GaitWear: A Smartwatch Application for In-the-Wild Gait Normalization Based on a Virtual Field Study Assessing the Effects of Visual and Haptic Cueing

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ABSTRACT
We explore the use of Virtual Reality as a way to simulate field studies via what is known as Virtual Field Studies. This is particularly relevant when inviting participants to the lab is not possible, as it can be used to simulate locomotion in crowded streets from the safety of the lab. We rely on this to assess the effects of four different cues in normalizing gait performance in a simulated environment: two baselines from literature (visual and haptic) that have been traditionally explored in the context of a controlled lab environment, and two novel haptic cues that combine temporal and spatial feedback. We compare these in a holistic manner for the first time, capturing not only gait and gaze performance, but usability, perceived workload, and participant preference. Our haptic baseline performed according to the results described in literature, and together with participants' gaze behavior and sense of embodiment we start to validate Virtual Field Studies in this domain. We further report that the haptic baseline was the preferred cue by participants, and led to an overall better performance. We conclude with our implementation of GaitWear, a smart watch application that produces this haptic baseline on the fly.

KEYWORDS
Virtual field study; virtual reality; gait normalization; haptic feedback; eye-tracking; wearable computing

1. Introduction

Conducting user studies can sometimes be challenging or even not possible at all. Our work follows on a a recent trend that looks at Virtual Reality (VR) as a way to simulate such studies via what is known as Virtual Field Studies [48,83]. These present several advantages over field studies in the real world: not only are they fully controllable and repeatable, but can be performed in isolation without worrying about participants getting too close to other pedestrians while walking (or changing their behavior to maintain a safe distance). This can be particularly relevant in times when conducting face to face studies comes with risks to the participant and the experimenter. For example, the COVID-19 pandemic has forced us to re-think our research

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methods, particularly when they involve the evaluation of prototypes out in-the-wild (such as in crowded streets or during lockdown). Further, and outside the context of the pandemic, researchers would not need to worry about participants being distracted by the prototypes being tested while, e.g., crossing the street; and can even produce such events to systematically assess the impact of those distractions.

Taken together, these properties make for a compelling use of Virtual Field Studies when assessing the effect of different prototypes on gait disorders – the study of these prototypes have been traditionally limited by long-established laboratory setups where the goal is to systematically explore various study parameters and not understanding the holistic impact of relying on these prototypes during everyday life outside the lab. We are particularly interested in exploring the use of Virtual Field Studies to tackle these disorders as they contribute greatly to a decrease in quality of life and increased mortality, and are common and often devastating companions of the ageing process [13]. Gait disorders increase from around 10% between the ages of 60 and 69 years, to more than 60% in those over 80 years of age [47]. Age is not the only source of these impairments, as strokes, Parkinson's disease, myelopathy, or sensory ataxia are some of the most known and studied neurological conditions with repercussions on patients' gait [63].

Our work was primary motivated by Parkinson's disease, the second most common neurodegenerative disorder that affects over 10 million people all over the world [67]. As the disease progresses, it affects patients' ability to walk: their gait pattern becomes characterized by a shortened gait stride, their walking speed decreases, their gait variance increases, and they can be affected by what is known as festinating gait – a sudden and often unexpected sensation of being stuck to the floor, particularly during gait initiation or turning [29]. As there is no cure or treatment that completely addresses the effect of Parkinson's disease on gait, these symptoms can be minimized with lifestyle changes and physiotherapy. Another approach, and the focus of our work, is what is known as *cueing.*

Cueing consists of sensory spatial and temporal stimuli that have been shown to minimize the effect of Parkinson's disease in a person's gait [8,30,51,61,78,80]. These can be delivered in a variety of manners, including visual, auditory, or as haptic cues. Further, as wearable devices such as Augmented Reality (AR) glasses and smart watches become more ubiquitous, cues such as floor-level visual stripes or haptic patterns can be easily produced out in-the-wild for the first time. On the other hand, the effect of these cues has been mainly observed in the controlled environment of the lab, and has focused on assessing participant performance (i.e., gait normalization – well spaced steps taken with an appropriate cadence). As such, very little information exists on the usability, preference, or visual and mental demand of these cues; particularly in real-world situations where a person is subjected to other external stimuli while engaging in everyday tasks such as way-finding or simply assessing if it is safe to cross the road. Attending to these competing stimuli has been shown to be particularly problematic for people with Parkinson's disease [6,56,74]. As such, our goals are:

(1) Contribute to existing work on haptic cueing via two new haptic stimuli.
(2) Characterize the effects of visual and haptic cueing in users' gait in a realistic scenario where other stimuli compete for their attention.
(3) Explore the feasibility of a Virtual Field Study to reproduce the realistic locomotion scenario described above.
(4) Design and develop a usable smartwatch application that produces haptic cueing out in-the-wild.

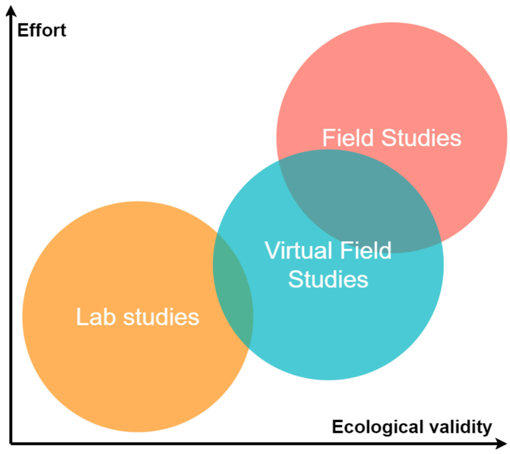

Figure 1. Virtual Field Studies as described by Mäkelä et al. [48], sitting between lab (low effort) and field studies (ecologically valid).

In sum, the contributions of this article can be summed up as follows:

(1) We develop a Virtual Field Study for assessing the effect of various stimuli on healthy participants' gait. This simulates a street environment with various competing stimuli that cannot be easily replicated in purely lab settings. Examples of said stimuli include other pedestrians, crossing lights, incoming cars, etc.
(2) We present the concept and implementation of two novel haptic stimuli that combine the temporal properties of standard haptic feedback (i.e., rhythm) with the spatial properties of auditory cues (i.e., left and right steps). We focus particularly on haptic stimuli as these (i) are easier to produce out in-the-wild when compared to visual cues, which would require some form of head-mounted display (HMD); and (ii) are potentially less distracting and mentally demanding when compared to visual or auditory cues in a real-world environment [71].
(3) We use our Virtual Field Study to compare our two novel haptic stimuli with state-of-the-art visual and haptic baselines. We compare these using not only standard performance metrics such as cadence, step length or velocity; but also usability (including the System Usability Scale [14]), subjective workload using the NASA TLX [28], preference and rationale, and participant gaze hits and dwell times on a variety of competing stimuli in our simulated street environment.
(4) Based on these results we develop GaitWear, an open source smart watch application that produces adjustable haptic stimuli aimed at users that can benefit from minimally distracting gait normalization support when out-in-the-wild.
(5) Finally, we provide several insights on Virtual Field Studies in the context of our research and discuss necessary future work. We base these on our own observations, participant feedback and presence questionnaire, and by comparing our results to those from pure lab studies in the state-of-the-art. With this, we aim to expand the work on this novel VR methodology as a complementary research tool during the pandemic.

2. Related Work

In this section we provide an overview of the state-of-the-art on Virtual Field Studies, gait disorders (particularly due to Parkison's disease), and several cues that have been shown some success in gait normalization (and the methodology behind this research).

2.1. *Virtual Field Studies*

The idea of using VR as a methodological tool for experimental studies was first explored outside Human-Computer Interaction. Blascovich et al. [12] presented a review of research within psychology that employed immersive virtual reality and argued that these types of studies have a positive impact on the realism-experimental control tradeoff, the representativeness of study samples, and replication. Fiore et al. [22] proposed applying the same concept to environmental policy experiments and found such VR studies result in valid responses.

While these types of studies are now well established for real world lab studies, the improved sensing and immersiveness of today's virtual reality systems motivated using VR to simulate field studies. Mäkelä et al. [48] describe this as Virtual Field Studies (see Figure 1), which they sit between traditional lab and field studies. It is close to the former as a controllable and relatively low effort setup, and to the latter in terms of ecological validity. While they demonstrated the validity of this novel methodology in the study of audience behavior and the effectiveness of public displays, various other examples exist.

Voit et al. [83] demonstrated that studies conducted in VR and in-situ produced similar insights when evaluating smart devices (e.g., a plant pot, a cup). Similarly, Moussaïd et al. [58] demonstrated accurate crowd behaviors in a high-stress evacuation scenario when conducting this experiment in VR. Others have evaluated the intrusiveness of an advertising app using a virtual supermarket [34], and have used virtual assistance to evaluate pervasive applications [10]. Recent work by Mathis et al. [52] validated the use of VR setups for evaluating user-centered aspects of security systems.

Closer to our goal of simulated locomotion scenarios, Schrom-Feiertag et al. [69] demonstrated that participants in real and virtual train stations exhibited similar way-finding, decision making and attention behaviors. Deb et al. [19] used VR to simulate a pedestrian crossing and observed, e.g., similar walking speeds to real world norms. Likewise, Agethen et al. [1] studied how immersion in a virtual environment affected participants' locomotion, and concluded that these types of simulations could be used to reliably analyze human locomotion when compared to real world performance. In another work, Janeh et al. [36] studied the effects of different cognitive tasks on velocity while walking for a long distance in VR compared to the real world, and found that velocity is decreased in VR. While this contradicted previous work that showed that long interactions in VR lead to reduced differences in gait [50,81], Janeh et al. attributed the difference due to the limitations of VR technologies at the time.

Following these positive results and continuous improvements in VR sensors and immersion, we aim to expand on this body of knowledge by using a Virtual Field Study to analyze various systems for gait normalization in the context of (simulated) in-the-wild locomotion. This will allow us to ensure the health and physical safety of our participants, while at the same allowing us to develop a richer understanding of the effects of these systems in real life scenarios.

2.2. Gait Disorders

Walking is assumed to be a simple, innate ability that we manage to execute seemingly effortlessly. However, walking is an extremely complex task that engages the whole nervous system and is particularly susceptible to a number of neurological disorders [21]. These disorders do not only affect a person's gait, but also contribute to an increased risk of falling [13] and in turn increased mortality [9]. People that suffer from these disorders tend to be afraid of falling, leading to decreased mobility and independence, and ultimately a decrease in their quality of life.

Examples of neurological disorders that tend to affect a person's gait include strokes, Parkinson's disease, myelopathy and sensory ataxia [63]. These tend to produce different effects on gait, and as such, we motivate the gait normalization approaches we explore later on the effects of Parkinson's' disease. This is considered the second most widespread neurodegenerative disorder after Alzheimer's disease, affecting over 10 million people worldwide [62].

The approach to gait normalization we focus on this work looks at a popular approach to improve a person's gait and balance: cueing.

2.3. Gait Normalization via Cueing

Cueing is defined as the provision of sensory stimuli to positively affect a person's gait, and can be categorized as *spatial* or *temporal* [8,33,51,54,57,78]. The former tends to rely on *visual* stimuli to inform a person of where an action should take place (e.g., where to place a step). The latter tends to provide temporal information via *audio* or *haptic* feedback to help a person time their actions (e.g., when to take a step). Previous work by Janeh et al. [35] explored ways to improve gait symmetry by equalizing step length through VR-based gait manipulation. Their VR manipulation tasks significantly increased step width and swing time variability for both sides of the body.

2.3.1. Visual Cues

The use of visual cues to facilitate the locomotion of people with Parkinson's disease has been a popular research topic since its first reference in 1942 [8,51,57,78,86]. These tend to explore the use of bright colored lines perpendicular to the direction of movement [38,76], and report improvements in participants' stride length and step length [57,78] and overall cadence (fewer steps per minute as opposed to festinating gait) [78].

Mixed Reality have also been used successfully in this domain. VR has been used primarily in the context of physiotherapy [15,26,45,46], exploring either traditional cues using (now simulated) colored lines or more interactive forms of visual feedback. E.g., Gómez-Jordana et al. [26] used animated footsteps that provided both spatial (where to place the next step) and temporal information (when to place the next step), which positively affected most gait parameters. Others have also observed positive carryover effects that lasted up to two months when participants repeated these locomotion exercises over several sessions (>12) [45,55]. Unlike previous work, VR allows visual cues to be placed anywhere with minimal setup and are easy to adapt to each participant (e.g., distance between lines/steps), or even simulate entire visual environments [11]. On the other hand, for participants to benefit from these carryover effects outside the lab various sessions are needed, which can be time consuming and costly.

AR has also been explored in this domain, particularly in the study of the effects of 3D visual cues such as staircases [39] and 3D bars [37]. These were not particularly successful at improving participants' gait parameters such as stride length or cadence, and the authors argue this is due to limitations inherent to the AR HMDs used: they were bulky and uncomfortable and presented a limited field-of-view (FoV). The latter forced participants to look down in order to engage with the cues, leading to neck and trunk flexion [85]. While Espay et al. [20] improved on some of these gait parameters such as stride length by allowing participants to familiarize themselves with the AR system for two weeks prior to the experiment, these hardware challenges can explain why the use AR in this domain is still limited to lab experiments and not field studies.

For a deeper understanding of the mechanisms underlying the gait improvements afforded by visual cues, we recommend the following literature: [2,4,5,15,17,24,49,64,66]. An important conclusion from a recent review by Canning et al. [15] is that VR systems that support the rehabilitation of gait and balance in Parkinson disease require collaboration among several stakeholders to maximize the usability, effectiveness, safety, and engagement.

2.3.2. Auditory and Haptic Cues

Auditory and haptic cues work as temporal stimuli, instructing a person on when to take a step. The effect of these cues on gait speed and cadence is not surprising [23,33,54,78], as sound, music and rhythm have been used throughout history and across cultures to stimulate and organize motor function [54,79]. Similarly to visual cues, several auditory interventions have been described in literature showing that carryover effects lasting up to eight weeks can be expected following a training period between three to six weeks long [40,80] – a time and cost consuming affair. Other works combined visual and haptic cues to improve training of lower extremities [43].

Because the focus of our work is on the use of cueing during everyday locomotion, we are more interested in haptic cues – arguably less distracting and invasive than their auditory (and visual) counterpart outside a controlled environment [71]. These have been shown to improve participants' posture [89], balance [65] and overall gait normalization [82]; while delivered via various form factors: footwear [61], gloves [72], headbands [60] and the wrist [72,82]. The latter is quite appealing due to the current availability and affordability of smart watches and fitness trackers. As such, our work will expand on these systems – explored as proof-of-concept in the lab – to provide an holistic approach via a Virtual Field Study where participants engage with a simulated street environment. A broader number of metrics will also be used: from gait parameters to cue usability and subjective workload, to visual engagement with various external stimuli in the virtual environment (via gaze hits and dwell time).

3. Materials and Methods

In this section we describe not only the study design and setup of our Virtual Field Study, but also the simulated street environment that supports it.

3.1. Simulated Street Environment

Our study took place in simulated sidewalk (see Figure 2), an environment that as has been argued before would present some methodological and safety challenges during a standard field study. The sidewalk was three meters wide, and participants were free to

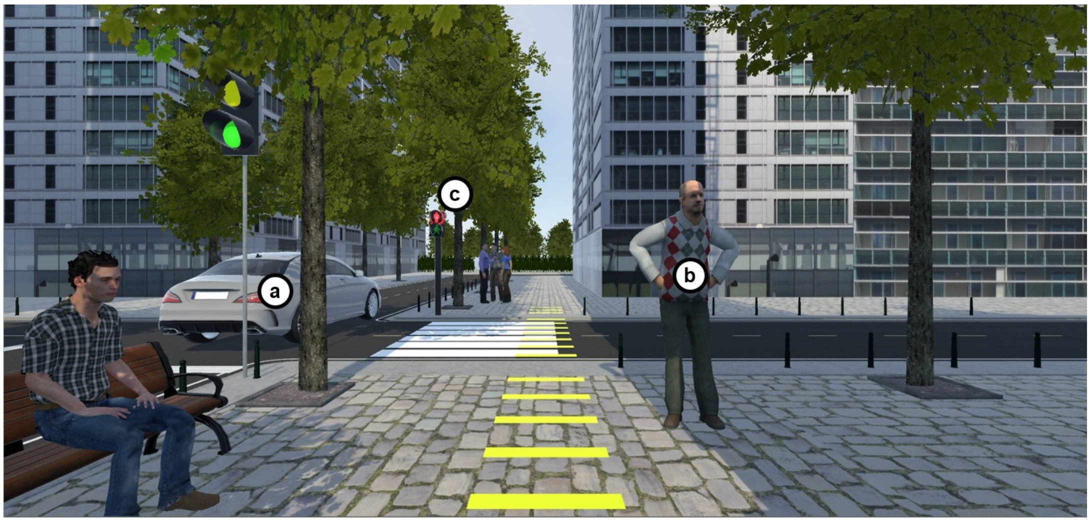

Figure 2. The simulated street environment in our Virtual Field Study. This scene includes various passive elements such as different pedestrians, trees, benches, or buildings. It also includes three active elements that can compete with the gait normalization cues being evaluated: a moving car (a) and pedestrian (b), and a changing crossing light (c). The yellow bars on the ground illustrate the stimulus presented in the visual cue condition.

walk towards a crossing line positioned five meters ahead of their starting point. The environment included various *passive elements* such other pedestrians with minimal animations, benches, trees, buildings, or a crossing line. It also included three *active elements* that produced systematic stimuli that could compete with the cues being evaluated. This included a car and pedestrian that would pass by participants to their left and right, respectively (see Figure 2: a and b), and a crossing light that would change from red to green (see Figure 2: c). These events took place after participants had walked 1.5, 2.5, and 3.5 meters, respectively.

The environment was developed using the Unity programming environment[1] and deployed on an HTC Vive Pro Eye VR headset (combined resolution of 2880×1600px, 615 PPI, 90Hz, 110° FoV). Several rendering choices were made to improve the realism of our scene, including the use of High Dynamic Range (HDR)[2], deferred shading[3], and a linear color space[4]. Our scene also included a 2D sound clip representative of typical city noises (e.g., people talking, cars honking), and the car that is enabled at 1.5m was accompanied by a 3D sound (i.e., *roll-off*) that would let participants know when it was about to enter their field-of-view. All the assets used were downloaded from the Unity Asset Store[5].

3.2. Experimental Setup

In addition to the VR headset, each participant was provided with a smartphone and two smart watches (two Huawei Watch 2) which they had to wear. The software for these was developed using Android Studio[6], and the former allowed the researcher

[1] https://unity.com/
[2] https://docs.unity3d.com/Manual/HDR.html
[3] https://docs.unity3d.com/Manual/RenderingPaths.html
[4] https://docs.unity3d.com/Manual/LinearLighting.html
[5] https://assetstore.unity.com/
[6] https://developer.android.com/studio

to control every aspect of the study: from inputting participants' IDs, to setting up gait baseline values, to selecting the study condition, to starting the trials in the VR headset and enabling haptic feedback on participants' smart watches. The latter simply produced different haptic feedback in response to instructions from the researcher's smart phone application. Finally, the communication between the researcher's device and both the VR headset and participants' smart watches was carried out using the Open Sound Control (OSC) protocol[7].

3.3. Experimental Design

Our study follows a within-subject design with four cue conditions, counterbalanced using a Latin square to minimize practice and carryover effects. These represent various examples of spatial and temporal cues that could feasibly be deployed in real-world prototypes using available (e.g., smart watches, fitness trackers) or upcoming wearable devices (e.g., AR headsets, smart glasses). We reiterate that our goal is two explore the feasibility of a Virtual Field Study in this domain by deploying two cueing baselines from literature in the context of real-world location – from which we can assess participant performance in comparison to expected results. Following this we can introduce and characterize two novel haptic cueing conditions:

Visual. Our main baseline implements arguably the most explored gait normalization cue: spatial stimuli as a set of horizontal bars laid out in front of participants [8,39,57,76,78]. These were bright yellow, 20cm wide and 80cm long, and extended for 10m in the direction a participant was facing – simulating the use of these cues out in-the-wild via, e.g., an AR headset (see Figure 2). Following [8,42], the gap between bars was adjusted for each participant to match 150% of their standard step length.

Haptic (1P1W). In addition the our spatial cue baseline, we implement a popular temporal cue from literature that produces rhythmic haptic feedback [61,72,82]. This is represented by a single pattern (*1P*) where 200ms long vibrations would play on a single smart watch (*1W*) at intervals that matched -10% of participants' cadence [84].

Haptic (2P1W). Our third cue expands on the state-of-the-art by implementing a haptic cue with not only temporal but spatial properties. Inspired by Google Maps' haptic feature that produces two distinct vibrations to indicate a user to turn right or left, our cue uses a single smart watch (*1W*) to produce two alternate patterns (*2P*) aimed at facilitating the coordination of right and left steps. The first pattern uses 200ms long vibrations as before, while the second plays two shorter vibrations in the same 200ms. Again, the time between each distinct vibration matches -10% of each participants' standard cadence.

Haptic (1P2W). The final cue expands on our novel 2P1W implementation by having the same pattern (*1P*) play alternatively in two individual smart watches mounted on participants' right and left wrists (*2W*). This attempts to reinforce the spatial property introduced in 2P1W, and to replicate the effects of auditory feedback using stereo cues – the latter being arguably more invasive and distracting than haptic feedback outside a controlled lab environment.

3.4. Metrics

In addition to traditional performance metrics seen in previous work such as mean *step length* (trial length ÷ num. of steps), *cadence* (num. of steps ÷ trial completion

[7]http://opensoundcontrol.org/

time), and velocity (cadence ÷ step length), our study also includes a variety of other objective and subjective metrics that would make sense to capture in a real field study. The former includes *gaze hits* and *dwell times* in both active (e.g., car) and passive elements of the scene (e.g., the crossing line). This is done via the embedded eye-tracker on the VR headset used (120Hz with 0.5° 1.1° accuracy) and the SRanipal SDK[8] that computes these variables automatically after we define which assets in the scene are of interest; with the goal of measuring the effect of different cues in participants engagement with the simulated street environment. Regarding subjective measures we employ questionnaires on general cue usability, workload assessment via the NASA-TLX [28], the System Usability Scale (SUS) [14], and user preference and rationale.

To assess the success of our environment we also ask participants to fill in the Immersive Tendencies Questionnaire (ITQ) [88] – which measures participants' capacity to be immersed – and the Igroup Presence Questionnaire (IPQ) [70] – which measures participants' subjective presence in a virtual environment. Finally, we ask participants some general questions about they perceive our simulated street.

3.5. Procedure

Our study that took place in a wide, well-ventilated, and empty lab. To comply with health and safety procedures participants were asked to disinfect their hands with an appropriate alcohol solution and to clean their face and wrists with disinfectant wipes. These were made available to participants when they entered the lab. Both the researcher and participants wore masks for the entire duration of the session.

Each session started with a brief introduction to the objectives and agenda for the study, and by having participants fill in the consent form, demographics, and the ITQ. After mounting both smart watches and helping participants adjust the VR headset comfortably on their heads, participants were then allowed to familiarize themselves with the street environment by walking freely for five minutes. This allowed them to understand the boundaries of the scene via the *chaperone* feature[9], which produces a visual artifact every time the participant is close to one of its edges. The goal was make them fell safe and perform as naturally as possible. We also removed the active elements in our scene so participants did not grow accustomed to them.

After being familiarized with the scene, participants were asked to perform five trials where they simply need to walk in a straight line for five meters until they reach a crossing line (see Figure 2): one for each cue condition (counterbalanced), and a first trial with no cues so the researcher could visually confirm various gait baseline values and adjust the cues' parameters accordingly. Each cue condition trial was preceded by instructions on how to calibrate the eye-tracker using HTC Vive's built-in procedure, and on the cues themselves (time each step to the haptic cueing, place each step on the visual cues).

After reaching the crossing line the trial would automatically end and participants were asked to remove the headset and fill in the our usability form, the SUS, and the NASA-TLX. Finally, after completing all trials participants were asked to fill in the IPQ, answer general questions about our simulated environment, and to rank the cues on preference. Upon a participant leaving the lab, the researcher thoroughly cleaned all equipment (e.g., smart watches, VR headset) with an appropriate alcohol solution.

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[8]https://developer.vive.com/resources/vive-sense/sdk/vive-eye-tracking-sdk-sranipal/

[9]`https://support.steampowered.com/kb_article.php?ref=6281-TOKV-4722`

3.6. Participants

Eight participants were recruited (3F) between 18 and 50 years of age (M = 25.50, SD = 8.99), and with the exception of two, all were students at a local institution. Using a 5-point Likert scale (higher is better), participants reported some degree of comfort and experience with VR (M = 2.50, SD = 1.20) and smart watches (M = 3.88, SD = 1.13). Further, and following the recommendations in [87], we calculated an average ITQ score of 105.40 out of 189 (SD = 8.47) which indicated our participants presented some tendencies to be easily immersed.

Due to the COVID-19 pandemic we abstained from recruiting participants with Parkinson's disease (as they were more likely to be at high risk of infection) or with other gait disorders (as their effects could vary greatly between participants). That being said, the recruitment of participants without gait disorders in a gait normalization study is not a novel approach (e.g., [72]), and several past works have shown that different cues affect a wide range of participants in a similar way (e.g., with and without Parkinson's disease [3,27]).

3.7. Pilot study

Our experiment builds on a pilot study that helped us shape the experimental design and procedure described above [18]. This preliminary study relied on six participants without gait impairments that except for one, were aged between 18 and 25 years (M = 27.0; SD = 11.52). Using a 5-point Likert scale, these reported being somewhat comfortable with VR technologies (M = 2.00; SD = 1.10). The main differences between the pilot and the experimental study described above are:

- **Study space**. The pilot study took place in an empty and quiet hallway, approximately 6.5m long and 1m wide, which we suspect could have had a negative effect on participants' locomotion due to fears of hitting the narrow walls while using the VR headset. As a result, we conducted the current experimental setup in a wider space (5x2m) and allowed participants to familiarize themselves with the VR scene and the *chaperone* feature that tells them they are about to leave the safety of the defined study space. The pilot study also allowed us to commit to a wired setup, as we wanted to avoid the added weight of the WiFi module on top of the VR headset. By placing the PC at the mid-point of participants' study path (2.5m), these were able to walk freely without feeling a cord pull.
- **Gaze metrics**. After analyzing the gaze results from the pilot study, which focused solely on the three active elements of the scene (the moving car and pedestrian, and the changing crossing light) and allowed us to assess the effects of the cueing conditions on perceiving these, we realized there was no reason not to gather gaze information in-between these systematic events. As such, we created four new types of gaze hitboxes for various passive elements in the scene (the floor, the crossing line, the buildings, and the trees), which allowed us to assess participants' gaze behaviors throughout the trials.
- **Subjective metrics**. Finally, the pilot study also enabled us to better quantify our study duration, allowing us to consider further subjective metrics that participants could fill in in-between conditions. These included the NASA-TLX, but also the ITQ (at the start of the study), and the IPQ and participants' preferences for the cueing conditions (at the end of the study).

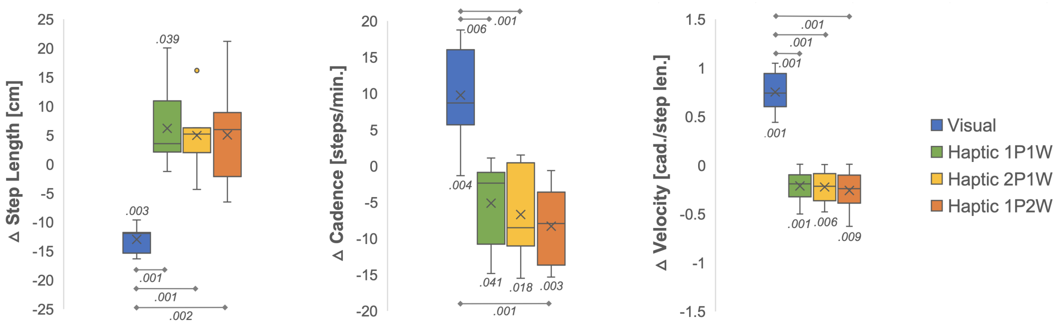

Figure 3. Performance metrics per cue condition, computed as a delta to participants' baseline performance. From left to right: step length (cm), cadence (number of steps per minute), and velocity (cadence/step length). We highlight when $p < 0.05$ between cueing conditions and the baseline with its value directly above or below the box plot, and between cueing conditions with its value above a line between conditions with performance results significantly different.

4. Results

We analyze our results starting from our objective metrics. We then conclude with our subjective metrics, and with participants comments about the cues and VR experience.

4.1. Gait Performance

Performance results were computed as a delta to participants' baseline performance (see Figure 3). This is because the cue parameters were personalized for each participant based on their baseline gait. This comparison to the baseline was analyzed using a paired-samples t-test, and between cues using a one-way repeated measures ANOVA with Post hoc tests (Bonferroni adjusted).

Step Length. We observed a statistically significant decrease in step length during interaction with the Visual cue when compared to baseline gait (t(7) = 15.97, p = .003); and an increase during interaction with Haptic 1P1W (t(7) = 2.527, p = .039). No significant differences were found between the baseline and Haptic 2P1W and 1P2W ($p > 0.05$). Cue results were significantly different (F(3, 21) = 19.20, $p < .001$, $\eta_p^2 = .733$), with Post hoc tests revealing significant differences between Visual and all Haptic cues ($p < .002$), but no differences between Haptic conditions ($p > .900$).

Cadence. We observed a statistically significant increase in cadence during interaction with the Visual cue when compared to baseline gait (t(7) = 4.14, p = .004); and a decrease during interaction with any of the Haptic cues (1P1W: t(7) = 2.51, p = .041; 2P1W: t(7) = 3.06, p = .018; 1P2W: t(7) = 4.48, p = .003). Cue results were significantly different (F(3, 21) = 39.79, $p < .001$, $\eta_p^2 = .850$), with Post hoc tests revealing significant differences between Visual and all Haptic cues ($p < .006$), but no differences between Haptic conditions ($p > .070$).

Velocity. Finally, we observed a statistically significant increase in velocity during interaction with the Visual cue when compared to baseline gait (t(7) = 10.48, p = .001); and a decrease during interaction with any of the Haptic cues (1P1W: t(7) = -3.70, $p < .001$; 2P1W: t(7) = -3.82, p = .006; 1P2W: t(7) = -3.66, p = .009). As before, cue results were significantly different (F(3, 21) = 77.54, $p < .001$, $\eta_p^2 = .917$), with Post hoc tests revealing significant differences between Visual and all Haptic cues ($p < .001$), but no differences between Haptic conditions ($p > 0.51$).

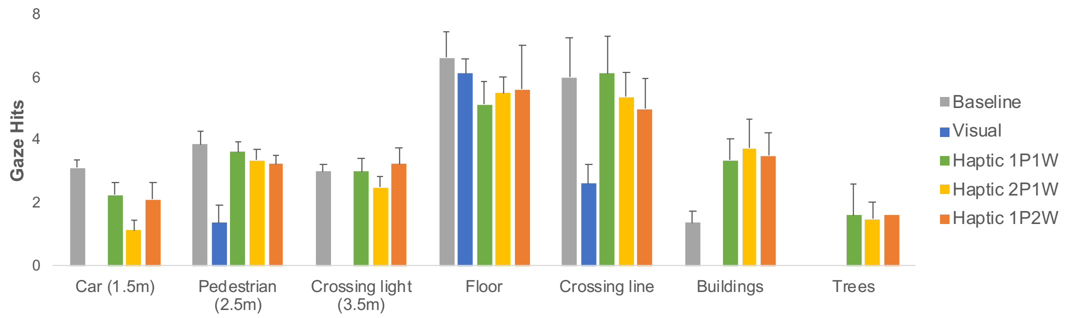

Figure 4. Gaze hits on the three active (left) and four passive elements (right).

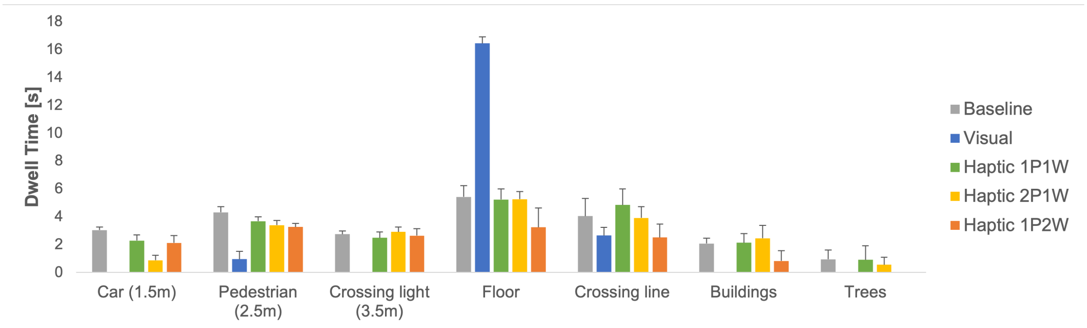

Figure 5. Dwell times on the three active (left) and four passive elements (right).

4.2. Gaze Performance

Gaze performance was assessed using four one-way repeated measures ANOVAs between all conditions (including the baseline). This included gaze hits (Figure 4) and dwell times (Figure 5) on both active and passive elements of the scene. Post hoc tests were carried out with Bonferroni adjustments.

Hits. These results were significantly different for both active ($F(4, 28) = 14.80$, $p < .001$, $\eta_p^2 = .680$) and passive elements ($F(4, 28) = 4.90$, $p = .004$, $\eta_p^2 = 0.41$). Regarding the former, Post hoc tests revealed a statistically significant reduction in gaze hits during the Visual condition when compared to all other conditions ($p < .036$); no other statistically significant differences were found ($p > .060$). Regarding gaze hits on passive elements, Post hoc tests show again a significant decrease during the Visual condition when compared to the baseline and Haptic 2P1W ($p < .040$); no other statistically significant differences were found ($p > .550$).

Dwell Time. As before, these results were significantly different for both active ($F(4, 28) = 24.90$, $p < .001$, $\eta_p^2 = .780$) and passive elements ($F(4, 28) = 9.73$, $p < .001$, $\eta_p^2 = 0.58$). Regarding the former, Post hoc tests revealed a significant reduction in dwell time during the Visual condition when compared to all other conditions ($p < .006$); no other statistically significant differences were found ($p > .080$). Regarding passive elements, Post hoc tests show an actual increase in dwell times during the Visual condition when compared to the baseline and Haptic 2P1W and 1P2W ($p < .004$); no other statistically significant differences were found ($p > .150$).

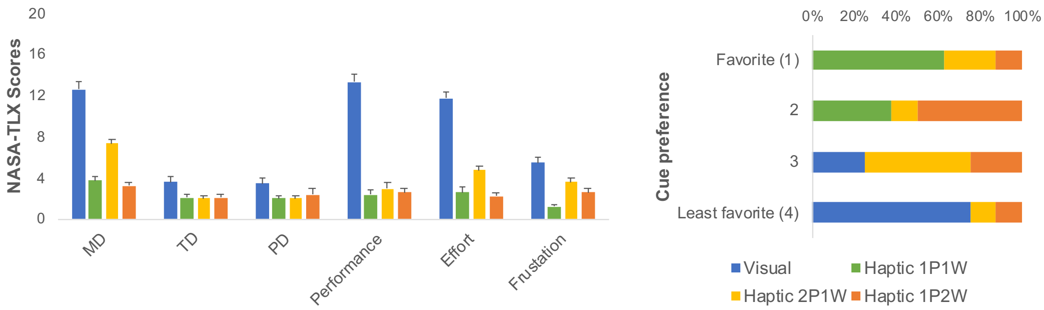

Figure 6. Left – NASA-TLX scores for individual scales: mental demand (MD), temporal demand (TD), physical demand (PD), performance, effort, and frustration (lower is better). Right – cue preference: from favorite (1) to least favourite (4).

4.3. Subjective Scales

Our subjective scales were analyzed using a Friedman test with Post hoc Wilcoxon signed-rank tests (Bonferroni correction applied).

Cue Usability. We observed significant differences between conditions on all usability scales used: ease of use ($\chi^2(3) = 15.81$, $p = .001$), comfort ($\chi^2(3) = 17.27$, $p < .005$), annoyance ($\chi^2(3) = 18.41$, $p < .005$), ease of understanding ($\chi^2(3) = 14.46$, $p = .002$), usefulness ($\chi^2(3) = 14.47$, $p = .002$), distracting ($\chi^2(3) = 17.03$, $p < .005$). Mean results and Post hoc results are presented in Table 1.

Perceived Workload. These results can be seen in Figure 6 – for the sake of brevity we only report on Post hocs tests revealing significant differences. While no statistically significant differences were found for the temporal ($\chi^2(3) = 6.65$, $p = .084$) and physical demand scales ($\chi^2(3) = 5.86$; $p = .119$), we observed significant differences for all others: mental demand ($\chi^2(3) = 21.07$, $p < .001$) and effort ($\chi^2(3) = 21.56$, $p < .001$), between the Visual condition and Haptic 1P1W ($p = .001$) and 1P2W ($p = .001$); performance ($\chi^2(3) = 17.25$; $p < .001$), between the Visual condition and all others ($p < .030$); and frustration ($\chi^2(3) = 18.53$; $p < .001$), between the Visual cue and Haptic 1P1W ($p = .005$).

SUS. There was a significant difference between SUS scores between Visual ($M = 40.00$, $SD = 4.81$), Haptic 1P1W ($M = 80.31$, $SD = 3.88$), 2P1W ($M = 58.75$, $SD = 5.51$), and 1P2W ($M = 81.88$, $SD = 3.20$) conditions: $\chi^2(3) = 21.91$, $p < .001$. Post hoc tests revealed a significant difference between the Visual condition and Haptic 1P1W ($p = .001$) and 1P2W ($p < .001$); no other differences were found ($p > 0.14$).

Preference and Rationale. Preference results can be seen in Figure 6, with 62.5% of participants reporting a preference for the Haptic 1P1W cue and 75% reporting the Visual cue as their least favorite. Comments on the former include how the stimulus was "intuitive and simple" (P1, P4), "easy to learn" (P2), and "natural" (P2, P5, P8). Regarding the latter participants shared their concerns about how they were "more concerned about stepping on the lines than the walking experience" (P1), and how it was more mentally demanding (P2-3) and the least "natural" cue (P5-6, P8).

4.4. Virtual Environment

Participants reported a mean IPQ of 62.25 ($SD = 7.07$). Further feedback on a Likert scale between 1 to 5 (higher is better) describes the realism of the walking experience ($M = 3.38$, $SD = 0.74$) and street ($M = 3.63$, $SD = 0.52$), the sense of embodiment

Table 1. Cue usability results using a Likert scale between 1 and 5 (higher is better). Standard dev. in brackets.

Usability question	Cue condition Visual	Haptic 1P1W	Haptic 2P1W	Haptic 1P2W
I found the stimulus easy to use	2.65 (0.74)*,**	4.38 (0.52)*	3.75 (0.71)	4.50 (0.53)**
I felt comfortable while using the stimulus	2.62 (0.52)*,**	4.63 (0.52)*	3.88 (0.99)	4.50 (0.53)**
I felt annoyed while using the stimulus	3.25 (0.71)*,**	1.25 (0.46)*	1.88 (0.83)**	2.38 (1.06)
I found the stimulus easy to understand	3.50 (0.93)*	4.50 (0.53)	4.13 (0.64)	5.00 (0.00)*
I found the stimulus useful	2.75 (0.71)*	4.13 (0.64)*	3.75 (0.88)	3.88 (0.83)
I felt distracted by the stimulus	4.00 (0.76)*,**	1.63 (0.52)*	2.63 (1.19)	1.75 (0.71)**

*Denotes statistically significant difference with $p < .030$.

($M = 4.75$, $SD = 0.46$), and if participants noticed the moving car ($M = 2.75$, $SD = 1.04$), the other pedestrians ($M = 4.50$, $SD = 0.53$), and the crossing light changing from red to green ($M = 2.25$, $SD = 1.16$).

5. Discussion

In this section we discuss our results around four main topics: participant gait results in the context of a Virtual Field Study; presence and gaze performance in our virtual environment; the takeaways from the novel haptic cues developed; and participant subjective assessment of the haptic cues.

5.1. Gait Performance

One of the main goals of our work was to explore the feasibility of gait normalization studies using Virtual Field Studies. This is not only important to enable such studies to take place during the COVID-19 pandemic, but also to ensure the safety and comfort of participants (particularly those suffering from gait impairments). To explore this we employed two traditional cues – Visual and Haptic 1P1W – that allow us to draw comparisons between expected performance from literature and what was observed with our experimental setup.

Regarding the former, and despite our visual stimuli representing 150% of participants' step length, this still resulted in a diminished step length when compared to participants' baseline gait. Likewise, participants under the Visual condition presented a higher cadence and velocity than during the baseline trial. While this deterioration in participants' gait performance has been observed before in VR [31,36,68,75], others have observed positive effects with this type of stimuli with healthy participants in similar virtual environments [7,26,44]. We argue this could have been caused by two limitations in our setup. First, a lack of practice due to a short engagement with the visual stimuli (only one trial) – we did not want participants to grow accustomed to the active elements in the scene, and we wanted a short procedure that could easily be replicated with participants with gait disorders. Second, participants could not see their feet from within VR, and thus could not coordinate their gait with the horizontal bars laid out in front of them.

In the Haptic 1P1W condition, where this motor-visual coordination was not necessary, we indeed observed the results expected (despite the smaller body of work surrounding this topic). Participants' cadence and velocity decreased when compared to the baseline – the haptic pattern played with a rhythm that matched 90% of participants' cadence – while the step length increased as expected [61,84]. The results for haptic cues 2P1W and 1P2W are also in line with the latest reports from Hoppe et al. where participants' gait is not expected to produce varying step lengths when walking to a slower cadence beat overground (i.e., not on a treadmill) [32].

5.2. Presence and Gaze Behaviors

Following these positive results, we also assessed our virtual environment via the Igroup Presence Questionnaire (IPQ) and through some general questions about their experience; and by measuring participants' gaze hits and dwell times with and without gait normalization stimuli. Regarding the former, participants reported a high level of presence (62.25 out of 86), which we can attribute in part to the street fidelity and vividness and sense of embodiment (3.63 and 4.75 out 5, respectively).

Regarding gaze performance we also observed the expected effects between the visual and haptic conditions. That is, the haptic stimuli did not produce significant differences to the baseline in regards to both gaze hits and dwell times (with either active or passive elements). On the other hand, in the Visual condition where participants had to coordinate their steps with the horizontal bars on the floor, these produced fewer gaze hits and higher dwell times than the baseline (and most of the other haptic conditions) for both active and passive elements. The former illustrated elements that could potentially put participants in danger, such as a moving car or a changing crossing light. These results illustrate not only that our setup is able to capture realistic gaze behavior – that is, participants seemed to be free to look around during the baseline and haptic cueing conditions similarly to what one would expect to observe during in-the-wild locomotion – but that haptic cues delivered via simple wrist worn devices can be indeed a safer and more comfortable choice if used outside the lab. No erratic gaze behaviors were identified that could indicate some confusion about the scene, instructions, or spatial audio.

5.3. Spatial Haptic Cues

In addition to the traditional Haptic 1P1W condition, we developed two novel haptic cues that included spatial properties (left and right) in addition to temporal information (when to take a step). Due to increasing availability of these devices, we explored this spatial feedback using both a single and two smart watches. We did this to replicate some examples of audio cues that use stereo to the same effect, and were hoping to observe some of the benefits previously demonstrated by visual cues with spatial and temporal properties [26].

Unfortunately, the new haptic conditions seem to wield very few benefits over the simpler 1P1W cue. Participants' cadence and velocity was improved when compared to the baseline, but no significant differences were found between haptic conditions. Step length did not increase when compared to the baseline (as had happened with Haptic 1P1W), and the gaze behaviors between haptic conditions remained largely the same. The only exceptions occurred during the interaction with passive elements in our virtual scene: the 2P1W cue produced a higher number of gaze hits when compared to the Visual cue; and both 2P1W and 1P2W produced shorter dwell times (e.g., on the floor) – no differences had been observed for these variables between the Visual and 1P1W conditions. In sum, these spatial properties did not seem to elicit any particular advantages when haptic cues were considered.

Figure 7. A screenshot from GaitWear, a simple smart watch application that produces the Haptic 1P1W cue out in-the-wild. This is enabled or disabled via the toggle widget or two subsequent wrist flickers.

5.4. Cue Usability and Participant Feedback

Following on the results above, we further explored the differences between the traditional and novel haptic cues via usability and feedback questionnaires. We are not particularly interested in comparing responses to the Visual cue as its gaze performance confirms our suspicions: it is not a useful gait normalization cue outside the lab. As before, very little significant differences were found between haptic conditions. This includes our usability, perceived workload, and SUS questionnaires. Finally, the majority of participants reported a preference for the Haptic 1P1W cue, followed by the Haptic 1P2W. As such, we recommend the former as a gait normalization cue for everyday use: it positively affects participants' gait; scores highly in usability scales (consistently over 4 out 5) and the SUS (80.31 out of 100); has a low perceived workload (under 4 for every scale, out of 20); is described by participants as "simple", "natural", and "easy to learn"; and requires a single wrist-worn device.

6. GaitWear

Building on our findings, we conclude our work by reporting on our implementation of a very simple, standalone application that provides the Haptic 1P1W cue on the fly via a wide range of smart watches running the Android Wear OS[10] (see Figure 7).

Carryover effects. As mentioned earlier, cueing is known for its carryover effects [29,55,80]. That being said, these effects have been shown to last for a widely disparate ranges of time (e.g., 15 minutes, 60 days) which in turn can cause users to be fearful of leaving their homes and ultimately impact their mobility and independence. As such, in GaitWear we provide two ways in which users can quickly enable or disable cueing: through a standard UI toggle; and via two wrist flickers in succession (which has been shown to be affected by a very low number of false positives during everyday use [41]).

Cadence regulation. The only other UI elements in GaitWear, other than the activation toggle, are the plus and minus controls to increase and decrease the desired cadence. This allows the application to adapt to the user's needs over time, particularly if their gait impairments are degenerative.

[10]https://wearos.google.com/

7. Limitations and Future Work

In this section we discuss three broad areas of future work following our work: the limitations and future work required to further validate Virtual Field Studies for gait normalization research; how can we expand the participant pool using this methodology during the COVID-19 pandemic; and how can we improve on GaitWear.

7.1. Virtual Field Studies

Despite our small sample size (N=8), our experimental setup produced not only the expected gait results in response to haptic cues, realistic gaze behaviors, but also a good sense of presence and embodiment. That being said, to fully validate this novel research methodology in this domain a wider research effort needs to take place. First, by conducting lab and field studies and comparing their results. The latter could be carried out with minimally invasive sensing equipment, such as wearable gait sensors (e.g., AX6[11]) and eye-trackers (e.g., Pupil Pro[12]). The results from this validation would also allow us to better understand the effects of both our VR scene and procedure. Regarding the former, we would be interested in exploring the effects of the vividness of a scene in a virtual field study. Despite our positive presence scores, it would be important to understand how much effort is required in designing and developing these VR scenes in order to obtain valid results that represent human performance in-the-wild – both in terms of visual and auditory vividness. Regarding the effects of our procedure, we would be interested in understanding if single trials where participants walk for five meters are enough to elicit valid and representative data. These are crucial in understanding the benefits and trade-offs of a virtual field study methodology.

Second, and following this validation, by conducting a Virtual Field Study with participants with a particular set of gait disorders. This would enable us to gather more insightful and focused usability, workload, and feedback assessment of various cues; and to draw a better understanding of the underlying mechanisms that are at play with each one. Further work could also explore the limitations found in our Visual cue implementation, particularly what level of avatar fidelity would be required for this to have the intended effect on participants' locomotion. This would allow us to have more fair comparison to the haptic cues; although we expect to observe very similar gaze performance results. If participants would report a preference for visual stimuli, this could be delivered out-in-the-wild via head-mounted Augmented Reality (AR). Finally, while we observed very simple metrics (e.g., number of steps, trial completion times), a more detailed gait analysis could have been conducted with the same setup. That is, using the rich motion sensors in participants' smart watches and VR headset, or via the VR position cameras setup in the lab.

7.2. Studies during the COVID-19 Pandemic

COVID-19 had a broad negative impact on the execution of user studies. In the study we present in this article, we opted for not using the additional wearable sensors that would be needed to show participants an accurate representation of their bodies in VR. This is because the additional on-body sensors would have not only required a

[11]https://axivity.com/product/ax6
[12]https://pupil-labs.com/

more complex health and safety protocol (e.g., more equipment to disinfect between participants), but would have also required a much closer interaction between the experimenter and participants for correct installation and set up of these sensors. This was unfortunately not feasible due to the social distancing guidelines in place at the time of the study. Another approach to provide participants with a body-reference would have been to use a depth camera that blends their bodies into VR; but this approach has been shown to negatively impact immersion and presence [53], which can in turn distract participants and impact the validity of our results. Nonetheless, and despite our positive embodiment results, the lack of a body avatar is a limitation in our experiment as body-references have been shown to affect locomotion performance [16,25]. Thus, an important direction for future work is to study the impact of this body-reference in virtual field studies, and the validity of the results they provide.

On a positive note, the COVID-19 pandemic has accelerated the investigation of novel research methodologies and practices, such as the one described in this work. One particular advantage of a Virtual Field Study in this context, and as VR adoption increases, is that it can be easily conducted remotely as highlighted in [77]. This diminishes the risk of contagion while also enabling a wider and potentially more diverse participant pool. The latter could have deep implications on human-computer interaction (HCI) research. Our experimental design is perfectly suited to such future work: short trials that can be carried out easily at home (provided that large object-free tracking space is available), simple metrics that can be computed with everyday VR headsets, and cues that are delivered via ubiquitous wearable devices such as a smart watch or a fitness tracker. Even participants' gaze parameters could be captured using an increasing number of VR headsets with eye-tracking capabilities (e.g., Pico Neo 2 Eye[13]), or via head pointing if this is not available (a known proxy for gaze [59,73]).

7.3. GaitWear

Finally, our GaitWear application should also be evaluated to assess if it mimics the results observed in our Virtual Field Study. Further, and while simple, it also still requires quite some input from a user to enable or disable it throughout the day, and to set cadence parameters. This interaction could benefit from a machine learning approach that would identify when the carryover effects were fading to enable the haptic cue; to set appropriate cadence parameters based on an on-going assessment of the user's gait; and learn when to disable the stimulus based on previous carryover performance – leading to not only an improved user experience but also battery life.

8. Conclusion

In this work we continued a research trend that looks at Virtual Field Studies as a novel research methodology. This was done not only in response to the COVID-19 pandemic, but also due to the inherent qualities of this approach: the safety of our participants as they engage with a simulated environment describing various competing stimuli, or the systematic control over different parameters such as distracting events (e.g., a car that passes by). While more work is needed to fully validate this methodology in the context of gait normalization research, we have taken the first step by demonstrating

[13]https://www.pico-interactive.com/us/neo2.html

that participants' performance under a traditional haptic cue is as expected, as well as their gaze performance and reported embodiment and sense of presence. This was done via the first holistic study that assessed various gait normalization cues not only in terms of performance but also usability, perceived workload, and preference. Finally, we discussed our takeaways from this approach and describe various opportunities for future research in this domain. We are particularly enthusiastic about the role VR can play in widening participation in HCI research via remote studies, not only in the context of the COVID-19 pandemic but as a proven research methodology that can endure in the future.

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