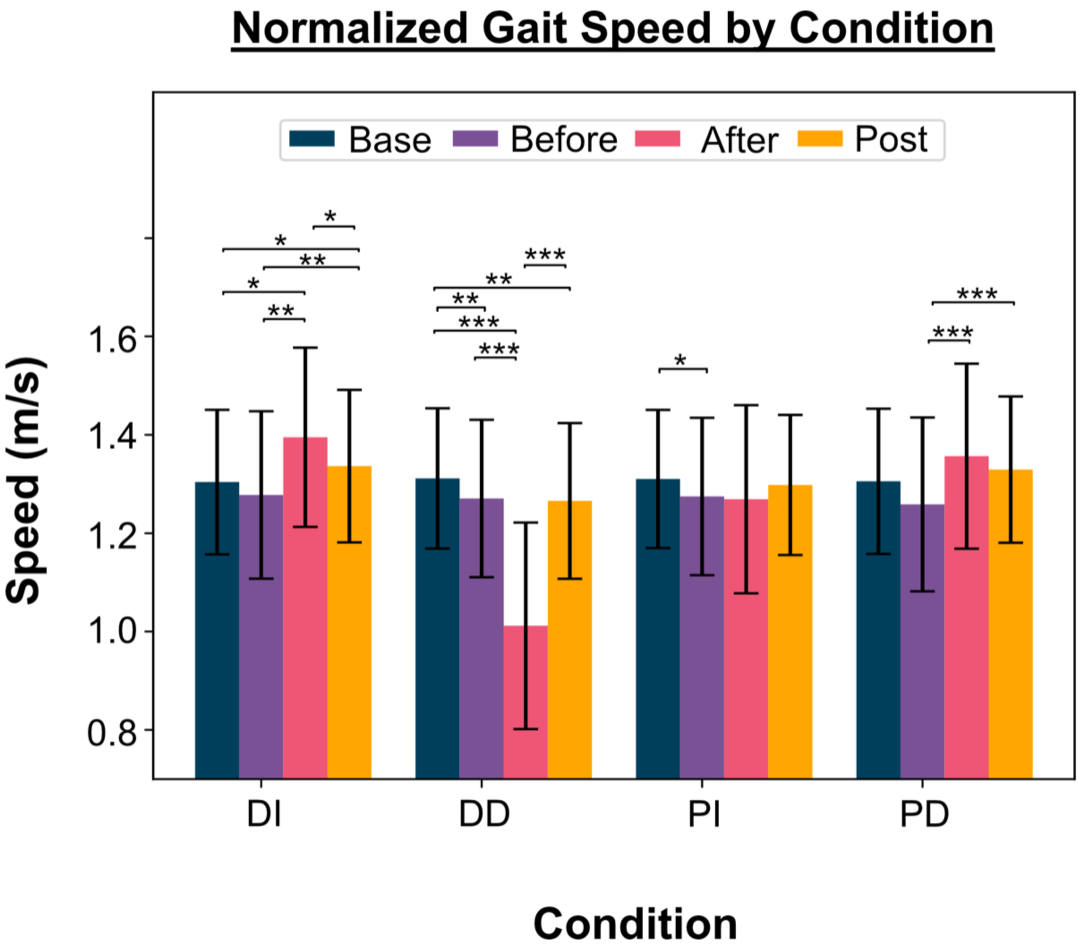

FIGURE 3.14: Normalized average gait speed values and standard deviation of each section and grouped by condition. DI - Distance Increase; DD - Distance Decrease; PI - Phase Increase; PD - Phase Decrease * - $p < 0.05$; ** - $p < 0.01$; *** - $p < 0.001$

There were surprising significant increases shown in the DD condition to both the base-post($t(36) = 5.42; p < 0.001$) and the before-after($t(36) = 5.81; p < 0.001$) comparisons. Additionally, all conditions showed increases to the before values compared to the base values with significant differences in the PI($t(36) = 3.44; p = 0.01$) and DD($t(36) = 4.64; p = 0.001$) conditions. Both PI and DD conditions shared similar changes as well as higher variability in the After section.

No significant changes between sections were seen in the DI condition. However, a noticeable decrease in the after vs the before sections was seen($t(36) = 2.03; p = 0.08$). There was no noticeable change in the post and base comparison.

Gait Speed

Figure 3.14 shows the normalized gait speed grouped by condition and split by Section. Repeated measures ANOVA revealed a significant effect of the Condition ($F = 28.0; p < 0.0001$) and an additional interaction effect with the sections ($F = 29.3; p < 0.0001$).

The DI and PD conditions showed very similar effects on the gait speed of the participants. Both conditions showed significant increases to gait speed in the after section compared to before, $p = 0.005$ and $p < 0.001$ respectively. Though both showed increases in the After section compared to the Base section only the DI condition showed significant difference ($p = 0.018$).

The PI condition, interestingly, showed almost no change in gait speed among the sections with the exception of the comparison between the Before and Base sections which showed a slight decrease in speed ($p = 0.03$).

The DD condition showed a significant decrease in speed in the after compared to the before ($p < 0.001$). Additionally, there was a significant decrease in the post compared to the base ($p = 0.003$). These significant differences indicate both an immediate and a carry over effect of the cue.

3.3.4 Change Ratio

The change ratio is used to highlight the differences in changes between the sections by condition as well as the difference between the immediate and carry-over effects. Change ratio is calculate as shown in Equation 3.9. Before-After comparison would show the immediate change of the cues. It compares the values immediately before and after the gradual cues. In both of these sections the avatar is shown however the Before section has the initial phase difference (0 rad) and distance (5m) while the After shows the avatar with the updated distance or phase difference depending on condition. The Base-Post comparison highlights the carry-over effect change. These two sections though the HMD is being worn no avatar is shown.

Stride Length

Figure 3.15 shows the stride length change ratio by condition. Repeated measures ANOVA showed a significant main effect on Condition($p < 0.001$) and an interaction effect of condition and section comparison(Before-After, Base-Post) ($p < 0.001$).

Multiple comparison analysis revealed significant differences between all pairs of conditions except DI and PI pair($p = 0.08$) and PI and PD pair ($p = 0.15$).

The DI condition showed increases in both the Before-After and the Base-Post comparisons, 6.2% and 2.6% respectively. The DI condition also showed the largest Before-After value which could indicate the effect of the cue on the stride length. Significant differences between the Before-After and Base-Post comparisons indicating the immediate and carry-over effects were different($p = 0.005$).

The DD condition was the only condition with negative change ratios, indicating the effect of the cues. It also had the largest magnitude of change among the conditions for the immediate (Before-after) comparison, a decrease of 12.6%, and the smallest Base-Post with only a 0.8% decrease. There was a significant difference between the Before-After and Base-Post comparisons highlighting difference in effects ($p < 0.001$).

The PI and PD conditions both showed increased stride lengths highlighted by the positive change ratios. Neither conditions showed significant differences between the Before-After and Base-Post comparisons indicating no difference in immediate vs carry-over effect.

Cycle Time

Cycle time change ratio by condition can be seen in Figure 3.16. Repeated measures ANOVA showed a significant main effect on Condition($p < 0.001$) and an interaction effect of condition and section comparison(Before-After, Base-Post) ($p < 0.001$).

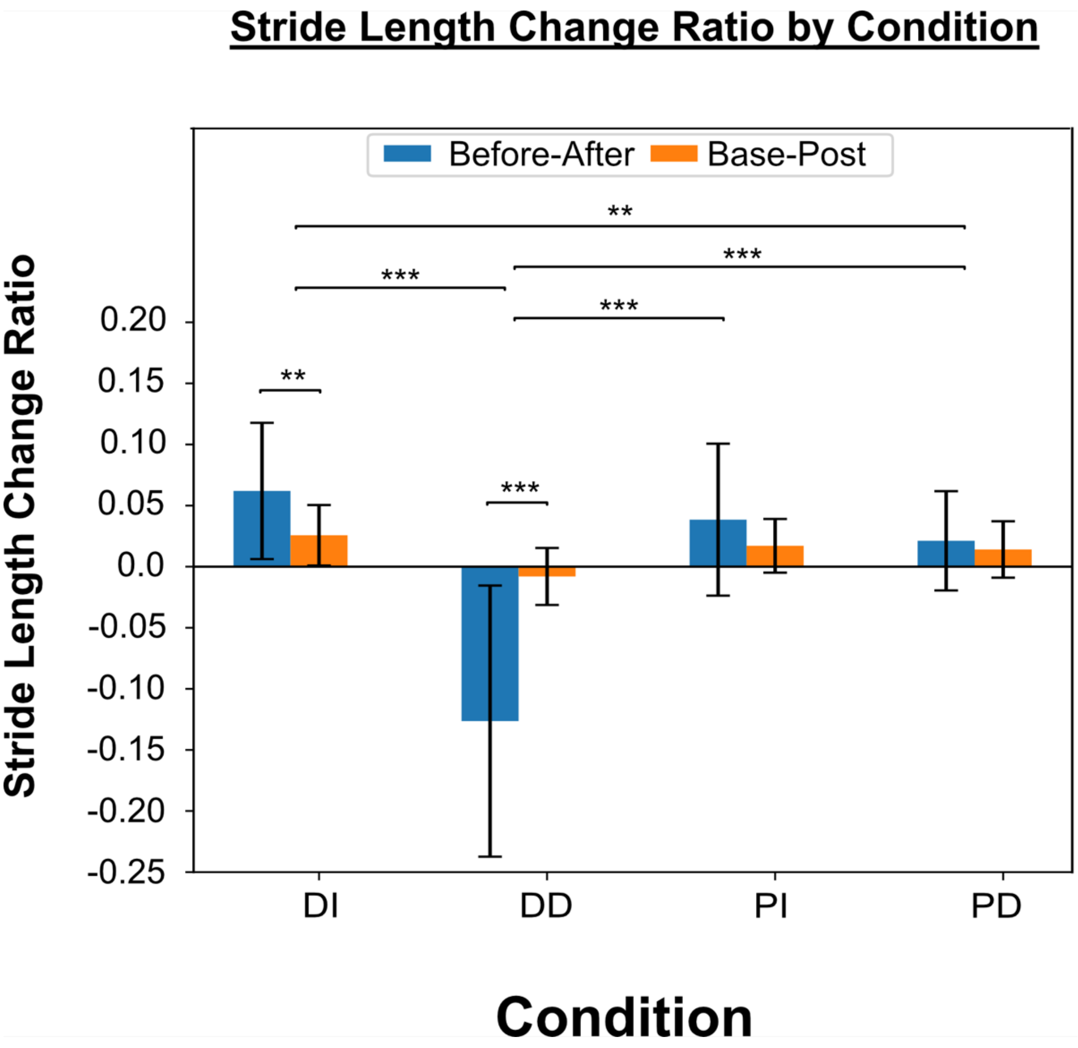

FIGURE 3.15: Stride length change ratio values showing the comparison between base and post (Base-Post) $= \frac{\text{Post}-\text{Base}}{\text{Base}}$ and the change between before and after (Before-After) $= \frac{\text{After}-\text{Before}}{\text{Before}}$.
DI - Distance Increase; DD - Distance Decrease; PI - Phase Increase; PD - Phase Decrease
* - $p < 0.05$; ** - $p < 0.01$; *** - $p < 0.001$

Multiple comparison analysis revealed significant differences between all pairs of conditions except DI and PD pair($p = 0.06$).

The DD condition interestingly had the largest magnitude of change among the conditions. An 11% increase was seen in Before-After analysis compared to significantly lower($p < 0.001$) 3% increase in the Base-Post. The PI condition also showed expected increases to cycle time in both the Base-Post and Before-After change values, 2.7% and 5% respectively.

The PD and DI conditions showed very similar trends both with decreases to the Before-After and almost no change in the Base-Post comparison. DI condition showed 0.2% and 3% decreases for Base-Post and Before-After respectively, while the PD condition the changes were 0.2% and 5% respectively. Significant differences between the Before-After and Base-Post values were found with ($t(36) = 2.38; p = 0.04$) in the DI condition and ($t(36) = 7.2; p < 0.0001$) in the PD condition.

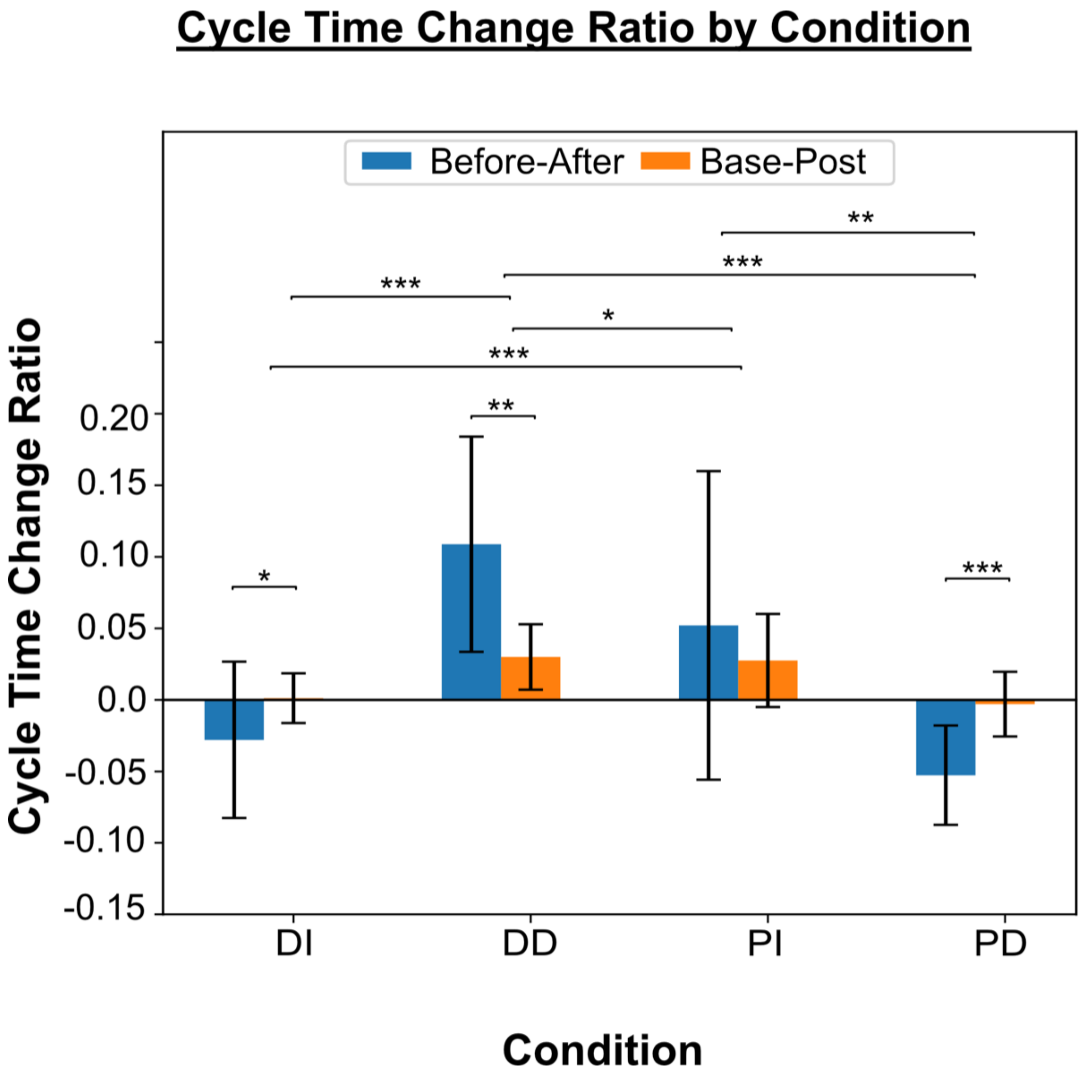

FIGURE 3.16: Cycle time change ratio values showing the comparison between base and post (Base-Post) = $\frac{\text{Post}-\text{Base}}{\text{Base}}$ and the change between before and after (Before-After) = $\frac{\text{After}-\text{Before}}{\text{Before}}$.
DI - Distance Increase; DD - Distance Decrease; PI - Phase Increase; PD - Phase Decrease
* - $p < 0.05$; ** - $p < 0.01$; *** - $p < 0.001$

Gait Speed

Gait speed change ratio by condition can be seen in Figure 3.16. Repeated measures ANOVA showed a significant main effect on Condition($p < 0.001$) and an interaction effect of condition and section comparison(Before-After, Base-Post) ($p < 0.001$).

Multiple comparison analysis revealed that except DI and PD pair($p = 0.41$) all other pairs of conditions showed significant differences in change ratios.

Both DI and PD conditions showed increases in gait speed for both comparisons. Additionally both showed significant differences between the Before-After and Base-Post values ($p = 0.013$) and ($p < 0.001$) respectively. The DI condition showed a 9.7% increase in gait speed the after section compared to the before. The PD condition showed a similar 8% increase in the same comparison. Both showed a significantly lower approximately 2% increase in the post compared to the base section.

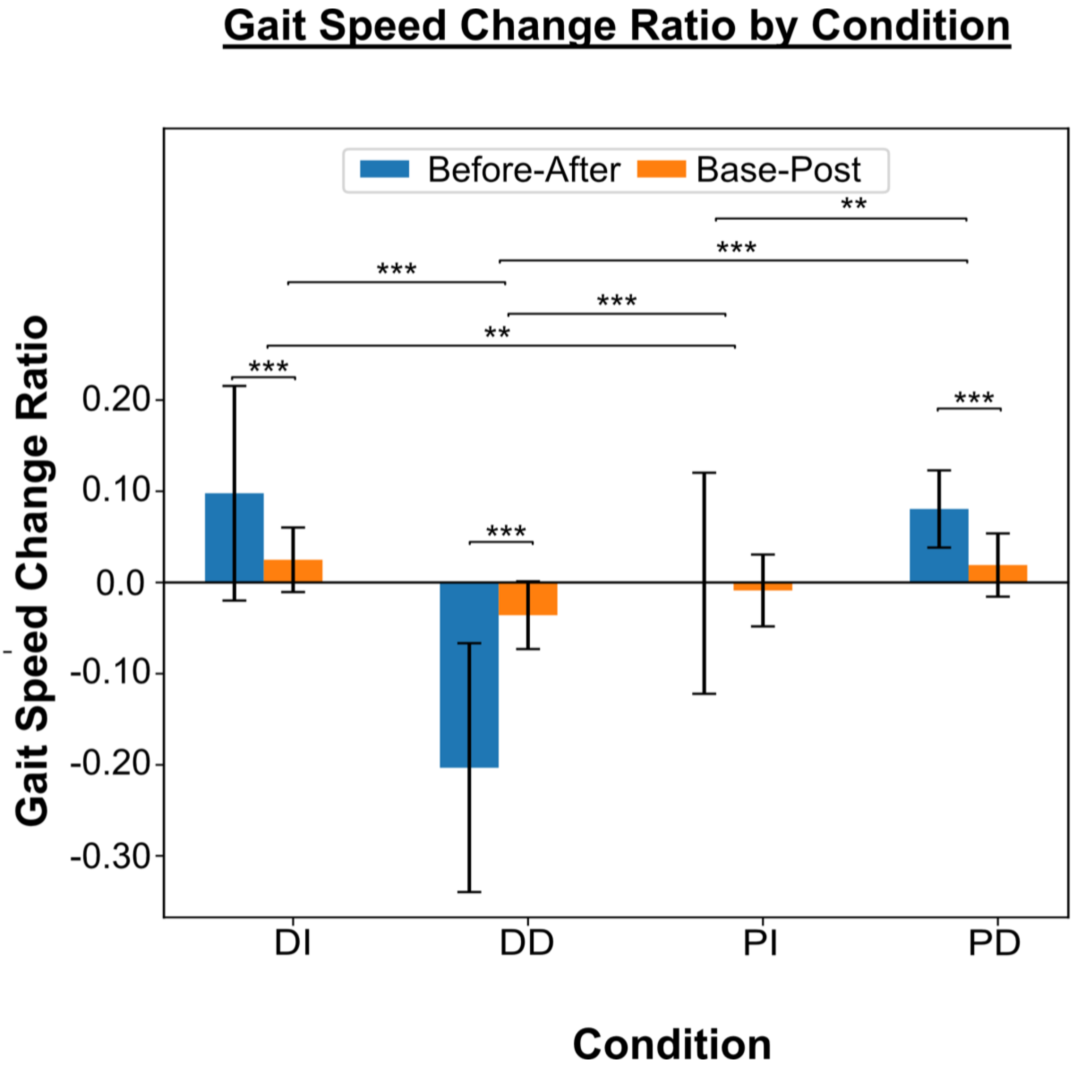

FIGURE 3.17: Gait speed change ratio values showing the comparison between base and post (Base-Post) $= \frac{\text{Post}-\text{Base}}{\text{Base}}$ and the change between before and after (Before-After) $= \frac{\text{After}-\text{Before}}{\text{Before}}$.
DI - Distance Increase; DD - Distance Decrease; PI - Phase Increase; PD - Phase Decrease
* - $p < 0.05$; ** - $p < 0.01$; *** - $p < 0.001$

The DD condition conversely showed decreases in both comparisons. The DD condition showed a 3% decrease in the Base-Post comparison and a significantly higher 20% decrease in gait speed Before-After comparison ($p < 0.0001$).

The PI condition showed almost no change in the Before-After (< 0.1%) and only a small decrease in Base-Post comparison (0.8%)

3.4 Discussion

The purpose of this study was to explore the effects of spatial and temporal cues through gradual changes to a synchronized walking avatar on elderly gait. To accomplish this improvements were made to the previous system to address the limitations in high variability gait synchronization. Improvements to the motion detection, phase estimation and real-time synchronization allowed for stable synchronization between the system and user. The newly designed system is able to synchronize with the high variability asymmetric or elderly gait. Additionally, it is able to synchronize in more extreme but common elderly gait scenarios such as hunched back, slow walking and bend over walking etc, validating the system's robustness. Changes to the gait parameters of stride length, cycle time and gait speed were used to observe the effects of the system. The normalized values were used to observe the significant changes between the difference sections (Base, Before, After, Post). Differences between the Before and After will reveal the immediate effect of the condition and the differences in the Base and Post would reveal the carry-over effect.

3.4.1 Stride length guidance

The results of this study further echo the findings of our previous study[52]. The significant difference between the before and after stride length values in both the DI and DD conditions indicate an immediate main effect of the spatial cues on the stride length.

The stride length in the DD condition after the gradual change was significantly shorter than before. It was the largest change in stride length among the conditions. Potentially because the participants feared passing through the avatar they made an effort to reduce their strides to maintain distance even though not instructed to do so[66, 67]. Though there was a slight decrease in the carry-over effect in the DD condition the difference was not significant which could be due to the shorter strides being more unstable, participants reverted to their stable and comfortable stride length[61, 68].

The DI showed significant increases to stride length. A significant increase immediately after the change. Additionally, we observed a learning carry-over effect in the DI condition with the significant increase in the post compared to the base. The gradual cues perhaps increased the learning effect allowing for significant increases to be seen[69].

The temporal conditions, PI and PD, did not have the same effects strength as the spatial conditions on the stride length. The temporal cues were primarily auditory and the spatial cues being mainly visual, gives dominance to the visual cue for spatial guidance and are more effective in triggering gait adjustments[43, 44, 66]. The significant difference found between the before and after in the PI condition could be attributed to the relationship between gait parameters and so the increase in cycle time caused an increase in the stride length [70].

3.4.2 Cycle Time

The PI and PD conditions, both showed the expected immediate changes in cycle time. The PI condition showed increases in the post compared to the base and the after to the before. Conversely the PD condition showed decreases after the cueing compared to before. Though, the PD condition had a strong immediate effect the carry-over effect was minimized potentially due to the turning in the trial. Turning increases cycle time and thus would negate the immediate reductions by the cues[71, 72].

The DI condition had similar decreases to cycle time as the PD condition. Both had significantly larger immediate effects than carry-over effects as a result of the turning[71, 72].

In the previous study, we saw the condition with increased distance and reduced phase difference showed the largest decrease in cycle time indicating these two cues can work together harmoniously[52].

The DD condition showed similar increases to the cycle time as the PI condition. These increases could be attributed to the relationship between gait parameters, decrease in stride length in the DD condition could have led to an increase in the cycle time[70, 73].

3.4.3 Gait Speed

There were three main effects seen on the gait speed by the difference conditions: increase, decrease and no change. The first effect is shown by the DI and PD conditions. Both showed increases in the Base-Post and Before-After comparisons. This could indicate both an immediate and a learning effect. However, the change in Base-Post was significantly less than in the Before-After comparison. This also can be partially attributed to the turn as stated in the previous research that gait generally slows during and following turning [71]. Additionally this reduced carry-over learning effect could be due to the disappearance of the avatar following the turn. Previous research suggests that the effects of the cueing diminishes when the cue is removed[74, 75]. Despite these limitations, the DI condition was able to illicit significant changes to the gait in the post section compared to the base condition. This suggests that the DI condition may be effective in providing gait training for elderly individuals to help increase stride length and gait speed.

The second effect is shown in the DD condition with decreases to speed in both the Base-Post and Before-After comparisons. Similar to the previous conditions the combination of the turns and disappearance of the avatar have led to the significantly smaller carry-over effect. The DD condition had the largest change in speed of the four conditions. Perhaps the cue was the most noticeable as the avatar gradually became much closer from more public space to social or potentially personal space. The participants may have tried to slow their gait to keep the avatar from getting closer and prevent themselves from walking into the avatar[66]. Despite significant effects in the SI condition some participants verbally indicated they didn't notice the increased distance but were always aware when the distance was reduced.

Lastly, the PI condition did not show any effect on the gait speed. This result is again the result of the relationship between the gait parameters[70]. The PI condition had approx. 4% increases in stride length before and after the cue and an approximate 5% increase in cycle time. This similar increases in both led to almost no change in the speed. Perhaps the PI condition would not be effective in gait training to increase speed but could be useful in shuffling gait which has short cycle times and stride lengths.

Chapter 4

General Discussion

4.1 Summary

In the previous two chapters we presented the results of two studies. In the first study we developed a synchronized walking avatar system to guide gait. Evaluation of the system was done on healthy young participants and the immediate effects were observed. The results showed that the synchronized walking avatar system could guide both spatially and temporally. Though simultaneous cues were provided the effects were largely targeted based on modality [14, 57]. Visual and spatial cueing provided through distance changes between the participant and avatar resulted in similar changes in stride length.

The second study aimed to improve on the system and to evaluate the immediate and carry-over effects on elderly gait. The results further validated the immediate effects shown in the first study. Distance changes led to significant changes in stride length and phase difference changes led to significant changes in cycle time. Additional results showed a learning effect of the cues on elderly gait despite no instruction to change gait. The second study showed that despite higher variability with elderly gait similar effects can be seen as with the healthy young participants which was not seen in other studies[76, 77]. These results are contrasted by previous studies' expectations that age would affect the outcome of the avatar-based method [78].

4.2 Synchronized Walking Avatar and Audio Cues on Gait Guidance

This thesis demonstrated the potential effectiveness of the developed synchronized avatar system in guiding individuals' gait. The avatar walking animation was modeled using healthy gait patterns and served as a natural visual reference to the participants. The visual cue in the form of the walking avatar may have activated the mirror neuron system[79, 80]. Participants were able to internalize and mimic the gait pattern of the avatar through observing the avatar's movements from behind leading to significant changes to their gait [81]. The study by Sangani et al. contrasts this showing no significant changes in step length when viewing the avatar from behind [29]. The distance changes between the participant-avatar dyad prompted a change in their stride length [82]. Whether instructed or not to maintain the distance, the participants likely modified their stride lengths to keep a constant distance from the avatar [83]. This change was likely subconscious and automatic not imposing any additional attentional load, making it ideal for gait guidance in impaired individuals.

The synchronized auditory cues complemented the visual feedback from the avatar providing rhythmic auditory signals, making it easier for participants to maintain a consistent pace and rhythm. The temporal gait guidance of the participant's gait was enhanced through the interactive and mutual synchronization between the avatar's and participant's rhythms [42]. The effectiveness of this interactive synchronization supports previous research studies, such as Muto et al. (2012), which showed temporal gait guidance through interpersonal mutual synchronization between system and user [84]. Hove et al. showed that interactive RAS, through audio cues synchronized to the participant, could help reinstate natural walking frequencies in gait-impaired Parkinson's patients[42]. The synchronization of the cues increased effectiveness as if they are not properly aligned with the individual's natural pace or if they become too cognitively demanding the effectiveness will be reduced [85]. The mutual synchronization of the system and participant reduced the increased attentional demand, gait variability, and reduced stability shown in previous studies [86, 87].

The visual cues in the provided by the synchronized walking avatar, along with the activation of the mirror neuron system, had significant effects on the participants' speed. In contrast, previous studies utilizing rhythmical visual stimuli, such as Naik et al.'s, demonstrated stride length guidance but reported no significant changes in speed, as observed in this study [88]. Other studies using rhythmical visual stimuli reported similar significant effects on stride length but no significant changes in gait speed as found in this study [89]. The reduced attentional demand using the avatar and subconscious reactions via the mirror neuron system when using the avatar could be the basis for the improved gait speed guidance in this study compared to the increased attentional demand found using other visual cues [90, 91].

The use of avatars was likely not the only factor behind the effects. Tsumura et al. showed that though both only avatar and combination avatar and audio cues affected stride length, only avatar conditions led to unintended significant changes to cycle time while avatar and audio cues did not[92]. Previous studies using avatars such as Kannape et al.'s study found reduced effects through increased cognitive demand participants tried to synchronize their steps to the avatar's [93]. Meerhoff et al. suggested that gait cycle disruptions, increased variability and reduced effects may be expected if the avatar's movements do not closely match the user's pace or rhythm[66]. The synchronization of the avatar in this system showed significant effects on the elderly gait parameters. In this study, by using the avatar synchronized to the user, we reduced the cognitive load for the user and highlights the importance of synchronization not just for the audio cues but also visual cues.

4.3 Spatial Guidance

In both studies the spatial cues in the form of distance changes showed dominance in the spatial guidance of gait. The significant difference between the before and after stride length values in both when the distance was increased and decreased indicate an immediate main effect of the spatial cues on the stride length. The increases and decreases in distance, though gradual and uninstructed in the second study, led to similar increases and decreases in the stride length as was shown in the first study with healthy young participants. The stride length in the distance decrease conditions after the change was significantly shorter than before. Distance decreases changes to stride length tend to revert to normal stride length for stability[61, 68].

Distance increase conditions tend to have a carry over effect though it can be limited by turning which reduced stride length.

The temporal changes to phase difference did not have the same effects strength as the spatial cues on the stride length. This is perhaps due to the temporal cues being mainly auditory and the spatial cues being mainly visual which tend to have dominance in spatial guidance and are more effective in triggering gait adjustments[43, 44].

4.4 Temporal Guidance

Conditions with phase difference changes showed the expected immediate changes in cycle time. Phase difference increased showed both an immediate and also carry-over effect through cycle time increases. Conditions with reduced phase difference showed a decrease in cycle time after the cueing compared with before the cueing. Although the immediate effect was clearly seen the carry-over effect is affected by turning. Previous research suggest that turning causes an increase in temporal parameters such as cycle time [71, 72].

The distance changes effects on the cycle time were largely restricted to the relationship between the gait parameters[70, 73]. These effects were overshadowed by changes to the phase difference.

4.5 Spatiotemporal Guidance

The combined cues provided by the system proved to be effective in guiding both spatial and temporal aspects of gait[94]. The system showed significant changes to the gait speed of the elderly participants. Increases to distance and decreases to phase difference, increasing the stride length and decreasing the cycle time, showed to be effective in guiding gait speed immediately after cueing. These conditions also target the common impairments found in elderly gait, short stride length and longer cycle times[1].

4.6 Limitations and Future Work

Our study evaluated the system on both healthy young and healthy elderly individuals. Although elderly gait shows higher variability and experiences some level of impairments compared to healthy young individuals, all study participants were still healthy. As a result, more research should be conducted to represent the broader elderly population, particularly those with mobility impairments or other health conditions.

Additionally, the potential effects of posture on the system effectiveness were not extensively evaluated. Preliminary testing showed the system was able to synchronize and provide cues to slow walking, hunched and bent over walking. However more research is necessary to properly evaluate the system in such walking conditions. Future research should explore alternative avatar designs such as smaller models that can be placed closer to remain within view such as child or pet models.

Additionally, further investigation is needed to understand the effects of turning and avatar on the carry-over effect. Finally, future research should examine the long term effects of the system and its potential integration with other gait training or rehabilitation systems. To assess its effectiveness in gait guidance and as a rehabilitation tool, future studies include a control group and a treatment group over a defined period of time.

4.7 Conclusion

This thesis demonstrates the use of synchronized walking avatar can significantly influence the spatial, temporal and spatiotemporal gait parameters of individuals. The results revealed both immediate and carry-over effects in elderly participants, suggesting its potential for gait training applications. Particularly, conditions with increased distance and/or reduced phase difference can be used to improve impairments commonly seen in elderly gait (shorter strides, longer cycle time, slower speed). Additionally, phase difference increase conditions can be potentially useful in shuffling gait to combat the shorter strides and short cycle times. Avatar-based AR gait training like this study present a promising approach to enhancing mobility and quality of life in the elderly. Utilizing advanced technology for personalized and engaging rehabilitation, it has strong potential for broad application in promoting the independence and well-being of older adults.

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