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RESEARCH ARTICLE

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

DANE A. L. MILLER[1], TAIKI OGATA[1], GAKUTO SASABE[1], LIANG SHAN[2], NOZOMI TSUMURA[2], AND YOSHIHIRO MIYAKE[1], (Member, IEEE)
[1]Department of Computer Science, Tokyo Institute of Technology, Meguro-ku 152-8550, Japan
[2]Department of System and Control Engineering, Tokyo Institute of Technology, Meguro-ku 152-8550, Japan

Corresponding author: Dane A. L. Miller (miller.d.aa@m.titech.ac.jp)

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ABSTRACT There has been a growing interest in augmented reality (AR) methods for gait guidance and rehabilitation. These methods have been effective in guiding spatial gait parameters, such as stride length, and temporal cycle times when paired with rhythmic stimuli. However, few studies have explored the simultaneous spatial and temporal guidance of gaits and have primarily focused on one of several aspects. Gait parameters are related, and changing one might have unintended effects on others; thus, simultaneous guidance is required. In this study, we designed and evaluated a system that provides simultaneous spatial and temporal guidance using a synchronized walking avatar in AR. The system requires a head-mounted display (HMD) and presents a walking avatar involving auditory cues synchronized with the foot-contact timing of the participant via a mutual entrainment model. Spatial feedback is provided by distance changes between the participant and avatar, and the effects on stride length are observed. Phase difference changes between the avatar and participant serve as temporal cues that are used to guide the cycle time. The stride length and cycle-time of eight participants walking along a straight corridor wearing the HMD were recorded and analyzed. Four experimental conditions were applied comprising combinations of increases and decreases in the spatial and temporal cues. Furthermore, the results demonstrated that spatial and temporal feedback had almost independent effects on respective gait parameters. These findings reveal that this combination of spatiotemporal cueing can be extremely effective in gait guidance without loss of effectiveness from single modality cues.

INDEX TERMS Augmented reality, mixed reality, multi-modal feedback system, mutual entrainment, synchronization.

I. INTRODUCTION

Augmented reality (AR) has gained attention in health fields owing to its potential efficacy in areas of gait guidance and rehabilitation [1], [2], [3], [4], [5]. In various fields, the use of AR has demonstrated improved motivation in task accomplishment, and its potential improvement to therapy sessions is worth examining [6], [7], [8], [9]. For health purposes, the auditory and visual cues provided by AR technologies can be used to affect a variety of human gait parameters [5], [10], [11].

Gait parameters are related and a change in one parameter causes unintended interference on other aspects of walking and maintaing balance [5]. This relationship is particularly

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important considering the guidance of gait-impaired individuals. For instance, a change in stride length will affect cadence, which, if different from the intended cadence, can lead to falls. AR offers a unique gait guidance technique in which the spatial and temporal parameters can be guided simultaneously [12], [13]. A multi-modal approach is important to an AR model of this type, as different modalities are known to affect the various gait parameters of a recovering human.

Audio cues, for instance, have been demonstrated to be effective and have dominance over visual cues in temporal guidance [10], [14]. Rhythmic auditory stimuli (e.g., metronomes) are popular tools for this purpose [11], [15], [16], [17]. Additionally, Baker *et al.* demonstrated the use of rhythmical audio stimuli can help reduce the attentional demand impose by other cueing strategies [12]. However, it is difficult to predict the optimal frequency to use during therapy sessions, and attuning audio cues to the needs of the patient requires trial and error, which often limits the efficacy of therapy [18], [19]. Miyake *et al.* developed the Walk-Mate model, in which the phase and frequency of an auditory cue and the foot-contact cycle of the participant are mutually entrained using a phase oscillator [20], which notably has indicated improved cycle-time guidance for patients with Parkinson's [21], [22], [23]. Additionally, Hove *et al.* observed that the Walk-Mate model allowed patients to return to 1/f frequency, which describes an inverse relationship between the intensity and frequency of the gait, as shown in healthy persons, resulting in a lower falling risk [24].

Conversely, visual cues, have been effective in the spatial guidance of gait recuperation [4], [5]. A common gait impairment is decreased stride length [16], [19], [25], and various studies have used projected lines and markers for spatial guidance during therapy [1], [2], [3]. Lim *et al.*, for example, used a multi-modal robot to project lines and footprint cues while emitting auditory beeps corresponding with the gait cycle, which successfully increased the participant's stride length [1]. Sekhavat *et al.* also increased a patient's stride length using projected cues on a treadmill and monitor display [3]. Although these methods were effective in stride-length recuperation, they required a great deal of concentration and some loss of efficacy.

Another method used virtual walking avatars to alter human gait parameters [26], [27], [28], [29]. The avatars provided the user with a sensation of walking with others, during which, humans tend to synchronize their strides [30]. Meerhoff *et al.* used a walking avatar projected on a screen and provided a participant with instructions to keep a given distance from it. The results demonstrated that the stride lengths of the participants were guided based on the apparent distance between the participant and avatar [26]. Additionally, the efficacy of different visual cues used to demonstrate gait information was compared, revealing that participants enjoyed more significant spatial guidance and faster response times when the cues are provided by a humanoid avatar,

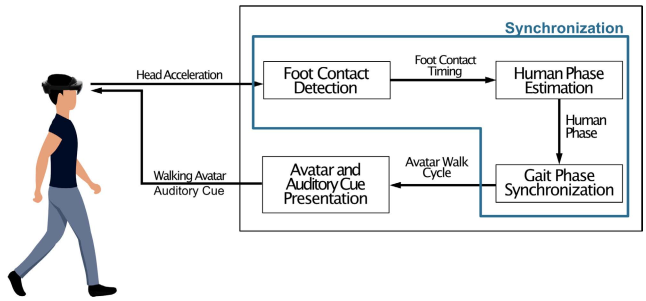

FIGURE 1. Flow of information through the system. Head acceleration data are obtained from the head-mounted display and used for foot-contact detection. The foot-contact timing is used to estimate the human phase. Thereafter, the system phase is synchronized with the human phase, and the synchronized walking avatar and auditory cues are presented.

compared with other appearances (e.g. point-light segments and fixed images) using the same gait information [27]. Shan *et al.* used a walking avatar synchronized to the foot-contact pace of a participant to indicate that increasing the arm and leg swing of the avatar led to significant changes in the patient's stride length [28]. The Walk-Mate model was again used by Shan *et al.*, in a separate experiment, where audio signals were synchronized to the avatar steps to subtly incorporate phase changes into the gait cycle of the participants. In this case, the spatial parameter was not considered, and stride length was not observed [28]. As with other AR cueing methods, the methods reviewed here are highly effective in guiding either spatial or temporal gait changes, but not both.

Simultaneous spatial and temporal guidance of human gait during therapy has been scarcely researched, despite its potential benefits. Attempts have been limited by the use of constant time metronomes or the choice of spatial cues provided. A solution to these problems might be beneficial in providing thorough gait rehabilitation programs that could speed up recovery and improve quality of life. The purpose of this study is therefore to develop and evaluate a system that can simultaneously guide the participant gait spatially and temporally. The system applies an AR-based walking avatar synchronized to the foot contact cycle of a participant to provide the cycle time and stride-length guidance. Auditory tones are synchronized, using the Walk-Mate model, to the avatar's steps to relay improved temporal guidance to the participant. Evaluations are being performed via experimentations using healthy young participants as a first step to developing a system for patients.

II. METHODS

A. AR SPATIOTEMPORAL GAIT GUIDANCE SYSTEM

The aim of the system is to use distance and phase difference changes provided by a synchronized walking avatar and audio cues in AR to deliver spatio-temporal cues to human participants for gait guidance. The system flow was implemented as shown in (Fig. 1). The phase and frequency of the avatar is first synchronized to the gait of the participant, and auditory

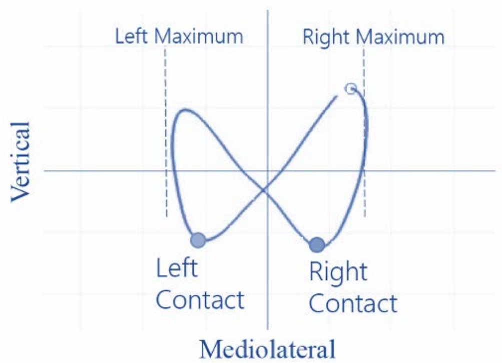

FIGURE 2. Head trajectory on vertical and mediolateral planes during one gait cycle. From the head trajectory, data of the left and right maxima are used to determine the next foot contact, which occurs at the minima.

cues matching the foot contacts are delivered. The system features four modules that handle foot-contact detection, human phase estimation, gait phase synchronization, and cue presentation. The first three modules are used to synchronize the avatar and participant gait cycles.

1) FOOT CONTACT DETECTION

The first step of the system flow is estimating the foot-contact timing for avatar synchronization. Using the method proposed by Shan *et al.* [28], head trajectory estimations are employed to determine the foot contact timing. Head acceleration readings from the head-mounted display (HMD) are used to estimate the head trajectory (Fig. 2). Trajectory minima are used to determine foot contact, and properties of the maxima are used to determine the swinging foot (Fig. 3).

2) HUMAN PHASE ESTIMATION

Human gaits are cyclic and can be represented numerically with $[0,2\pi]$. Zero refers to the left-foot contact, and π denotes the right-foot contact. The human gait phase, $\dot{\theta}_h$, is thus estimated using the following equation:

$$\dot{\theta}_h = \frac{\pi}{\Delta t}, \tag{1}$$

where Δt represents the time interval between consecutive foot contacts.

3) GAIT PHASE SYNCHRONIZATION

Finally, gait synchronization between the participant and avatar is completed using the Walk-Mate model shown in (Fig 4) [20]. The model accepts the human phase, θ_h, as input and outputs the avatar walking phase of the system, θ_m. The module consists of two sub-modules for synchronization and phase difference control.

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

$$\dot{\theta}_m = \omega_m + K_m \sin(\theta_h - \theta_m), \tag{2}$$

where θ_m represents the avatar walking rhythm phase, and ω_m denotes its natural frequency. K_m refers to the coupling

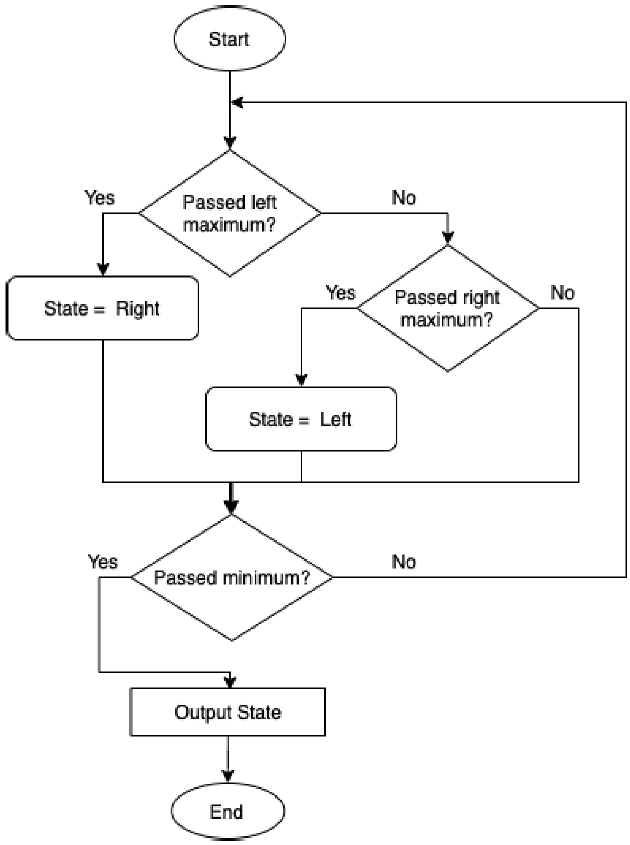

FIGURE 3. Foot-contact detection and identification process for one full step. Using the minima and maxima of the head trajectory, the last foot to make contact with the ground is determined.

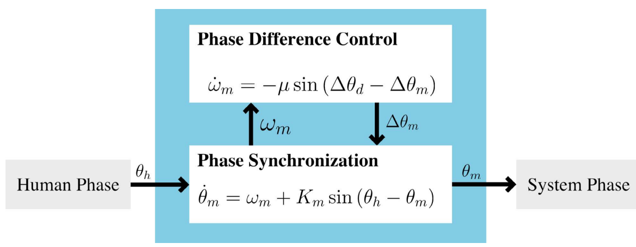

FIGURE 4. Walk-Mate model proposed by Miyake *et al.* [20]. The model accepts the participant phase as input. Using the two sub-modules for phase synchronization and phase difference controls, the system synchronizes its phase to that of the participant. Finally, the module applies the system phase to the avatar and delivers auditory cues.

constant, whose function is assumed to be symmetrical for simplicity. 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:

$$\dot{\omega}_m = -\mu \sin(\Delta\theta_d - \Delta\theta_m). \tag{3}$$

where μ is the control gain of the module.

Temporal feedback and guidance are provided through changes to the phase difference between the participant and avatar [28].

Here, $\Delta\theta_m$ is the phase difference between the sensory input, θ_h, and the motor output, θ_m:

$$\Delta\theta_m = \theta_h - \theta_m, \tag{4}$$

where $\Delta\theta_d$ represents the target-phase difference. A difference of zero indicates perfect synchrony. A positive value indicates that the system is slightly behind, and negative indicates that the system is slightly ahead.

4) CUE PRESENTATION

After the system phase is provided by the Walk-Mate model, the avatar phase is set to match the system phase and is presented to the participant, as shown in Figure 5. Spatial feedback is delivered through changes in the distance between the participant and avatar. Based on previous studies, we assumed that changes in the stride length are directly proportional to changes in distance. Audio cues are also provided, synchronized to the foot-contact timing of the avatar. Temporal feedback is then provided through changes to the phase-difference between the user and the avatar. It is expected that changes in the cycle-time of the user are proportional to changes in the phase difference as shown in previous studies.

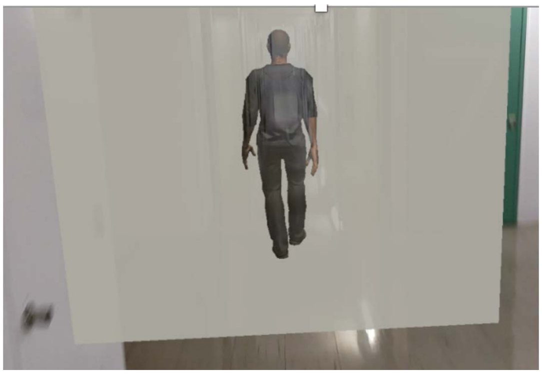

FIGURE 5. View of the avatar from the head-mounted display. The back of the avatar is observed as the participant walks down the corridor. A translucent white screen is used to make the avatar more visible under bright lighting conditions.

The avatar was created using Adobe Fuse, and it was put into motion using Mixamo. The model and motion data were imported into Unity 3D where the Walk-Mate model was used to control the animation and audio.

III. EVALUATION EXPERIMENT

A. PARTICIPANTS

Eight participants were recruited for this experiment, including three females and five males aged 23.75 ± 1.47 years. Their heights ranged in 1.65 ± 0.09 m, with weights 60.0 ± 10.45 kg. The participants reported no visual, auditory, or locomotive impairments 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.

B. TASK AND CONDITION

The participants were instructed to walk down a straight 55-m corridor while observing the walking avatar in the front, whose foot-contact timing had been synchronized to that of the participant. During each trial, simultaneous spatial and temporal feedback was delivered to each participant. After the 30th stride, simultaneous changes were made to both the distance and target phase difference between the avatar and participant to elicit changes in the participants' gaits.

1) Spatial feedback was provided using gait-distance changes made by the avatar following participant synchronization. The following instruction was provided: "For the following trials, while wearing the headset, please try to maintain the same initial distance by modifying your stride length. If the distance increases, increase your stride length. Likewise, if it reduces, reduce your stride length."
2) Temporal feedback was provided using target-phase changes made by the avatar following participant synchronization. Additionally, audio signals were synchronized with the foot contacts of the avatar.

Distance changes consisted of increases or decreases of 2 m between the participant and avatar, where the initial distance was 5 m. Similarly, target-phase changes consisted of a $\frac{\pi}{4}$-rad difference after the 30th stride, where the initial phase difference was 0 rad. Combinations of the two changing parameters resulted in four distinct conditions that were tested:

- Distance decreasing & Phase Difference decreasing ($D_D P_D$)
- Distance decreasing & Phase Difference increasing ($D_D P_I$)
- Distance increasing & Phase Difference decreasing ($D_I P_D$)
- Distance increasing & Phase Difference increasing ($D_I P_I$)

For each participant, each condition was randomly conducted twice. The order was counterbalanced between the participants. After eight practice trials, during which participants grew accustomed to the system, eight real trials were conducted. The participants were not informed of the four conditions being tested. Following each trial, participants were given a 1- to 2-min break to reset and prepare for the next trial. Additionally, the comments on the previous trial were considered during the breaks.

After every four trials, a 5-min break was given. The total experiment lasted 1.5 h, including practice trials with a combined total of 40-min rest across all trials.

C. SETUP AND CONFIGURATION

From preliminary experiments, we determined the initial parameter values suitable for the study. In the first Walk-Mate sub-module, as shown in (2), θ_m, ω_m, and K_m were set to 0, 6, and 0.5, respectively. μ, the control gain of the phase difference submodule in (3) was set to 0.32.

The participants were required to wear the HMD before the program was started to aid in step detection and adjust the avatar according to the height of the participant. The initial distance and phase differences between the participant and avatar were set to 5m and 0rad, respectively.

D. DATA ANALYSIS

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 [31]. Time-series data were used to reveal the changes of parameters (i.e., stride length & cycle time) caused by the cue changes and generated by the avatar during the trials so that the human gait changes could be measured. Changes to the simultaneous spatial and temporal cues occurred at the 30^{th} stride for each of the four conditions. The averaged normalized length and cycle time of strides 20-29 were later compared to those of strides 36-45. The intervening strides allowed for gait adjustments.

Normalized values were applied to decrease the impact of participant height on the trends [32] and were calculated using the following equation:

$$Norm_X = X_i/(h_i/\bar{H}), \quad (5)$$

where $Norm_X$ represents the normalized value of X, which represents cycle time 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. To eliminate inertial management unit (IMU) noise, which would otherwise lead to incorrect readings, extraneous values were eliminated based on the 3-Sigma standard deviation threshold.

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. Three independent factors were tested: before/after, distance increase/decrease, and phase increase/decrease. Multiple comparison analyses were conducted using the Holm–Sidak correction method with a significance level of 0.05.

E. SYSTEM HARDWARE

The experimental system featured three components: the AR HMD (Microsoft HoloLens 2 Mixed Reality HMD with WiFi-5), ankle-mounted IMUs (TSND121, ATR-Promotions), and a controller (Android, ASUS Zen Pad Tablet). The IMU and HMD configurations are shown in Fig. 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 small ankle IMUs 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 [31].

FIGURE 6. Participant walking while wearing the head-mounted display (HMD) and ankle-attached inertial measurement units (IMUs).

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.

IV. RESULTS

A. TIME SERIES DATA

1) STRIDE LENGTH

Fig. 7 displays the decreased stride length of the participant caused by the decreasing distance between the participant and avatar. Similarly, Fig. 8 displays the increased stride length caused by the increasing distance between the participant and avatar. The first highlighted region (steps 20-29) shows the average before the change, and the second highlighted area (steps 36-45) shows the values after the change.

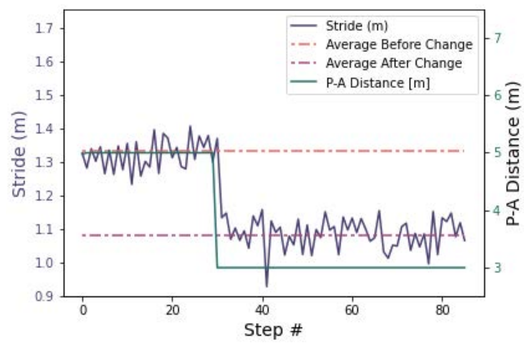

FIGURE 7. Changes in stride length per condition with decreased distance and increased phase difference. The data reveal the change in participant's stride length when the participant-avatar (P-A) distance decreases.

2) CYCLE TIME

Fig. 9 displays the decreased cycle time caused by the decreasing phase difference between the participant and avatar. Similarly, Fig. 10 displays the increased cycle time caused by the increasing phase difference. The first highlighted region (steps 20-29) shows the average before the

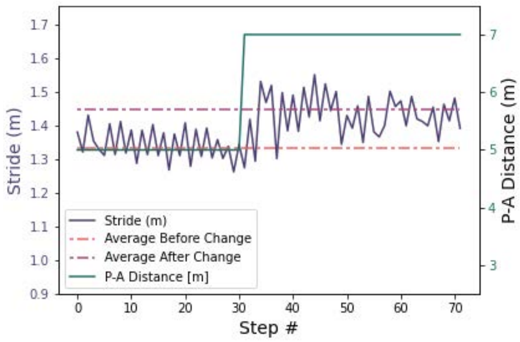

FIGURE 8. Changes in stride length per condition with increased distance and decreased phase difference. The data reveal the change in participant's stride length when the P-A distance increases.

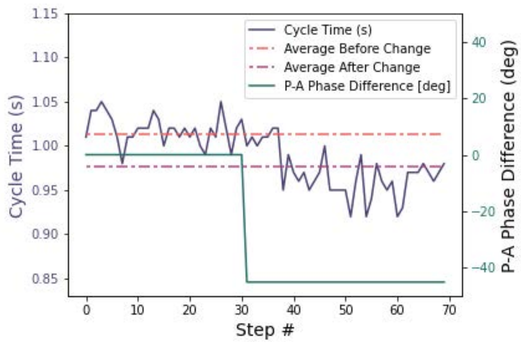

FIGURE 9. Effects of decreasing P-A phase difference on cycle time. The data demonstrate a step response of decreased cycle time caused by the decreased phase difference.

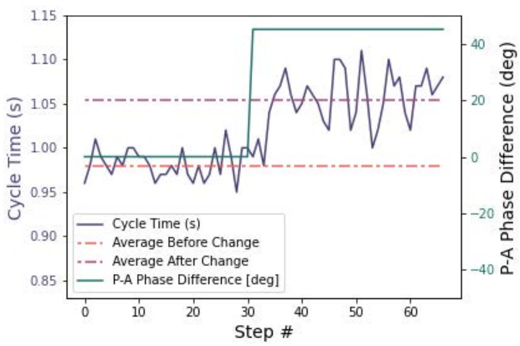

FIGURE 10. Effects of increasing P-A phase difference on cycle time. The data show a step response of increased cycle time caused by the increased phase difference.

change, and the second highlighted area (steps 36-45) shows the values after the change.

B. NORMALIZED VALUES BEFORE AND AFTER CUES

Fig. 11 displays the average normalized stride length (cm) between conditions before and after cueing. Data from strides 20–29 are used to calculate the average before the change, and strides 36–45 are used after the change. The intervening strides allow for gait adjustments). Repeated ANOVAs revealed significant correlations between before and after

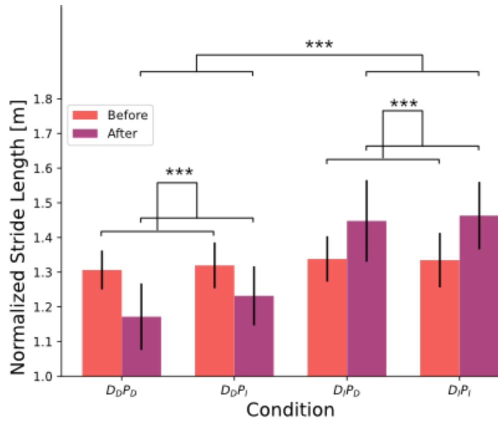

FIGURE 11. Normalized stride length before and after cueing. Pink values show the normalized average stride length before the change in spatiotemporal cues (strides 20–29). Purple values indicate the normalized average stride length after changes (strides 36-45). There were no significant differences between the results before the change based on distance. However, there were significant differences ($p < 0.001$) between the values before and after the changes when the distance was increased or decreased. A similar significant difference ($p < 0.001$) was observed between the values after the change when distance was decreased or increased. *** denotes a significant difference of $p < 0.001$ between conditions.

and distance increases and decreases ($F = 25.7; p = 0.001$). Multiple comparison analyses using the Holm–Sidak method revealed significant differences (p<0.001) in all combinations of distance increases and decreases before and after cueing, apart from the comparison made before the increase/decrease conditions (p=0.06). From Fig. 11, the conditions with decreased distances (D_DP_D and D_DP_I) had lower stride lengths after the change than before the change. Conversely, conditions with increased distance (D_IP_D and D_IP_I) showed more increases in stride length after the change than before the change.

Similarly, Fig. 12 displays the average normalized cycle time (s) between conditions before and after cueing. Multiple comparison analyses revealed significant differences (p<0.001) in all combinations of phase difference increases and decreases before and after cueing, apart from the comparison made before the increase/decrease conditions (p=0.69). From Fig. 12, the conditions with decreased phase differences (D_DP_D and D_IP_D) exhibited lower cycle times after the change than before the change. Additionally, conditions with increased phased difference (D_DP_I and D_IP_I) also showed more increases after the change than before the change.

C. STRIDE LENGTH AND CYCLE TIME CHANGE RATIO

We analyzed the change ratio of each condition to observe their differences. Fig. 13 displays the conditions with an increased distance between the participant and avatar (D_IP_I and D_IP_D) in which stride length increased. Similarly, a decrease in the distance (D_DP_D and D_DP_I) showed a decrease in stride length. Multiple comparison tests revealed significant differences between the conditions, apart from those with similar increases (D_IP_I and D_IP_D) or decreases (D_DP_D and D_DP_I) in distance. The significant difference

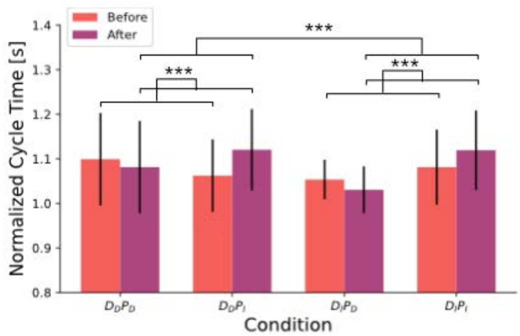

FIGURE 12. **Normalized cycle time before and after cueing. Pink values demonstrate the normalized average cycle time before the change in spatial and temporal cues (strides 20–29). Purple values indicate the normalized average cycle time after changes (strides 36-45). There were no significant differences between the results before the change based on cycle time. However, there were significant differences ($p < 0.001$) between the values before and after the changes when the phase difference was increased or decreased. A similar significant difference ($p < 0.001$) was found between the values after the change when the phase difference was decreased or increased. *** denotes a significant difference of $p < 0.001$ between conditions.**

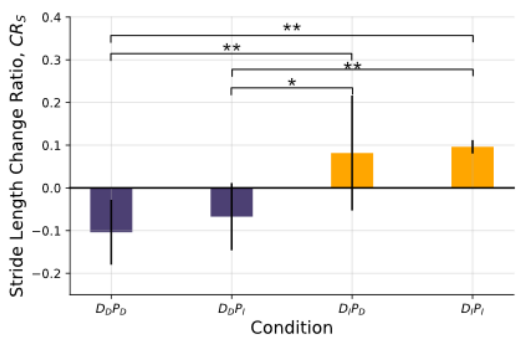

FIGURE 13. **Change ratios of stride length per condition. The results demonstrate significant differences in all conditions. The significant difference between D_DP_I and D_IP_D conditions was $p < 0.05$, whereas all other significant differences were $p < 0.001$. * denotes a significant difference of $p < 0.05$ between conditions. ** denotes a significant difference of $p < 0.01$ between conditions.**

between D_DP_I and D_IP_D was $p < 0.05$, whereas all other significant differences were $p < 0.001$.

Fig. 14 displays the conditions with an increased phase difference between the participant and avatar (D_DP_I and D_IP_I) in which cycle time increased. Similarly, a decrease in the phase difference indicated a decrease in the cycle time. Multiple comparison tests demonstrated significant differences between D_DP_I and D_IP_D (p<0.05).

V. DISCUSSION

This study explored the efficacy of combining audiovisual cueing methods using a synchronized avatar to adjust the human spatial and temporal gait parameters (i.e., stride length and cycle time).

The results support previous studies that demonstrated dominance effects of different audiovisual and spatiotemporal modalities on gait parameters [5], [10]. However, those studies generally did so at slower cycle times [16].

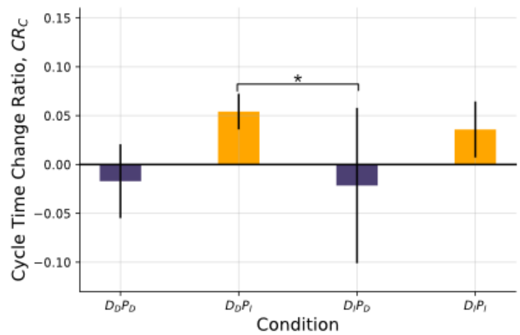

FIGURE 14. **Change ratios of cycle time per condition. Results show significant differences ($p < 0.05$) between D_DP_I and D_IP_D conditions. * denotes a significant difference of $p < 0.05$ between conditions.**

Despite its simultaneous spatial and temporal cueing, this study revealed that each gait parameter could be driven somewhat independently with insignificant interference among parameters.

The changes in distance between the avatar and participant exhibited a significant effect on the stride length of the participants. That is, an increase (decrease) in distance led to an increase (decrease) in stride length.

Suteerawattananon *et al.* indicated significant changes in stride length when using visual (spatial) cueing. However, this effect was not seen in the combined audio and visual cueing strategy [5].

Although the distance changes had a significant effect on the stride length of the participants, the phase difference also demonstrated a noticeable but insignificant difference on the stride length. This may have been caused by the reduced attentional demand of following the avatar compared with past studies that required participants to align their strides with marker cues or verbal corrections. This interference between cues reflected higher differences in change ratios when the cues were constructive (both increasing or both decreasing) compared with when they were destructive (one increasing while the other was decreasing and vice versa).

The phase difference changes were demonstrated to have an effect on the cycle time of the participant. When the phase difference between the participant and avatar increased the cycle time of the participant also increased. Similarly, when the phase difference was decreased the cycle time also decreased. Our system, with simultaneous spatial cueing, was able to produce similar effects of changing phase difference between the participants and virtual avatar on the cycle time of participants as studied by Shan *et al.* who only used temporal cues [28]. This shows that we were able to guide the cycle time despite the influence of the changing stride length.

The change ratio of cycle time appeared to have a larger effect under destructive conditions (D_DP_I and D_IP_I). More research is required to identify the reason for this, however, it may be related to the healthy participants of our experiment having an easier time controlling their pace. Notably, verbal feedback from participants indicated that the D_DP_D condition made it a bit difficult to maintain fast cycle times. This could be the result of participants working hard to maintain stability while walking. Reduced stability has been shown at larger stride lengths and slower speeds ($D_I P_I$ condition) [33].

Simultaneous guidance of stride length and cycle time was achieved through simultaneous spatial and temporal cueing. Previous studies (e.g., Rochester *et al.*) demonstrated decreased step frequencies (larger cycle times) when using rhythmic feedback cues [18]. This could result in lower stability and greater risk of falling [33]. Another study indicated that the combination of visual (spatial) and auditory (temporal) cues together were as effective as auditory cueing alone for improving cadence (cycle time) and gait speed. However, it was not as effective in stride-length guidance [5].

In this study we successfully decreased cycle times while increasing the stride length, which provides similar findings as those of Baker *et al.*, which reported significant increases in walking speed when using a combination of auditory (temporal) and attentional (spatial) cueing strategies compared with no significant changes when using only auditory cueing [19]. Baker *et al.* used an attention-cueing strategy consisting only of verbal instructions and a metronome, and it did not employ any external stimuli for spatial guidance. Thus, it required greater attentional demands on the participants than the trials performed in our tests. Although the auditory cues successfully reduced the attentional demand in the study by Baker *et al.*, our system with its additional external visual cue given by the walking avatar further reduced the attentional demand and demonstrated a better performance.

The potential applications of this study pertain to rehabilitation and training for gait-impaired individuals. With the reduced attentional demand compared to other methods this system will be useful in gait rehabilitation of neurodegenerative diseases such as Parkinson's disease. Notably, young healthy participants were evaluated in our study. Thus, additional testing with gait-impaired individuals is required. Additionally, this study examined the step response to singular changes made in the middle of the trial. The effects of real-time continuous changes are yet to be explored. Although this study demonstrated that the gait parameters of stride length and cycle time can be targeted both simultaneously and independently, cycle time was more difficult to guide. This suggests that more factors should be considered for simultaneous cycle-time guidance in future works.

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DANE A. L. MILLER was born in Kingston, Jamaica, in 1994. He received the B.Sc. degree (Hons.) in computer science from The University of the West Indies, Mona Campus, Jamaica, in 2016, and the M.S. degree in artificial intelligence from the Tokyo Institute of Technology, Tokyo, Japan, in 2021, where he is currently pursuing the Ph.D. degree in artificial intelligence.

From 2018 to 2019, he was a Research Student with the Tokyo Institute of Technology. His research interests include human–machine interaction, augmented reality, and rehabilitation systems.

TAIKI OGATA received the B.E., M.E., and Ph.D. degrees from the School of Engineering, The University of Tokyo, Japan, in 2004, 2006, and 2009, respectively. From 2009 to 2011, he was a Project Researcher with the Intelligent Modeling Laboratory (IML), The University of Tokyo, where he was a Research Associate with the Research into Artifacts, Center for Engineering (RACE), from 2011 to 2018. Since 2018, he has been a Specially Appointed Associate Professor with the Tokyo Institute of Technology. His research interests include cognitive science, human–machine interaction, and co-creation engineering. He belongs to the Japan Society for Precision Engineering (JSPE), the Society of Instrument and Control Engineers (SICE), and Society for Serviceology.

GAKUTO SASABE was born in Japan, in 1992. He received the B.E. degree from the Tokyo University of Agriculture and Technology, and the M.E. degree from the Tokyo Institute of Technology, Tokyo, Japan, in 2018. He joined Panasonic Corporation, Osaka, Japan, in 2018. After working on the development of the delivery of the Auto dish-serving system as a Robotics Technician, he is currently involved in the development of semiconductor manufacturing equipment as a Software Engineer.

LIANG SHAN was born in China, in 1995. He received the B.E. degree from the University of Electronic Science and Technology of China, Chengdu, China, in 2017, and the M.E. degree from the Tokyo Institute of Technology, Tokyo, Japan, in 2019. He joined August Robotics, Shenzhen, China, in 2019. Since 2021, he has been with AutoX.

NOZOMI TSUMURA was born in Japan, in 1995. He received the B.E. and M.E. degrees from the Tokyo Institute of Technology, Tokyo, Japan, in 2019 and 2021, respectively. During his bachelor's degree, he studied the effects of auditory and visual stimuli on people's gait. In the master's course, he designed DNA nanostructures using DNA complementarity and investigated the behavior of their aggregates. He joined PHC Corporation, Japan, in 2021. Currently, he develops medical storage equipment and is mainly in charge of software development.

YOSHIHIRO MIYAKE (Member, IEEE) received the B.S., M.S., and Ph.D. degrees in biophysics from The University of Tokyo, Tokyo, Japan, in 1983, 1985, and 1989, respectively. From 1989 to 1996, he was an Associate Professor at the Kanazawa Institute of Technology. In 1996, he joined the Tokyo Institute of Technology, where he is currently a Professor at the School of Computing. He has engaged in the fundamental research of human communication science and human–computer interaction. He is currently studying the design principle of co-creation system based on the interaction between human and artifacts. As an application of it, he is also developing gait assist wearable robot WALK-MATE and gait analysis system for early diagnosis. He is a member of ACM, IECE, and SICE.