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Situated Visualization in Motion

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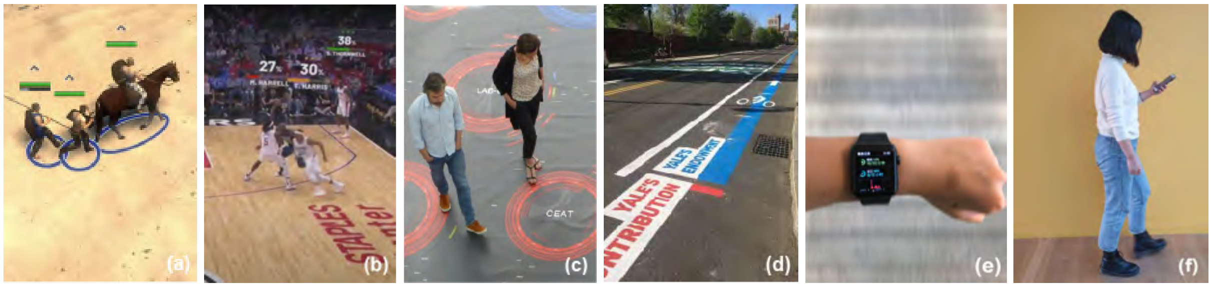

Moving visualization & stationary viewer. Stationary visualization & moving viewer. Moving visualization & moving viewer.

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 [44, 45]. (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 checking financial charts on her phone while walking to a meeting.

ABSTRACT

Ultimately, the goal of my thesis is to inform the design of situated visualization in motion. We define visualizations in motion as visual data representations that are used in contexts that exhibit relative motion between a viewer and an entire visualization. Actually, there are already meany scenarios that involve visualizations in motion such as sports analytics, video games, wearable devices, and data physicalizations. However, the relative movement between viewers and visualizations in scenarios above has not called much attention in visualization community. To approach this topic we have already engaged in several research projects: We illustrated a set of situated visualization in motion scenarios, we proposed a research agenda, and two experiments to understand how well static viewers can read data from moving visualizations. For our next steps, we plan to study visualizations in motion in more complex contexts: sports and video games. To complete my thesis, I will likely extend my work with an alternative application scenario, such as the one with wearable or mobile devices.

1 INTRODUCTION

On a high level, I study how situated data visualizations can help people use their data of personal interest. Situated visualizations are attached to data referents and as such often involve viewing scenarios with relative motion between the viewer and the visualization. Examples include real-time updating scores in sports (see 1b) where the score bar is connected visualization to the athlete's head and moves with the athlete's movement; moving health bars in video games (see 1a) where health bars move with the game characters; physicalizations (see 1c, 1d) where visualizations are stationary, for example printed on the road and viewers walk by to read them; and even wearable equipment that moves with the wearer's movement (see 1e, 1f). In all these scenarios, there exist relative motion of *entire* visualizations with respect to a viewer. 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.*

We do not consider animation as part of or between visualizations as part of the visualization in motion spectrum. Animation has specific goals. It is used to express highlights, smooth transitions of data points in time [4, 13, 50, 57], or to morph between different representations [8, 14, 18, 43, 47]. Instead, *visualization in motion* studies the effect of the relative motion relationship between *entire* visualizations and viewers that has not a-priori encoding goals but is part of specific representation scenarios. In *visualization in motion*, relative motion relationship between the visualization and the viewer can be categorized into three groups: a) moving visualization & stationary viewer, b) moving viewer & stationary visualization, and c) moving visualization & moving viewer.

2 RELATED WORK

I discuss related work based on our *visualization in motion* classification as well as application scenarios for each category. To complete the related work, I also present relevant past work on motion as part of animation from the visualization community and related research from psychology.

2.1 Moving Visualization, Stationary Viewer

In this category, a stationary viewer reads from a moving visualization and may require to move eyes and/or head to possibly track the visualization in order to read it accurately. It is important to recall that our definition focuses on *entire* visualizations moving, rather than only parts of them.

Several companies (like FootoVision [15] or SportsDynamics [51]) now commercialize tools that embed visualizations in videos (e. g., 1b). Such tools may be used by team coaches and players but also non-expert audiences during replays or debrief sessions on TV. In contrast to these moving visualizations, several static sports visualizations have been developed in research as well. These tools add statistical analysis visualizations for sports such as table tennis [12, 58, 61], soccer [3, 52, 62], basketball [6, 27], cycling [25], badminton [39, 63], or tennis [40]. Consistently, here, the visualizations stay still; for example, in VisCommentator [12] visualizations are embedded on static video screenshots.

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As illustrated in 1a, video games are another domain that frequently involves moving visualizations attached to game entities. Past work on game visualizations has mainly focused on the retrospective analysis of player cooperation and performance (e. g., [1, 16, 26]).

Furthermore, with the development of artificial intelligence, recognizing objects and labeling them in video frames has been a common method in object tracking [31]. In this domain, visualizations are mostly simple rectangles, sometimes with labels and/or a categorical color code, that visualize the position, size, and potentially type of the the tracked objects. Finally, interaction more broadly can result in visualizations in motion when a user applies an interaction like panning, zooming, rotating, or changing viewing position to an *entire* visualization. In HCI, the impact of these operations has been studied for interactive user interfaces [21, 24], more specifically, in navigating maps [46]. With the combination of visualizations in motion and diverse interaction techniques, future applications in this scenario need more exploration.

2.2 Moving Viewer, Stationary Visualization

Under this category, a moving viewer focuses on a stationary visualization and experiences additional optical flow during self-motion in the world. A main consequence of viewer movement is changes in 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 display, data physicalization, and AR/VR research.

Past research has looked at moving viewers in front of wall displays, for example as part of basic perception experiments [7], as input to change a visualization or its presentation—e. g., through proxemic interaction [5, 23, 42] or hybrid images [22]—, or to visualize viewer movement [11].

Apart from the scenarios that I illustrate in the teaser 1d and 1c, in a previous study on how people approach and explore data physicalizations, Taher et al. [53] provide evidence that body movement is an important part of both data exploration and presentation. The authors pose further research questions regarding to which extent movement leads to better insights or more accurate reading due to changes in view points.

Thanks to head-mounted devices, two previous papers that combined sports visualization and AR/VR([54, 55]), included the possibility for users to move around and observe their previous basketball shooting trajectories in a 3D space.

2.3 Moving Visualization, Moving Viewer

Relative motion might also exist when both visualization and viewer move independently at the same time. This motion can range from visualizations on mobile phones while walking (1f), smartwatches worn on the arm during a run (1e) to more significant changes in motion when visualizations are projected onto approaching traffic and seen from a moving vehicle.

A relevant research area for this scenario is wearable and mobile visualization. Several previous studies on mobile phones have shown that walking increased workload and reduced performance in reading tasks [34, 49, 56]. As cognitive resources need to be similarly shared between navigation and reading data, it seems reasonable to expect similar negative effects for visualizations in motion.

So far research on wearable visualization has largely concentrated on smartwatches [9, 35, 36]. Much of the past work did not specifically design for or study moving viewers. Exception are, for example, Schiewe et al.'s [48] work on visualizations for real-time feedback during running activities. Amini et al. [2] interviewed quantified-selfers about their in-situ data analysis activities and showed the variety of reasons for why people checked their fitness trackers during sports activities.

2.4 Additional Related Work

Although *visualization in motion* has not received much attention in the visualization community, animation as a research direction has been studied more extensively. Previous work on animation focused on how to animate between different arrangements of data points [13, 19, 57], changes in data (e. g. graph) topologies or dimensions over time [4, 14], for zooming into data [8, 50], morphing from one representation to another [18], or for changing perspective in 3D scenes [43, 47]. Overall, a commonality between animation in visualization and *visualization in motion* is the joint interest in motion. However, to distinguish *visualization in motion* and animation, I emphasize here again, our focus is on *entire* visualizations exhibiting relative motion with the viewer. Real-world visualizations in motion have to often deal with additional complexities due to changing context conditions and unpredictable motion characteristics.

Motion relationships between viewers and visual targets have been discussed in psychological studies. The work most closely related to ours concerns dynamic visual acuity. Dynamic visual acuity (DVA) [28, 29] describes the ability of an observer to discriminate an object when there is relative motion between the observer and the object. In contrast to our work, the visual targets in DVA experiments are often Landolt C, optotypes on Snellen charts, or strings of numbers. In DVA experiments participants generally identify the orientation of optotypes, or read numbers, rather than reading visualizations with magnitude proportions as in our case. Previous research on DVA [10, 30, 33, 59], in which stationary participants were asked to identify the orientation of Landolt Cs moving at different angular velocities, found that with increasing velocity visual acuity decreased. Similar decreases in acuity were also found for moving participants judging stationary targets [17, 20, 38].

3 Preliminary Methods And Results

The work I present in this section was conducted with Petra Isenberg, Anastasia Bezerianos, and Romain Vuillemot. I use the word ”we” to describe this set of collaborators.

In our recent submitted work, we proposed a research agenda of *visualization in motion*, we conducted magnitude proportion perception experiments to evaluate the impact of speed and trajectory on readability of *visualizations in motion*. Currently we are extending this work through research on two specific visualization in motion scenarios.

3.1 Completed Work: A Research Agenda

As Fig. 1 shows, visualizations in motion may be overlaid in 2D, may be physicalized, or shown in 3D virtual worlds; which are drastically different viewing contexts with varying types of motion. Therefore, We focused our research agenda on four broad properties: a) characteristics of motion, b) spatial relationships between the viewer(s) and the visualization(s), c) the situatedness of visualizations, and d) potential techniques to generalize visualizations in motion.

Characteristics of motion: In physics, motion is described as the phenomenon in which an object changes its position over time [60] according to a frame of reference. To discuss *visualizations in motion*, we also need a reference. Imagine that we take the 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” reference. 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. In *visualizations in motion*, the relative motion should have a sufficient magnitude – beyond eye saccades or simple head movements that all human viewers would exhibit. We discussed specific properties of motion that we expect to impact the effectiveness of moving visualizations: speed, trajectory, acceleration, and direction of motion.

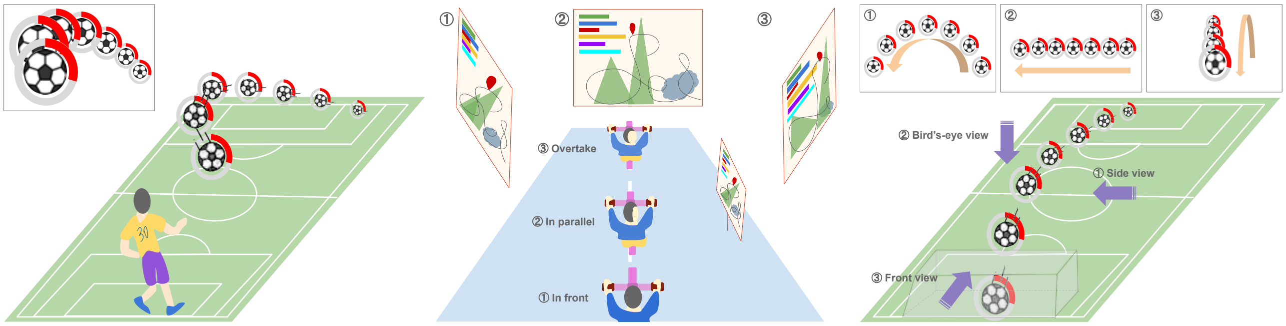

Figure 2: Left: Shows how a soccer ball's size and position changes on a viewer's retina. Center - : Changes of a moving cyclist's perception of a static map and bar chart. Right: Different perspectives of a soccer kick-on scenario.

Spatial Relationship: Here, we consider the spatial relationship between the visualization, the viewer, and the world. We first discuss the viewing distance, which is the linear distance between the visualization and the viewer. See Fig. 2 - Left, when a visualization moves towards the viewer, the visualization will become bigger as viewing distance decreases. We then consider the spatial relationship between the viewer and the visualization. See Fig. 2 - Middle – we consider that the viewer and the visualization have local coordinate systems. The relationship between these two coordinate systems impacts how viewers see a visualization in their field of view when tracking. We also take the spatial relationship between the viewer and the world into account. Similarly, the world has its coordinate system as well. The relationship between the viewer coordinates and the world-coordinates describes how the viewer looks at a specific scene. See Fig. 2 - Right, the same movement, seen from different perspectives will lead to different images on viewer's retina.

Situatedness: As in all non-motion related visualization scenarios, contextual factors, the connection of visualization to data referents, and the visualization choice and design will impact the effectiveness and efficiency with which data can be read and understood under motion. In addition, the autonomy and predictability of the movement can also have an impact on the reading performance of visualizations in motion.

Techniques: Research on visualizations in motion can draw from and inspire available technology and can perhaps even shape future technologies. Here, we list a few technologies where visualizations in motion are already or might become very important. As illustrated in Fig. 1, moving visualizations are common on static screens while physicalization can fix the visualization as stationary. More advanced techniques such as AR/VR can produce visualizations in 3D. Thanks to the mobility of AR/VR and wearable equipment, it gives a broad potential application context for moving visualizations and moving viewers.

3.2 Completed Work: Empirical Perception Experiments

To explore the impact of motion characteristics on the readability of visualizations, we conducted magnitude proportion perception experiments on Prolific [41]. We asked participants to read a proportion from a simple moving visualization. In our speed-evaluation, we had three conditions: `Static` (0 cm/s), `Slow` (15 cm/s), and `Fast` (30 cm/s). Among them, `Static` was our baseline. In our trajectory-evaluation, we had four speed × trajectory conditions: `Slow` × `Linear`, `Slow` × `Irregular`, `Fast` × `Linear`, and `Fast` × `Irregular`. Among them, `Linear` trajectory was our baseline. All our trajectories were derived from the movement trajectory of players in real soccer games. Our between-subjects condition was visualization type: `Donut` charts vs. `Bar` charts. The proportions we used were: 18%, 32%, 43%, 58%, 72%, and 83%. We also added 0% as attention check. The target slice of the chart was in red and the other one was in grey.

Speed-evaluation Results: Appendix Table 1 shows the participants' mean absolute error per speed, the pairwise differences in absolute error across two speeds per chart type, and the differences across two representations. Table 1–Left shows that high speeds did have an influence on readability. Looking at the pairwise differences (Table 1:Middle), there is evidence that `Fast` caused more errors than `Static` and `Slow` conditions in both `Donut` and `Bar` in the respective experiments. But for both chart types in practice the differences were small, around 1–2 percentage points. Table 1: Right gives some evidence that `Donut` was more accurate than `Bar` in all speeds. This evidence is more pronounced on `Fast` and `Slow`. It appears that `Donut` can be read slightly more accurately than `Bar` when in motion.

Trajectory-evaluation Results: Appendix Table 2 shows the participants' mean absolute error per speed × trajectory condition, the pairwise differences in absolute error across two conditions per chart type, and the differences across two representations. Looking at the mean absolute errors (Table 2: Left), the trajectory type did have an impact on reading accuracy. Looking at pairwise differences (Table 2: Middle), we have evidence that `Irregular` trajectories caused more errors than `Linear` ones for both `Donut` and `Bar`, in particular at `Fast` speed. When comparing the two representations directly (Table 2-Right), there is evidence that participants' answers were always more accurate with `Donut` than with `Bar` by 1–2 percentage points under the same kind of trajectory. This effect is particularly strong at `Fast` speed.

Evaluations Summary: Overall, our results showed that speed and the regularity of trajectories impacted participants' performance. Higher speed and irregular trajectories generally led to more errors. However, in practice participants were still able to quite reliably read proportions from moving charts, with an accuracy close to 95%.

4 Proposed Work And Discussion

I first talk about my current work in progress and then discuss potential future projects.

4.1 Work in Progress: Focusing on Specific Application Scenarios

After proposing a research agenda for *visualization in motion*, and confirming that practically, viewers could read data accurately from simple moving charts we wanted to concentrate on the challenges of real-world scenarios.

We continue with the viewer-motion context that we used in our previous evaluations – moving visualization & stationary viewer. One promising scenario (see related work) is real-time sports coverage. Here, athletes as data referents are themselves in motion and we have at our disposal relevant data such as movement statistics, past records, trajectories, etc. To explore this scenario in depth, we focus on one specific sport, swimming, for the following reasons. As other sports it has rich dynamic data and we have started seeing an increase of real-time moving graphics during competitions (e.g., record lines), sometimes attached to athletes (e.g., country flags). This indicates that audiences may be open to the addition of more complex moving data representations. Moreover, it is a sport where the movement of athletes themselves is constrained in lanes, making it an appealing starting point for our investigation. Another candidate scenario is video games, which have extensive dynamic data. Since game players often need to rely on real-time data displays (e.g., health bar, force gauge, etc.) to develop their strategies to win, there is an excellent demand for adequate visualizations of real-time data for video games. Furthermore, with the prevalence of the moving visualizations used in video games (see 1a), we imagine that more data can be displayed with situated visualization and move with their data referents.

To categorize existing situated visualizations in swimming, we analyzed all 16 available swimming videos of the 2020 Tokyo Olympics from the official Olympic Aquatics YouTube channel [37]. We categorized present visualizations by data items, representations, display positions, and camera position and perspectives. So far, only real-time speed text and world record scale lines are moving with swimmers' movement. For video games, we gathered 50 games by using a commercial ranking website called Metacritic [32]. From these 50 games, we abstracted 160 samples of visualizations in motion. We classified these samples by their representations, embedding locations, information dimensions, and movement autonomy. We are currently conducting a crowdsourcing survey to explore which kind of swimming-related data general audiences are interested in, in order to identify opportunities for additional visualizations to be added to swimming competition coverage.

Video games produce rich dynamic datasets during gameplay that are often visualized to help players succeed in a game. Often these visualizations are moving either because they are attached to moving game elements or due to camera changes.

We want to understand to what extent this motion and contextual game factors impact how players can read these visualizations. To ground our work in existing practices of moving visualizations in video games we conducted a systematic review. To cover a diverse selection of video games we made use of a commercial ranking website called Metacritic [32]. In total, we reviewed 50 games from 17 genres. For each game, we watched game-plays on YouTube for approximately 5 to 15 minutes and video-recorded relevant parts of the videos where the game showed visualizations in motion. From these 50 games, we extracted 160 examples of visualizations in motion. We categorized these examples according to multiple dimensions related to situated visualization and motion characteristics: visualization representations, data referents, embedding locations, data dimensions, and movement autonomy. We are now implementing our video games, designing moving situated visualizations for video games. We plan to explore how embedding positions and encoding representations affect the effectiveness of visualizations in motion for video games.

4.2 Future Work: Investigate Moving Viewers' Scenarios

So far, my research has been focused on stationary viewers & moving visualizations. We showed that although speed and trajectory had an impact on the readability of visualization the impact on participants' correctness was small. Practically, participants could still reach somewhere close to an exact answer. So far, my research has targeted static viewers and how readability would be affected when viewers are moving is still unclear. Thus, I plan to investigate moving viewers' in my future work. To ensure the continuity of my research, I plan to combine moving viewers with moving visualizations. Example scenarios include when a runner reads their personal running statistics such as how long they have run or how many calories they have burned while running. Previous research on smartwatches about visualization design only involved stationary participants and static charts. Blascheck et al. [9] presented that data representation and number of data items affected how quickly people could perform a simple data comparison task. This study was far removed from actual situations of smartwatch use where bouncing arms or the tiny movement of viewer's head/body will lead to relative movement between viewers and their wearable devices.

I have some research questions related to the scenario above:

- How would motion characteristics affect how quickly people can get information at a glance on wearable devices such as a smartwatch?
- Currently, we noticed that when a smartwatch works in an exercise-recording mode, dynamical updating text is used to represent information rather than simple charts. However, no research shows that this kind of dynamical updating text is the best way to present data. We want to know how visualizations should be designed (their representations, sizes, colors, position, etc.) in this scenario.

5 Questions For The Panel

I have several questions that I would like to discuss as part of the doctoral colloquium:

- In our research agenda, we proposed a classification of *visualization in motion* including stationary viewers & moving visualization, moving viewers & stationary visualization, and moving viewers & moving visualizations. What we did and we are still working on was all about stationary viewers & moving visualizations. I would like to receive feedback on the most promising scenarios to explore as a final PhD project.
- If we would do experiments with wearable devices, I would like to discuss ideas on how best to study scenarios involving moving viewers with wearable devices.

6 Conclusion

My thesis aims to inform the design of situated visualization in motion. We proposed a research agenda with diverse dimensions that we imagine would impact the readability of the visualization in motion. We evaluated the impact of speed and trajectory on the readability of the visualizations under motion. We are working on specific scenarios that can narrow down this topic. We plan to investigate scenarios with moving viewers in the future. Ultimately, we would like to propose a design space for this new research topic and provide practical design considerations and guidelines for potential application scenarios.

Acknowledgments

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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).

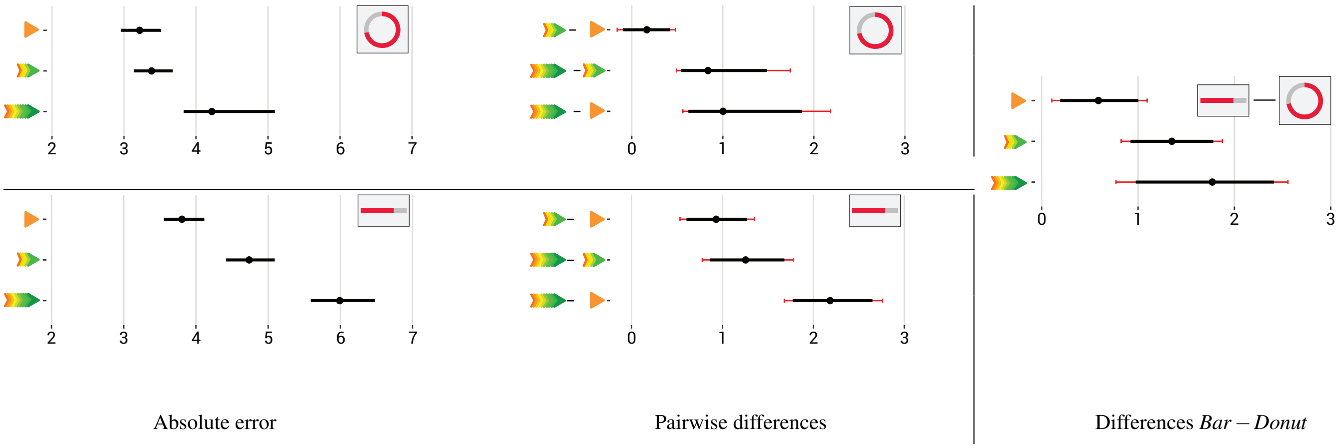

Table 2: *Absolute error* analysis for Experiment-Trajectory. Left: Average mean absolute error in percentage points for each chart type. Middle: Pairwise comparisons for each speed × trajectory condition and representation. Right: Differences of mean absolute error across representations. Error bars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