Embedded temporal data visualizations in an urban environment for casual exploration

T. Nagel[1] , C. Huber[1,2] , E. Petzold[1], and S. Humbert[1]

[1]Human Data Interaction Lab, Mannheim University of Applied Sciences, Germany
[2]Data and Web Science Group, University of Mannheim, Germany

Figure 1: *Hand-held mobile device displaying a grouped area chart embedded onto the street visualizing the progression of traffic by type for two lanes. Time labels are shown along their axis, with arrows and legends hovering slightly over-head.*

Abstract

We investigate situated and embedded visualizations to enhance casual urban data engagement. Presenting a design concept for embedding temporal data visualizations onto flat surfaces, we explore features that integrate these visualizations within their physical contexts. Through a mobile application utilizing location-based augmented reality to visualize traffic, we demonstrate the feasibility of our designs in real-world settings. This approach not only aims to improve understanding of urban phenomena but also to enrich user experiences, offering a novel method for urban data visualization that emphasizes user engagement.

CCS Concepts
• ***Human-centered computing*** → ***Information visualization; Mixed / augmented reality;*** *Ubiquitous and mobile devices;*

1. Introduction

Mixed Reality (MR), placed on the Reality-Virtuality continuum [MK94], merges the real world with virtual enhancements. This integration extends beyond external displays to the user's perceptual experience, forming a unified blend of physical and digital elements [SSW21]. Since their emergence, MR and AR have been recognized for augmenting urban space engagement [Azu97].

The spectrum of AR technologies ranges from head-up displays (HUDs) and head-mounted displays (HMDs) to more accessible mobile devices [CBHH17]. Recent advancements in consumer mobile technology, coupled with new solutions to address the challenge of spatial registration in outdoor settings [EBC*21] have enabled the creation of embedded visualizations in urban environments, aligning with our work's focus on handheld AR for its low barrier to entry and a broad audience reach [BSL*23].

Situated analytics involves data representations organized around objects, places, and persons in the physical world [TWD*18]. Closely related are situated visualizations, which provide data within the physical context to which it relates [WF09]. Expanding on this, the concept of embedded visualization further explores the direct integration of visual data into physical spaces [WJD17]. Shin et al. [SBB*23] distinguish between situated analytics and situated visualization by the integration of the analysis process. While immersive and situated analytics centers on enhancing task engagement and facilitating decision-making [DMI*18], our work explores situated visualizations for casual, everyday use [PSM07].

Urban data visualizations bring local data on urban phenomena directly to the community [VMH12]. Similarly, situated visualizations are designed to offer insights into data right at the point where they are needed, or where they have been collected [BKT*22]. The critical need for accurate alignment between virtual content and physical objects has been underscored in numerous studies (e.g. [TPH*23,HFS*21]). Our focus is on exploring accurately embedded visualizations in outdoor urban settings.

This work extends these concepts by deploying AR as a medium for embedded urban data visualization. We aim to make urban data not only engaging but also relevant to the immediate surroundings of the general public. Our contribution is two-fold: the systematic exploration of a design concept including selected visualization idioms, and the design of a demonstrator both tackling the challenge of designing spatially situated visualizations that strike a balance between tightly embedding virtual charts and representing multidimensional temporal data [EBC*21].

2. Design Concept and Characteristics

In our exploration of a design space for situated visualizations of temporal data in an urban environment, we focus on crafting experiences where the visualization is intricately tied to its physical and perceptual context [WJD17] and introduce an early design concept.

Embedding visualizations onto street-level. The observer, along with their mobile device, must be in close proximity to the data's real-world counterpart—e.g. near the traffic that the data represents. Consequently, the virtual visualization is not only placed on a canvas but is designed to appear as though it naturally belongs there, directly overlaying the street surface. This approach leverages proxemic interactions and spatial relation, aiming to enhance the engagement of pedestrians with the data by situating it within their immediate urban environment and onto surfaces, rather than floating abstractly or being tethered to specific objects.

Physical interaction with the data is facilitated through various perspectives—side and front views are encouraged, while vertical (up and down) interactions are limited due to the life-size and ground-level nature of the visualizations. This design principle supports use cases where individuals stand in-situ to explore an AR.

Temporal Directionality. Rendering temporal data in embedded visualizations challenges the conventional linear representation of time and affects the apparent flow direction, depending on the observer's gaze angle. Furthermore, cultural perceptions
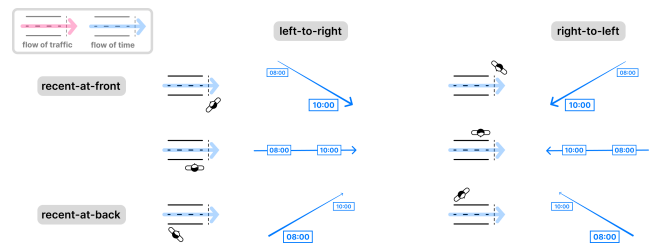

Figure 2: *Apparent temporal direction based on observer's gaze angle for an embedded visualization on street-level whose time axis is aligned with the direction of the traffic flow. Top row shows recent-at-front, bottom row recent-at-back. Left column shows apparent left-to-right, right column apparent right-to-left time flow.*

of time significantly influence these representations; while Western cultures often depict time flowing from left to right on timelines, other cultures might visualize the progression of time differently [CRTP*20]. Exploring this concept with street traffic, we show how the observer's position and viewpoint can lead to different flow interpretations (Fig. 2). Although each visualization in the left column depicts time flowing from left to right, 3D foreshortening may influence how the observer perceives this temporal directionality (cf. Fig. 5).

Temporal Situatedness. In our context, *temporal directionality* refers to the visual flow of time, distinct from the concept of *temporal indirection* as introduced by Willet et al. [WJD17], which describes the temporal gap between when a physical presentation is displayed and the actual moment it represents. Instead, we use the term *temporal situatedness* [TWD*18] to denote when the data's temporal reference closely aligns with the time of the observation. Satriadi et al. [SCS*23] classify temporal data into live, historic and predictive, with live data exhibiting the highest degree of temporal situatedness. All three are relevant for urban data.

Visualization Idioms. Bressa et al.'s recent survey on situated visualizations highlighted a general lack of details on the specifics of visualization design within this field [BKT*22]. Thus, we aim to not only provide a comprehensive account of our design considerations, but to explore suitable visualization idioms for embedding temporal data in a street setting. We opted to explore temporal scale [AMST23], view cardinality [LSS23], and spatial view (cf. *visual encoding* [SBB*23]). Figure 3 presents a range of our exploratory designs. In terms of temporal scale, two visualize temporal data as discrete (B, C), three as continuous (A, E, G), and three combine discrete and continuous axes for different temporal aggregation levels (D, F, H). While most adopt a many-to-one view cardinality, visualization A employs a one-to-one approach, and F and H a many-to-many. All but two use a 3D rendition of the visualizations, with E showing an example of a flat 2D rendering, and F and H showing 2.5D ridge plots. Additionally, our designs incorporate multidimensional data. Traffic volume is represented by height (or width in the case of violin plots). The encoding of further attributes, such as lane position, leverages spatial positioning as an effective channel. For differentiating types of traffic, color coding is utilized.
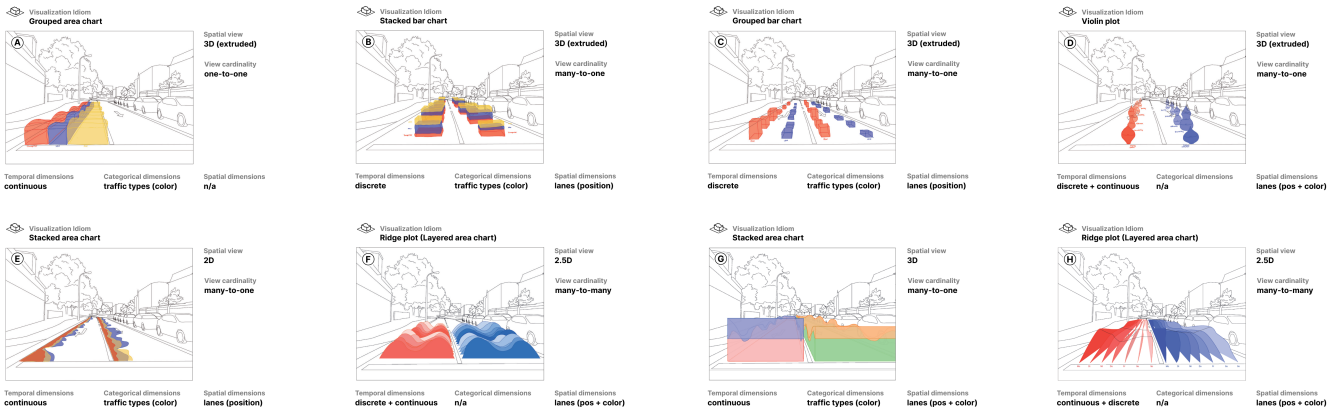
Figure 3: *Explorations of various visualization idioms for the case of traffic data embedded into the street lanes, ranging from continuous grouped area charts, to discrete stacked bar charts, to grouped bar charts, to violin plots, to flat area charts, to layered area charts for multiple time axes.*

⬦ **Spatial Proportions.** For embedded urban data visualizations, we propose a hybrid scaling approach, combining abstract visualization methods with real-world physical dimensions [SBB*23]. This is exemplified by integrating 3D stacked area charts, a traditional abstract representation, with scales that match real-world measurements, such as the width of street lanes. This blend facilitates a more intuitive and contextually relevant understanding of data, linking abstract concepts to tangible urban elements, thereby enhancing the user's perceptual and cognitive engagement with the visualization.

Our work represents an early exploration into a broader realm of possibilities, aiming to spark further investigation rather than providing a conclusive overview of a full design space.

3. Demonstrator

In our demonstrator, we chose street-level traffic such as cars, motorcycles, and trucks, due to their prevalence in central urban locations and their proximity to pedestrians. Similar to space-time cubes [BDA*17], we map temporal data to a spatial dimension, yet visualize single-location traffic, distinct from flow visualizations that connect spatial locations in 2D [NPD17] or in AR [LYR*23].

Data. Computer-vision based tracking systems installed at various locations track and classify individual vehicles into traffic categories. The data includes lane information, often indicating the subsequent turning behavior of vehicles. The data was processed to a granularity of hourly intervals, to facilitate more efficient processing and visualization in the AR environment. The designated test location was chosen for its high traffic volume, central location, and complex traffic dynamics. Additionally, the site's sidewalk and crossing layout are helpful for AR observations.

Design Decisions. We synchronized the visualization's temporal flow with real car traffic to enhance intuitive data interaction and understanding (⬦). While time flow is perceived as right-to-left from the opposite street side, changing the directionality as the observer crosses the street (see Fig. 2, right column) is impractical due to the loss of object permanence and visual continuity, and

conflicting flow directions. Utilizing near-real-time data, offset by 1 hour, and extending to the most recent week of historical data, our approach achieves high temporal situatedness (⬦). We adapted the chart's width to the street lanes, with a maximum height of an average person, allowing viewers to discern minor variations while retaining an unobstructed view over the virtual objects (⬦).

For our prototype we implemented three idoms (⬦): a grouped area chart colored by traffic type (Fig. 4 left), layered area charts (ridge plot) visualizing two temporal aggregation levels (Fig. 4 center), and a stacked area chart with two traffic types (Fig. 4 right). We chose those to demonstrate a wide variety of properties (cf. Fig. 3) with a small set of visualizations all based on the same base chart type. See Appendix for a short video.
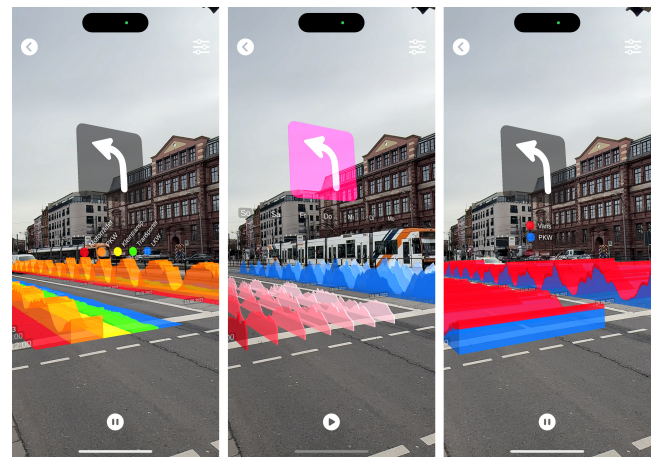

Figure 4: *All views visualize traffic progression for the two lanes, featuring a grouped area chart with color coding explained in the legend (left), a ridge plot capturing traffic frequency across two temporal granularities (center), and a stacked area chart for two types of traffic (right).*
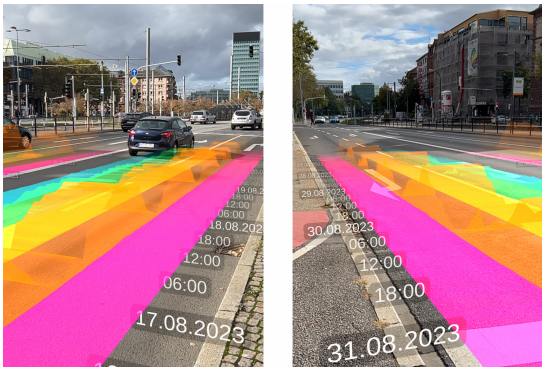
Figure 5: *While the labels are always oriented towards the viewer, the temporal directionality depends on the viewer's perspective and can change from recent-at-back (left) to recent-at-front (right).*

We show axis labels for the temporal dimension (Fig. 5), and a legend detailing the color coding of the traffic types and/or the lanes (Fig. 4-1 and 4-2). Both use situated label placement [LYBP23], yet as the visualization is embedded, the labels are both close to the physical referent (i.e. the street), as well as to the virtual object (i.e. the time axis). While the visualization is world-absolute [SBB*23], the time labels are world-relative and are always shown on the near side of the observer. Labels and legend are not billboarded but flip to always face the viewer. The time axis labels are anchored to their respective marks when navigating through time (dragging the timeline on the mobile screen, or while animating). The legend floats slightly over-head, anchored to both the start of the timeline and the pedestrian crossing.

Although the labels display timestamps, discerning the flow of time may remain challenging (cf. Fig. 5). Therefore, we introduced animation across the timeline to emphasize temporal progression. Users have the option to pause this animation and manually slide along the timeline to select specific time windows or areas of focus.

Implementation. Our use case demanded high AR precision, robust error correction, and resilience under varying lighting and weather conditions. We utilized Geospatial Anchors and Streetscape Geometry [Goo23], which operate seamlessly without the need for additional data input or manual landscape mapping, and Unity AR Foundation [Uni23], a framework that integrates natively into the device for accessing all relevant sensors.

The chosen visualizations (A, F, G) feature a geometric hierarchy that integrates lane-specific visualizations along a square Bézier path (40 meter in real world). This path is segmented into equidistant temporal markers, matched in width to the actual lane size, and hosts one or more charts. The core anchoring utilizes latitude and longitude coordinates for the path's start, control, and endpoints to secure Geospatial anchors via the Google Geospatial API. These coordinates enable the construction of custom Unity mesh objects for the area charts, with mesh resolution mirroring the data resolution to minimize complexity. This approach ensures efficient hardware performance and supports high frame rates, facilitating smooth rendering and responsive interaction with low positional or rotational drift.

Our experiments with different materials revealed that self-illuminating materials delivered the most realistic outcomes, as they bypass the need for complex real-time shadows, such as ray-tracing, which remains challenging to execute convincingly on mobile AR platforms at a high quality. To enhance the narrative of data points receding into the past and away from the viewer, we integrated a fading function into our material shaders. This function gradually reduces the material's opacity between specified inner and outer distances from the viewer, applying the same fadeout effect to labels for consistent visual treatment. Within the timeline, we differentiated between main and sub-labels, allowing sub-labels to fade out earlier (Fig. 5), thus improving the legibility of main labels at the visualization's distant end.

For a heightened immersive experience, we implemented occlusion management, ensuring parts of the visualizations and legends occluded by physical geometry are hidden. Complementing this, a raycast-based scrubbing feature was developed to facilitate a more intuitive and precise interaction, allowing users to manipulate the timeline directly with touch-and-drag actions.

4. Discussion and Conclusion

Our design concept, alongside our exploratory designs and prototype implementation, has unveiled promising avenues for embedded urban data visualizations. By contextualizing data within its physical context, we hope to enhance public understanding and interaction with urban phenomena, transforming the way citizens perceive and engage with their urban surroundings.

On the other hand, new challenges emerged. While our demonstrator employed high temporal situatedness, visualizing data in ultra real-time would introduce additional challenges [KK13], such as blending between the physical cars currently being detected on the road, and the visualization of the newly captured data. Second, utilizing mixed reality in real-world street settings introduces limitations due to the need for heightened attentiveness and the inherent dangers of navigating close to moving traffic. Engaging with MR while attempting to cross streets or change sides, where one must simultaneously observe AR content and traffic signals, presents significant safety concerns [TPH*23]. Consequently, we have deliberately excluded views from pedestrian crossings in Fig. 2, recognizing that such positions are not suitable for prolonged observation. Conversely, in safer environments such as parks or city squares, users have the flexibility to explore the visualization from a full 360° perspective. Thirdly, the legibility of geopositioned abstract chart data presents limitations in terms of accuracy and efficiency [QJ20]. Furthermore, perspective foreshortening complicates comparisons between visualization marks at varying distances [BSL*23]. However, our approach mitigates these concerns focusing on conveying overall trends rather than precise data points, and targeting casual visualization use rather than detailed analytics.

In summary, our approach synthesizes the principles of AR and urban data visualizations to create an immersive, interactive experience that brings urban data to life in the very streets and spaces it describes. This integration of technology and urbanism opens up new possibilities for public engagement and casual exploration.

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