Embedding Climate Data Into Urban Space: A Situated AR Design Probe

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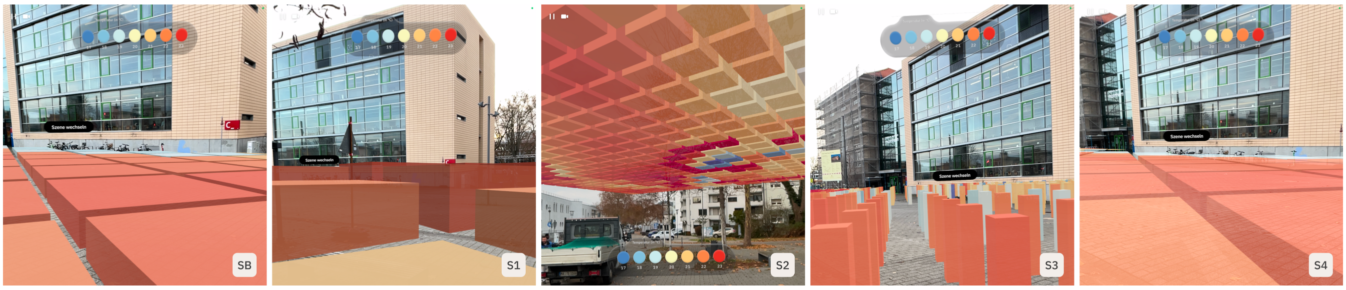

Figure 1: *The five variants of the embedded visualization of hyperlocal temperature data used in the evaluation. SB shows the baseline visualization idiom, encoding temperature through color only. S1 additionally encodes temperature through varying heights, S2 anchors the visualization in the sky, S3 increases the gap between visual elements, and S4 reduces translucency of the colored bars.*

Abstract

Existing urban climate visualizations often fail to convey phenomena at the micro scale, such as temperature variations caused by small-scale changes in the urban landscape. We explore how embedding climate data visualizations directly into urban space can support situated understanding of such phenomena. Focusing on hyperlocal temperature data, we developed a set of prototypical embedded visualization variants and evaluated them through a situated AR design probe conducted in a real urban setting. The study combined qualitative and quantitative feedback to explore how different encodings and anchoring strategies affect perception, interpretation, and preference. Our findings highlight tensions between spatial reference and environmental awareness, between perceptual clarity and obstruction, and between local precision and broader spatial comparison. Rather than validating specific design choices, this work surfaces design tensions that can inform future research and practice in embedded urban climate visualizations.

CCS Concepts

• ***Human-centered computing*** → ***Visualization design and evaluation methods;*** *Ubiquitous and mobile computing design and evaluation methods;*

1. Introduction

As a result of global climate change, phenomena such as heat waves, tropical nights, and extreme weather events are increasingly experienced at the microscale, where local temperature variations are influenced by small-scale urban features such as building geometry, surface sealing, vegetation, and shading [YWSM23]. While urban climate visualization has been identified as a prominent application area in a recent survey [MOM*24], urban climate data is often still presented through abstract representations that are difficult for citizens to relate to their immediate surroundings and everyday experience [DB22]. In immersive analytics, it is an open question how added spatial context influences peoples' interpretation of information [EBC*21]. For urban climate data, this motivates investigating how embedding hyperlocal information directly into the urban environment affects sensemaking and user experience.

Prior work on urban climate visualization spans from expert-facing analysis tools for spatiotemporal exploration [SMP*19, RNW*25] to public-facing systems for outreach and casual en-

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gagement [PSM07], including tabletop installations in an exhibition setting [HNS25] and narrative or storytelling approaches [BPR24]. While these systems provide valuable access to urban climate data, they typically present it through non-situated, detached representations, such as maps, dashboards, or virtual 3D city models. In parallel, a growing body of XR applications addresses sustainability topics [CBFG*23]. Reflecting on his earlier work [WF09], White highlighted that viewing environmental data in situ can support a deeper understanding of influencing factors compared to abstract map-based views [VCD*21]. Similarly, recent works emphasize the potential of embedding real-world data in situated and experiential contexts to make climate impacts more tangible [Mah24a]. Situated data visualizations more broadly explore how data can be contextualized within real-world settings [BKT*22], while embedded visualizations further emphasize a strong referential link between data and physical space [WJD17]. Despite this, urban climate data is rarely embedded directly into real urban space, and little is known about how concrete design choices shape perception and preference when such visualizations are encountered in situ [EBC*21].

We address this gap with an early-stage AR design probe that embeds hyperlocal temperature data from a real urban site directly into its physical environment. Our contributions are threefold: (1) an exploratory prototype that investigates different encoding and anchoring strategies for embedding urban climate data; (2) a formative in-situ evaluation combining qualitative and quantitative feedback; and (3) a synthesis of recurring design tensions that highlight challenges and opportunities for future research.

2. Design Process

Our design process followed an iterative, user-centered path, combining early participatory input, exploratory prototyping, and formative evaluation (see Appendix). To ground the work in local concerns and perspectives [Mah24b], we began by empathizing with a diverse user group, including members of the public, politics, urban planning, and local NGOs. In this phase, we conducted two identically structured workshops in two cities, where participants discussed relevant urban issues, meaningful locations, and ideas on embedded urban data visualization. We then selected urban temperature as a hyperlocal, publicly relevant climate phenomenon based on workshop insights, societal relevance, and data availability.

Prototyping progressed iteratively from low-fidelity sketches to wireframes and 3D renderings with a virtual city model. These artifacts were not only used to explore visualization ideas but also as design probes to reflect on comprehensibility, visual effectiveness, and communication potential. Throughout this phase, we explored several visualization strategies for different levels of abstraction and spatial integration. For the final prototype, we adopted a rapid AR prototyping approach to enable formative in-situ testing and early feedback. After evaluating several tools, we chose Scenery due to its support for outdoor visual positioning. This choice reflects a deliberate trade-off: prioritizing speed and situated testing over technical completeness. The resulting prototype is therefore not intended as a final system, but as an exploratory artifact to surface design challenges and inform future high-fidelity implementations.

3. Prototype

The prototype embeds microclimate temperature data as AR visualization for a formative in-situ evaluation. We implemented five visualization variants (Figure 1), which systematically vary visual and spatial design parameters while keeping the underlying data and spatial alignment constant.

Data and Referent. The visualization is based on a fine-grained, continuous urban microclimate model of near-surface air temperature. The model integrates spatial information such as topography and land use classification with measurements from approx. 400 climate sensors installed throughout the city proper, which provide real-time temperature, humidity, and wind data (cf. [BGHB24]). The resulting dataset consists of $5\,\mathrm{m} \times 5\,\mathrm{m}$ cells with an hourly temporal resolution. The model is citywide and has several million grid cells to explore temperature patterns. Each cell refers to its corresponding physical (albeit artificially defined) area. However, from a street-level viewpoint, meaningful perception is inherently limited by distance and occlusion. Thus, and to ensure performance, we restricted the spatial extent to a specific site and its surroundings. Temporally, a single summer evening hour was chosen to accentuate spatial temperature variation when different areas begin to cool.

Design and Encoding: The prototype visualizes temperature values for each grid cell directly at their corresponding real-world locations. Each cell is represented by a 3D block scaled to its real-world footprint, forming a spatially continuous composition in which users remain situated as they move through space [NHE25]. While the underlying zones are continuous, small gaps between blocks are introduced in the baseline design to support visual separation. We chose a (3D) bar representation to preserve a direct grid-to-location mapping, using a familiar and widely used idiom. We implemented five visualization variants as a design probe. SB serves as the baseline, while variants S1–S4 each modify a single visual parameter (see Appendix). The baseline (SB) encodes temperature through color and uses ground-anchored, opaque blocks with a height chosen so viewers can look over them to preserve situational awareness. Variants explore alternative design choices by additionally encoding temperature through height (S1), anchoring blocks in the sky (S2), increasing spacing between elements (S3), or increasing translucency (S4). We followed established color selection guidelines [CSH20] and used a perceptually validated diverging red-yellow-blue color scheme to distinguish warmer and colder areas, consistent with common temperature metaphors (e.g., warming stripes). Colors were mapped to the local temperature range to emphasize spatial variation [GBC20] and discretized into 7 classes to support quick readings. A simple legend was included to support interpretation. Interaction was intentionally minimal and limited to viewpoint changes through natural locomotion; no selection, filtering, or temporal interaction was implemented.

Hardware and Implementation. The prototype was deployed on an 11" iPad Pro, selected for its integrated LIDAR sensor, enabling real-time occlusion. It was implemented using Scenery, a no-code AR prototyping environment. Visualization geometry was generated through a Python-based data preparation pipeline and exported as universal scene description (USD) models. Spatial anchoring was done via a Visual Positioning System (VPS) based on the Google ARCore Geospatial API [HTB25].

4. Formative Evaluation

Aims and Design. Our formative study serves as an early design probe situated at a relevant urban site to surface design tensions and inform future research on embedded urban data visualizations. While conducted *in situ*, it was not *in the wild*, as participants engaged in guided exploration rather than autonomous everyday use. The study combined qualitative and quantitative feedback in a mixed-method evaluation to explore participant preferences regarding different encoding and anchoring strategies. The evaluation was conducted on-site using the tablet-based AR prototype and included the five visualization variants. Participants first explored the baseline (SB), followed by each variant in turn (S1-S4). After each comparison, they completed a short questionnaire. This procedure was repeated for all variants. Quantitatively, we used the PREVis "Understand" subscale [CHII25] to assess perceived readability of the embedded visualizations and collected pairwise preferences between the baseline and each variant. Participants were encouraged to think aloud while moving freely through the environment and to articulate observations, questions, and comparative reflections. See the appendix for details on the study design.

Setting. We conducted the study on a public urban square near campus under overcast conditions with moderate temperatures and regular pedestrian activities. The setting naturally included incidental background dynamics (e.g., variations in lighting and scene structure). Prior work suggests that such background complexity has limited impact on visualization perception, though it may influence distraction and experience [SD21]. The site was chosen to provide a naturalistic urban setting and consisted of an approximately 300m × 300 m area.

Data Analysis. Qualitative feedback was audio-recorded and transcribed using the local Whisper-V3-Large model [RKX*23]. Rather than coding entire transcripts, we first extracted salient statements: Two researchers independently reviewed all transcripts (consulting the original audio where needed) and selected excerpts relevant to participants' interpretation, interaction, and embodied experience with the AR visualizations. The combined excerpts formed the analysis corpus, which was subsequently open-coded and iteratively clustered through discussion and consensus.

Results. Five participants from the university community were recruited via an open call, including students and researchers. Quantitatively, responses indicate that all variants were generally well understood, with no notable differences. Preference judgement, however, showed clear tendencies: participants favored the sky-anchored variant (S2) and the high translucent variant (S4) (see Figure 2). This is reflected in the qualitative feedback, where participants articulated perceived advantages of S2 and S4 (see Section 5). Four transcripts were available for qualitative analysis (out of five, due to technical issues). From these, we identified 16 codes grouped into five thematic categories. A full overview of codes and categories is in the appendix; in the following section, we discuss relevant findings and illustrate them with representative quotes.

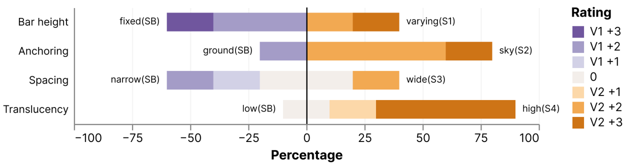

Figure 2: *Pairwise preference ratings between baseline (SB) and single-parameter variants (S1-S4) of our prototype.*

5. Findings

Situated understanding and sense of place were repeatedly emphasized by participants as key benefits of embedding the visualization directly in the urban environment. One participant explicitly valued seeing such visualizations *"in the city, in our environments"* (P1), highlighting the relevance of the data when encountered in situ rather than abstractly. Several participants connected the displayed temperature patterns to recognizable urban features, using the physical surroundings to interpret the data. Hyperlocal differences were described as *"warmer toward the building and cooler toward the street"* (P4), and lower temperatures near vegetation were noted as *"making sense"* (P5). One participant also related the visualization to reflective consideration of place-specific interventions and remarked: *"Overall, I find it quite neat, because it might help to identify where surfaces could potentially be unsealed."* (P5).

Safety and visual obstruction influenced participants' preferences across the visualization variants. Participants consistently favored the sky-anchored visualization for its unobstructedness, which allowed them to better see real-world elements such as the pavement and other pedestrians. Two participants explicitly connected this to a reduced sense of risk, stating that they did not *"fear walking into people"* (P1) or *"falling into a hole"* (P2). In contrast to floor-anchored variants, the sky-anchored visualizations were described as *"not standing in the way"* and not preventing viewing the ground (P4). Increased transparency was discussed as a possible mitigation, with some participants reporting improved visibility of their surroundings. However, others noted that they *"still could not (fully) see objects on the street"* (P2), and that they felt that the bars continued to be in the way regardless.

AR readability and understanding were generally rated as good across all variants. Differences emerged, however, regarding height encoding and translucency. Fixed-height blocks were perceived as easier to look over, though at the cost of reduced value discrimination: *"the differences are not as easy to discern"* (P4). Conversely, varying heights enhanced local salience but restricted distant visibility: *"it's hard to see things in the distance, but the things you do see are easier to recognize right away"* (P4). Color encoding and the legend were understood by all participants. Legibility of colors in the high translucency variant was seen ambivalently: Some participants described them as *"slightly distorted where [bars] overlap"* (P4), while others noted that *"you can definitely still recognize the colors"* (P5).

Approximate accuracy rather than precise readings shaped how participants interpreted the visualization, despite the underlying climate model having a high spatial resolution. One participant noted: *"I don't think it has to be 100 percent accurate. It just needs to be roughly right, and that's completely sufficient for me as* *information."* (P1). Another participant similarly emphasized that fine-grained precision was less relevant than gaining an overall impression: *"It's the big picture"* (P2).

Spatial indirection between referent and visualization were affected by design choices. In particular, the sky-anchored variant weakened the connection to the user's immediate position: *"That connection is somewhat lost [...] I couldn't see what was happening exactly at my position."* (P4). All participants reported difficulty connecting virtual cells back to the ground, noting that *"Perspective plays a role here. You have to somehow map the square at the top onto the surface below. I find that a bit more difficult."* (P5).

Locomotion-based interaction was required to explore surrounding areas beyond the immediate vicinity, and several participants moved to further apart areas to inspect specific phenomena. Related, the perceived spatial affordances of the virtual bars influenced bodily navigation: floor-anchored bars were perceived by one participant as *"slightly irritating that I can walk into it, or am expected to"* (P2), while the variant with wider gaps (S4) was described as *"the most inviting to walk through"* (P4). As physical movement was the primary means of accessing spatially distributed data, one participant wondered what would happen when walking beyond the visible borders: *"Does that mean the data stops there, or could I keep walking and it would continue loading?"* (P5).

6. Discussion

Balancing Spatial Reference and Environmental Awareness. Contrary to our expectations, the sky-anchored variant was preferred despite its weaker connection to the physical spaces it represents. Participants described it as less obstructive, allowing greater awareness of their surroundings and easier perception of overall temperature patterns. While this placement did not always support a quick and precise reading of the connection between sky-anchored bars and their ground cells, for some a general overview was sufficient. This highlights a tension between precise local reference and unobstructed perception. To address this, we are currently investigating idioms such as floating orbs or continuous isosurfaces.

On Constructed Referents in Embedded Visualization. The sky-anchored placement also foregrounds a more fundamental issue of referent indirection [WJD17]. In contrast to embedded visualizations with physically defined and visually obvious referents (e.g., sensor data attached to a pole [NHE25] or traffic data aligned with a street [NHPH24]), our climate model relies on artificially defined zone referents. While the physical ground is continuously visible, the explicit boundaries of these zones become legible only when the virtual partitioning is rendered. Participants noted that connecting sky-anchored bars back to their corresponding ground areas required mental effort. Future designs might mitigate this by reinforcing referent cues, e.g., by rendering subtle ground grids, highlighting the currently occupied zone, or visually linking elevated blocks to their ground areas through connective cues (e.g., vertical rays or projection lines) [BSPQ17].

Spatial Continuity and Data Boundaries. When embedded visualizations represent spatially continuous data, they can evoke an expectation of continuity beyond the visible extent. Although no participant crossed the boundary of the loaded area, one questioned what would happen when they would. This suggests that embedded representations of continuous phenomena create assumptions of spatial completeness. More broadly, embedded urban visualizations must communicate spatial extent not only for continuous but also for distributed datasets (e.g., citywide sensor networks). Future designs, therefore, should consider how to indicate distant referents and existing additional data beyond the immediate surroundings while preserving the situated experience. Possible approaches include progressive loading strategies, visual cues indicating continuation, or complementary overview mechanisms that preserve embeddedness while extending spatial awareness.

Comparison in Urban Contexts. A defining characteristic of embedded data visualization is the tight coupling between referent and visualization. While this strengthens situated interpretation, it inherently complicates aggregation and comparison, tasks that conventional visualization systems typically support well. In our study, participants often relied on approximate readings and local overviews. However, some relocated physically to compare more distant areas, revealing the effort required to compare the referent the viewer is currently situated in with nearby or remote referents. This raises a broader challenge: how can embedded visualizations support comparison across referents in larger urban areas? Design approaches such as virtual proxies [LSS23], and other representations and interactions for non-visible referents [APHD23] might help bridge this gap. Relatedly, future work could investigate comparisons across time, e.g., between midday and night temperatures.

Uncertainty between the model and the real world. Our prototype visualized modeled climate data rather than live measurements. This might lead to discrepancies between representation and the people's immediate sensory experience. Temporal indirectness is another challenge [WJD17]; we displayed a summer evening, while the evaluation took place on a cooler fall afternoon. More generally, urban environments are dynamic with evolving sceneries, whereas climate models reflect specific update cycles. As embedded representations are increasingly used for participatory urban planning [Rea23], future systems should more explicitly communicate model scope, uncertainty, and temporal framing – and potentially visualize projected impacts of climate interventions.

7. Conclusion

We presented an early-stage AR design probe that embeds hyperlocal climate data directly into its physical urban context. Through systematic variation of encoding and anchoring strategies and a formative in situ evaluation, we identified recurring design tensions that pose challenges and opportunities for embedded urban climate visualization research.

Our findings show that hyperlocal embedding can foster situated understanding of place, as participants linked temperature patterns to recognizable urban features. At the same time, embedded data visualizations introduce trade-offs: design choices affect readability, environmental awareness, referent coupling, and interactions. Overall, these tensions indicate that embedding urban climate data needs careful design of the conceptual relation between humans, data, and surroundings. Future work should explore integrated strategies to support exploration and sensemaking in situated urban visualizations.

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