Situated Visualization in Motion

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Abstract—We define visualization in motion and make several contributions to how to visualize and design situated visualizations in motion. In situated data visualization, the data is directly visualized near their data referent, i. e., the physical space, object, or person it refers to [1]. Situated visualizations are often useful in contexts where the data referent or the viewer does not remain stationary but is in relative motion. For example, a runner looks at visualizations from their fitness band while running. Reading visualizations in such scenarios might be impacted by motion factors. As such, understanding how to best design visualizations with motion factors is important. We define visualizations in motion as visual data representations used in contexts that exhibit relative motion between a viewer and an entire visualization. We propose a research agenda to understand what research opportunities and challenges are under visualization in motion [2]. Next, we investigate (a) how motion factors can affect the reading accuracy of visualizations [2], (b) how to design and embed visualizations in motion in a real application scenario [3], and (c) the user experience and design trade-offs of visualization in motion through a case study [5].

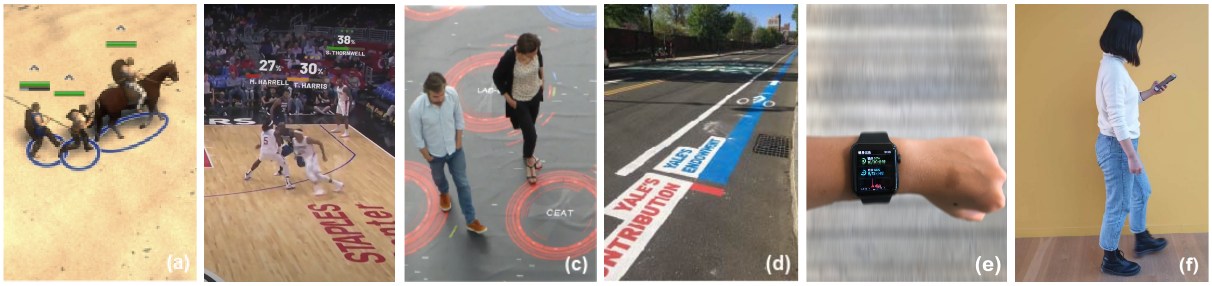
With the development of computing technology, visualizations have moved off the paper and onto interactive media. The relative movement relationships between the viewer and visualizations can be under motion. For example, embedded dynamic representations have been common for years in video games (Fig. 1a, [5]) to show character health; match-related charts are attached and move with players in sports videos (Fig. 1b, [3]); physicalizations are printed on the road (Fig. 1c and 1d) to allow people to walk by and read; people can read exercise data from a smartwatch while running (Fig. 1e, [6]); navigate a map on a smartphone while walking (Fig. 1f, [7]). We call visualizations such as these *visualizations in motion* and define them as follows:

> Visualizations in motion are visual data representations used in contexts that exhibit relative motion between a viewer and an entire visualization.

Motion factors, which are factors that affect or describe the movement of an object, such as distance, speed, and displacement, have played a role in the visualization community for a long time, in the form of animation. Animation is frequently used to highlight parts of a visualization, to provide smooth transitions of data points in time, or to morph between different representations. Instead, *visualization in motion* is concerned with the relative movement between *entire* visualizations and the viewer. Imagine, a dynamic scatter plot is updating in real-time. A simple data point may move from one coordinate to another due to a data update. Nevertheless, the movement of this data point happens inside the plot. The entire plot does not change its position during this process. A scatter plot would become a *visualization in motion* if the entire plot changed its place — jumping from the top-left corner of the screen to the bottom-right.

Yet, *visualization in motion* is not only concerned with visualizations moving on a screen. Apart from moving visualizations, *visualization in motion* also involves cases where the viewers are in motion. Imagine the scatter plot mentioned above was an augmented 3D chart. Some data points could hide others when seen from different perspectives. A viewer wearing a head-mounted display might need to go around to see them. In this scenario, the visualization (3D plot) does not change its position, while the viewer does. A similar scene would happen if this scatter plot were a data physicalization. Viewers in the physical world also might need to go around to see the whole physicalized plot due to the overlapping of some parts between different viewing angles.

To appear in IEEE Computer Graphics and Application. Digital Object Identifier: 10.1109/MCG.2024.3462129.



Moving visualization & stationary viewer. Stationary visualization & moving viewer. Moving visualization & moving viewer.

FIGURE 1: Visualization scenarios that involve different types of relative movement between viewers and visualization: (a) 0 A.D. game characters with attached health meters; (b) an augmented basketball match from the tool Clipper CourtVision; (c) a walkable visualization of the general organization of scholars at ENAC in France; (d) an on-street bar chart that can be driven or walked by created by the *Respect New Haven* activist group; (e) a runner looking at her fitness data; (f) a person navigating a map on her phone while walking to a meeting.

Based on the movement status of the visualization and viewer, we classify *visualization in motion* into 3 categories:

	Stationary viewer	Moving viewer
Stationary vis		×
Moving vis	×	×

Moving visualization & Stationary viewer: A stationary viewer sees an entire visualization move and is required to move their eyes and/or head to track the visualization to read it accurately possibly. Examples include sports analytics, where charts are attached to moving players or equipment; video games, where health bars are embedded over the head of game characters; and simple visualizations (e. g., rectangles, labels/colors) used in object tracking to label the target objects. Interactions like zooming, panning, rotating, and changing view position can also lead to *visualization in motion*, such as navigating a map.

Moving viewer & Stationary visualization: A moving viewer focuses on a stationary visualization and experiences additional optical flow during self-motion in the world — the consequence of viewer movement is changing the viewing angle and orientation towards the visualization. The effect of this type of motion has been researched sparsely in visualization, for example, in wall-sized displays, data physicalization, and AR/VR research.

Moving visualization & Moving viewer: Both visualization and viewer might also move independently simultaneously with relative motion between both. This motion includes a small scale of changes, like in wearable and mobile visualizations — reading a visualization (e. g., heart rate, calories burned) from smartwatches worn on the arm during a run (Fig. 1e); but also includes larger changes in motion, such as when visualizations are projected onto approaching traffic and seen from a moving vehicle.

While stationary viewers may also experience illusory motion with stationary visualizations (e. g., stroboscopic motion or the phi phenomenon), we exclude this scenario as no relative motion between the viewer and visualization is present. The impact of relative motion will depend on the type and magnitude of the relative motion itself. Some types of relative motion, such as saccadic eye movements or simple head movements, will likely not lead to an interesting impact on reading visualizations, while higher magnitudes of relative motion will lead to a more measurable impact, depending on the scenario.

The definition of *visualization in motion* points to a research space that is much larger than the previously outlined scenarios. In our work, we first propose associated challenges that point to possible research directions of all these three categories. Next, we concretely explore the category on **Stationary viewer & Moving visualization**:

- How do motion characteristics affect the readability of *visualization in motion* and to what extent?
- How can we design and embed *visualization in motion* in a real application scenario?
- How is the user experience of *visualization in motion* and what are the trade-offs in design?

A RESEARCH AGENDA

In this section, we highlight new possibilities for research on *visualization in motion* and show important factors that need further exploration. We summarize important future research from the following 4 aspects[1]. A full version of our research agenda can be found in our TVCG paper [2].

Characteristics of motion: In physics, motion is described as the phenomenon in which an object changes its position

[1]Some aspects of these themes may be interrelated. It is not possible to provide distinct boundaries between themes. Rather, we highlight the base properties that may affect visualization reading and their research opportunities. Of course, combinations between aspects need to be further researched as well.

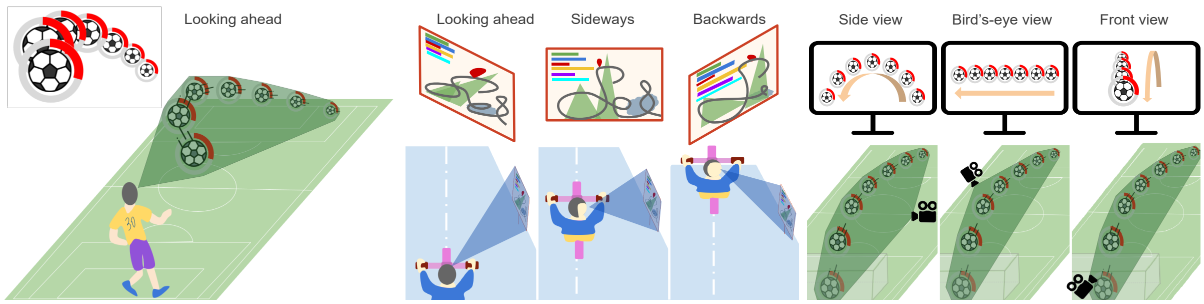


FIGURE 2: Left: Changes to the perception of a soccer ball's size and position based on the distance between viewer and visualization. Center: Changes of a moving cyclist's perception of a static map and bar chart based on changes between the viewer and the visualization space. Right: The same physical motion of a soccer ball will lead to different trajectories on the viewer's retina based on the relationship of viewer to world space.

over time according to a frame of reference. To research visualizations in motion, we, thus, first have to consider appropriate reference points. Taking the human viewer as the reference, a visualization can exhibit relative motion or relative immobility. If we consider a human viewer to be a fixed point of reference (even if the viewer is actually moving), relative motion exists if a visualization moves relative to this fixed viewer due to a different speed or motion trajectory. If both the human and the visualization do not move or move at the same speed along the same trajectory (e. g., a human reading a stationary visualization on a moving airplane), there is no relative motion. The relative motion may impact the effectiveness of visualization perception due to motion characteristics, which include *moving speed* (how fast the spatial relationship between viewer and visualization changes), *movement trajectory* (the path along which the spatial relationship between viewer and visualization changes), *acceleration* (he change rate in speed), and *direction of motion* (to where in a reference space the visualization seems to be moving). A main research challenge relevant to motion characteristics includes understanding how well people can track and to what extent they can read visualizations moving very fast, along irregular trajectories, in unpredictable directions, and/or with changing speeds. We explore this challenge and explain it more specifically later in this paper.

Spatial relationship between viewer and vis: As mentioned before, the application scenarios of visualization in motion can be in a space. Thus, we discuss the potential impact of spatial relationships between the viewer and the visualization on visualization in motion design. We define the *viewing distance* as the linear distance between the viewer and the visualization, which may affect how the visualization appears on the viewer's retina. For example, as illustrated in Fig. 2-Left, the closer the ball is, the bigger the ball size the player can perceive. We also consider the coordinates between the viewer and the visualization (*viewer vs. visualization space*): A visualization has an inherent local coordinate system. The viewer of this visualization can be modeled using a local coordinate system that changes with head and/or eye movement. The relationship of these two coordinate systems in a world impacts how a person sees a visualization in their field of view. For example, in Fig. 2-Center, a cyclist riding past a static map can see the visualization morphing over time as the visualization-to-viewer coordinate system transformation changes. Furthermore, the relationship between the viewer's coordinate system and the world-coordinate system (we call *viewer vs. world space*) describes how the viewer looks at a specific scene. Example presented in Fig. 2–Right shows how the same movement would be seen from different views.

Situation, context, and design: In our exploration, visualizations in motion are typically displayed and related to the environment and, thus, have a specific context. The influence factors on visualization in motion design not only include *contextual factors* (with or without a background), *connection to data referents* (close or far away), and *visualization design parameters* (representation type, visualization complexity, representation decoration, visualization size, and color selection) but also include the *autonomous of motion* (under or out of the viewer's control) and *predictability of motion* (the viewer knows where the visualization will go). To what extent the autonomy and predictability of motion play a role in how well visualizations can be tracked, and read is still an open problem.

Technology: Here we list the technologies that can be used to generate visualization in motion. *Stationary screens* typically show visualizations moving on the screen while the audiences sit static (Fig. 1a and 1b). *Physicalizations* mostly involve moving viewers who might need to go around to see the stationary data physical representation (Fig. 1d and 1c). *Mobile and wearable devices* already carry visualizations that are dynamically updated and can be experienced by wearers when exercising (Fig. 1e and 1f). *AR/VR* is another technique to build 3D scenes with visualizations, where viewers are commonly free to move their viewpoints and positions. Besides, a number of future technologies for which visualizations in motion can help to produce promising application scenarios, like visualizations to display on holographic projections, visualizations on or by drones, or visualizations embedded in robots.

In summary, *visualization in motion* includes wide research opportunities and challenges for design as well as for in-depth empirical research. Some inspiration and hypotheses for empirical studies can be derived from psychology and broader HCI, but almost no work has explicitly looked at moving data representations, except ours.

A SET OF EMPIRICAL EVIDENCE

We began our concrete exploration with a basic question: How accurately can people read *visualizations in motion*? We chose to start with studying the effects of different speeds and trajectories on representation type as we hypothesized that these basic characteristics of motion could highly influence the readability of different representations.

We conducted two crowdsourcing experiments: **Experiment-Speed** and **Experiment-Trajectory**. In both experiments, we tested 2 visual representations: `Donut` and `Bar`. We used magnitude estimation tasks that required people to read a quantitative value from a proportion visualization, similar to tasks that would be required in two promising application domains (e. g., sports analytics and video games). The magnitude proportions that we tested per visual representation are 18%, 32%, 43%, 58%, 72%, and 83%. We also added 0% as an attention check percentage. For each experiment, we recruited 60 participants per visual representation. In total, we had 240 participants. For **Experiment-Speed**, we had 3 speed conditions: `Static` condition moving at 0 cm/s (baseline), `Slow` speed moving at 15 cm/s, and `Fast` speed moving at 30 cm/s. For **Experiment-Trajectory**, we had 4 trajectory × speed conditions: slow × `Linear` & `Fast` × `Linear` (as in our speed experiment but used as baselines in the trajectory experiments), `Slow` × `Irregular` showing a slowly moving stimulus, and `Fast` × `Irregular` showing a fast moving stimulus. Our speeds and trajectories were all ecologically validated from real soccer matches.

Our full paper, with details, can be found at TVCG [2]. Here, we only highlight our main findings that are the most interesting to visualization researchers and practitioners.

Experiment-Speed: Table 1 shows the participants' mean absolute error per speed (Left), the pairwise differences in absolute error across two speeds per chart type (Center), and the differences across two representations (Right).

Impact of speed: High speeds did have an influence on human readability. `Fast` speed caused more errors than `Static` and `Slow` speed conditions in both `Donut` and `Bar` representations. However, the differences were small for both chart types in practice, around 1–2 percentage points.

Comparison across visual representation: `Donut` was more accurate than `Bar` at all speeds. This evidence is more pronounced on `Fast` and `Slow`. It appears that donut charts can be read slightly more accurately than bar charts when in motion (<3 percentage points).

In summary, speed affected reading performance — reading accuracy decreasing with higher speeds. However, in practice, participants were still able to quite reliably read proportions from moving charts, with an accuracy that was close to 95%. Although at high speeds, `Donut` was more accurate than `Bar`, their practical differences were small.

Experiment-Trajectory: Table 2 shows the participants' mean absolute error per speed × trajectory condition (Left), the pairwise differences in absolute error across two conditions per chart type (Center), and the differences across two representations (Left).

Impact of trajectory: Trajectory type did have an impact on reading accuracy. `Irregular` trajectories caused more errors than `Linear` ones for both `Donut` and `Bar`, in particular at `Fast` speed.

Comparison across visual representation: Participants' answers were always more accurate with `Donut` than with `Bar` by 1–2 percentage points under the same regularity of trajectory. This effect is particularly strong at `Fast` speed. For all speeds and trajectories, participants' answers were consistently more accurate on `Donut` than on `Bar`. These differences are particularly visible for `Irregular` trajectories and `Fast` speed, where accuracy differences reached up to 4.13 percentage points for some of the larger proportions.

In summary, the regularity of the trajectory impacted participants' performance — the reading accuracy decreased with irregular trajectories and higher speeds as well. Participants again performed better on `Donut` than on `Bar`; the difference was more pronounced than in the speed experiments but still remained small in practice.

Overall, our results showed that both speeds and trajectories impacted the reading accuracy of visualization in motion — higher speed and irregular trajectories would lead to more errors. The good news is that people can still get reliable information from moving simple charts, which provide empirical evidence to support embedding visualizations in motion into real application scenarios. Practically, when designing visualization in motion, donut chart might be a better choice than bar chart in practice.

A TRY IN PRACTICE

After demonstrating that people could read visualization in motion, we began to practice — how to design and embed visualizations in motion. Many real application scenarios, like augmented sports analytics (Fig. 1b), contain simple moving

TABLE 1: *Absolute error* analysis for Experiment-Speed. Left: Average mean absolute error in percentage points for each chart type. Middle: Pairwise comparisons for each speed and representation. Right: Differences of mean absolute error across representations. Error bars represent 95% Bootstrap confidence intervals (CIs) in black, adjusted for pairwise comparisons with Bonferroni correction (in red).

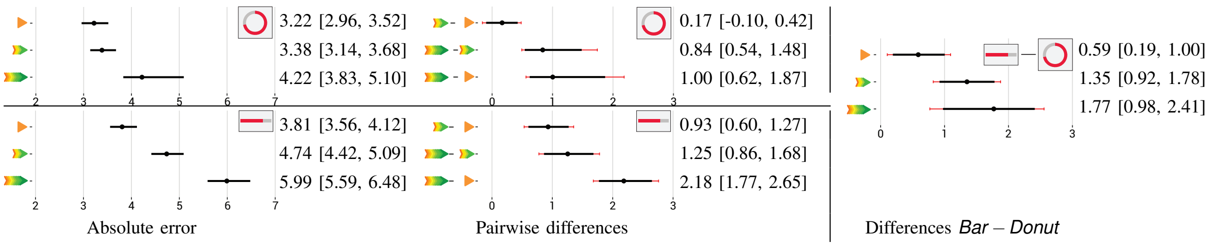
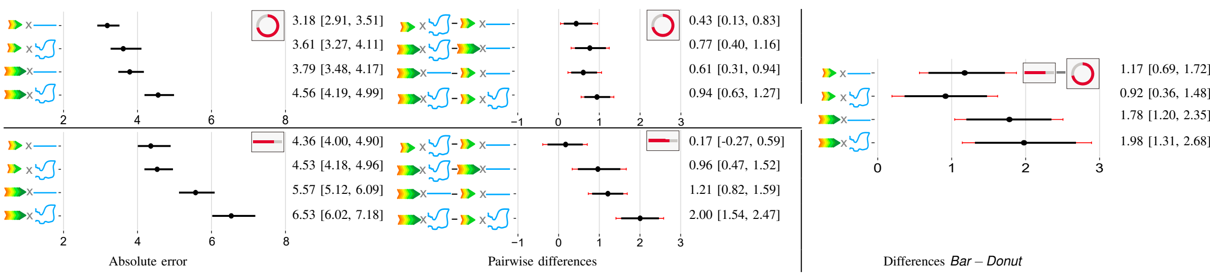


TABLE 2: *Absolute error* analysis for Experiment-Trajectory. Left: Average mean absolute error in percentage points for each chart type. Middle: Pairwise comparisons for each speed × trajectory condition and representation. Right: Differences of mean absolute error across representations. Error bars represent 95% Bootstrap confidence intervals (CIs) in black, adjusted for pairwise comparisons with Bonferroni correction (in red).



visual representations related to athletes' performance and race metadata. Nevertheless, creating, embedding, and testing designs for visualizations in motion remains difficult. Real-world contexts contain busy backgrounds and various motion characteristics. As such, visualizations in motion need to be designed to be informative but not distracting from the audience's primary motivation, such as watching the race. Considering that our empirical experiments showed that participants performed better on linear trajectories, we selected swimming as our target motion context. It has approximately linear trajectories and rich and dynamic data that is already visualized but to a limited extent.

We conducted a systematic review to investigate the visual representations used, the data encoded, and the movement status of the visualizations embedded in swimming races. Next, we ran an online survey to clarify the real data needs of swimming race audiences. We also conducted an ideation workshop to collect diverse visual representations designed for the swimming context. After that, we developed *SwimFlow* [4] to investigate the significance of the full motion context in the design process and the impact of instantaneous visual feedback of motion effects on the design decisions of *visualization in motion* (screenshots of examples made by *SwimFlow* can be seen from Fig. 3). We ended this work by conducting a design evaluation and proposing a set of design considerations for *visualization in motion*.

Our full paper is available at TVCG [3]. Here, we only highlight the **systematic review** from which we obtained a first swimming data matrix, the results of **online survey** that indicates what data the general audiences are interested in seeing, and the **design evaluation** that pointed out design challenges.

Systematic review: To understand how to support the design process of embedded visualizations best, we studied how visualizations are currently embedded in swimming broadcasts. Our results are shown in Fig. 4, a first data matrix illustrating what swimming data can be visualized and what part of them have already been visualized, statically and dynamically. The majority of the available swimming data has not been visualized yet. Furthermore, more than half of the data that was visualized were under motion, which indicates that audiences might be interested in seeing more visual data representations that move with swimmers.

Online survey: Despite many types of data tracking that may interest audiences, currently, visualized data in swimming races are quite limited, and embedded visualizations in motion are even rare (Fig. 4). One of the possible reasons behind this scarcity of embedded visualizations could be designers not being aware of what audiences want to know. Thus, we conducted an online survey with 80 swimming enthusiasts to investigate what data general audiences are interested in seeing in swimming races.

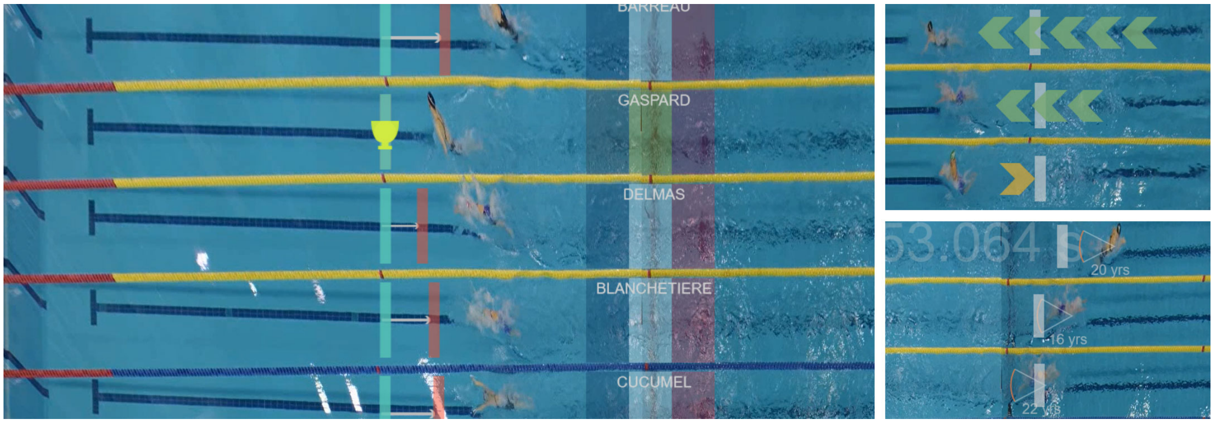


FIGURE 3: Embedded representations added to a swimming video of the 2021 French Championship using our technology probe [4]. These show dynamically updating visualizations that move with the swimmers: distance to the leader and predicted winner (left), speed distance to a personal record (top right), and current speed and swimmers' ages (bottom right). The left and bottom right images show stationary embedded representations of the swimmers' names, nationality, and elapsed time.

Our participants' interest in each data item is depicted in Fig. 5. Out of the data items that received an interest level above 70%, 20/30 belonged to `dynamic` updating data, while the remaining 10/30 were `static` data. Participants found all `time-related`, `speed-related`, `predictions`, `swimming techniques`, and `record-related` interesting, while `external` data received the least interest. Three data items that move with swimmers (current speed, flags, and record lines) received high-interest rankings (>89%). The world `record` was ranked as extremely interesting. Some data items with high-interest levels were not yet part of current broadcasts, like the `distance` between the current leader and other swimmers. Participants also expressed interest in other subtle differences between swimmers, including `time-related` and `speed-related` data (e. g., lap time differences and speed differences to a record and/or other swimmers). Participants additionally showed a keen interest in `swimmer's metadata`, explained as they care about who fights for their country.

Tool development & Design evaluation: To understand the difficulties of embedding visualizations in motion in real application scenarios. We then developed a technology probe — *SwimFlow* [4] that allows users to design and embed visualizations in motion into a swimming video and browse the rendering effects immediately. We recruited 8 professional designers with rich experience in graphics design to do design evaluation. Participants were asked to design visualizations in motion on a static video frame with a hidden play/stop button and progress bar (`Motion-limited mode`) and on a playable video with an enable play/stop button and a draggable progress bar (`Full-motion mode`).

Most participants (7/8) preferred to do design in `Full-motion mode`— directly on the playing video and see the motion-coupled effects between visualizations and swimmers simultaneously. Participants explained that designing, embedding, and previewing the effects visualizations in motion in its context in real-time can help much from the following aspects: (a) *Motion identification:* can correctly recognize the motion characteristics of moving entities (swimmers), like the movement direction and acceleration. (b) *Accessibility to dynamic data updates:* can be aware of the updating frequency of a data item, which helps to assign the movement status per item and check how the corresponding visualization would change. (c) *Flexibility of motion control:* can polish the design in detail and check design behavior at specific moments, such as turning. (d) *Instantaneous preview:* demanded much less mental effort to imagine the motion effects and can do a quick design-reflect-redesign phase. (e) *Context awareness and confidence:* can avoid adding too many visual representations (especially text) to overwhelm audiences. (f) *Expectation match:* give confidence in their final design, as what they have designed will be exactly the same product the audience will see.

Participants also expected improvements in our technology probe to further help with designing visualizations under motion context, e. g., more flexible specification of visual encoding, video editing functions, and rich animation effects to spot highlight moments.

In summary, we have taken the first step to embed *visualization in motion* into real applications. We found that designing visualizations in motion and the dynamic updating data directly in its context was extremely helpful. Particularly, the ability to see design changes reflected immediately with moving referents is important. However, further exploration is needed to match users' advanced requirements.

Dynamic Data					
Time related	Elapsed time	Current lap	Average lap	Lap differences to other swimmers	Lap differences to a record
Speed related	Current speed	Average speed, Speed history	Acceleration, slow down	Speed differences to other swimmers	Speed differences to a record
Distance related	Distance swam	Remaining distance	Distance differences to leader	Side-by-side distance between two swimmers	Trace of movement
Predictions	Record break	Winner	Completion time	Next passing	
Swimming techniques	Distance per stroke	Reaction time	Diving distance	Stroke count	
Static Data					
Swimmers' metadata	Nationality	Name	Lane number	Age, Gender	Height, weight
Record related	World record	Competition record	National record	Personal record	
External	Social Media followers	Social Media discussion	Sponsor		

FIGURE 4: Swimming data matrix with example data items. Yellow: the data items visualized statically in current races; Purple: the data captured and shown in motion.

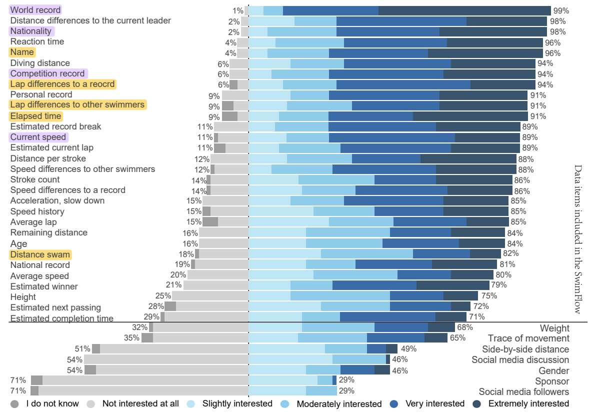


FIGURE 5: Participants' interest level in seeing visualizations per swimming data item. A black horizontal line separates the data items included in our technology probe [4]. Yellow: the data items visualized statically in current races; Purple the data visualized in motion.

A SET OF DESIGN TRADE-OFFS

In practice scenarios (e. g., sports and video games), *visualizations in motion* are typically attached to moving referents, inform users of useful data, or provide helpful information. However, reading from visualizations is not the users' unique task in such scenarios. Instead, watching the race or playing the game is their primary task. Thus, it is important to explore how to best design visualizations in motion in practice. We used video games as our testbed because it has a primary game task and players need as well to read from in-game visualizations (e.g., health bar) to help with game actions. We conducted a systematic review to see how the in-game visualizations in motion are currently designed. We developed our own video game, *RobotLife*, that allowed us to inject our self-designed visualizations in motion (Fig. 6). We evaluated different visualization designs (Fig. 6) with 18 game players to investigate their user experience. Our full paper will be available at TVCG [5]. Here, we only spotlight the **design trade-offs** that may interest visualization practitioners.

: The `non-integrated design` is highly readable for moving robots because it was visible even behind occluding objects. Its embedding location (over the data referent) helped to find robots, but participants found it less aesthetically pleasing and thought it was less immersive. Its typical visual representation requires less experience and effort to read but also lacks innovation and might disappoint participants who look forward to a novel user experience.

: Participants did not have a clear preference for the `partial-match design` and always treated it as a trade-off option to balance overall considerations. The embedding location of the `partial-match design` (overlap with data referent) could give a somewhat immersive experience. The visual representation of the `partial-match design` may excite players at some level, bringing both task challenge and game attractiveness.

: The `fully-integrated design` has a good integration in our game context and, as such, gives players an immersive experience. However, it may not be ideal for reading-based tasks, especially with dynamic changes and multiple types of motion. The embedding location of the `fully-integrated design` (into the referent) is rare in FPS games, which enhances realism but also brings extra challenges for players due to its high integration level. The visual representation of the `fully-integrated design` could not be seen everywhere. Its rarity, however, had a novelty effect and brought a unique gaming experience.

In summary, our evaluation showed that each design had specific advantages and shortcomings. Not only do the *embedding location*, *visual representation*, and *visual encoding* affect user experience, but the *motion conditions*, the *context*, and the *tasks the visualization supported* also play a significant role. Rather than simply saying which design was best, there are trade-offs to consider based on concrete scenarios and user needs.

FIGURE 6: (a) `Non-integrated design`: a horizontal bar chart positioned outside of the robot; (b) `Fully-integrated design`: a vertical bar chart integrated into the texture of the robot; and (c) `Partial-match design`: a circular bar (donut) matching a part of the robot's shape.

DISCUSSIONS AND CONCLUSION

Visualization in motion has gained a lot of attention in the visualization community—especially with mobile, wearable, and immersive technologies evolving. For example, Islam et al. [6] proposed a dedicated research agenda for fitness trackers, in which they discussed the updated challenges of perceiving and displaying visualizations that typically need to be read under motion and within a brief time. A more recent work from Grioui et al. [7] showed that walking can reduce the reading accuracy of a smartwatch visualization. Meanwhile, reading can slow down walking speeds and also have some impact on walking posture. Regarding practically using visualizations in motion, Lin et al. [8] proposed Omnioculars to embed visualizations that can move with players in a re-built AR basketball race. Recent work from Chen et al. [9] developed iBall that can attach visualizations in motion into a real basketball race video based on gaze interaction.

In conclusion, we proposed *visualization in motion* as a new research direction that focuses on the relative motion relationship between the visualization and its viewer, as well as a first research agenda. We focused on the category of moving visualizations & stationary viewers and proposed empirical results, practice framework, and design trade-offs. Our research agenda includes a much larger set of promising broad research directions for *visualization in motion* than the work presented in this paper. In addition, delving into application scenarios also opens up new research spaces related to visualizations in motion. Particularly, visualizations in AR/VR pose a rich and diverse set of motion-related challenges in the context of moving visualizations and moving viewers. We, thus, invite more visualization researchers and those who have an interest in motion factors and context to join in this emerging research direction.

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ACKNOWLEDGMENT

We thank our jury members (Gilles Bailly, Morten Fjeld, Niklas Elmqvist, Wendy Mackay, Uta Hinrichs, and Melanie Tory), advisors (Petra Isenberg and Anastasia Bezerianos), collaborators (Romain Vuillemot, Federica Bucchieri, and Victoria McArthur), and all participants relevant to the work presented here. Partial of this work was supported by the Agence Nationale de la Recherche (ANR), grant number ANR-19-CE33-0012 and ANR-19-STHP-0004.

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