

Challenges and Opportunities for Immersive Visualizations for Running

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Abstract

Running is a popular activity that is becoming increasingly data-driven. However, existing wearable technologies to support runners are limited. For example, the widely used smartwatches are small and hard to read while running. Mixed Reality shows promise to improve the experience of runners as it can provide them with information such as pace, heart rate, and cadence in-situ, in less-obtrusive fashion than with smartwatches. We present our exploration of first-person egocentric immersive pace and cadence visualizations along the spectrum of situatedness, and discuss challenges and opportunities that emerged from this research.

CCS Concepts

• **Human-centered computing** → **Visualization; Ubiquitous and mobile computing.**

Keywords

Visualization, Mixed Reality, Running.

ACM Reference Format:

Ang Li, Liam Shatzel, Maxime Cordeil, and Charles Perin. 2026. Challenges and Opportunities for Immersive Visualizations for Running. In *Proceedings of CHI 2026 Workshop on Next Steps for Augmented Reality On-the-Move: Challenges & Opportunities*. ACM, New York, NY, USA, 5 pages.

1 Introduction

Running leads people through demanding terrain, environmental conditions (e.g., rain, low-sight), and cognitive tasks (e.g., way-finding). Moreover, this activity has associated analytical tasks: keeping a set target pace, understanding and projecting personal physical performance such as heart-rate, assessing parameters of the running course such as remaining distance or elevation, and eventually allocating physical resources effectively. Still, accessing

and processing this information remains a secondary task, compared to the primary (situated) task at hand, but the respective information is necessary to support the primary task.

This kind of situation comes with high attentional, perceptual, physical, and cognitive demands on the person. Consequently, technology must not ‘get in the way’, as this can be detrimental to the experience of the person or even hazardous. For example, shifting [17] a runner’s attention from their environment to the display breaks the running flow [8, 10, 29], even more so as the intensity of the activity increases, or when people develop body fatigue which reduces their cognitive abilities [5]. Consequently, while visualizations can improve runners’ performance in completing data-centric tasks while running (e.g., [9, 12]), information must be communicated effectively and efficiently to minimize distraction.

The problem is that runners primarily rely on smartwatches, with which accessing this information while running interrupts natural arm movements, diverts attention from the environment, breaks the running flow, and leads to hazards like tripping. Additionally, smartwatch screens offer a reduced display area, limiting the ability to track and show multiple metrics at the same time [3].

Mixed Reality immersive visualizations offer a promising alternative to displaying running metrics on smartwatches. Indeed, not only can visual representations help runners better access information while running [9], compared to smartwatches, Mixed Reality can also more seamlessly show information into the runner’s surroundings, offer a larger display space, and support less obtrusive access to data [25, 27]. While current headsets remain bulky, the industry is pushing towards minimized, everyday glasses. We leverage today’s devices to understand how to design for this future.

In this paper, we ground our exploration of immersive visualizations for running in canonical theories in situated visualization [25, 27] to explore the spectrum of situatedness through two case studies: i) immersive pace visualization, and ii) immersive cadence visualization. In Willett et al.’s definitions [27], situated and embedded visualizations sit on a continuum, where situated visualizations are “in proximity to data referents”, while embedded visualizations are situated visualizations that are not only in proximity to, but also “spatially coinciding with data referents”. We explore the two case studies following this continuum of situatedness.

*The first two authors contributed equally to this research.



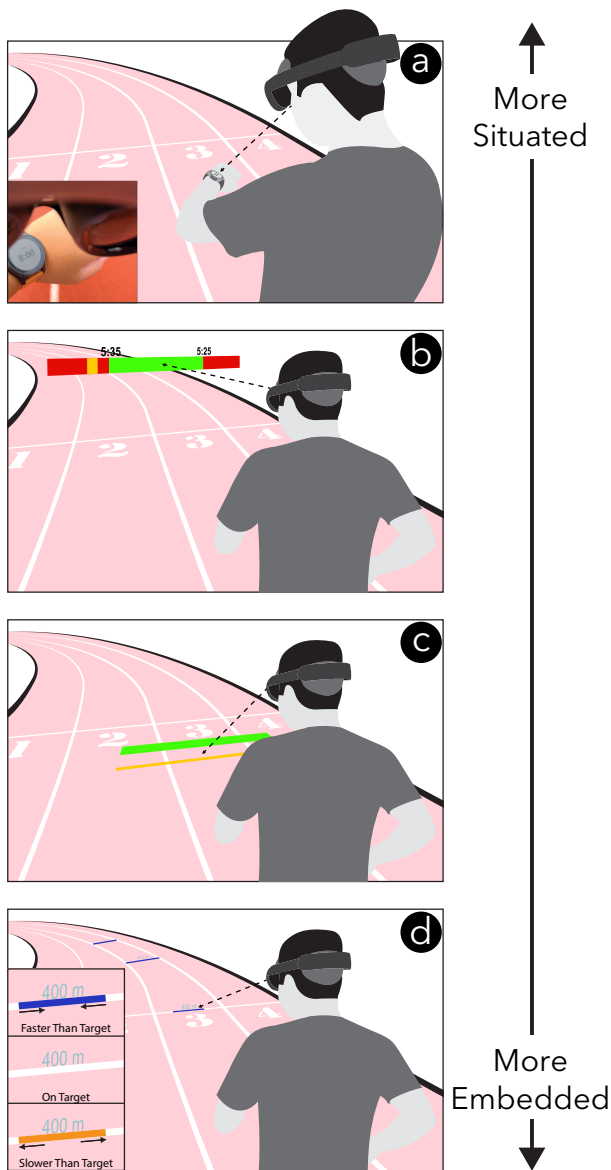


Figure 1: Four pace visualizations we studied [12], on the continuum of situatedness: a) Watch: situated on the runner’s wrist, with no spatial anchoring; b) Speedometer: situated to the display of the head-mounted display, in the line of sight; c) Laserbeam: situated to the runner’s body while spatially anchored into the ground in front of the runner; d) ShrinkingLines: embedded onto the track, with strong spatial anchoring.

2 Case Study 1: Immersive Pace Visualizations

Running takes many forms, ranging from fitness-focused non-competitive runs, to cross-training or warming up for other activities, to a wide range of structured workouts, to races.

Workouts are particularly interesting because during workouts, specific metrics-based performances must be achieved. For example, an interval workout consists of alternating (usually regular) periods (typically expressed in terms of time or distance) at a target value (or within a range of values) for a given metric. Such an interval workout can be expressed as “run 10 times 3 minutes at marathon pace with 1 minute jogs in-between”, or as “alternate 2 minutes at Zone 2 pace and 2 minutes at Zone 2 pace for 30 minutes.”

For such workouts, the goal is to run at the target pace(s), and for this, runners typically rely on their smartwatch. In this case study, we implemented and evaluated four pace visualizations for interval training on an outdoor track [12], as illustrated in Figure 1.

► **WATCH** – Figure 1a): is the standard wearable used by runners to perform running workouts. The most basic display is a number that shows current pace.

► **HUD-LIKE SPEEDOMETER** – Figure 1b): this HUD-like pacing gauge is fixed to the runner’s view. It is a reproduction of a standard pace gauge found on popular smartwatches like Garmin’s that runners use to perform interval training. It is our least embedded visualization.

► **LASERBEAM** – Figure 1c): is an adaptation of Nike’s “Breaking2” projection technique¹, where a car-mounted projector casts a beam ahead of the runners, indicating the target pace. Our setup anchors the visualization to the runner’s body. Two beams are spatially mapped on the ground in front of the runner, based on the per-second distance resulting from the target (represented by the green beam) and the current pace (represented by the yellow beam). LaserBeam is more embedded than Speedometer, as it coincides with the surface of the track in the physical environment, indicating pace with world-scale distance predictions on the track.

► **SHRINKINGLINES** – Figure 1d): shows animated lines embedded along the track to encourage steady pacing [12]. Distance markers on the ground resemble the physical lines on a track that runners rely on for pacing and racing. The closest line starts shrinking when the runner starts running. Upon reaching a line, the runner is on target pace if the line exactly shrinks out, ahead of target pace if there is still a remaining part of the line, and behind target pace if the line starts growing backward in orange. Ideally, when finishing a lap, if the runner’s pace remained close to the target pace, they should see minimal visual cues along the track, as if they had run naturally without any technological assistance. This design is our most embedded design.

Our evaluation of those immersive visualizations [12] showed that more embedded visual representations enhance both performance and experience. LaserBeam yielded the most consistent pacing, received the highest user preference ratings, and was perceived as the least disruptive to running flow; and ShrinkingLines was the second-most preferred and was rated as less disruptive than both the Watch and the Speedometer conditions.

¹Nike’s “Breaking2” Project: <https://www.nike.com/au/running/breaking2>

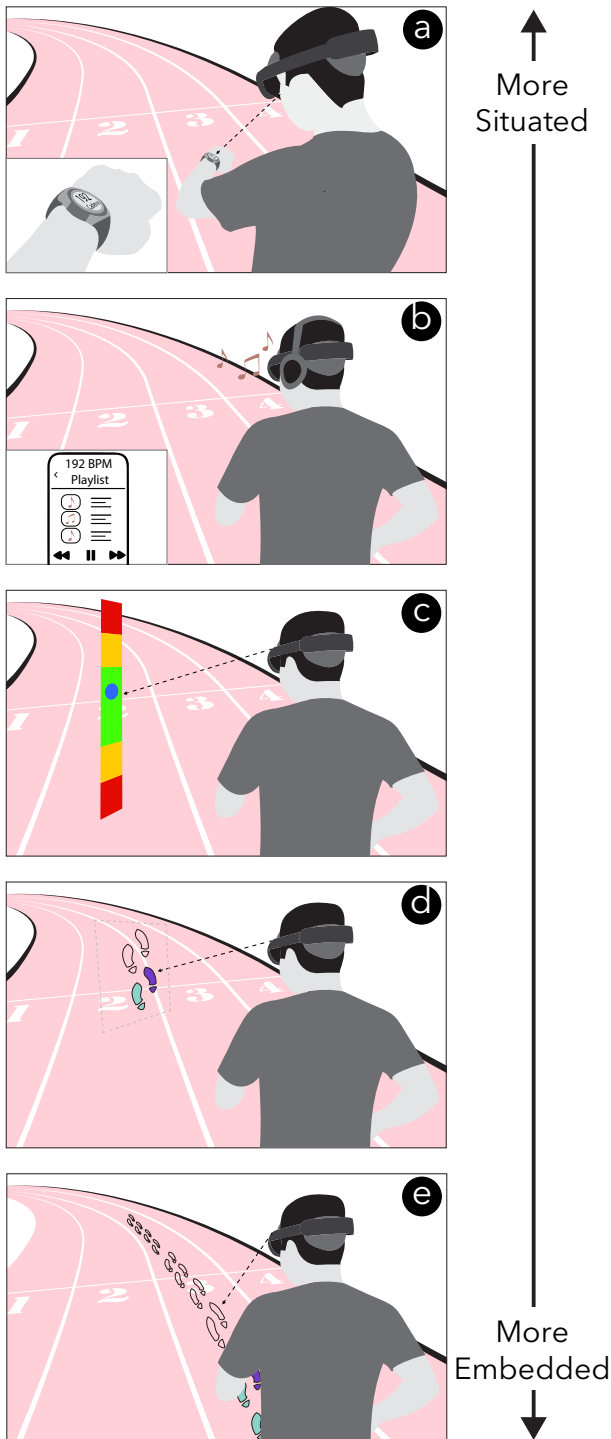


Figure 2: Five cadence visualizations we designed, on the continuum of situatedness: a) Watch: situated on the runner’s wrist; b) Sonified Cadence: with sound playing at a target bpm rate; c) Placement Targets: similar to the HUD-like Speedometer; d) Floating Footsteps: with footprints hovering over the ground in the line of sight; e) Feet on Ground: with footprints embedded on the ground.

3 Case Study 2: Immersive Cadence Visualizations

This case study considers a different scenario than the pace-based workout in Case Study 1. Runners have long relied on training techniques to improve running form, with the goal of improving running efficiency and performance, as well as to reduce the risks of injury [4, 20]. In fact, over 80% of runners get injured at some point in their running career [1].

We know that improving cadence and stride length can reduce load rate on joints [7, 13], which in turn can improve running form and gait [1] and reduce the chances of injury. With recent technological advances and the development of new sensors, runners now have access to advanced running dynamics metrics such as ground contact time, cadence, stride length and running power, and there is also evidence that accessing such information while running can help improve running form [24].

Consequently, in this case study, we investigate how cadence visualizations can help people run at a given target cadence. Previous work has shown that using music [14, 26] or audio feedback [2, 6, 16] to encourage a runner to match their steps to a target beat can increase cadence, thus reduce load rate. However, some runners do not use music while running, and others may find these interventions not suitable for their music taste [19]. In this research, we extend previous work that used Mixed Reality to alter cadence and stride length for rehabilitation (e.g., [15, 18, 21–23]) to running.

► **WATCH** – Figure 2a): existing smartwatches such as the Apple Watch, Garmin, Coros and Suunto models, can show cadence in real-time or retrospectively. This is typically shown either with a number, or with a speedometer-like visualization. It is the least situated design we are considering.

► **SONIFIED CADENCE** – Figure 2b): uses music or sound at a specific beat per minute (bpm) rate, which the runner should match [2, 14]. This approach can interfere with the runner’s preferences (e.g., they like to listen to music or podcasts) and experience (e.g., they like to listen to the wonders of nature, or to their breathing).

► **PLACEMENT TARGETS** – Figure 2c): abstract, non-embedded design that shows a vertical bar with the runner’s current cadence shown with a dot on the bar (akin the Speedometer pace visualization in Figure 1b). Following existing smartwatch screen designs, it shows a red, a yellow, and a green zone. If the dot is in the green zone, the runner is on their target cadence, but if it is in the yellow or red zones, they need to adjust their cadence.

► **FLOATING FOOTSTEPS** – Figure 2d): shows each target footstep to achieve a given cadence as a footprint that hovers over the ground, and superimposes the actual foot placement as visual feedback. This design, inspired by previous work that showed visual cues [28], is more spatially embedded than the Placement Targets, but vertically offset from the ground so that it is in the runner’s line of sight.

► **FEET ON GROUND** – Figure 2e): is the most embedded design version of the Floating Footsteps. Here, target footprints are shown directly on the ground in front of the runner, who should place their feet on the semi-transparent footprints. This increased embeddedness comes at the cost of not being directly in the line of sight of the runner who has to look down.

4 Hardware and Software Challenges for the Research Community

Embedding visualizations in the real-world is difficult, especially outdoors. The **form factor** of current pass-through headsets (e.g., Meta Quest Pro) is not suitable for high-exertion and outdoor activities. In our study [12], the bulky headset caused discomfort and sometimes readjustment while running. One of its infrared cameras broke during an extreme temperature event. Current headsets also bring challenges around social acceptability that future technology, with more appropriate form factors, could help address.

Existing Mixed Reality headsets's limited *spatial memory* makes it challenging to maintain world-locked anchors in large outdoor areas. When conducting our study on an outdoor running track, we observed an increasing drift in the *ShrinkingLines* visualization due to accumulated SLAM errors. At the time we conducted Case Study 1, privacy-focused SDK restrictions (e.g., Meta XR SDK) blocked access to raw RGB camera data. This restriction has since been lifted² for newer headsets such as the Meta Quest 3, offering opportunities to customize computer vision algorithms to re-align visualizations with physical objects (such as lane markings) dynamically.

While creating a precomputed mesh for the ground plane in the cadence case study, we found it difficult to compute a continuous surface due to the resolution of the initial SLAM data. We addressed this issue by inputting points based on the average location of surrounding point (taking the minimum and maximum z-axis points for the current bounding box and uniformly distributing points across the x, y, and z axes within the bounds).

Pre-computing runners' footsteps for embedded cadence visualizations is also non-trivial. We are looking into using an Inverse Kinematics model of the runner's torso and legs to define the distance that they should move to create virtual footsteps, as stride length and cadence have an inverse relationship. Validating whether a runner is hitting the footstep placements is also challenging when the measurement data comes solely from the headset. We are considering using horizontal bands to validate where the runner has stepped, by processing the vertical movement of the headset.

While generating a model of a running track is relatively straightforward, it is more challenging to model more complex environments like trails in forests or mountains, which are needed to generate precomputed ground mesh of the actual running surface, and especially important when embedded visualizations must be placed on uneven ground. We are currently exploring generating meshes from point clouds captured with glasses in those environments.

Such challenges call for community efforts to develop pipelines, libraries and frameworks for researchers to build on, in order to accelerate research on AR on-the-move.

5 Research Opportunities

► **EMBEDDED RUNNING DATA VISUALIZATIONS** – In a survey of immersive visualizations for running [11], we identified a shift from *peripersonal* displays towards *extrapersonal* displays, in which the information is embedded in the surrounding environment. We then provided empirical evidence that immersive visualizations can help

people both achieve better pace regularity and be in heightened state of flow [12]. Instead of performing a symbolic calculation on a peripersonal watch or HUD, runners could rely on spatial perception by having information directly mapped over the environment (i.e., they “outsourced” the cognitive load of pacing to the environment). Embedded AR visualizations on-the-move are particularly promising for those situations where people are not simply moving, but also engaged in strenuous activities and therefore have limited available perceptual, cognitive, and interactive bandwidth.

► **INTERACTION IN MOTION** – Interacting with immersive visualizations while running (e.g., filtering a run to see the performance of the last split) is an unsolved challenge. Common Mixed Reality interactions (raycasts, direct touches) are obtrusive to perform while running, as they require stabilizing hands, which breaks the natural arm swing, which in turn disrupts momentum and flow. Opportunities are numerous to research inputs that are compatible with the running activity and do not compete with locomotion mechanics (e.g., gaze, voice commands, or cadence-based inputs like “stomp to select”).

► **A METHODOLOGICAL GAP** – Most HCI methods for prototype development, testing, experiments with human participants, and data collection are ill-suited to real-world, outdoor, dynamic environments. This raises myriad questions regarding how to prototype such systems, how to prompt participants, how to collect participants' responses to stimuli, and how to maintain some internal validity while aiming for external validity, to name a few. Not only do we lack appropriate methods, conducting such empirical research is also very challenging, time-consuming, and costly. It is a hard direction to take, but one that is worthy as we believe that real-life scenarios in outdoor settings where access to computing devices is cumbersome and obtrusive, are those that can truly benefit from Mixed Reality.

Acknowledgments

This research was funded in part by NSERC Discovery Grant RGPIN 2019-05422.

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²<https://developers.meta.com/horizon/documentation/spatial-sdk/spatial-sdk-pca-overview/>

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