Running with Data: a Survey of the Current Research and a Design Exploration of Future Immersive Visualisations

Ang Li, Charles Perin, Gianluca Demartini, Stephen Viller, Jarrod Knibbe, and Maxime Cordeil

Abstract— This work investigates the current research on in-situ visualisations for running: visualisations about data that are referred to during the running activity. We analyse 47 papers from 33 Human-Computer Interaction and Visualisation venues and identify six dimensions of a design space of in-situ running visualisations. Our analysis of this design space highlights an emerging trend: a shift from on-body, peripersonal visualisations (i.e., in the space within direct reach, such as visualisations on a smartwatch or a mobile phone display) towards extrapersonal displays (i.e., in the space beyond immediate reach, such as visualisations in immersive augmented reality displays) that integrate data in the runner's surrounding environment. We explore this opportunity by conducting a series of workshops with 10 active runners in total, eliciting design concepts for running visualisations and interactions beyond conventional 2D displays. We find that runners show a strong interest for visualisation designs that favour more context-aware, interactive, and unobtrusive experiences that seamlessly integrate with their run. These findings inform a set of design considerations for future immersive running visualisations and highlight directions for further research.

Index Terms—Running, Jogging; Survey, Taxonomy; Human-Subjects Qualitative Studies; Personal Visual Analytics; Mobile; Augmented/Mixed/Extended Reality, Immersive

1 Introduction

Running has become increasingly data-driven [4,35] as people run with wearables that track their activity. These wearables capture data such as pace, heart rate, and distance, which are available in real-time and visualised in-situ, while running. These visualisations are commonly displayed on wrist-worn or hand-held devices with small displays, such as smartwatches or mobile phones.

Previous work has explored how to best visualise data on these small devices, considering, for example, *glanceability* [8] (i.e., how people perceive and recall patterns from visualisations on smartwatches) and providing design spaces for visualisation on wearables [24,32]. This prior work has been limited, however, to the predominantly stationary use of smartwatches and has not yet considered the implications of use in motion [25,35,54]. For example, when running, the limited screen sizes of these devices makes reading data on such a display obtrusive, (i.e., runners have to raise an arm or divert their visual attention from the road ahead to the display.) This is disruptive to the running flow [38] and potentially hazardous.

Extended Reality (XR) devices have the potential to solve these challenges. They seamlessly integrate visual information directly into the surrounding environment, affording a larger display area and more in-situ and unobtrusive access to data [39,73,79]. In addition, XR devices afford interaction modalities such as gesture and gaze as alternatives to current obtrusive interactions on small displays. Industrial efforts have started to explore displays beyond hand-held and wrist-worn. For example, commercial smart glasses[1,2] have begun to bring visualisations into the runner's direct line of sight, though they do not yet support data-rich representations, and are currently bringing smartwatch-like visualisations into a non-interactive, monochrome, heads-up display (HUD). A recent collaboration[3] between Nike and Snap Spectacles has demonstrated the use of XR glasses that display 3D immersive content such as spatial dashing lines to motivate the runner. But these immersive visualisations are not data-driven.

This paper aims to provide insights in the design space of future immersive visualisations for running, beyond watches and phones. To begin, we survey research that has investigated visualisations using all kinds of display technology for runners. Our aim is to understand what types of visualisations and tasks need to be supported for data-driven running. We focus on the purpose, interaction space, device, data, visual encoding and embeddedness of previously explored techniques. Our survey shows an emerging trend towards presenting running data beyond traditional 2D displays into the larger space and surrounding environment of the runner, with running data closely coinciding with the physical space.

To further explore the possibilities of leveraging the surrounding space for running visualisations, we conducted an ideation workshop with runners who frequently use their tracked data in situ. Using immersive Head-Mounted Displays (HMDs) as a research medium, participants proposed design sketches and storyboards of immersive and interactive visualisation designs. Our analysis of the proposed designs allowed us to identify opportunities for designing embodied and immersive running visualisations.

Overall, our work collates existing attempts in the Human-Computer Interaction (HCI) and Visualisation research communities and compares them with insights from runners. We contribute the following:

- Through a scoping review, we establish a design space of in-situ visualisations for running, covering purpose, interaction space, device, data, visual encoding, and embeddedness. Our analysis reveals an opportunity to present running data in the more unobtrusive extrapersonal space, especially with XR technologies.
- Through a workshop, we explore and describe new opportunities for in-situ running visualisations in XR, that are more controllable, context-aware, and integrated into the environment, while also supporting tasks beyond performance tracking.

2 Scoping Survey for In-situ Running Visualisations

To understand the current research space of in-situ running visualisations and to identify potential opportunities beyond existing efforts, we conducted a scoping survey. We describe our survey's scope, methodology, and resulting analysis in the following subsections.

2.1 Survey Scope

There is an increasing interest in designing and exploring in-situ visualisations for sports and exertion within the HCI and Visualisation

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[1] Engo Eyewear
[2] ActiveLook
[3] Snap Spectacles x Nike

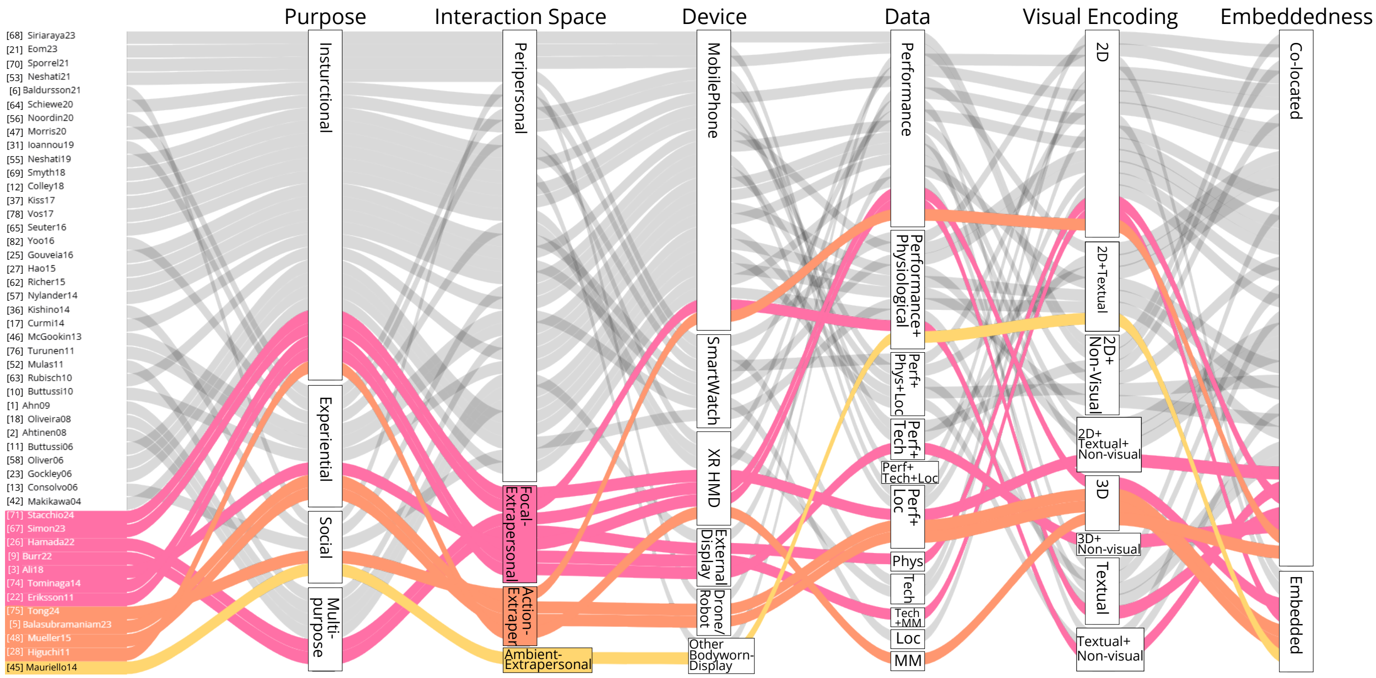

Fig. 1: The design space of in-situ running visualisations based on our scoping survey of 47 papers. The research in the *focal* (pink), *action* (orange), and *ambient* (yellow) areas of the extrapersonal space is highlighted. This reveals an emerging trend that shifts the display of real-time running visualisations from the peripersonal space to the extrapersonal space. An interactive version of the visualisation is available at `https://runningwithdata.github.io/` (generated using existing code [20, 30] with permission). Some Labels of the dimension of Data are collapsed for readability: Perf(ormance), Phys(iological), Loc(cation-based), Tech(nical), and M(ulti)M(edia).

communities [29, 40, 51, 59, 60, 81]. Specifically, Yao et al.'s [81] framework of Visualisation in Motion emphasises the opportunities and challenges of using visualisations when viewers and visualisations are in relative motion. For instance, a moving viewer with moving or static visualisations. The authors discuss the feasibility and design challenges of presenting visualisations effectively in dynamic conditions. Similarly, Lin et al.'s [40] SportsXR framework underscores the importance of immersive, situated, and context-dependent analytics for sports, identifying immersive sports visualisation as a promising but under-explored research domain. Running serves as an excellent proxy for such scenarios, because runners often engage in various data-driven tasks (e.g., maintaining pace, monitoring heart rate, and optimising running gait) during their workouts [35, 50]. While these frameworks establish the problem space, our work defines a comprehensive design space for in-situ running visualisation.

Real-time visual cues have been shown to provide beneficial instant feedback during physical activities [4, 33, 72]. Most existing systems focus on hand-held or on-body devices (such as smartwatches and mobile phones) that deliver feedback within the confined small display. Researchers have considered technology beyond those small displays, including drones [5, 6, 48, 74], external displays [74], and XR devices [26, 71]. In those cases, the display of running data visualisation is extended to the less obtrusive peripersonal and extrapersonal spaces.

As the volume of research on in-situ running interfaces continues to grow, there is an emerging need for a comprehensive design space that encompasses the range of devices involved, the variety of running data tracked and encoded, and the spatial context in which data is presented (both peripersonal and extrapersonal), for different running objectives. Therefore, we conduct a scoping review to map out the current landscape, identify key gaps, and inform future design directions for in-situ visualisation for running.

2.2 Selection Criteria and Analysis Process

To capture the breadth of research relevant to in-situ visualisation for running, we reviewed work from the last 20 years (from 2004 to 2024) that was broadly concerned with representing and running data to runners in real-time. We used the following query in the ACM Digital Library[4], IEEE Xplore[5], and the Scopus database[6]: `("visualisation" OR "visualization" OR "representation") AND ("running" OR "jogging") AND ("real-time" OR "in-situ") AND (LIMIT-TO(LANGUAGE, "English"));`

We then included a paper if it met all of the following criteria: a) it proposes new designs for data visualisation during running; b) it describes the designs sufficiently; c) the designs support runners in-situ (i.e., we exclude visualisations of running data for post-hoc analysis); and d) the paper includes at least one case where a design is used to inform users while running (but it may not be exclusive to running). We then propagated the search with forward and backward referencing (i.e. we reviewed papers that were cited or cited each selected paper, and added to the selection those that fitted the criteria). In total, we selected 47 papers from 33 venues, of which 11 were published in journals, and the remaining 36 were from conference proceedings.

We started the analysis process with the lead author reading all selected papers and identifying an initial set of dimensions. These dimensions included visualisation-specific dimensions (e.g., data types and encodings), technology-specific dimensions (e.g., devices and display sizes), task-specific dimensions (e.g., purpose and goal), and more generic aspects (e.g., publication year and venue). As a team, we iteratively refined those dimensions over multiple meetings and arrived at six dimensions which we describe next.

2.3 A Design Space of In-Situ Running Visualisations

We present the six dimensions of the design space of in-situ running visualisations extracted from the literature. We describe the values we found in each dimension, and synthesise the results in Figure 1. An interactive version of the visualisation is available at `https://runningwithdata.github.io/`. We provide in-line line

[4] ACM Digital Library
[5] IEEE Xplore
[6] Scopus

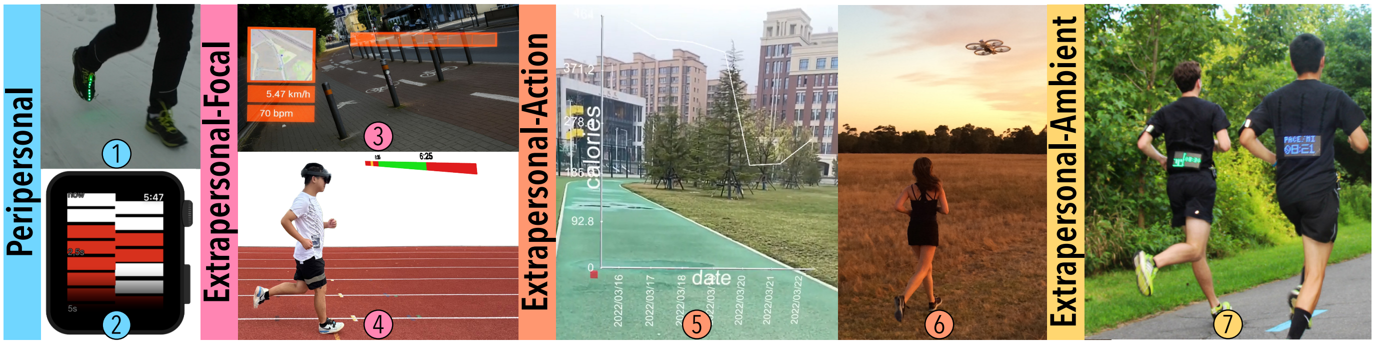

Fig. 2: Selected prior work representative of the peripersonal [12, 64], and the focal [39, 71], action [48, 75], ambient [45] of the extrapersonal interactive space [61]. Copyrights and permissions have been acquired from the corresponding authors and publishers.

charts to show the temporal distribution of a pattern in the surveyed period (from 2004-2009, 2010-2014, 2015-2019, 2020-2024).

► **Purpose** — Purpose refers to the runners' needs a visualisation is designed to address. We found three kinds of purpose: Designs with *Instructional* purpose (27 papers) focus on how well the runner runs [4, 33, 72]. Designs with *Experiential* purpose (nine papers) focus on how the runner feels while running [50, 72]. Designs with *Social* purpose (five papers) focus on how the runner runs with others [50].

Six papers aim at multiple purposes. For instance, some integrate *instructional* and *experiential* purposes, with gamified approaches [1, 9, 26] improving runners' experience while facilitating technique and performance training. Others integrate *instructional* and *social* purposes, for example, by using telepresence for virtual competitions between runners [18], and by sharing performance data between runners [2, 52].

► **Interaction Space** — Interaction space dictates how the data can be accessed and interacted with, for example, by directly tapping on a wearable or by distant gazing at a virtual object. Drawing on Previc's definition for 3D interaction space [61], we categorise interaction spaces as either *Peripersonal* or *Extrapersonal* (Figure 4-centre).

The *peripersonal* space refers to the area that immediately surrounds the runner's body, serving as the main area where visuomotor operations such as grasping and manipulating take place [61]. Thirty-five papers present running information in the peripersonal space, with data visualised on, for instance (see Figure 2-1,2), shoes [12], ground [6], smartwatches [24, 64], or mobile phones [18, 27].

The *extrapersonal* space refers to the region beyond the immediate reach of the runner, where interaction is less about direct manipulation but more about navigation, orientation, and perception within the broader environment [61]. Twelve papers present running information in the extrapersonal space. The extrapersonal space can be further divided into *focal*, *action* and *ambient* spaces [61].

The *focal* space (seven papers) refers to the focus zone of the runner's extended field of view, often used for visual target searching and reading critical information for decision-making or monitoring. For instance (see Figure 2-3,4), having skeletal representations of running gait on a moving display in front of the runner [74]; and a HUD-style display in XR HMD [67, 71].

The *action* space (four papers) refers to the area circling the runner and beyond the peripersonal space; it often includes distant manipulation, navigation and orientation activities. For instance (see Figure 2-5,6), flying drones programmed along a route at a constant speed for pacing and navigational purposes [5, 48] and canonical 2D visualisation (e.g., line charts) spatialized in AR, with gesture pointing for annotation [75]. Hamada et al. [26] used a pair of AR glasses, encoding the target running pace into a 3D virtual avatar that ran ahead of the runner. This could have been another example of the action space. However, due to technical limitations, the avatar was fixed to the runner's view instead of referenced to the ground, which caused its behaviour to align with the focal space instead.

The *ambient* space (one paper) refers to the vast area that extends from slightly beyond the peripersonal space to the most distant boundary area of the runner's perception, without the need to draw continuous attention or to perceive visual hints in detail. The social fabric research by Mauriello et al. [45] (see Figure 2-7) can be considered an ambient approach. In a group running setting, it embedded runner-specific data into the fabric displays worn on their back. The focus was not to have runners pay continuous attention to the displays, but to be aware of the condition of other runners as a group.

► **Device** — Running visualisations involve various devices that collect and present data to runners in real-time. We identified five categories of devices. *Mobile phone* is the most frequently used device (24 papers). *Smartwatch* and *Augmented Reality/Mixed Reality Head Mounted Display (XR HMD)* come next (seven papers each). *External display*, such as screens mounted on treadmills [1, 9], or carried by a moving device [74] appears in four papers. *Drone/Robot* appears in three papers. *Other body-worn device*, such as fabric displays on shirts [45] and shoes [12], appears in two papers.

► **Data** — Runners rely on a wide range of data to monitor their activity and inform their decision-making in-situ, for example, runners might adjust their running strategy based on their current pace or heart rate. The data can be directly tracked by the system, or derived from other data sources, but it has to be **communicated** to the runner through a means of representation to be included. We exclude data that is solely used to derive other metrics. We identify a combination of heterogeneous, multi-dimensional data in the literature, that we organise into five categories: *Performance*, *Physiological*, *Technique*, *Multimedia* and *Location-based*. We further identify the exact data used in each paper, colour-coded based on its category, as shown in Figure 3.

Performance data directly relates to the outcome of the run (e.g., duration, distance and pace). It is the most common data type (42 papers). Speed/pace (25 papers) is the most frequent *performance* data. *Physiological* data (15 papers) indicates the runner's status, such as their heart rate, number of calories burned, and breath frequency. Physiological data is not a direct outcome of the run but could be used to reflect the outcome. Heart rate (thirteen papers) is the most frequent *physiological* data. *Technique* data (seven papers) informs how correctly the runner runs. This includes foot strike type, ground impact force and gait, for example. Foot strike type (four papers) is the most frequent *technique* data. *Multimedia* data (two papers) corresponds to the raw imagery streamed in a run. In both cases, this takes the form of raw video footage. *Location-based* data (twelve papers) includes the location and navigational information. GPS coordinates (twelve papers) dominate this category. In five of those papers, GPS data was used for navigational purposes [46, 48, 55, 71]. In other cases, it was used to simply plot the runner's path [2, 21].

► **Visual Encoding** — To characterise data representations used in the literature, we use Shin et al. [66]'s classification of visual encodings (2D, 3D and non-visual), to which we add a *Textual* category, given the prevalence of textual representations on (running) watch faces [32, 35].

2D encodings (34 papers) refer to graphical representations that

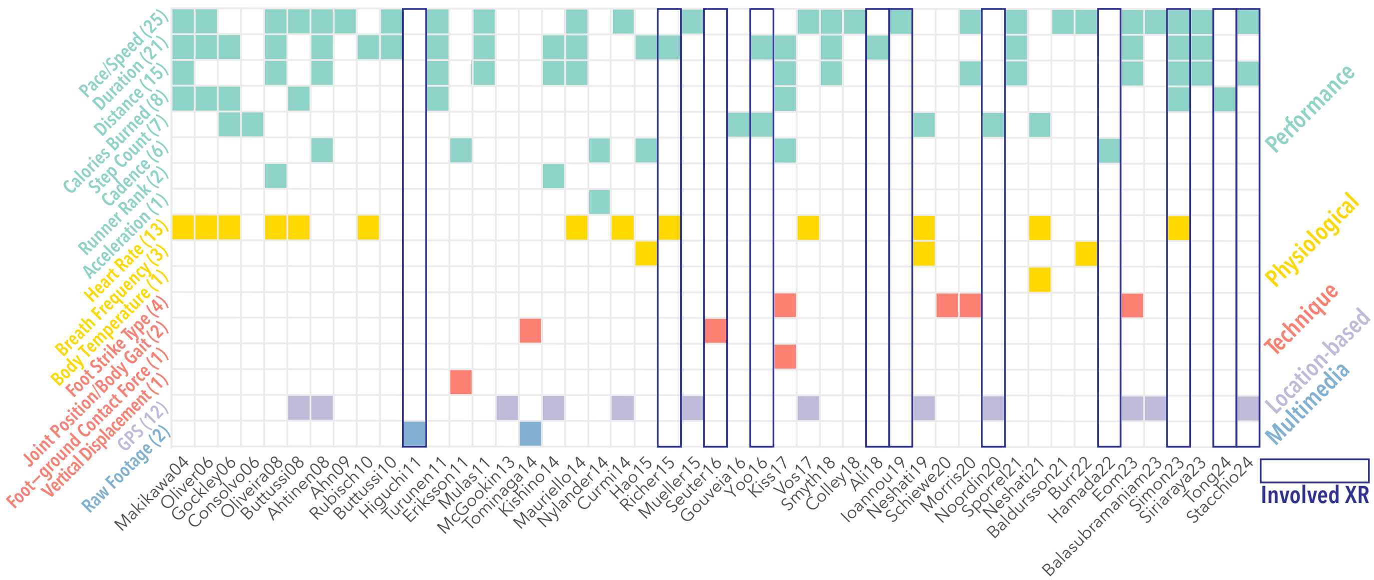

Fig. 3: Types of running data found in the literature, coloured by their high-level categorisations.

encode data with canonical 2D visualisations, such as scatter plots [57], line charts [2], map [78], 2D visualisations in a 3D space [75], as well as icons and labels [18, 23]. *3D* encodings (five papers) include 3D objects such as avatars [26], drones [48], and 3D visualisations (e.g., [14, 15]); *Non-visual* encodings (14 papers) refer to representations that encode data through non-visual means. All non-visual encodings we found use audio, for instance, music selected at a target tempo [63], rhythmic beeps [57], or spatialised audio from which the runner can infer the relative performance to history records [68]. *Textual* encodings (19 papers) refer to the use of alphanumeric characters [13] as the primary and sole carrier (i.e., as opposed to labels used inside graphical representations) of data values. While *2D* and *3D* encodings are graphical representations that leverage visual variables such as size, length and colour, textual encodings are symbolic representations that require semantic interpretation.

► **EMBEDDEDNESS** — We find Willett et al. [79]'s framework for embedded representations useful in describing how situated running visualisations are. In Willett et al.'s framework, embeddedness is a continuum of which *embedded* and *co-located* are two extremities [73, 79]. *Embedded* visualisations, which "spatially coincide with data referents [79]," are a subset of situated visualisations. *Co-located* visualisations refer to the non-overlapping (i.e., non-embedded) situated visualisations that are merely "in proximity to data referents [79]."

Forty papers feature *co-located* visual representations of running data (e.g., on smartwatch or cockpit-style AR displays [64, 67, 71]). Seven papers feature *embedded* visual representations. These represent running data on shoes [12], cloth [45] and on the ground around the runner [6]. In two cases, data such as pace has been embedded into the physical entity of a *drone* [5, 48]. Gait data has been embedded in the form of a 2D skeleton on the mirror footage of the runner [74], and pace has been embedded into a 3D virtual pacer [26].

2.4 Motivations and Tasks

The design space we presented describes **what** the *purpose* of in-situ running visualisations is and **how** those visualisations are implemented (in terms of *interaction space, device, data, visual encoding* and *embeddedness*). We complement this design space with a discussion of **why** in-situ visualisations for running are important.

The most common motivation mentioned in the papers we surveyed is the need to provide "unobtrusive access to data" while running. Papers describe this notion using the term "obtrusiveness" as well as synonyms. Papers from the pre-smartwatch era (before 2013, according to our survey) use the term "portability" [42]. Smartwatch-era (around 2013 and onwards) papers use the terms "glanceable interface" and "glanceability" [18, 24, 45, 46, 55], pointing at the challenge of improving the efficiency of reading visualisations. More recent papers, concerned with embodied and immersive interfaces, motivate their work to address the challenges of "disruption" or "distraction" [6, 12] that occur when runners need to take an unnatural posture to hold a smartwatch or mobile phone up while running. This challenge is exacerbated when showing multiple visualisations simultaneously, given the limited display space on smartwatches [53].

Other motivations for in-situ running visualisation include "increasing motivation for running" (ten papers), "improving the running technique to reduce injury" (six papers), and "socialising with others while running" (four papers).

While all of the surveyed papers involve an underlying task of data monitoring, few specify whether additional tasks are considered. Tasks beyond data monitoring include in-game activities introduced via gamification (seven papers), navigation (five papers), and interacting with other runners (two papers). Two papers describe additional analytical tasks: one supports gestural annotation for AR running data visualisation [75]; the other supports tasks such as data inquiry and comparison on a smartwatch display via tapping [53].

2.5 Evaluation Set-up and Scale

While outside of the design space, we thought it important to document the type of evaluation that was involved in previous research. The majority of papers we reviewed (37 out of 47) conducted some sort of evaluation on their proposed visualisation. Twenty-one of those were conducted in the field, and 16 in a more restricted lab environment. Not all evaluations involved ecologically valid running tasks. For example, some had restricted conditions outdoors (one paper); others non-realistic short running times (four papers); and others vague descriptions of the evaluation design (two papers).

Overall, we found that even though evaluations are often carried out, they tend to lack realism, as they take place in indoor settings (easier to control), for artificial tasks (easier to measure), failing to capture the complexities of a real outdoor running environment. Consequently, this limits the exploration of embedded and extrapersonal visualisations, which are highly integrated with the environment.

2.6 Conclusion on the Design Space of In-situ running

Our analysis of existing in-situ running visualisations reveals a strong focus on instructional running, with the main task considered being performance monitoring. Most visualisations for running data are co-located, leaving embedded visualisation, especially those with 2D encodings underexplored.

While emerging technologies such as XR provide new opportunities to display data anywhere in the surrounding environment, past work has largely focused on traditional devices such as smartwatches and mobile phones, with small screens that are either wrist-worn or hand-held within the peripersonal space. This leaves the use of other areas in the peripersonal space, and the vast extrapersonal space for displaying running data ripe for exploration.

3 Ideation Workshops with Runners

Our review of previous work highlights that i) existing devices have limitations for visualising data in-situ while running; ii) visualising data in the extrapersonal space in embedded manners could address some of the limitations of existing systems, and XR device is a promising way to achieve this; and iii) existing systems support little beyond data access and data monitoring tasks, although runners perform a wider range of tasks with a wider range of complexity when running [35].

To pursue this research opportunity, we ran four ideation workshops with 10 runners in order to elicit visualisation designs in the surrounding space of the runner, for meaningful tasks the runner would engage in while running.

3.1 Methodology

We designed the workshop format to be based on common real-life running scenarios, and to elicit immersive visualisation designs in peripersonal and extrapersonal spaces beyond the traditional smartwatch- or mobile phone-based displays.

3.1.1 Procedure and Apparatus

Participants first gave their consent for the collection of information and completed a demographic survey. Then, we presented to them the goal of the workshop. We highlighted existing challenges such as limited displays and obtrusive interactions with information while running; we also presented the potential of XR in improving these, extending the display space to the surrounding peripersonal and extrapersonal areas. Participants then engaged in the main workshop activity, in which they were asked to review and propose interactive running features for common running scenarios prepared by the researchers (see "Ideation Scenarios" next).

In the first part of the activity, workshop participants individually chose any scenarios that were related to their running experiences, refined those scenarios by adding or removing tasks and data types that were relevant or irrelevant, and then, in a group discussion, shared their experiences and challenges with those scenarios. In the second part of the activity, participants engaged in speculative XR design for every scenario chosen: without being exposed to the device's capability and limitation, they were asked to individually speculate what could be done in terms of immersive design for in-situ running visualisations, with the premise that the information could be displayed anywhere and in any form. Participants were asked to sketch their ideas on papers. In the third part of the activity, participants were invited to wear a Meta Quest Pro[7], a high-end Mixed Reality headset with pass-through technology that has the capability to display virtual objects we prepared in various locations ranging from the user's surroundings to their own body — we prepared a generic virtual watch face that anchored to the left wrist; a HUD-like display with generic textual information; a generic 2D icon that was mapped on the ground; and a 3D cube that floated in the environment. The former two objects would move with the user, while the latter two were independent of the user's movement. Participants were then asked to review and amend their proposed design, followed by participants demonstrating and enacting their designs to the group. To avoid introducing potential researcher bias that could influence participants' revised designs, all virtual objects were generic and representative of common interfaces that participants were already familiar with. The entire process lasted around two hours.

[7]Meta Quest Pro

The workshops were audio-recorded for later analysis. We report results from the workshops with reference to the dimensions we established for the survey (all dimensions listed in subsection 2.3 except **Device**, given that participants were instructed to ideate in XR). We also report common challenges mentioned by participants.

Although we do not envision runners wearing bulky headsets while they run, we chose to use a Meta Quest Pro headset as a research proxy in the third part of the activity for 3 main reasons. First, compared to other devices that are capable of displaying visualisation in the extrapersonal space, such as external displays and drones, XR can be used to seamlessly integrate the data and its representation with the surrounding environment [19, 73, 79]. This enables workshop participants to fully use the peripersonal space beyond traditional smartwatch displays, and the vast extrapersonal space. Second, XR can map data to various visual encodings defined in subsection 2.1, which is not the case with external displays and drones. Third, XR is intrinsically multi-modal, which enables participants to envision in-situ running visualisations in coordination with multiple interaction modalities.

3.1.2 Ideation Scenarios

With insights from the research team's running experiences, we elaborated four scenarios for ideation (an additional one, scenario 5, was suggested by participants). Each scenario featured a persona, and described the potential data and activities involved in that scenario so that participants could relate their own experiences. We describe the scenarios concisely below, and the full scenarios are available in supplemental materials.

Scenario 1: 5k Run — A recreational runner plans a fixed-distance route for 5 kilometres, often including hills for increased intensity, aiming to build fitness and mental endurance. They maintain a steady pace, synchronise breathing with cadence, and track calories, duration, heart rate, and pace via glanceable visuals.

Scenario 2: Interval Running — A competitive runner conducts interval training involving high-intensity sprints and recovery jogs, using alerts for interval transitions. They closely monitor metrics such as duration, speed (peak, average, minimum), and breathing rhythm and compare their performance with personal bests.

Scenario 3: Group Run — A social runner participates in local or remote group runs, sharing running tips, maintaining a collective pace, and encouraging other runners. They track real-time data (duration, speed, distance) to support friendly competition and achieve common running goals.

Scenario 4: Open-route Exploration — A casual runner explores a new neighbourhood by running freely at a comfortable pace, focusing primarily on the surroundings. They mark interesting locations encountered, use real-time navigation data to choose paths, and monitor their distance from home to manage the run safely.

Scenario 5: Marathon* — This scenario was not prepared by the researchers. Instead, it was suggested by participants (P2, P7, P9) during the workshop session. Participants brought the marathon scenario up when they were reviewing **Scenario 1: 5k Run** and **Scenario 2: Interval Running**. They related to their own marathon experiences, suggesting there should be a scenario that is more enduring and less casual than **Scenario 1** but less intense than **Scenario 2**.

3.1.3 Participants

A total of ten participants took part in the study. They were assigned to one of four workshops based on their availability. One workshop had four participants and three workshops had two participants.

We collected participants' level of experience in running and in immersive devices with a Likert scale (from 1: no experience to 5: very experienced). All of the participants identified as frequent and data-driven runners (average level of expertise in running of 3.2/5) and ran on a weekly to daily basis: one participant ran 5–7 hours a week, three ran 3–5 hours, four ran 1–3 hours, and two ran 1 hour or less. Regarding the use of running devices, five ran only with a smartwatch, three only with a mobile phone, and two with a smartwatch and a mobile phone. All expressed strong interest in immersive devices, with the level of

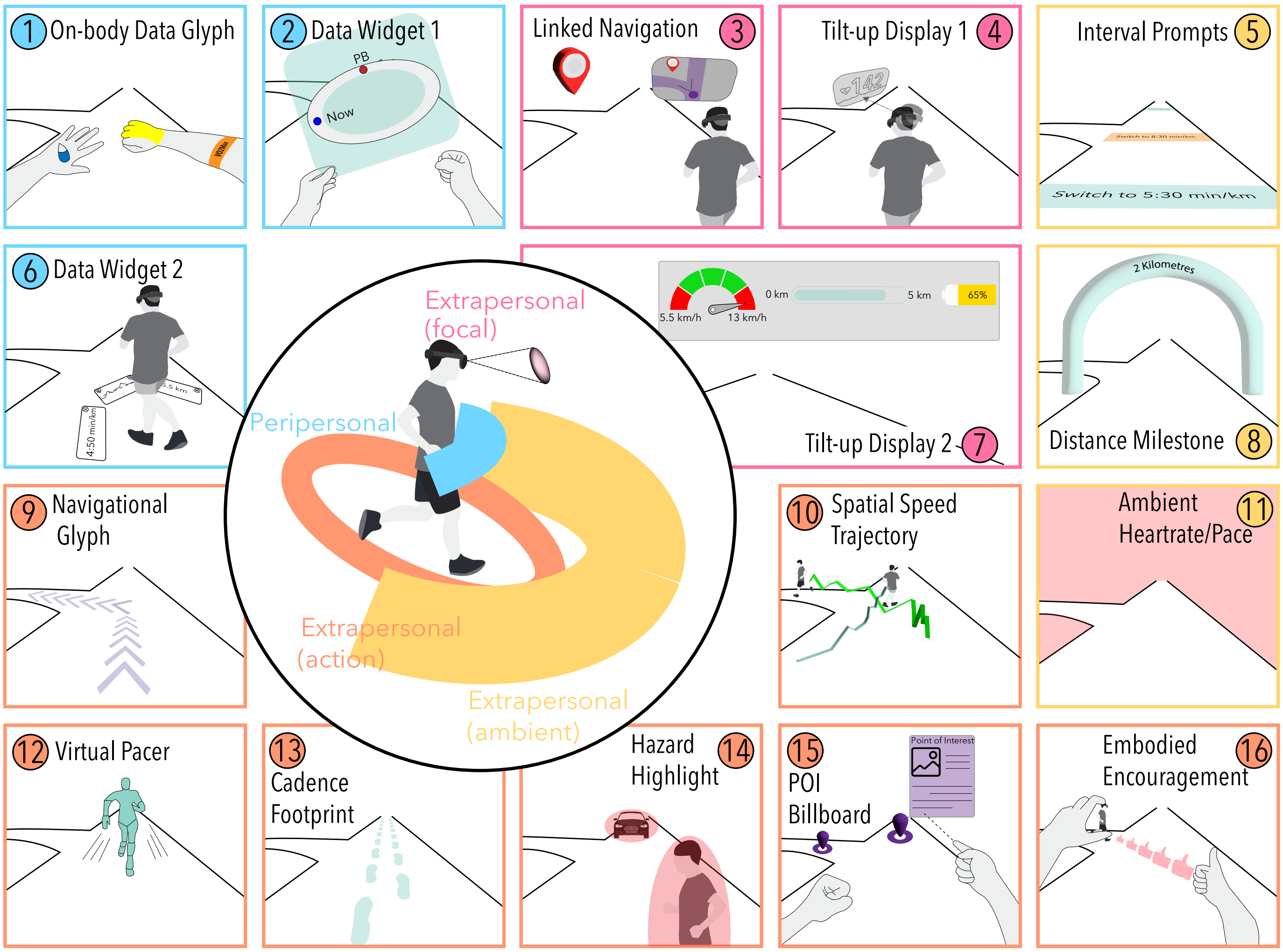

Fig. 4: Selected immersive designs proposed by the participants in our preliminary workshop (redrawn for clarity), mapped to the action spaces defined in Previc's 3D spatial interaction framework [61]. The colour of the outline of the designs refers to its corresponding interaction space.

experience with XR averaging at 3.1/5. None had previously run with an XR headset.

3.2 Results

Participants produced a total of 46 design ideas for in-situ running visualisations in XR. They produced designs for all scenarios: 29 for *5k Run*, fifteen for *Open-route Exploration*, fifteen for *Group Running*, four for *Marathon*, and two for *Interval Running*. Participants sometimes used the same design across multiple scenarios, and sometimes proposed variations of a design to suit their needs in different scenarios.

▶ **PURPOSE** — The designs have *instructional* purposes (27 designs), *experiential* purposes (nine designs), *social* purposes (four designs), and *multiple* purposes (six designs). All of the *multipurpose* designs aim to address both *instructional* and *experiential* purposes, with four using a virtual pacer/running companion (e.g., Figure 4-12) and two introducing gamified elements that require runners to match their cadence with spatial objects embedded along a route (e.g., Figure 4-13).

▶ **INTERACTION SPACE** — Following the dimensions for 3D spatial interaction by Previc [61], we group the elicited designs into four spatial interaction spaces: peripersonal, extrapersonal-focal, extrapersonal-action and extrapersonal-ambient.

Peripersonal Space — Sixteen designs are in this space, manifested by a range of direct gestural interactions for various activities, which is a trait of the peripersonal space. These include layout arrangement for running visualisation (five designs, e.g., Figure 4-2); menu selection (four designs, e.g., Figure 4-6), and voice input for selection (one design). Four designs included object manipulation such as dropping a pin/emoji to register a location/emotion, or dropping a friend's icon to start tracking their stats on a floating leader board/map in a *group running* scenario. Two designs were visualisations embedded to the runner's hands and arms (e.g., Figure 4-1), with the body surface serving as a larger display compared to a smartwatch. The underlying activity involves data monitoring. One design included making a specific gesture to trigger a feature (taking a photo with a framing gesture).

Extrapersonal-focal Space — Nine designs are in this space. The main activity in the designs is monitoring running data (eight designs). While five of those eight designs are specified to be always within the runner's peripheral view, three of them require the runner to slightly tilt their head up or look in a certain direction in order for the visualisation to appear (e.g., Figure 4-4,7). The one design not for monitoring was proposed for location searching. It featured a 2D map interface in the runner's focal zone, and envisioned a linked 3D visualisation to appear in the space when the runner looked towards the direction of a point of interest shown on the map (Figure 4-3).

Extrapersonal-action Space — Eighteen designs are in this space. Sixteen of those were proposed for navigational tasks, with usages of location-based data. The remaining two proposed gestural interactions to select and send encouragements to another runner (e.g., Figure 4-16). In addition to navigation, five designs facilitate pacing (e.g., Figure 4-12,13); two designs facilitate distant interaction to manipulate an information board (e.g., Figure 4-15); one design envisions receiving running related information via spatial audio, which had been seen in previous studies [49, 77].

Extrapersonal-ambient Space — Three designs are in this space. They embed visualisation for pace altering (see Figure 4-5) and for milestone notification (see Figure 4-8), or propose an ambient colour-changing feature for pacing activities (see Figure 4-11).

► **DATA** — Participants indicated thirteen types of running data in their chosen running scenarios. The most common data types include duration (ten participants), speed/pace (eight participants), distance (seven participants), heart rate (seven participants), and GPS (six participants). While most data types participants used have been visualised in the previous research we surveyed, we report the ones that have not. VO_2 Max (suggested by P2, P9) is derived from heart rate and running distance. It serves as an indicator of endurance. Fat burned (suggested by P1, P5) can be derived from heart rate with consideration of body weight and running duration. It reflects running performance, similar to calories burned. Running type (suggested by P4, P5) can be derived from speed. It reflects the running intensity. Body battery (suggested by P2) is a metric on Garmin watches[8], which can be derived from heart rate, stress score, sleep quality, with consideration of the ongoing activity. It reflects the runner's stamina – "I would stop running when it is below 20%, otherwise I would pass out" (P2).

► **VISUAL ENCODING AND EMBEDDEDNESS** — In terms of visual encoding, 18 designs rely on *2D* encoding, 15 leverage *3D* metaphors, and 12 use *textual* representations. We categorised four designs that were primarily about interactions as 'not applicable.' In terms of embeddedness, 25 designs have representations *embedded* into the surrounding environment and seventeen have *co-located* representations. The four about interactions were again categorised as 'not applicable'.

With insights from both visual encoding and embeddedness, we further conducted an inductive grouping of the designs, which revealed the following patterns:

HUD-like Data Widget — Sixteen designs represent running-related data in the form of widgets, made of simple text, numerical values, icons or graphs that follow the movement of the runner and stay within their peripheral vision, in a HUD style display. These designs mostly represent physiological or performance-related data (eight instances, see Figure 4-4,7); two were navigational, with GPS data embedded in a 2D map (see Figure 4-3); two widgets show the ranking of runners in a *Group Running* scenario; and the remaining four widgets are in the form of a menu where data needs to be organised, or toggled on and off by gestures (see Figure 4-2). We note that these designs resemble traditional 2D visualisations and interfaces commonly seen on smartwatches and mobile phones and are familiar to runners.

In-situ Visualisation — Twenty-one designs consider the spatial capability of XR devices and place visualisations in the environment. Ten of these designs are in the form of icons or glyphs that are embedded on the ground for navigation (see Figure 4-9) and running instruction (see Figure 4-5, 13), and in the form of exergames (e.g., having gamified elements like coins or monsters that the runner has to collect or avoid). Four designs are in the form of a virtual avatar (see Figure 4-12), running either as a pacer or a navigator. Three designs (see Figure 4-15) are about the *Open-route Exploration* scenario and show textual and graphical information about nearby points of interest situated at crossroads for runners to make in-situ decisions on the direction to go to. One design proposes a trajectory visualisation, trailing the runner's path, with the height of the trajectory proportional to the runner's current speed (see Figure 4-10). One design proposes a hazard detection feature (see Figure 4-14), which embeds glowing circles to moving objects in the scene, to notify the runner of potential collision hazards during their run. One design suggests the manipulation of the ambient colour for pacing or heart rate zoning – changing the ambient environmental colour to red to indicate the runner is too fast, yellow to indicate the runner is too slow, and no manipulation when the runner is on the target pace or heart rate (see Figure 4-11).

Body-Centric Visualisation — Five designs are directly embedded or anchored to the runner's body. Two of these (see Figure 4-6) are anchored around the foot of the runner, with widget-like designs embedded on the ground. The participants who proposed these envisioned slightly leaning in the direction of a widget to toggle them on and off. Two designs anchor location-based markers/emojis on the palm of the runner, where markers can be dropped to register a) points of interest and b) emotion at the place. One design (see Figure 4-1) is embedded in the hand/arm of the runner – the participant suggested that data types of a more frequent usage should be placed at a more salient area, saying: *"I want my body hydration and body battery level on the back of my hand, while having VO_2 Max on my arm. Because I need to pay close attention to the first two data to determine when to stop, while I would only need to check my VO_2 Max once or twice."*

[8]Garmin's Body Battery

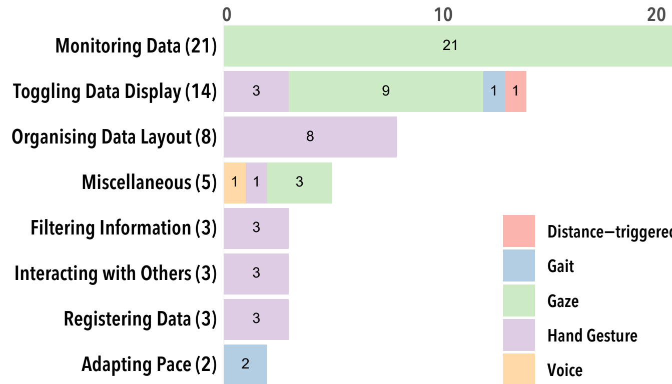

Fig. 5: Generalised tasks based on the participant-proposed designs, colour-coded by their interaction modality.

3.3 Challenges and Tasks

We collated the illustrations and audio recordings that described participants' designs; then we extracted tasks supported by the designs. We identified eight running tasks (see Figure 5). The most frequently mentioned task is *monitoring data*, manifested by 21 designs, underlying a strong analytical demand for well-informed decisions to be made in-situ. *Toggling data display* (14 designs), and *organising data layout* (eight designs) come next, jointly indicating the demand for the customisability of the spatio-temporal appearance of the immersive running visualisations. The rest of the activities range from more performance/analytics-oriented tasks (e.g., *adopting running pace*, and *filtering information*), to more experiential activities (e.g., *registering data*, such as points of interest, current feeling and emotion, and *miscellaneous* tasks such as replying to messages, and switching music).

We further analysed the challenges that the participants mentioned they had faced during a run. Many participants mentioned the limitations of the devices they use to access the data. The most common issue was related to the size of the display – P2: *"I have to switch screens of my watch manually when I access different data (e.g. heart rate, speed, and distance),"* P6: *"(My watch) can only fit up to four data types on watch screen at a time. Sometimes hit the wrong button when trying to look at other data,"* P7: *"Sometimes my smartwatch screen is not big enough to display all metrics that I want to see,"* P10: *"My sports watch is too small to see."* Another common issue was with the obtrusive interaction with the device while running – P3: *"I have to flick my arm every time when I want to check the data on the watch,"* P4: *"Taking my phone out for display while running is very disturbing,"* P5: *"Reading data on my phone screen makes me feel dizzy and unsafe (while running),"* P8: *"Using my phone (putting in the passcode, opening app) when I am running is inconvenient."*

4 DISCUSSION

Devices such as mobile phones and smartwatches have been the standard to visualise running data such as heart rate and pace. However, both our survey and workshop highlight a growing interest in moving visualisations beyond those small, flat displays, towards more immersive devices such as an *XR HMD*. This emerging trend uses immersive technologies to create richer, more embodied visualisations for runners [26, 39, 75].

Our ideation workshop elicited a diversity of immersive visualisation and interaction designs from runners. All participants raised the challenges of having a limited display size on wearables, and the obtrusiveness of accessing data on those while running. Many of the designs they proposed address those challenges by visualising running data with 2D encodings embedded in the peripersonal and extrapersonal spaces, with more embodied and engaging interactions and for tasks beyond data monitoring.

With this in mind, we synthesise insights from both the survey and the workshop. We discuss alignments and discrepancies between existing research and the perspective of runners to inform future research.

4.1 Visualising a Wealth of Running Data

We found through our survey (see Figure 3) that seven out of eleven papers that made use of XR devices provided visualisation for only a single type of data. While it is understandable that the exploratory purpose of these works may limit the type of data visualised, in our workshop we saw that runners need to access multiple data types in coordination in running scenarios, as evidenced via visualisation design snippets such as Figure 4-1,3,4,6,7. This is not surprising, given that state of the art smartwatches used by runners also display multiple data types on a single screen [35].

In the workshop (see subsection 3.2), we also found that participants used visualisations of derived data: data computed based on multiple directly tracked data, such as VO_2 *Max* and *body battery*. Visualising those more abstract derived data types might result in more abstract visualisations, which might be more difficult to interpret and require incorporating additional contextual information [7]. Immersive and situated visualisations are a promising way to integrate contextual information seamlessly in the surrounding environment.

While immersive devices afford a large display that could show multiple designs simultaneously, simply applying standard visualisations like those found on smartwatches and mobile phones would likely overwhelm runners with information, keeping in mind the intensity and focus required by the running activity [43]. Immersive technologies offer an extra depth dimension compared to flat devices, with opportunities to show abstract running data at meaningful spatial locations. For instance, an avatar visualisation (Figure 4-12) could serve as a virtual pacer, like in previous work [26], but instead of visualising a single data type (target pace), additional information could be visualised (e.g., the location of the avatar could communicate navigational data).

Embodied visualisations of multiple data types provide an opportunity for addressing both performance and experiential needs, something that participants of our workshop expressed. Embodied visualisation designs like virtual avatars (Figure 4-12), and pacing footprints (Figure 4-13), both fulfil performance needs and experiential needs, compared to rather traditional designs like data widgets (Figure 4-2,6).

4.2 Exploring Context-aware Running Visualisations in the Extrapersonal Space

The workshop results highlighted that the running scenario and context influence the visualisation the runner might want to use. For example, design snippet 7 (Figure 4-7) contains a progression bar for distance, and a simple textual visualisation for pace—it was designed for the *5k run* scenario. The same design applied to the *marathon* scenario, however, included a pacing gauge with simple textual or icon-based visualisations for distance, duration, calories and heart rate.

Several designs are in fact inherently context-aware, as they situate data only at relevant locations (e.g., Figure 4-5,8,14,15). This aligns with Lin et al. [40]'s vision of SportsXR, that analytics in sports must be *"situated, highly dynamic, concise, and context-dependent to play an auxiliary role."* Future research should consider context-aware running visualisations that dynamically shift between different levels of detail and interaction modalities based on the runner's status, activity and context. While adaptive approaches that dynamically adjust visualisation properties based on users' cognitive load have been explored in some prior work [41] in a sedentary setting, an opportunity remains to extend this into running and the broader exertion scenarios, and to be adaptive to other physiological and environmental factors.

Our work integrates insights from Previc's [61] 3D interaction space, further extending current frameworks by detailing how the spatial environment can be segmented. The extrapersonal-focal space supports decision-making tasks, for example, with AR glasses displaying running metrics in the focal zone of the runner [71]; or with immersive visualisation widgets to monitor running data in real-time (Figure 4-4,7). The extrapersonal-action space facilitates goal-oriented tasks and distant interactions, and is supported, for instance, with *Drones/Robots* [5, 48], immersive projections [6], footprints (Figure 4-13) and avatars (Figure 4-12) that embed the target pace to their moving speed, acting as a pacer with navigation capabilities. Lastly, the extrapersonal-ambient space enhances situational awareness, providing unobtrusive cues, for example, by showing interval and distance milestones in a situated manner (Figure 4-5,8), and ambient colour changes (Figure 4-11) to indicate the current pace.

The interaction space of the design space we introduced in subsection 2.3 demonstrates the potential of immersive technologies to expand running visualisation and interaction beyond traditional displays. However, embracing extrapersonal visualisations must account for the challenges of motion. For example, Yao et al. [81] found that increased speed and path complexity of the moving visualisation can negatively affect one's ability to read the information on it. Future research should explore how to use these spaces to coordinate running-related data without overwhelming users, especially in the extrapersonal-action and the extrapersonal-ambient space, where greater relative motion exists between the visualisations and the runner.

4.3 Supporting Unobtrusive Running Experiences Beyond Data Monitoring

Our survey of the literature highlighted that most existing running visualisations support simple data monitoring activities. While visualisation designs from our workshop also include supporting data monitoring (Figure 5), we see a broader range of activities for which they envision using visualisations. This shows a desire from runners to gain proactive "control" over the interface. For instance, design snippets 2 and 6 in Figure 4 allow runners to choose what information to display and where; designs 4 and 7 let the runner control when to display the running visualisation, which is shown when the runner slightly tilts up their head' or winks/gazes at a specific direction; design 13 provides runners to anticipate and proactively adapt their pace to the target pace, at their own rhythm, thanks to embedded pacing indicators along a predefined route. These findings highlight research opportunities for designing immersive in-situ running visualisations that provide runners with control over them. Runners want visualisations to appear at the right time (evidenced by the activity *Toggle Data Display*), in the right place (evidenced by the activity *Organise Data Layout*), and in the right amount (evidenced by the activity *Filter Information*). More control over such factors would contribute to an enhanced sense of flow when running [16].

Another challenge for achieving a state of flow when running with technology is that of having to perform inefficient interactions with those technology, which presume a "stop to interact" paradigm [44] – we refer to this as the obtrusiveness of interaction while running. Participants in our workshop raised that concern of obtrusiveness of interaction, citing small displays and manual input on traditional devices as significant barriers. Immersive technologies can help address the obtrusiveness of monitoring data while running, with careful design considerations. Indeed, supporting interaction needs as identified in Figure 5 can easily incur obtrusiveness and affect the runner's flow [38]. Evidenced by our findings from the workshop, for example, when it comes to the activity of *Toggle Data Display*, the gesture based interactions (e.g., Figure 4-2,15) would be arguably more obtrusive than the gaze-based interactions (e.g., Figure 4-3,4,7). The former requires hand gestures to toggle performance/location information of runners, while the latter only requires runners to look at a certain area. The gaze-based interactions would in turn be more obtrusive than the gait-controlled interactions (showcased in Figure 4-6), where runners need to subtly change running direction to toggle selection on a semi-circle layout. The more unobtrusive the interaction is, the more integrated it is with the running activity itself. We thereby argue that future interaction design for immersive visual interface while running should be proposed to naturally align with the running activity, instead of parting from it.

This is in line with the "interaction in motion" framework [43] that uses the locomotion activity as the primary interaction channel. This framework consists of two dimensions for designing interaction in motion: i) the relevance between the interaction and the locomotion activity, and ii) the level of constraint the locomotion activity has on the ability to interact. Tailored interaction should be given to tasks that are highly constrained by and related to the locomotion, as opposed to the more generic interactions for tasks that are weakly constrained by, and related to, the locomotion [43]. Applying this framework to the running context, we argue that tailored interactions should be prioritised for use in more serious types of running (e.g., performance-oriented running, high-intensity interval training) and when the runner is under high cognitive load, whereas a higher tolerance of obtrusiveness should be given to interactions that are used in casual running and when the runner is under low cognitive load.

There is a promising opportunity to integrate multi-sensory channels for more unobtrusive real-time running feedback, especially with the emergence of immersive technologies, which are multi-modal in nature. In fact, 13 papers from our survey conveyed information with non-visual modalities. Those papers argued that these additional modalities would bring more unobtrusive experiences to accessing running data in real-time. However, we found no instance of an immersive system that made use of its multi-modal nature for running.

4.4 Designing for Social and Collaborative Running

Our survey results show that little research on running visualisation has been dedicated to social aspects of running. However, participants in our workshop demonstrated interest social running and group running. We discuss this in relation to the matrix for Computer-Supported Cooperative Work (CSCW) [34].

Synchronous and co-located — Running with other people at the same time and in the same area is the most represented social running scenario mentioned by participants in our workshop (seven designs). Participants envisioned inter-runner interactions, such as keeping track of other runners' performance via a linked visualisation between a performance leader board and an overview map of the performances along the running course (three designs); sending gestural signals to motivate fellow runners (two designs, e.g., Figure 4-16); or sharing the navigation information about the running route with embedded visualisations (two designs, e.g., Figure 4-9,10). We found similar attempts to foster synchronous and co-located running in previous works, with exergame and common tasks to motivate group dynamics [1], and with wearable fabric displays to share personal performance information [45].

Asynchronous and co-located — Running asynchronously in the same area was envisioned four times in our workshop. The motivation in this case was to run against historical performances of oneself or of other runners, via map-based and virtual avatar-based visualisations (Figure 4-2,12). In this context, one design from the workshop allows the runner to express their emotion in-situ for future runners to view.

Synchronous and remote — Only one design from the workshop was envisioned for synchronous group running in different locations, which involved using an arbitrary ranking board. Previous research has looked at sharing physiological data of a runner with spatialised audio [49] and a web-based interface [17]; and at projecting the relative speed of another runner via a drone [6].

Asynchronous and remote — No design from the workshop addressed this scenario. This was expected, given our focus on eliciting visualisation designs for real-time and in-situ running. Previous research, however, has been conducted for this scenario, with a common approach being to use previous records of other runners as a comparator of the current run [13, 18, 36]. However, in all the previous works, the comparator is not updated over time but based on a static record of the final outcome. A replay of historical records could be incorporated to better fit the real-time usage.

Overall, running is an activity that people experience in the moment, right now, right there. Therefore, it is not surprising that the most promising quadrant of the CSCW matrix is the Synchronous Co-located. The Asynchronous Co-located quadrant also makes sense for running, given that many runners run in the same area as others, but at different times. Immersive technologies have the potential to strengthen social connections and motivate runners in their run. While the workshop designs are mainly envisioned to support runner-to-runner interaction, we captured insights from the literature that could also be beneficial, by fostering runner-viewer/coach interaction [17, 52, 80]. We also encourage future research to explore the two less obvious quadrants of the CSCW matrix that can be very relevant in some contexts (e.g., a pandemic forbids runners from running with others).

5 Limitations

Our workshop results do not include many technique-focused designs. Although 2 participants mentioned that they would pay attention to their running technique – such as breath frequency – when discussing the *interval running* scenario, no particular design elements were proposed for it. The participants we recruited are all frequent runners; yet, they do not possess professional running expertise, such as athletic track or hurdle running, where running technique is crucial. Future opportunities remain to work along with field experts in competitive running to devise insights for running training.

We also acknowledge the methodological limitations of our ideation workshop. Our participants ideated immersive visualisations for running without engaging in actual running activities during the design sessions. While we could capture rich, imaginative ideas, the absence of an in-situ running context during ideation might have encouraged proposals that are visually or conceptually appealing but potentially impractical or overly complex in real-world scenarios. For instance, designs involving extensive multimodal interaction or highly detailed extrapersonal displays might prove too cognitively demanding or visually distracting when applied in real running conditions. Nonetheless, this does not invalidate our exploration of the design space of in-situ running visualisation.

Like recent research in this space [26,39], our work is constrained by current technology, and we certainly do not envision that people should start wearing a bulky headset while running. Instead, this research paves the way for meaningful visualisation designs once hardware limitations are addressed, including their low see-through resolution, bulky design, lagging spatial tracking, discomfort when sweaty, and low adaptability to extreme outdoor conditions.

6 Conclusion

Our work investigated the existing research efforts and the future potential of immersive visualisation for running. Through a scoping survey, we established a comprehensive design space for data-driven running, spanning across purpose, interaction space, device, data, visual encoding, and visualisation embeddedness. We highlighted an emerging trend towards displaying visualisation beyond conventional screens of watches or phones, to the surrounding peripersonal and extrapersonal areas. Through an ideation workshop with frequent data-driven runners, we identified a preference for embedded data visualisations in the extrapersonal space, which inform contextual information pertinent to running. Runners involved in our ideation workshop expressed demands for a variety of tasks beyond data monitoring, favouring unobtrusive and embodied interaction with data.

Taking into account findings from both our survey and workshop, we highlight opportunities for future research to design derived and multidimensional data visualisation, providing richer insights with contextual awareness. Our findings also lead us to believe that the extrapersonal space has a strong potential in presenting running visualisation unobtrusively, and therefore further research should be done in that direction.

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