Susceptibility to Periodic Vibrotactile Guidance of Human Cadence

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ABSTRACT

In this paper we introduce a new guidance method that employs periodic vibrotactile cues to help users walk at a desired speed. We also explore walker's *susceptibility* to periodic vibrotactile guidance (PVG): specifically, adjustments of their stride frequency in response to cues that are clearly perceived; and finally, how long users can maintain their stride frequency after the guidance cue stops. While wearing a vibrotactile display on one wrist, each participant was given five vibrotactile tempos, logarithmically spaced across the participant's walking frequency range. We compared realtime stride frequency with cue tempo under conditions that varied cue tempo and presence / absence. Our results suggest that most individuals (here, 13 of 15) can synchronize their cadence with a vibrotactile cue with 95% accuracy (mean error, all participants: -1.5%, $SD = 8.1$) for a guidance tempo within their physical ability. Once a tempo was matched, walkers could maintain it for at least 30 seconds after the cue was turned off, showing promise for intermittent guidance as a solution to stimulus adaptation and annoyance. This finding informs design of spatiotemporal guidance systems, by showing how the informationally narrow but nevertheless underused haptic channel may have utility in guiding pedestrians' speed, without a need to learn abstracted signals, and through a continuous control system.

Index Terms: H.5.2 [Information Interfaces And Presentation]: User Interfaces—Haptic I/O; H.1.2 [Models And Principles]: User/Machine Systems—Human Factors

1 INTRODUCTION

New technologies emerge daily that aim to use sensing and computation to assist in our daily activities: task and time management, navigation and location services are but a few. Many are framed as guidance tools: they can save us time or improve our performance in some task (like walking in an unknown neighborhood) by providing immediate information or by making a task (finding the nearest coffee shop) easy enough to be done in parallel with another.

However, this potential is often undermined by usability challenges, with one of the most crucial being sensory load. Whatever the communication channel, signals deployed at a conscious level are likely to be intrusive. Additionally, most such tools rely on vision and audition as their medium for user communication. By their nature they are used in multi-task scenarios, so perceptual competition is the norm; the result often overwhelms, and routinely jeopardizes safety. Meanwhile, the tactile modality is often suggested as an underutilized alternative, but has other potential drawbacks (its own sensory load, nonperceptibility, annoyance).

In this research, we examine the use of vibrotactile (VT) guidance cues to provide pedestrian cadence guidance, ultimately at a non-attentional level. While walkers are able to synchronize to auditory stimuli [6, 16], VT cues may be less attentionally demanding, and conflict less with situational awareness and/or other listening tasks. We have previously reported sensorially optimal locations on the human body for processing pedestrian guidance cues [13], and a validated algorithm that can measure realtime cadence well enough for interactive cadence guidance, with a commodity smartphone sensor [14]. Here, we demonstrate that given a periodic VT cue in a single-task scenario, walkers can adjust their step frequency to match it with minimal reported effort.

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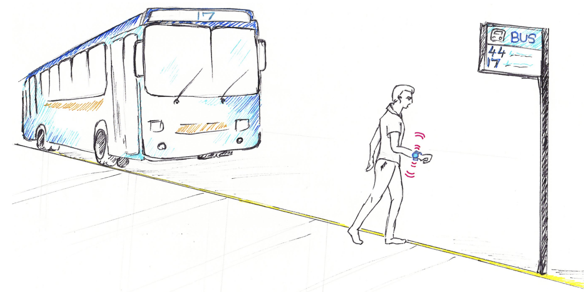

Figure 1: Periodic Vibrotactile Guidance regulates a walker's step frequency with subtle cues – to help him arrive at the bus stop at just the right time. Or, help a runner train at the right cadence, or a rehab patient exert the right effort.

2 APPROACH

Human walking is a repetitive movement whose rate is primarily characterized by stride length and frequency. Under normal circumstances, the walker (or runner) can control either to achieve a desired speed: when one parameter is constrained to increase or decrease, speed changes proportionally while the unconstrained parameter is relatively independent of this change [16].

We propose a simple way of guiding human cadence with VT cues: we map a desired walking frequency to the tempo of a *Periodic Vibrotactile Guidance* (PVG) cue, and ask the pedestrian to match walking tempo to it. This guidance can subsequently be incorporated into feedback control to maintain or adjust the walker's locomotion speed as desired or dictated by an application.

This means of communicating rate information fits well with known capabilities of the haptic channel, and could be helpful to pedestrians and athletes who need to efficiently manage the timing of repetitive movements (walking, running, rowing). Direct-mapped rather than abstract, *PVG* should require minimal learning, and have a lower steady-state impact on cognitive processing than symbolic cues [18, 24]. By freeing cognitive and attentional resources needed to attend to ones' surroundings, they may improve safety directly and indirectly. Their simplicity may allow them to be combined with other methods of VT communication, for example when the system conveys higher-level activity information.

From a control perspective, *PVG* operates on a continuous spectrum. Tempo and its inverse, the inter-cue interval, can be any positive real number. Continuous control affords many alternatives for control configuration and gain adjustment to achieve smooth, efficient regulation of cadence and speed. These include flexibility in judicious deployment of 'silence' breaks: long periods of VT stimuli should be avoided because too long or too many vibrations can become irritating to some users, and over-stimulation produces adaptation and loss of sensitivity [9]. For experimental control in the study reported here, we held cue rate constant within each trial. Deployment of closed-loop control remains for future work.

2.1 Contributions

Our quantitative contributions demonstrate empirically the potential effectiveness of *PVG*, with:

1. Data on the effect of tempo and repetition on walkers' ability to match stride to a VT cue, confirming a broad ability to do so given a comfortably realizable tempo; and

2. Evidence of walkers' ability to maintain cued frequency at least 30s after cue-off, important for avoiding cue adaptation.

This creates new opportunities for systems to help pedestrians control walking speed easily and accurately. We also share an experimental methodology with utility for future cadence-control development, and discuss implications for application design.

3 Related Work

3.1 Perceptual Overload and Safety

Vulnerabilities arising from our dependency on eyes and ears for interacting with consumer electronics (music players, GPS guidance tools, phones containing both) are well-cited. This reliance contributes to overload and inefficiency in visual and auditory perception [11, 17, 25], while the graphical and auditory interfaces themselves often fail when their target modalities are unavailable or inconvenient [27]. In other cases, in competing for required resources they undermine primary task performance [26]. Motor vehicle authorities increasingly acknowledge risks inherent in electronic device usage while driving, citing distracted driving due to texting or talking on the phone as directly responsible for upticks in collision statistics [21]. rendering them vulnerable to crossing streets more slowly while using a phone [10] and inattentional blindness [12]. But pedestrians interacting with their devices are also at risk of attentional lapses [12, 20], which become dangerous when crossing streets [10] and may be exacerbated by a false sense of security [19].

The two obvious approaches to reducing visual and auditory, and ideally cognitive, load are to (a) limit the secondary task (*e.g.*, by not using a guidance tool), which is less desirable to the user; or (b) replace audiovisual cues, and their conscious processing, with VT cues that require little effort to interpret [4]. Examples include vibrations on the left or right side of the torso as turn direction indicators [26], alarms to warn of safety issues such as an unduly slow street-crossing or oncoming traffic or cues that influence walking speed to make travel more efficient and retain mental capacity for other situated tasks.

3.2 Spatial Vibrotactile Guidance

While spatial guidance systems typically provide event-driven cues rather than continuous control, their findings are informative as to cue interpretability, attentional load and evaluation.

One class uses direct-mapping of vibratory stimulus to direction, *e.g.*, Ertan et al.'s system to guide blind users in unfamiliar indoors areas with a 4-by-4 vest-embedded array which rendered a stop signal or cardinal direction [7]; or Bosman et al.'s use of tactors on both wrists to augment space perception in unimpaired wearers [4]. Tsukada & Yasumura achieved 8-direction guidance outdoors with a tactor belt [26], and Koslover et al. compared VT and skin-stretch signals with visual and auditory cues [15]. All of these systems have found users able to interpret direct-mapped spatial guidance with high accuracy.

In a different shared-display approach, Rukzio et al. coordinated a palmar VT phone display with a public 8-light display. The lights toggled on/off in a rotation, and the phone vibrated when the direction on the public display matched the user's route direction [22]. Van Erp et al. investigated more abstracted VT navigation cues, displayed around the waist using four distance-coding schemes. Two schemes related distance and tempo of stepping rhythm (faster tempo indicated shorter distance) and the others communicated departure, arrival, and intermediary phase by three distinct tempos of one rhythm [27]. Their VT system was a successful direction indicator but the distance indicators for walking needed improvement.

We envision a future system in which speed-control and direction cues are combined, with sufficient care taken to disambiguate them.

3.3 Guidance of Locomotion

Study of guiding *how fast* to walk is less common, yet pace guidance has obvious utility for mobile, GPS-enabled navigation apps. These currently tend to assume an average walking speed applied to everyone to predict time-of-arrival and suggestions for departure time. In reality, people walk at different speeds. When arrival time is important (catching a bus or train, going to a meeting), walking speed may be as important as direction (Figure 1).

Walking is a repetitive task with a variable speed controlled as: walking speed = stride-frequency $\times$ stride-length [16]. Individuals walk at a preferred frequency, which minimizes energy expenditure and depends on the person's body. A walker may adjust both stride frequency and length to control walking speed [6]. Laurent & Pailhous measured walker response to both metronomic cues and constraints on step length, and found that good pace control can be accomplished by constraining and controlling just one of the two parameters, due to their relative independence [16]. Danion et al. successfully used auditory cues to impose stride frequency and visual feedback to impose stride length [6]. Bonnard & Pailhous went a step further and imposed the relationship between stride frequency and length by visual and auditory cues at the same time [3]. While their results show humans' ability to synchronize stride frequency with auditory cues and match stride length with visual cues they do not guarantee the same results for haptic cues.

Haptic guidance of locomotion has received a lot of attention from the health and sports community. Force-feedback has particularly been used for gait rehabilitation. Veneman et al. designed and evaluated an exoskeleton robot for gait rehabilitation that uses force-feedback to guide its users [28]. Using programmable footplates is another approach that is explored by Schmidt et al. [23].

Ferber et al. used haptic cues delivered through foot pedals to maintain target intensity level on a stair-climber exercise machine while doing a mental task [8]. Two methods embodied velocity-control ("on" when outside a target zone), and another gave metronomic VT cues at 2x the desired stepping rate. Results showed issues with perceptibility and signal understandability, and reported increases in average parameters (velocity, power and variance) rather than performance in step-level tempo matching. However, user reactions are relevant here: likeability and comprehensibility did not correspond to increased effort, and the tempo-matching scheme was deemed hard to follow, and produced the greatest interference with a simultaneous task of any method tested.

In our own design we emphasized perceptibility, comprehensibility and low cognitive processing effort. Feet are not ideal for mobile cuing (sensitivity is low in the feet, and degrades with movement body-wide [13]), so we proceeded with wrist-worn tactors.

3.4 Controlling Step Rate

In the present work, we explore the use of continuous control on stepping frequency. The obvious alternative is discrete: a *bang-bang* (on-off) controller [2] that gives rate-control cues ("walk faster / slower") when speed goes outside a specified band. This approach is simple to implement, and can be attempted with sensor sources subject to noise and dropouts, such as GPS.

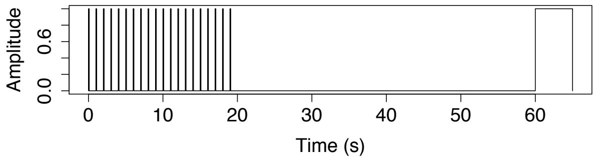

Figure 2: VT stimulus vs. time during a trial with a 1Hz guidance signal: 20s of cue with 1s interval, 40s of silence, a 5s stop signal.

However, when the control action is not well matched with system responsiveness (here, the walker's variable response to the cue; or a runner's heart-rate in reaction to a change in pace on a hilly route), the result oscillates between thresholds. The resulting discomfort can be experienced with many currently available heart-rate and GPS-based running speed regulation products. Oscillation is best mitigated by widening the control band, which undermines precision. Guidance into multiple bands of desired velocity (for greater precision) does not improve stability, and can make the system harder to learn or conceptually understand.

Continuous control does need reliable data with accuracy, refresh and phase delays commensurate to control bandwidth requirements. Our implementation uses our RRACE algorithm, which derives realtime step frequency estimates from a commodity smartphone accelerometer, with a phase delay (within 2 steps) [14].

4 Experiment

To ascertain the feasibility of low-level VT guidance of stride frequency, we needed to measure how well humans can synchronize their walking frequency with *PVG*, and how well they can maintain their walking frequency once the cue stops.

We hypothesized that *H1*: most people can follow the tempo of *PVG* with an accuracy $>=$ 90%; *H2*: tempos near an individual's natural walking frequency will be easier to follow (exhibiting lower cue divergence than extreme tempos); *H3*: error will be negative (walking cadence $<$ cue) for tempos that are faster than one's typical cadence and positive (walking cadence $>$ cue) for tempos that are slower than one's typical cadence; and *H4*: magnitude of error will increase when the cue is turned off.

4.1 Apparatus and Context

Our setup consisted of a wrist-worn VT display (Section 4.1), cadence sensing (four Android smartphones running a custom step-detection algorithm – Section 4.1), and a control laptop (Section 4.1). The laptop managed the procedures (Section 4.4) and sent commands to the VT display wirelessly while the phones constantly measured walking frequency.

To reduce measurement noise due to cornering, we collected data on a straight, wide, level walkway in a quiete residential area within a university campus. 350 meters accommodated one minute of walking by the fastest-moving pilot participants.

Client Side: VT Cues

To deliver tactile cues to the participant's wrist, we used Tam et al.'s *Haptic Notifier* [24] (Figure 3). Relevant parts of this system are (i) an *Arduino Fio* microcontroller [1] with built-in *XBee socket*, (ii) *XBee series 2 radio* to communicate with the experimenter's laptop, (iii) three synchronized eccentric-mass tactors with the vibration frequency of $\sim 190Hz$ [13], and (iv) a lithium polymer battery.

To avoid communication delay between laptop and Arduino wrist controller, the Arduino logged the start / end of each trial and the time when haptic cues were turned off during the trial, according to the its clock. This data was communicated to the laptop (server side) at the end of each trial. *Arduino* timestamps were converted to computer time in post-processing (Section 4.4).

We displayed two types of vibrations, all delivered at $\sim 190Hz$: the guidance cue (periodic vibrations, each 100ms and at an interval

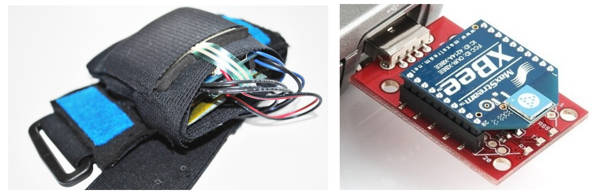

Figure 3: The *Haptic Notifier* (left) and the *Xbee* USB radio (right).

defined by the guidance tempo) and the stop signal (a single 5s vibration at the end of a trial), as illustrated in Figure 2.

Server Side: Experimenter's Laptop. The experimenter ran the main control code on a laptop that acted as the server. It: (a) measured participant's fast and slow cadences and derived the mid levels from those through experimenter's key presses which revealed start, end, and number of strides; (b) logged synchronization times from the wrist-worn Arduino, and the Android phones; (c) read the trial order from a pre-generated table; (d) ran the study step-by-step and sent commands such as *"start the trial"* to the Arduino; (e) requested, received, and recorded Arduino logs at the end of each trial.

Cadence Measurement: RRACE. For experiment redundancy, we used four Android phones equipped with *RRACE* (Robust Realtime Algorithm for Cadence Estimation) to measure users' walking frequency [14]. *RRACE* measures stride frequency via frequency-domain analysis of accelerometer signals available in common smartphones; in principle one is adequate. We placed two phones in participants' front pockets and the other two in a small backpack: while *RRACE* is especially robust to orientation and body placement, here we used locations previously shown to provide the highest accuracy. These phones logged the 3-D acceleration of user's thighs and torso and measured and recorded user's cadence every 200 milliseconds. Duplication provided robustness to issues such as the Android operating system terminating *RRACE* due to perceived CPU over-usage, or inadvertent button presses. We used the median of all active cadence estimations (with refusal of outlier measurements) to improve measurement accuracy.

4.2 Experiment Design

Our experiment had two factors: guidance tempo (to assess response to divergence from natural step rate), and repetition (learning). Each trial consisted of $20s$ with VTG and $40s$ without. We chose these times according to the results of our pilot study which showed that participants need about 5-10s to synchronize their stride frequency with the cue and can maintain their cadence for about 25s. Therefore, we made sure the cue-on part of the trial was longer than 10s, and the cue-off part longer than 25s. The final timing (20s of VT cue and 40s of silence) was determined by a fatigue-driven need to run the full study in under an hour.

An experiment session contained 16 regular trials (5 guidance rates $\times$ 3 repetitions + 1 dummy). Trials were put into out-return pairs for practical reasons; because 15 is an odd number, we added a dummy trial at the end (whose data was not used) to make sure the participant finished the experiment near the starting point.

Factor 1 – Guidance Rate: We coordinated five guidance rates to each individual's own fastest and slowest walking frequencies (Section 4.3).

Factor 2 – Repetition: To ascertain learning (performance improvement as a result of exposure) we presented every guidance rate three times, arranged in three blocks, each consisting of the five rates in random order.

4.3 Computing Experimental Guidance Rates

In an initial calibration step, we measured participant i's slowest and fastest cadences using RRACE, then matched that participant's two extreme custom guidance rates (cue tempos) $g_i[1], g_i[5]$ to his/her slowest and fastest demonstrated cadences, respectively. We then distributed the middle rates evenly on a logarithmical scale; *i.e.*, the ratio of each two consecutive tempos ($\frac{g_i[n+1]}{g_i[n]}$) is constant. Reference frequency $f_r(t)$ was then set to one of $g_i[1..5]$.

4.4 Procedures

After introduction and consent, we asked the participant to walk at his/her slowest and fastest comfortable walking speeds. For each, we measured the time required for twenty strides (t_{20}). Our experiment program computed the inter-step interval ($\tau = t_{20} / 20$) and thence walking frequency ($f = 1 / \tau$), to define this participant's $g[1]$ and $g[5]$ (slowest and fastest stride frequencies). We sent the tempos to the wrist-worn Arduino client, and synchronized the phones and Arduino clocks with the control laptop.

We next explained the task, the wrist display and the experiment format, then carried out a representative practice trial. Participants were explicitly instructed to try to (a) walk at the tempo of the cue, and (b) continue to walk at that same cadence after the cue stopped. This was repeated until participant was in full understanding of the protocol, and then the 15 actual trials (plus the dummy trial) were run. A session took about 45 minutes and we thanked each participant with 10 dollars.

Pairing of Trials: Participants walked away from the experimenter on a straight walkway for odd-numbered trials, stopped when they felt the sustained VT stop signal, then turned around. When they felt the new guidance cue they began walking again, proceeding until they again felt the stop signal (in some cases passing the experimenter). To conclude close to the experimenter, the experiment ended with a dummy trial number 16 with a random cue frequency; its data was not used.

4.5 Metrics

We described users' stride frequency with *cadence* and *cadence ratio*. Cadence is the walker's stride frequency, whereas cadence ratio is cadence divided by *middle cadence*, defined as the geometric mean of that walker's fastest ($g_i[5]$) and slowest ($g_i[1]$) stride frequencies, which was the guidance tempo $g_i[3]$ in this study (Eq. 1). Cadence ratio was used to *normalize* participants' cadences to their own middle cadence, to minimize offset and scale deviation due to individual variability in natural walking frequency and range.

$$\bar{f}_i(t) = \frac{f_i(t)}{g_i[3]} \quad (1)$$

We then measured departure from the guidance cue with *cadence error percent*, defined as the difference between participant i's cadence (f_i) and the tempo of the jth guidance signal (the tempo of the guidance signal at time t), normalized to the latter and presented in percentage points:

$$e_i(t) = \frac{f_i(t) - g_i[j(t)]}{g_i[j(t)]} \times 100\% \quad (2)$$

4.6 Analysis Technique

Cadence was measured every 200 milliseconds on all of the phones, each datapoint timestamped with the phone clock, and analyzed in (non-overlapping) two-second windows. We converted the timestamps of all the data from the phones to the computer time

We grouped the cadence measurements from all the phones at each window, removed outliers and used their median for subsequent analysis, and removed the first 4s where the participant is

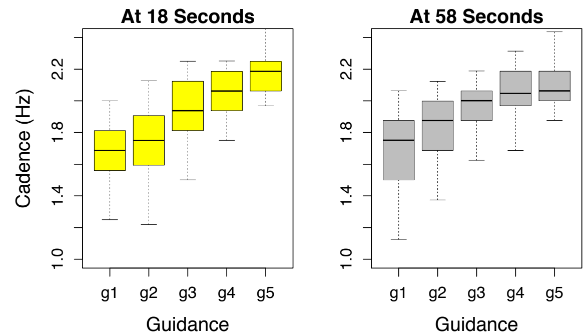

Figure 4: Cadence by guidance rate (average of all participants and all repetitions), when cue is on (left/yellow, at 18s); and off (right/gray, at 58s). Despite inter-individual variability, the cue-linked cadence increase is clear in both cases. Guidance rates are individual-specific and thus cannot be shown.

transitioning from a stationary position to natural walking. One datapoint/2s in 56s of usable trial yielded 28 datapoints/ trial.

We separated data into VT cues on/off; then used Linear Mixed Effect Model (LMEM) for statistical analysis of each region, with post-hoc pairwise comparisons with Bonferroni adjustment for multiple comparisons. To assess the effect of cue-off over time, we compared datapoints at different times in the cue-off region.

4.7 Results

4.7.1 Data Summary

15 participants (9 male), aged 19-31 years (mean=24.9, SD=3.6), 152-196cm tall (mean=169.7, SD=11.2), and weighing 39-90kg (mean=63.4, SD=14.2) took part. 4, 2 and 9 participants respectively had none,$<$5 years, and $>$5 years of prior musical training.

Stride frequency increases with cue tempo ($g_1 ... g_5$) even 38 seconds after turning off the cue (at $t = 58s$) (Figure 4. The fastest VT cue shows less success at making users walk faster (g_5 and g_4 are too close in Figures 4 and 5).

Cadence error percent demonstrates how well people are following the VT cues: positive (or negative) error percent means the participant's cadence is faster (or slower) than the cue tempo. Figure 6 shows that when the cue is on, users closely follow the cue tempo (average error $< 4\%$) except for the fastest (average error -7.7%). When we turn off the VT cue, step rate diverges more from cue tempo and (unsurprisingly) tends towards the middle stride rate.

Individual post-cue divergence is best seen by viewing data from a single participant (second repetition) as a set of time series. Figure 7 is scatter plots with a smooth curve fitted by the *LOESS* method [5]; P4 was chosen randomly from 12 of the 15 participants showing a similar response pattern. Consistently with the aggregate views, 20 seconds into the trial when the cue stops, cadence error starts to grow, although for some tempos, it quickly plateaus. For slower guidance cues (g_1 and g_2) cadence error is generally positive, and negative for faster cues (g_4 and g_5).

4.7.2 Statistical Analysis

We expected to see a correlation between music background and cadence error but we found no hint of a correlation.

We separately analyzed guidance and non-guidance periods to investigate whether cadence error percent is significantly different (a) under different guidance conditions when the cue is on and off, (b) at different points in time since the start of the trial when the cue is on, and (c) at different points in time after the cue is stopped.

VT Cue On: The statistical analysis of LMEM of the data showed that for cue-on, guidance rate and time from trial start have a significant effect on cadence error percent ($p < 0.05$). Pairwise comparisons show that each two of the guidance tempos differ significantly from each other. These factors also interact with each other

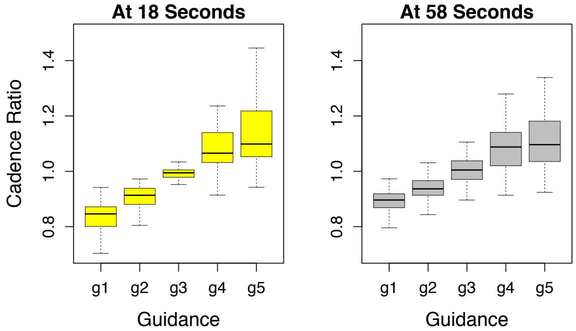

Figure 5: Cadence ratio by guidance rate, when cue is on (left, at 18s) and off (right, at 58s). Cadences normalized to the participant's middle tempo), in contrast to non-normalized cadences of Figure 4, show less individual variance and the difference between the 5 levels is clearer.

($p < 0.05$), with a simple explanation: under slower guidance tempos, walkers start with a positive error that shrinks as the cue continues, and under faster tempos participants start with a negative error that then shrinks.

In the temporal response, the first measurement after the 4s transition period removed for this analysis (Section 4.6) was significantly different from the rest of the measurements during the cue-on region, but there is no significant differences between subsequent 4s windows in the guidance period. This indicates that participants aligned their walking rate with the cue tempo early on, attained stability by 4s, then maintained it thereafter.

VT Cue Off: Similarly to cue-on, when the guidance cue is off, guidance rate and time into trial (or since cue-off) significantly impact cadence error percent ($p < 0.05$). They also interact with each other in the cue-off region, with an explanation similar to above. Pairwise comparisons show that each two of the guidance tempos are significantly different from each other.

Temporally, two of the first measurements after stopping the cue were significantly different from two other times near the end. This means that the error increases in amount when the cue stops but the change in error is so slow that that there is little difference except for points sufficiently far apart in time.

4.8 Discussion

Our experimental results confirm that periodic VT cues can easily affect pedestrian's walking frequency when consciously followed (less than 5% divergence in four out of five cue rates and less than

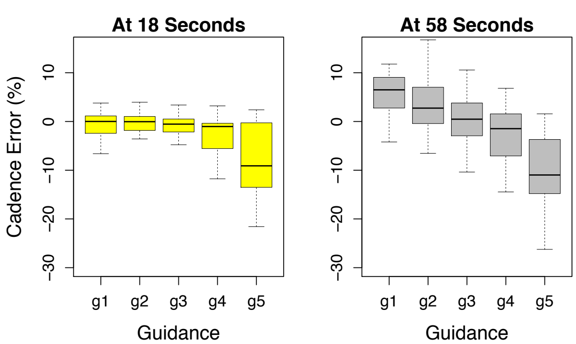

Figure 6: Cadence error percent by guidance rate, when cue is on (left, at 18s) and off (right, at 58 seconds). At the end of the cue-on phase (left), the smallest error is seen in the lower three levels, g_1, g_2, and g_3 (means: -0.5%,0.4%,-0.6% respectively) and the largest with g_5 (-7.7%). After the cue stops, absolute value of error grows faster for g_1 and g_2 (they increase 5.6 and 3.0 respectively) than all other rates.

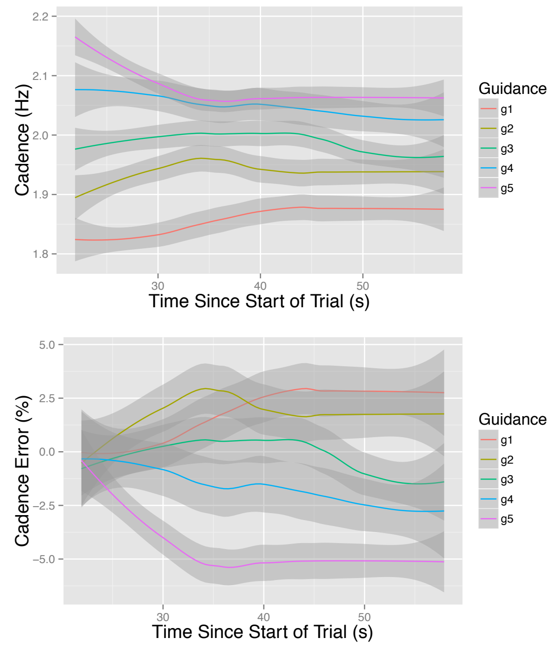

Figure 7: Scatter plot of P4's *cadence* (top) and *cadence error percent* (bottom) during trials 6-10 by guidance rate with smooth curve fitted by the *LOESS* method. Bands represent the confidence interval of the *LOESS* method. From guidance cue off (20s) to trial end (60s), cadence converges toward the walker's typical cadence and cadence error tends to grow (further from zero) at least initially, then stabilizes in some cases.

10% during the fastest) (*H1* accepted). Our results showed that for tempos distributed across an individual's full walking range, divergence from cued tempos near and lower than individual's natural walking frequency is lower (*H2* rejected). Error increases when the cue is turned off (*H4* accepted), but this increase happened at a subtle rate within the 40s window we observed.

When a user tries to synchronize steps with a cue, the direction of error and its upper bound is generally predictable: positive when the cue is faster than walker's typical cadence and negative when slower (*H3* accepted). A benefit of this predictability is the possibility of mitigating overall error in a closed-loop control system by anticipating the worst case scenario and adjusting the cue to compensate, i.e. by applying a model of the walker's response to this low-level stimuli.

5 Conclusions and Future Work

In this paper we proposed *PVG*, Periodic Vibrotactile Guidance, for regulating pedestrian stride frequency. An exemplar application is guiding a commuter toward the closest bus stop at the optimal walking speed, not sweating when there is time for a stroll nor missing the bus when a slightly faster pace would be sufficient. Other applications for *PVG* include athletic training (a long-distance or sprint runner or rower, seeking to maintain a step-level pace) and rehabilitation (displaying desired step frequency to a patient instructed to achieve a given effort or mobility level, and no more).

Our results confirm that taction and in particular stimuli applied through a wearable wrist display, are a viable choice for such applications. It is not used in larger task of locomotion, and does not compete for perceptual or motor resources that other tasks (listening, reading, even texting on a mobile device) might; simple to learn, it is likely to be cognitively lightweight as well.

Whether audible or tactile, periodic guidance has a potential for more stable, comfortable cadence regulation than the common alternative, bang-bang velocity control, although this premise remains to be tested. Specifically, its continuity allows for deployment in close-loop control systems (most simply a proportional-integral-derivative (PID) controller) that can further improve user performance by adjusting the cue based on current state, previous error and future predictions, with gains adjusted to the user's needs and physiological responsiveness. An interesting next step will be to explore the control parameter customization needed for different task scenarios and individual differences.

Our experiment tested individuals' ability to match stride frequency with a VT cue displayed to the wrist. Most (13/15) could synchronize at 95% accuracy across their full range of walking speed, with a 5-10% lag behind cues faster than their natural cadence, and 5% lead ahead for slower cues, without significant training. In day-to-day applications such as pedestrian guidance this error ratio will be negligible relative to other factors: a 5% error for a 15 minute walk is equal to 45 seconds, and is predictable enough for a planning algorithm to compensate for. In applications that require more accuracy such as training athletes, users' focus and effort could improve accuracy.

We saw walkers maintain their stride frequency within a manageable bound after cue-off; divergence was slow enough to contemplate use of (at least) 30s 'silence' breaks between cued periods, important for avoiding irritation and adaptation. The length of breaks can be further optimized by a closed-loop control algorithm.

Future Work

As we proceed stepwise to a fully viable control approach, the most immediate next step after verifying conscious cue-matching ability is to examine non-conscious step-matching to VT cues. This is an essential component of a viable control approach for users unlikely or unable to fully concentrate on step rate for any length of time.

Set up as a dual-task scenario, important cases to consider will be distracting auditory, visual and cognitive tasks with qualities similar to those that we do while walking and exercising (listening to music or podcasts, talking on the phone, navigating a map, or perhaps even regarding our surroundings). Workload imposed by the *PVG* system on any of these tasks, and of these tasks on step-matching performance, are of keen interest.

Finally, we anticipate that using *PVG* in a simple closed-loop format will be key to its applicability. Many variables remain to be investigated on this topic: *e.g.*, whether modifying vibration intensity in proportion to target tempo divergence will improve performance, and the many possible means of incorporating silence periods to mitigate adaptation and improve acceptability.

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