

Cross-Modal Envelope-Synchronized Audio-Tactile Cueing Wristband for Improving Older Adults' Walking Speed in Public Transportation Environments [†]

Jun-Yuan Chiu  and Jo-Han Chang ^{*}

Master Program of Innovation and Design, Department of Industrial Design, National Taipei University of Technology, Taipei 10608, Taiwan; aa0955372350@gmail.com

^{*} Correspondence: johan@mail.ntut.edu.tw; Tel.: +886-02-2771-2171-2824

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Abstract

This study aims to investigate the effects of a synchronous rhythmic–auditory stimulation (RAS) and vibrotactile wristband system on walking performance and subjective responses of older adults in a public transportation context. In the experiment, five older participants walked along an indoor corridor under two sequential conditions: (1) normal walking and (2) walking with the auditory–tactile synchronous cue. For each condition, walking speed and stride length were measured, followed by a five-point Likert questionnaire assessing perceptual comprehension and behavioural effectiveness. Neither the paired-sample *t*-test nor the Wilcoxon signed-rank test reached statistical significance. However, the synchronous cue condition exhibited a small increase in overall walking speed, and questionnaire results indicated high comprehensibility of the cueing device. These findings suggest that cross-modal synchronous prompting has potential benefits, and they warrant future studies with larger samples and refined stimulus designs to confirm its practical value.

Keywords: envelope-synchronised cues; audio-tactile integration; rhythmic acoustic stimulation (RAS); gait-speed facilitation; gerontechnology

1. Introduction

The world's population is ageing rapidly. In 2020, the number of people aged over 60 years old surpassed 1 billion and is projected to reach 2.1 billion by 2050 [1]. Mobility is critical to the independence and overall health of older adults [2]. Nevertheless, gait deteriorates with advancing age, manifesting as reduced stride length and joint range of motion [3]. This degradation typically slows walking speed, which is recognised as a key indicator of functional capacity [4]. Walking speed is associated not only with mobility but also with life expectancy and mortality risk [5]. Among community-dwelling active older adults, the average gait speed is about 1.2 m/s, whereas individuals with speeds less than 0.8 m/s are categorised as slow walkers and commonly experience mobility limitations [6]. Slower gait affects everyday tasks such as crossing streets within limited signal times or catching public transport. Research on public health shows that older adults who do not use mass transit—whether by choice or due to structural barriers—walk more slowly and display faster functional decline than regular users; conversely, habitual transit use helps maintain physical activity and walking ability [7]. These findings underscore the



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importance of improving or preserving gait speed in later life to enhance autonomy and ensure safe ambulation in station environments.

Many older adults struggle with time-critical tasks such as catching a bus because of reduced walking speed and balance—84–93% of pedestrians aged ≥ 65 in England cannot traverse a signalised crossing within the standard green phase [8]. Within urban transit hubs, slow-walking seniors also contend with long platform distances, crowding, and non-waiting vehicles, factors that correlate with lower public transport use and further gait decline [7]. Without timely intervention, mobility and social participation are curtailed; therefore, strategies that offer real-time assistance are urgently needed.

While conventional rehabilitation improves muscle strength and gait over weeks or months, instantaneous cues can correct walking behaviour in situ. Sensory ageing complicates the challenge: both auditory and tactile sensitivities decline with age [9]. Accordingly, the present study targets cross-modal cues that fuse sound and touch, because synchronous multisensory stimulation enables one modality to compensate when another is compromised and has been shown to enhance attention and reaction speed in older adults [10]. Rhythmic-auditory stimulation (RAS) provides gains in gait speed and stride length among people with Parkinson's disease [11]. Recent single-session trials of wearable vibrotactile feedback systems have produced instantaneous gait speed increases of 14–18% in community-dwelling seniors [12], and follow-up studies suggested a similar efficacy in larger samples [13]. Building on these findings, we developed an envelope-synchronised audio-tactile wristband-plus-headphone system and evaluated its immediate effects on gait speed in a simulated metro station corridor to help older adults move faster and more safely, bolster their confidence in using public transport, and sustain an active lifestyle.

2. Literature Review

2.1. Audio-Tactile Cueing Technology and the Concept of Envelope Synchronisation

Roy et al. laid the theoretical and practical groundwork for dual-modality gait cueing by showing that when isochronous acoustic pulses and equally spaced vibrotactile envelopes are delivered simultaneously, step-to-beat variability is markedly reduced and cadence stability emerges within minutes [14]. Their results demonstrated an auditory temporal dominance: if the sound leads the vibration by more than the brain's temporal window of integration (TWI), the multisensory benefit disappears, whereas a slight tactile lead causes minimal disruption. Designers must align the energy envelopes of the two cues and keep their onset asynchrony inside the cognitively permissible TWI to sustain cross-modal synergy. Audio-tactile integration thus combines the temporal clarity of rhythmic sound with the body-anchored immediacy of vibration; envelope synchronisation concurrently heightens perceptual attention and motor rhythmicity, making it one of the most promising multisensory technologies for modern gait intervention and rehabilitation devices [14].

2.2. Cue Parameters

We selected the standard pitch A4 (440 Hz) as the rhythmic reference because it lies near the peak of human auditory sensitivity, offering high recognisability while limiting confusion with environmental noise [15]. Prolonged exposure to sound levels ≥ 85 dB can damage hearing, whereas levels < 70 dB are generally considered safe [16]. Accordingly, headphone output was kept below 70 dB, ensuring audibility in typical public spaces without jeopardising listeners' hearing. Vibration amplitude is greater than 200 Hz, and tactile sensitivity declines markedly in older adults, yielding higher detection thresholds than in younger adults [17]. Commercial wrist-mounted devices deliver vibrations in the 0.5–1 g range, which is sufficient for perception yet remains comfortable [12]. These

parameters, 440 Hz at <70 dB and 0.5–1 g vibration, balance perceptual salience with safety, providing a reliable foundation for the audio-tactile gait-cueing system.

3. Materials and Methods

3.1. Device Design

3.1.1. Hardware Architecture and Components

Both modules use an ESP32-WROOM-32 (Espressif Systems, Shanghai, China), whose dual-core MCU integrates 2.4 GHz Wi-Fi, Bluetooth Low Energy, and ESP-NOW (Figure 1). On the wristband, ESP32 controls the micro-button, transmits timing packets, and drives the motor driver, while on the headphone, it receives the packets, scales the audio amplitude, and streams the signal to the amplifier. Each module contains an independent 3.7 V, 400 mAh Li-Po cell (type 602035) and a 5 V/2 A boost-charger board with a USB-C port. The board supplies a regulated 5 V rail, ensuring stable operation throughout the experiment while allowing convenient re-charging. The wristband carries an L9110S dual-channel motor driver integrated circuit and a 10×3.4 mm eccentric rotating mass (ERM) motor (model 1034, rated 3–5 V). The L9110S delivers (UMW/Youtai Semiconductor Co., Ltd., Shenzhen, China) up to 0.8 A continuously per channel (2.5–12 V), providing sufficient current for the ERM, which spins at $10,000 \text{ r min}^{-1}$ (166 Hz) and generates up to 0.5 g peak acceleration at full voltage. The headphone module employs a MAX98357A class-D I²S amplifier (Analog Devices, Wilmington, MA, USA). At 5 V it can deliver up to 3 W into 4Ω ; here one MAX98357A drives two 8Ω dynamic speakers (left/right, 0.5 W each). A $12 \times 12 \times 5$ mm tactile micro-switch on the wristband serves as a start/reset key. The headphone unit hosts an identical switch for power/pair/play and a 0–100 k Ω rotary potentiometer for volume control. The potentiometer is read by the ESP32 ADC, and firmware linearly scales the audio gain accordingly.

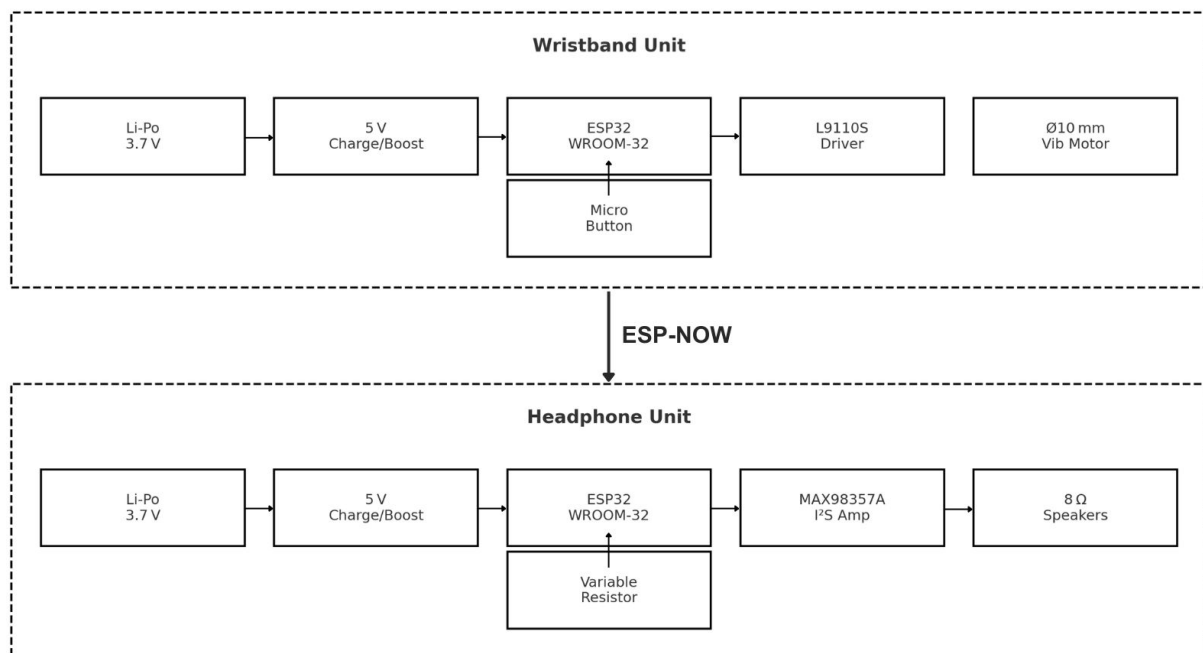


Figure 1. Cueing system consists of two wirelessly linked modules: a vibrotactile wristband and a headphone unit.

3.1.2. Ergonomic Design

The wristband enclosure was manufactured by stereolithography 3D printing in photosensitive resin and measures $48 \times 30 \times 30$ mm. Its interior is partitioned to include the ESP32 board, L9110S driver, ERM motor, and the 400 mAh battery. A wide silicone

strap distributes pressure evenly and remains comfortable during prolonged wear. Silicone was chosen because age-related degeneration of the skin barrier—manifested as water loss and decreased pressure tolerance [18,19]—makes low-irritant, hypoallergenic, and sweat-resistant materials especially desirable for older users.

The audio module is a circumaural headset whose ear cups (Ø 90 mm, depth 30 mm) fully enclose the pinna and house 40 mm/8 Ω dynamic drivers. Circumaural architecture improves cue clarity and attenuates environmental noise for middle-aged and older listeners [20,21]. Both the ear cups and the telescopic headband are padded to enhance stability and prevent slippage across different head sizes. With one cue issued every 1.4 Hz (typical cadence in the experiment), the 400 mAh Li-Po cells provide 3.3 h (wristband) and 3.4 h (headphones) of continuous operation—ample for the complete test protocol.

3.2. Experimental Procedure

Following the walkway length recommendations of Fritz and Lusardi [22], a 20 m straight course was marked within an indoor corridor. The first 5 m of the course served as an acceleration zone, allowing participants to reach their natural walking speed. The middle 10 m constituted the steady-state zone, which functioned as the data capture segment for consistent gait analysis. Finally, the last 5 m were designated as the deceleration zone, enabling participants to gradually slow down after completing the steady-state segment.

A side-mounted 1080-pixel camera recorded each trial for frame-by-frame extraction of the step count and elapsed time within the steady-state zone. Two spatiotemporal variables were computed.

$$\text{Stride length (cm)} = \text{distance} / \text{number of steps} \quad (1)$$

$$\text{Walking speed (m s}^{-1}\text{)} = \text{distance} / \text{time} \quad (2)$$

Because rhythmic–auditory stimulation (RAS) is most effective when the cue tempo is 10% faster than natural cadence [23], each participant's baseline gait frequency (f_{nat}) was multiplied by 1.10 to obtain the target tempo (f_{RAS}). The resulting vibration inter-pulse interval (Δt , ms) for the wristband was calculated as follows.

$$\Delta t = \frac{100}{1.1 f_{nat}} \quad (3)$$

The test sequence consisted of two walking conditions (Figure 2). First, participants completed a baseline walk without wearing any device. Second, they performed a walk under the cue condition, during which they wore a wristband and headphones that delivered a calibrated rhythmic–auditory stimulation (RAS) cue set at 110% of their baseline cadence. Immediately following the second walk, participants were asked to rate six statements using a five-point Likert scale, where 1 indicated “strongly disagree” and 5 indicated “strongly agree.”

The first three statements assessed perceptual comprehension:

- “I could clearly feel the wristband vibrations.”
- “I could clearly hear the rhythmic sound through the headphones.”
- “I understood the relationship between the rhythm and my walking.”

The remaining three statements evaluated behavioural effectiveness:

- “The rhythm helped me walk faster.”
- “My steps felt more stable with the device.”
- “I felt more confident about walking after using the device.”

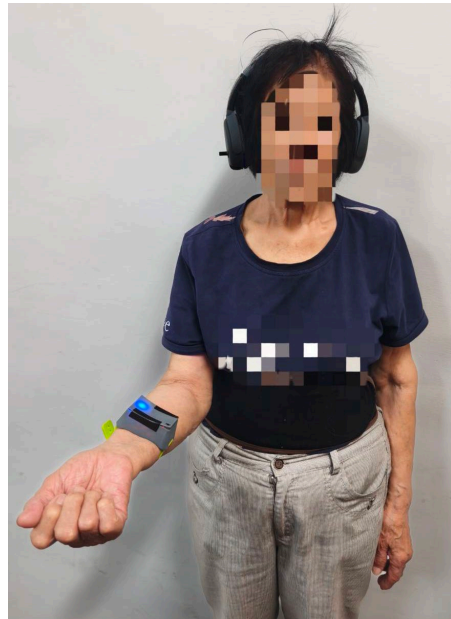


Figure 2. An older adult participant wearing the synchronous audio-tactile cueing system. The participant provided written informed consent for image capture and publication.

4. Result and Discussion

4.1. Paired-Sample Comparison of Walking Speed and Stride Length

A paired-sample *t*-test was performed to compare the same participants' gait performance with and without the cueing device, focusing on mean walking speed and mean stride length. Descriptive statistics indicated that wearing the device increased the mean walking speed from 0.956 ms^{-1} at baseline to 1.002 ms^{-1} , and a rate of 0.046 m s^{-1} . As summarised in Table 1, both walking speed and stride length changed in the expected direction, yet neither reached statistical significance (speed: $t(4) = 1.189$, $p = 0.300$; stride length: $t(4) = -1.569$, $p = 0.192$). With only five participants, the present data do not provide significant evidence that the device alters walking speed or stride length.

Table 1. Paired-sample *t*-test results and median changes.

Measure	<i>n</i>	Median (Pre-Intervention)	Median (Post-Intervention)	Mean Difference (Post-Intervention – Pre-Intervention)	Standard Deviation	Standard Error	95% Consistency Index	<i>t</i>
Average walking speed (m/s)	5	0.91	1.00	+0.046	0.0866	0.0387	[−0.061, +0.154]	1.189
Average step length (m)	5	0.54	0.55	−0.016	0.0234	0.0105	[−0.046, +0.013]	−1.569

The direction of change was uniform: every walker exhibited a slight speed increase while wearing the device ($+0.046 \text{ m s}^{-1}$, 5%), whereas stride length shifts were smaller and inconsistent (mean difference = -0.016 m , -2%). The associated effect size for speed is moderate (Cohen's $d = 0.53$). Given a sample of only five, the statistical power is low, so medium effects such as this are unlikely to reach conventional significance thresholds.

4.2. Behavioural Impact: Perceptual Comprehension Domain

Figure 3 summarises the post-trial Likert ratings for the three perceptual comprehension items (Q1–Q3). Median scores were high overall but showed a notable spread. Q2 (I could clearly hear the rhythmic sound) and Q3 (I understood the relation between the rhythm and my walking) both achieved a median of 5—the scale maximum—with inter-quartile ranges (IQRs) of 3.5–5 and 3–5, respectively, indicating strong consensus that

the auditory cue was clear and intuitively synchronised with the gait. By contrast, Q1 (I could clearly feel the wristband vibrations) yielded a median of 3 (IQR = 2.5–4), reflecting a neutral central tendency and greater dispersion. Several participants found the vibration salient, whereas others perceived it only weakly. The variability in Q1 suggests individual differences in tactile sensitivity or in the wrist-contact positioning of the ERM motor.

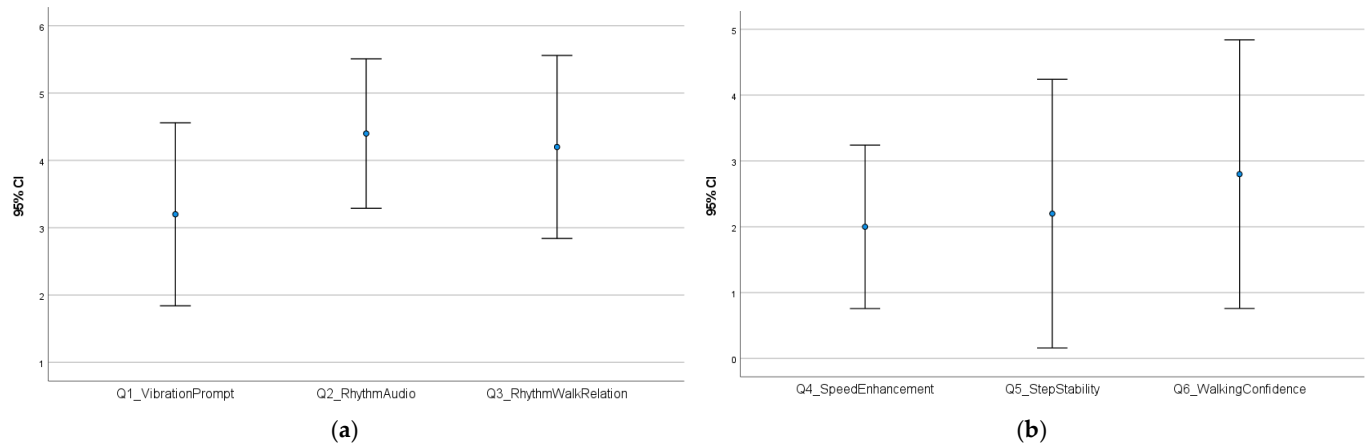


Figure 3. (a) Perceptual comprehension domain (Q1–Q3). (b) Behavioural effectiveness domain (Q4–Q6). Mean scores ($\pm 95\%$ CI) for questionnaire items ($n = 5$).

Medians for the three effectiveness items (Q4–Q6) fell below the neutral point, indicating that participants generally did not perceive a clear positive benefit from the device (Figure 3b).

- Q4 (the device helped me walk faster) and Q6 (the device made me more confident about walking) each showed a median of 2 with broad IQRs (1–3 and 1.5–4.5, respectively), suggesting mild disagreement or reservation.
- Q5 (the device made my steps more stable) scored even lower, with a median of 1 (IQR = 1–4), reflecting overall disagreement.

Across Q4–Q6, scores did not reach neutrality, implying that most participants did not feel the cueing system appreciably increase speed, improve gait stability, or heighten confidence. Score dispersion was substantial: IQRs of 2, 3, and 3 for Q4–Q6 and positively skewed distributions (skewness = 0.61 for Q5, 0.52 for Q6) indicate marked inter-individual variability; a few high ratings lifted the mean, but most responses clustered low. Although the small sample precludes firm conclusions, the consistent direction—speed gains without perceived subjective benefit—point to latent value in the device and opportunities for refinement (e.g., stronger or better-positioned haptic cues).

5. Discussion

Wearing the synchronous audio-tactile device increased mean gait speed by 0.046 m s^{-1} (5%), a non-significant change ($p = 0.300$) yet directionally consistent with the 11–19% RAS-induced gains reported for people with Parkinson’s disease [11]. This alignment suggests that cross-modal rhythmic cueing retains potential value for healthy older adults. Conversely, mean stride length decreased by 2% (-0.016 m), with mixed individual directions. Kurz et al. found that seniors often shorten strides to achieve faster cadence—especially when entraining to an external rhythm—indicating a possible compensatory strategy [24].

Regarding perception, the vibration salience item (Q1) yielded a neutral median (3/5). This echoes Gescheider et al.’s observation that tactile thresholds rise above $\sim 200 \text{ Hz}$ in ageing skin; if vibration strength falls below 0.5 g , many elders fail to detect it reliably [17]. Although our housing combines a rigid resin shell with a silicone strap, an overly thick

interface might dampen transmission; future designs should thin the contact layer or use elastic fillers to enhance vibration delivery.

For subjective benefit, all three effectiveness items (Q4–Q6) scored below neutrality, implying that most participants did not feel faster, steadier, or more confident. Heart and Kalderon showed that older adults often resist unfamiliar technology during first exposure because of cognitive load and habit disruption, particularly when the gadget is bulky or interaction modes are unfamiliar [25]. Therefore, even when signal-level synchrony is optimal, user acceptance and adaptation remain critical to perceived efficacy.

Finally, we employed only two consecutive walks without counterbalancing, leaving results vulnerable to learning and order effects. Bailey et al. recommend crossover designs or additional balanced trials when testing gait interventions in older cohorts [26]. It is still required to incorporate randomised crossover protocols and enlarge the sample to ≥ 28 participants to achieve 80 statistical power.

6. Conclusions

We developed and preliminarily validated a synchronous audio-tactile cueing system designed to provide real-time gait assistance for older adults in public transport environments. Although mean gait speed rose by 5%, the increase was not statistically significant owing to the small sample size; the slight (2%) reduction in stride length likewise warrants further investigation as a possible compensatory strategy. Nonetheless, the uniform speed-increase trend and high scores for perceptual comprehension demonstrate the system's feasibility and developmental potential.

1. Enhance vibration salience: Increase motor amplitude beyond 0.5 g and refine strap thickness and conformity to meet the elevated tactile thresholds reported for older adults [17].
2. Improve form factor and comfort: Reduce device bulk and simplify interaction elements to lower cognitive load and psychological resistance during first-time use, following design insights for older adopters [25].
3. Strengthen experimental validity: Introduce a control group, randomise trial order, and employ crossover or counter-balanced protocols to mitigate learning effects, as recommended for gait studies with seniors [26].
4. Disentangle modality-specific effects: Test four conditions—no cue, audio-only, vibration-only, and audio + tactile synchrony—to isolate the relative benefits of uni- and multimodal prompting. Future work should also explore varied cue tempi and longer-term usage, mirroring approaches that revealed substantial RAS benefits in clinical and longitudinal contexts [11].

While statistical significance was not achieved, the present work offers a theoretically grounded and practically viable multisensory cueing direction with clear avenues for enhancement and scaled evaluation.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data are not publicly available due to ethical restrictions and participant privacy. De-identified data may be made available from the corresponding author upon reasonable request and with appropriate approval.

Conflicts of Interest: The authors declare no conflict of interest.

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