Visualization in Motion: Perception, Design, and User Experience

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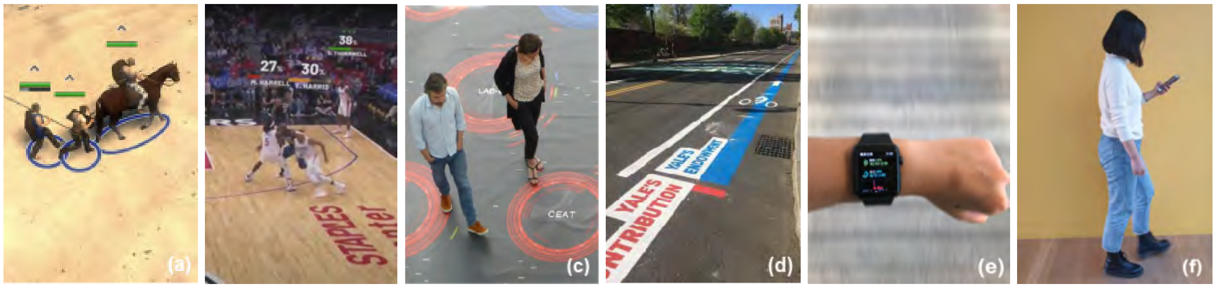

Moving visualization & stationary viewer. Stationary visualization & moving viewer. Moving visualization & moving viewer.

Figure 1: Scenarios that involve different types of relative movement between viewers and visualization: (a): game characters with attached health meters, (b): an augmented basketball match from Clipper CourtVision. (c): a walkable visualization of scholars at ENAC in France. (d): an on-street bar chart that can be driven or walked by. (e): a runner looking at her fitness data. (f): a person checking financial charts on her phone while walking to a meeting.

Abstract

We proposed *visualization in motion* as a new research direction that focuses on the relative motion relationship between the visualization and its viewer. Here, we introduce our concrete work on the exploration of how the motion characteristics have an impact on the perception, design, and user experience of visualizations, extracted from a set of our work published at TVCG [1–3].

Index Terms: Visualization in motion, situated visualization.

1 Introduction

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 (1a, [2]) to show character health; match-related charts are attached and move with players in sports videos (1b, [3]); physicalizations are printed on the road (1c and 1d) to allow people to walk by and read; people can read exercise data from a smartwatch while running (1e); navigate a map on a smartphone while walking (1f). 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 [1].*

Motion factors, have long influenced visualization, most commonly through animation to highlight, transition, or morph data elements over time. In contrast, *visualization in motion* is concerned with the relative movement between *entire* visualizations and the viewer. Based on the movement status of the visualization and viewer, we classify *visualization in motion* into 3 categories:

Moving visualization & Stationary viewer: The entire visualization moves while the viewer remains still, requiring eye or head movement to follow it.

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Moving viewer & Stationary visualization: The viewer moves while the visualization remains fixed, which creates changing viewing angles and optical flow during self-motion.

Moving visualization & Moving viewer: Both viewers and visualizations move and create relative movement between them.

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 concretely explore the category on **Moving visualization & Stationary viewer**:

- How do motion characteristics affect the perception 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?

2 Perception: A Set of Empirical Evidence

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 a series of crowdsourcing experiments with 2 visual representations: `Donut` and `Bar`; 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; and 4 trajectory × speed conditions: slow × `Linear` — & `Fast` × `Linear` —, `Slow` × `Irregular` showing a slowly moving stimulus, and `Fast` × `Irregular` showing a fast moving stimulus.

Our full paper, with details, can be found at TVCG [1]. Here, we only highlight our main findings that are the most interesting to the visualization community:

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.

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`.

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.

3 Design: A Try in Practice

Next, we applied *visualization in motion* to a real application scenario. We selected swimming as our context as it has approximately linear trajectories and rich and dynamic data that is already visualized, but to a limited extent.

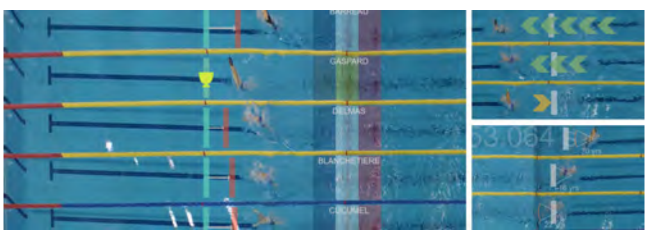

Figure 2: Embedded representations added to a swimming video of the 2021 French Championship using *SwimFlow*, show updating visualizations that move with the swimmers: distance to the leader and predicted winner (left), speed differences to a personal record (top right), and current speed and swimmers' ages (bottom right). The left and bottom right images show stationary embedded representations of the swimmers' names, nationality, and elapsed time.

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. We then ran an online survey to clarify the real data needs of swimming race audiences. We next conducted an ideation workshop to elicit visual representation designs for the swimming context. After that, we developed *SwimFlow* 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* (Fig. 2). 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]. Part of our work has been used at the 2024 Paris Olympics: as swimmers approach the edge of the pool, the speed displayed to the public is replaced by the distance difference, breaking the display rules that have been in place since the 2000 Sydney Olympics.

4 User Experience: A Set of Design Trade-offs

In practice scenarios such as sports watching or game playing, reading from visualizations in motion is not the users' unique task. Instead, watching the race or playing the game is their primary task. Thus, it is important to understand how to best design visualizations in motion in practice. We used video games as our testbed (Fig. 3) because it has a primary game task and players also need to read from in-game visualizations (e. g., health bar) to help with game actions.

Figure 3: (A): Non-integrated design; (B): Fully-integrated design; (C): Partial-match design.

Our full paper is available at TVCG [2]. Here, we only spotlight the design trade-offs that may interest visualization practitioners:

Non-integrated design offered strong readability, particularly under occlusion, due to its placement directly over the data referent. However, its conventional appearance was perceived as less immersive and aesthetically engaging. Partial-match design served as a balanced, middle-ground option—neither strongly favored nor rejected—offering moderate immersion and a visually dynamic form that added a layer of game-like challenge and appeal. In contrast, the fully-integrated design was praised for its contextual integration and immersive qualities, but its high visual blending and dynamic behavior made it difficult to read in fast-paced tasks. Its rarity enhanced perceived novelty but also introduced usability challenges.

Overall, our findings suggest that no single design excels universally. Instead, user experience is shaped by the interplay of embedding location, visual representation, encoding type, task demands, and motion dynamics. Effective design thus requires careful consideration of context-specific goals rather than adherence to a one-size-fits-all solution.

5 Conclusion

Visualization in motion has gained rising attention in the visualization community—especially with mobile, wearable, and immersive technologies evolving. We provided basic knowledge on how motion characteristics affect the perception, design, and user experience of visualization. We invite visualization enthusiasts and those who have an interest in motion factors and context to join in this emerging research direction.

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