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MISSING THE CITY FOR BUILDINGS? A CRITICAL REVIEW OF PAN-SCALAR MAP GENERALIZATION AND DESIGN IN CONTEMPORARY ZOOMABLE MAPS

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ABSTRACT

Most of the maps used today are what we call pan-scalar maps, i.e. interactive zoomable applications comprised of numerous maps of a particular area at different zoom levels (i.e., scales). We argue that such maps require a pan-scalar map design, which may differ significantly from established map design axioms and standards. This review is twofold. First, it reviews current practices in pan-scalar map design. Second, it summarizes and synthesizes literature about pan-scalar map design, as well as human-computer interaction (HCI) best practices for pan-scalar maps. The review of practices is based on an analysis of the design of three popular pan-scalar maps: Google Maps, OpenStreetMap, and France's IGN Classic. Discussion centers on both stellar and subpar contemporary pan-scalar map design practices to help guide future practical pan-scalar designs and research on pan-scalar maps broadly.

Keywords pan-scalar maps and multi-scale maps and interactive maps and cartographic generalization and map design

1 Introduction

To paraphrase George Orwell: "All maps have scale, but some maps have more scale than others."

A majority of maps used on a daily basis today are multi-scalar – i.e., a single interactive map comprised of many maps of the same area designed at different scales. Such interactive web- or app-based maps are frequently tasked with representing a part of the world using anywhere from 2-24 scales. These maps offer user interactivity that allows a user to change the map visualization by panning and zooming and selecting or filtering out data. Such changes are made depending solely on the whim of a user's needs, desires, and hand, verbal, or input-device interaction.

Multi-scale, zoomable maps, however, can be problematic to research, particularly when it comes to trans-scalar generalization and cartographic design. Such maps are far more than the sum of their parts. The most user-friendly and well-designed multi-scale maps are not merely 20-some individually generalized and designed representations stacked together in an app. They are more than "multi-scale" and "zoomable." These phrases oversimplify the fact that many contemporary maps are in fact *panoptic* by design. Such visualizations, or methods of communication, are actually dependent on designs that effectively allow users to transcend scales.

We propose that interactive, multi-scale, zoomable maps are better described as *pan-scalar maps*, because they are designed with the assumption that you will necessarily zoom back-and-forth across many scales to actually use them effectively. We define pan-scalar maps as interactive, multi-scale, zoomable maps designed as a single cartographic product – i.e., an application, a map website / API-based page, or a cartographic interface on a navigation device. What differentiates pan-scalar maps from other online or print maps is that the cartographic representations at different scales are never meant to be consumed individually. They are part of a pan-scalar cartographic product, allowing the user to spatialize themselves within the map product across both space (horizontally) and scale (vertically). Each representation at an individual scale is incomplete, and when designed well, specifically generalized to facilitate panscalar navigation.

Pan-scalar maps represent a magnificent technical development in the history of cartography. However, on the usability side, they continue to present new challenges both for cartographers and map users. Cartographers struggle with how to generalize data across so many scales while still elucidating their communicative message and thematic arguments. Map users, on the other hand, though often enjoying the freedom to move horizontally and vertically through map space, are susceptible to pan-scalar disorientation stemming from issues of cognitive load and shifting cartographic representations across scales. Research demonstrates that pan-scalar map disorientation among users, even if only occurring briefly, negatively impacts both map reading and user experience [1].

As cartographers and data engineers continue to add more levels of granularity and a wider scale range to their pan-scalar maps – from the entire Earth to hallways inside of buildings – little research has explored how to help map users avoid cognitive overload and what we call "cartographic vertigo", while zooming in and out of a map. The LostInZoom Project [2], of which this research is a part, is attempting to fill our knowledge gap in this area of research. By re-envisioning multi-scale, zoomable map design as a pan-scalar map design process, we argue cartographers can begin developing truly pan-scalar generalization and design techniques, rather than use uni-scale generalization and design techniques that often prove inadequate.

The rest of the paper proceeds as follows. After a brief historical perspective in Section 2, we review the design of three current pan-scalar maps: Google Maps, OpenStreetMap, and IGN France. We chose these three for our sample, because all are designed by cartographic practitioners rather than academic researchers, and all three are supported by different types of organizations. Then, in Section 4 we review the research literature of pan-scalar (or traditionally referred to as "multi-scale") map design. We review the second domain of pan-scalar interaction design in Section 5. Section 6 wraps up our analysis by drawing conclusions from these reviews and presents a research agenda for future research on pan-scalar map generalization and interaction design.

2 Historical Perspective on Pan-Scalar Maps

The history of multi-scale zoomable – or again, what we prefer to call pan-scalar – maps is too lengthy and complex to summarize in this article. Several comprehensive historical perspectives on web mapping and pan-scalar maps have already been written [3, 4, 5]. Instead, we provide a brief overview of what researchers and practitioners have meant by "multi-scale," "zoomable," and make an argument for more accurately describing these maps as pan-scalar. We also provide a framework to contextualize our reviews throughout this paper.

Though web maps existed as early as 1994 with the release of Mapserver, the first multi-scale zoomable web map arrived in 1996 with MapQuest. In MapQuest, it was already possible to pan and zoom across different maps at different zoom levels. In the following years, web mapping technologies developed, but the use of these maps really democratized with the launch of Google Maps in 2005 in the United States and in 2006 in several European countries.

The addition of APIs to reuse such interactive maps in any website, and the possibility to create mashups with one's own datasets boosted broad interest in web mapping beyond the relatively small community of professional and academic cartographers. In the following years, institutional geoportals from National Mapping Agencies (NMA), such as the Géoportail launched in 2006 in France, facilitated the switch in use from paper static maps, to web, or mobile, multi-scale zoomable maps.

At the same time, web mapping techniques followed the development of the internet broadly, including the standard defined by the Open Geospatial Consortium (OGC). New standards such as the Web Feature Service (WFS) or the Web Map Tile Service (WMTS) helped make pan-scalar maps easier to use, and facilitated the development of more detailed

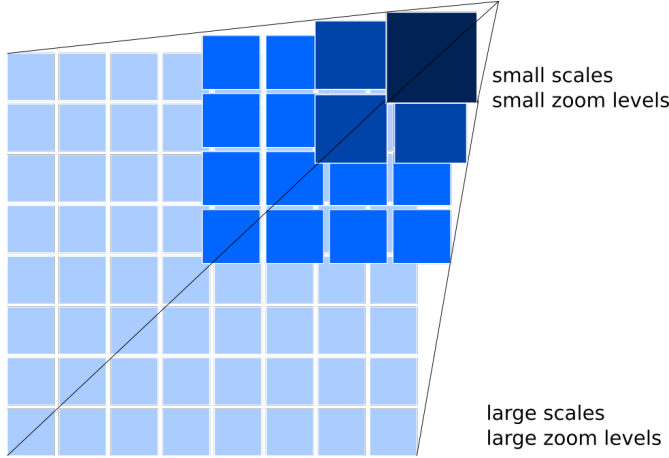


Figure 1: Quad-tree pyramidal structure of the WMTS standard, followed by most of the current multi-scale zoomable maps.

zoom levels (currently going from 0 to 22, Figure 1). These standards are still in use by open source web mapping tools such as Geoserver, OpenLayers, and Leaflet, making it relatively easy for a trained geographical information scientist to build a multi-scale map.

Of course, one needs data to build a map. Open data has also had a dramatic impact on facilitating the ubiquity of pan-scalar maps. Crowd-sourced, open-source data projects such as OpenStreetMap offer cartographers of all backgrounds access to pan-scalar data that would have been prohibitively expensive to acquire in the past from NMAs or large corporations (e.g., Google, Microsoft, Apple).

We can see with this brief historical summary that multi-scale maps were very quickly adopted by users, and mainly driven by data and software engineers at technology companies, rather than cartographers. This is why we believe it is important to begin defining cartographic best practices for pan-scalar map design. The following section derives guidelines from the analysis of current multi-scale maps, while the further sections review research papers on multi-scale map and interaction design. In the remainder of the paper, we refer to and use established WMTS zoom levels rather than mathematical scales when discussing multiple scales of a pan-scalar map.

3 Learning From Current Practices in Multi-Scale Map Design

The need to better understand cognitive mapping to improve map design is widely accepted in cartographic research. Over thirty years ago, Lloyd argued that "[c]artographers hoping to provide better maps for people to read should understand the cognitive processes used to read maps." [6]. Several years later, MacEachren further ushered in the new cognitive paradigm of cartography, noting that "[c]onsidering how people learn about space and how they deal with the spatial aspects of their environment on a daily basis will allow us to devise maps, and map presentation strategies, that facilitate thinking and problem solving rather than memorising." [7]. Mark and colleagues support similar position by stating that : "It is important not to minimize the linkage between the environment and the representational schemes that are used to navigate through it. As Hutchins (1995) argued, the environment provides a context for learning with constant feedback and adjustment" [8]

In this section, we methodically review the way we use cognitive mapping in pan-scalar maps for the critics of current and past design practices. Specifically, we ask how map users may spatialize their cartographic location during pan-scalar map exploration. We start by reviewing how cognitive mapping during multi-scale zoom may take place. We then present a methodology for testing cognitive mapping techniques among users. Finally, we extract from our methodological approaches different identified and likely "lurking" practices that seem to be relevant for map-user cognition across spaces and through multiple map scales .

3.1 Cognitive Mapping and the Structure of our Mental Representation

Unfortunately, there is no unique definition of what cognitive mapping is. A widely prevalent definition from Roger M. Downs and David Stea is that "cognitive mapping is a process composed of a series of psychological transformations by which an individual acquires, codes, stores, recalls and decodes information about the relative locations and attributes

of phenomena in his everyday spatial environment" [9] Golledge and colleagues proffered an equally authoritative perspective, arguing that "[c]ognitive mapping is the process of encoding, storing, and manipulating experienced and sensed geo-referenced information" [10].

Even the term, "cognitive mapping," continues to be up for grabs, as researchers continue to devise nearly synonymous terms (e.g., mental maps, cognitive representation, mental representation, topological schemata, cognitive collage, cognitive spaces). Much of this disparity is due to the inherent multidisciplinary nature that the study of cognitive maps requires [11]. Debate and disagreement most often centers on the term "mapping," not "cognitive."

For example, Tversky argues that our mental representations "lack the coherence of maps" [12], and that our internal representations distinguish themselves from the metrical objectivity of a cartographic map. In other words, mental maps are cognitive distortions of perceived reality, and they are inherently missing parts and patchy [13]. In his review of cognitive mapping, Kitchin built on previous work by Hart, Moore, and Golledge, to argue that cognitive mapping is "the marriage between spatial and environmental cognition," where spatial cognition is based on the reconstruction of spaces in thought and environmental cognition is about the "awareness, impressions, information, images, and beliefs that people have about environments" [11]. Or as Couclelis argued several years before, our cognitive maps are "an attempt to represent our understanding of the structure of the environment." [14].

While emphasizing the "regionalization and hierarchical organization of cognitive space, and the active role of salient cues in structuring spatial cognition" in cognitive mapping, Couclelis and her colleagues also present a theory that a sense of "homeness" also plays a role in anchoring structures [15]. They hypothesize "home" to be our dominant anchor, with nearly all other cues evaluated relatively based on different degrees of familiarity. This argument parallels Marcella Schmidt di Friedberg's who notes that, between "the familiar and the unfamiliar," the question of cognitive orientation is also we come to "feel at home" [16], p98.). It also builds on Tuan's sense of place, where he argues that mental maps give you "a degree of assurance that we would not otherwise have" [17].

3.2 Spatialization across Places and through Scales

Through movements in a physical environment, there are for Sholl two types of structure in visual flow: (1) a dynamic one, formed from self-to-object relations (or egocentric frame of reference); and (2) an invariant structure composed with object-to-object relations (allocentric frame of reference) that remain stable during the movement and argued to be important "for the formation of cognitive maps" [18]. The hierarchical and stable structure formed from object-to-object relations can also be called "the anchoring structure of a cognitive map" [10]. Those spatial abilities structuring our mental representation of space are gradually built by stages during childhood (egocentric, allocentric, geocentric) [19]. In the third stage (geocentric), we finally acquire the ability to make new connections and relations such as proximity, separateness, looseness...

For Golledge and his colleagues, disorientation is a matter of contradictions between (1) allocentric and (2) egocentric frame of references during a movement in a physical world. Adding that "Visualization concerns the ability to imagine or anticipate the appearance of complex figures or objects after a prescribed transformation (e.g. paper folding)" and "orientation is the ability of an observer to anticipate the appearance of an object from a proscribed perspective" [10].

But what about the exploratory movement in pan-scalar maps? Do we use the same cognitive processes and have the same perceptual needs to spatialize ourselves while panning and zooming in interactive, multi-level zoom maps? Can cartographic objects in pan-scalar map design act as this "anchoring structure" stabilizing the exploration in mostly allocentric fashion? And are current design techniques and practices efficient and sufficient for spatialization across space and through scale? Could we design better pan-scalar maps that reduce cognitive load and prevent users from getting lost in zoom?

3.3 The ScaleMaster: or How and Why to Decompose a Pan-Scalar, Interactive Map

The ScaleMaster diagram of Brewer and Battenfield, "where the scaleLine replaces the timeLine", is a formal tool (Excel sheets) designed to formalize the rules for manual map design and "emphasize changes to the map display" [20]. ScaleLine from ScaleMasters is composed of scale intervals (Figure 2). The objectives are multiple: (1) to formalize the changes of symbols in the progression of scales (2) to formalize the geometric changes between scales, (3) to identify the data sets used at a given scale for manual map design [21]. Brewer and Battenfield worked with a group of their students to develop a first ScaleMaster with a starting corpus of annotations formalizing changes in the progression and persistence of map elements (elimination, selection, enlightenment...). Several works have then appropriated this tool in their multi-scale map design or cartographic generalization process. For example Touya and Girres have worked on the automatic generation of multi-scale maps from ScaleMasters while emphasizing the potentiality to make maps between the existing scales [22].

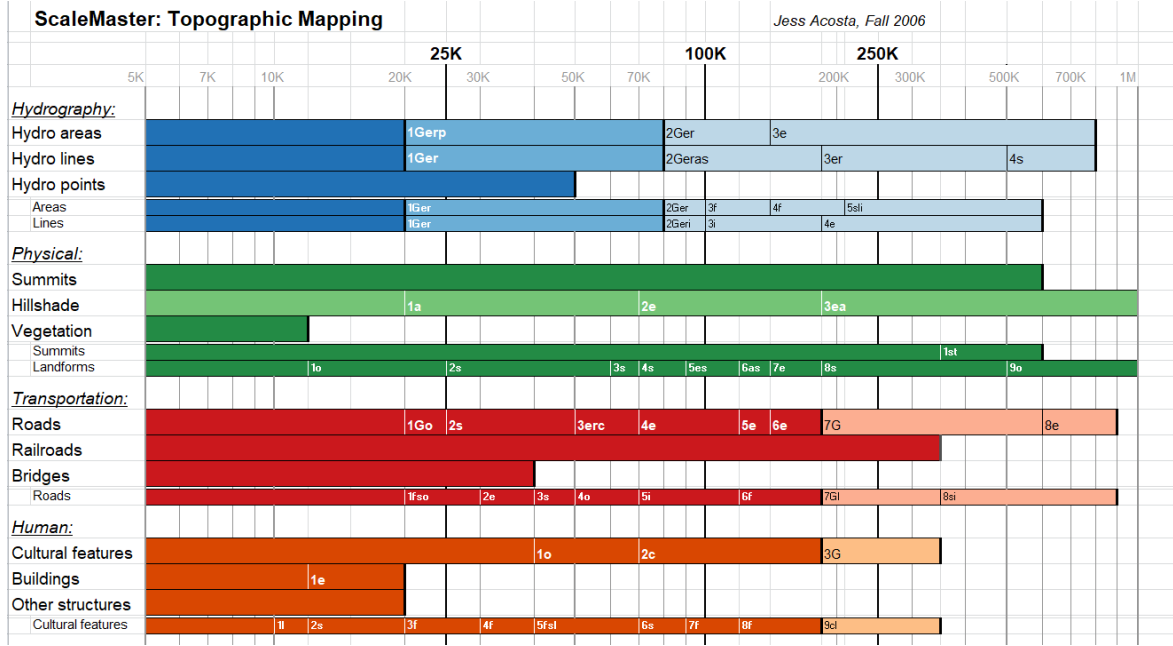


Figure 2: First conception of a ScaleMaster from Brewer and Buttenfield work [21].

In this paper we review the design of three contemporary, pan-scalar maps (including one comprised of zoomable paper maps drawn at different scales): Google Maps, OpenStreetMap, and IGN France’s IGN classic. While Google Maps and OpenStreetMap are interactive web mapping platforms used by millions in their daily lives, the IGN France map is unique: a pan-scalar map comprised of four paper maps at different scales (1:25K, 1:100K, 1:250K, 1:1M). Each of the four representations were originally designed by IGN France to be shown at a particular scale. However, by scanning them into the Géoportail application, they now comprise a pan-scalar map.

Inspired by Brewer and Buttenfield, we use ScaleMaster to standardize and formalize changes while zooming and exploring each of the three maps. In our methodology, however, we go a step further. The timeline of exploration is also examined in addition to the scale line of zooming. We focus on map design practices that account for pan-scalar map exploration. For example, we account for generalization changes between scales based on empirically or theoretically justifiable reasons.

Using Styling Wizard (for Google Maps) and Maptiler (for OSM), two vector styling tools, we were able to deconstruct the composition of pan-scalar maps at each zoom level (Figure 3). These tools allowed us to choose which layers to display at each zoom level and provided some additional information about map parameters, including cartographic scale, when different cartographic representations appeared or changed, and their size and color. Though our research is quantitative in nature, our preliminary analysis leads us to believe that tiled vector styling tools may also be useful for qualitative analysis of cognitive differences across different pan-scalar maps at the same scale in future research.

Initially, we did descriptive assessment of using the three pan-scalar maps. We each explored the three different maps and then wrote down a qualitative summary of our cognitive experience while zooming in, zooming out, and panning across the maps of both familiar and unfamiliar areas. Analysis through writing is dynamic rather than static and lends itself well to the work of finding clues, patterns, as well as opposing logical issues confronting different map users [23]. We met and discussed our notes, before conducting a simplistic textual analysis on how we each placed ourselves during pan-scalar map navigation.

These early explorations led to the identification of common techniques and visual cues that repeatedly came up and were empirically or theoretically already accepted in the literature as normal means of cognitively processing information during map exploration.

We realize our methodological approach is not foolproof and this study represents a fresh start, not a destination, in the study of pan-scalar maps. However, we very much follow the argument proposed by Mackness that “[g]eneralisation must be based on process rather than graphical appearance” (Muller, 1989, p. 203). In other words, generalisation should focus on the phenomenon being mapped (...) rather than the geometric primitive by which it is stored in the

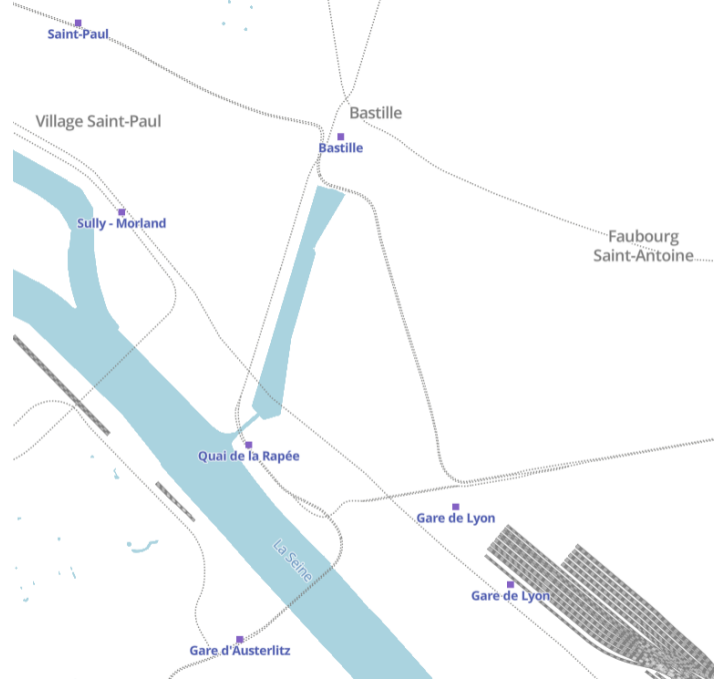


Figure 3: Image captured in the Maptiler tool that shows only rivers and rail features.

database" [24]. The forthcoming analysis is a first attempt at the systematic study of pan-scalar map design relating to how it can mitigate cognitive distortion, location dementia, and cognitive processing loads for map users.

For this study, we used ScaleMaster to analyze particular and common geographic entities in the maps (including rivers, urban areas, bus stations, and administrative borders) representing but a fraction of all map ontologies (e.g., water, roads, transportation networks, relief, points-of-interest, vegetation, administrative districts). We constructed a ScaleMaster for each of the three pan-scalar maps (OSM, Google Map, Scan IGN) (Figure 4). The data that support the findings of this study are openly available in a ScaleMaster form¹.

Our hope is that this first analysis, and the resulting categories below, will lead to critique, comment, and iterative improvement in the future. In other words, our initial findings are just that – outcomes that further exploration on pan-scalar maps can add to, revise, and improve upon.

3.4 Memories of Scales: Exploring Pan-Scalar Map Design

Rather than describe the full ScaleMaster models for each of the three surveyed pan-scalar maps, we instead highlight several practical, pan-scalar map-design rules unveiled by our ScaleMaster analysis.

At IGN, one of the more onerous tasks facing print-map cartographers is to manually enhance (i.e., beautify) geographical elements in maps produced by automated algorithms. This includes changing the placement of labels, reorganizing data layers, resizing elements, standardizing colors, and changing typography, among many other things. For example, contemporary text-placement algorithms still struggle to adequately place and filter text at different map scales based on desired levels of map generalization. Corrections are made based upon semiological codes and an “average” map user’s expected level of spatial understanding. In this case, print cartographers have the challenge of making universal decisions for a single, ubiquitous map scale that the user will experience.

As mentioned in the introduction, however, pan-scalar maps are designed to be explored with movement (typically map panning and zooming across multiple cartographic scales). One’s spatialization of location in the map throughout the zooming process can be impacted by what one has perceived, memorized, and recalled not only from current geographical knowledge but also from previously explored scales and tiles in the pan-scalar map itself. As Merleau-Ponty notes regarding sense of perception broadly: “At each successive instant of a movement, the preceding instant is not lost sight of. It is, as it were, dovetailed into the present, and present perception, generally speaking, consists in

¹<https://zenodo.org/record/7243846>

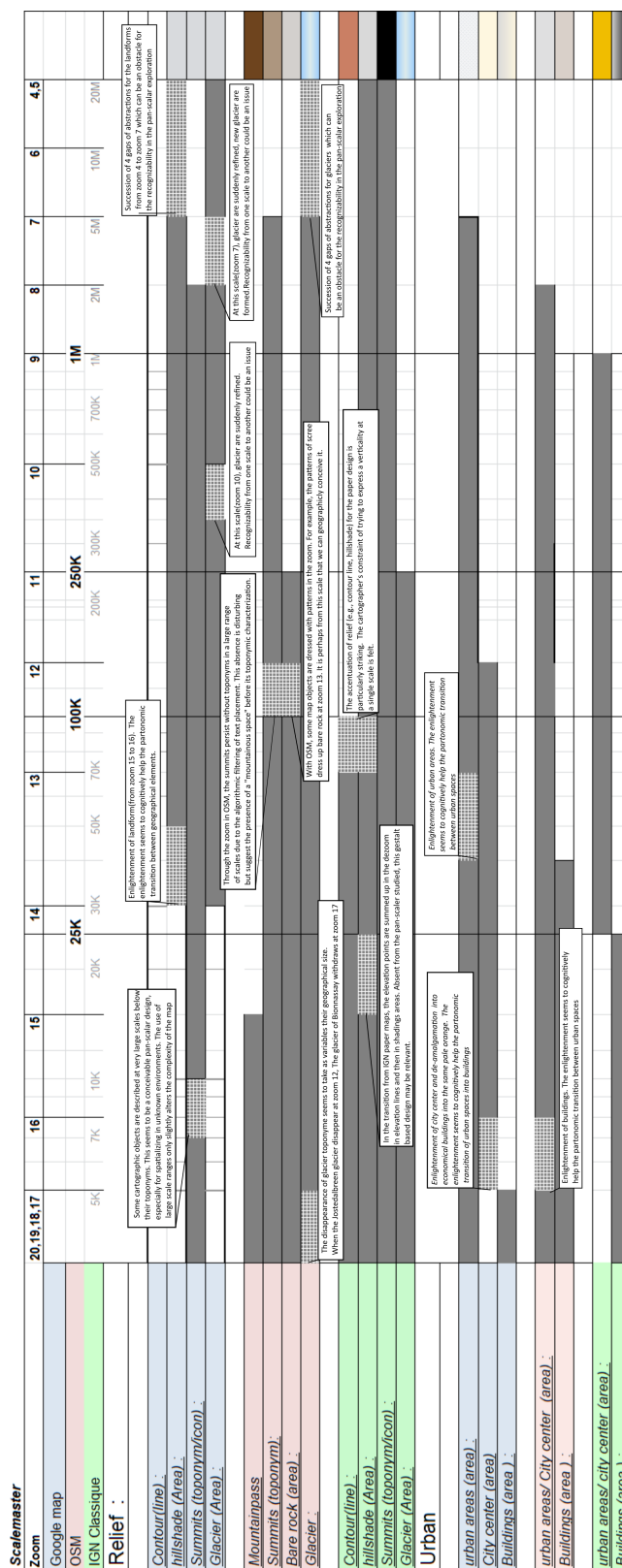


Figure 4: Extraction of the Scalemaster analysing the urban and relief theme for Google Map, OSM and IGN scan. The grey line represents the zoom level from which the map element is visible.

drawing together, on the basis of one's present position, the succession of previous positions, which envelop each other [25].

In other words, one's sense of perception at one scale is comprised and shaped by previously perceived scales, as well as expectations based on experience with previously viewed scales. Below we discuss two pan-scalar map design practices extracted from our ScaleMaster analyses as they relate to what map users may have already perceived and memorized from preceding scale viewings.

3.4.1 Label Elimination with Scale Increase

Our ScaleMaster analysis demonstrated that Google Maps and OSM both label urban neighborhoods when zoomed in over a metropolitan area. However, at zoom level 16 (out of a total of 24), both automatically remove the neighborhood names.

This decision makes sense from a user perspective, as at smaller scales, if a user was indeed cognitively processing the map by looking for neighborhoods, she would already know that she is in, say for example "Quartier Latin" in Paris while zooming. Even if not, she could zoom out to retrieve the labels before zooming in again.

Removing labels when they begin to clutter makes sense, as at larger scales, all labels begin to present a map clutter surcharge. This is obvious when contrasting Google Maps and OSM with the IGN France pan-scalar map produced from paper maps (the map on the far right in Figure 5). Many of the labels included at "in-between" zoom scales are likely unnecessary for spatialization and may in fact impede map user cognition via cognitive overload. Many of the labels, in particular here neighborhood labels, will have already been focused on and memorized at previous zoom levels. In this case, as is often the case with pan-scalar maps at larger scales, less of one element leads to better user experience.

3.4.2 Label Appearance Across Scales Signifies Magnitude of Mapped Features

Google Maps and OSM both use a relatively small range of font sizes to label all map elements. This design decision allows these maps to avoid clutter when zooming across scales and helps avoid label collisions [26]. City labels in Google Maps and OSM gradually begin to appear through the zooming process as one moves from small to large scale. The size of these city labels changes throughout, continually becoming smaller as one zooms into larger scale (i.e., higher zoom) levels. The decision to make these label font size changes at particular scales varies depending on the map producer, but both OSM and Google Maps continually shrink the city labels as one zooms in so that they become the same size as "lesser" important cities at previous zoom levels (see Figure 5.)

Thus, urban hierarchy and sense of importance is not established merely by label font size, as is tradition in print cartography, but rather through persistence across zoom levels. In addition to starting out at smaller scales with a larger typeface, being visible across many scales reinforces location and importance of place cognitively – i.e., scales of appearance and visibility across scale and space. Of course, the downside of this technique from a cognitive standpoint is that understanding urban hierarchy on these pan-scalar maps requires exploration. Depending on where a map user begins her exploration, she may not access enough zoom levels to make sense of urban hierarchy. In the pan-scalar exploration of Google Maps, if a great quantity of places appear, some places of "greater importance" (such as some religious places) see their toponym darken, helping the hierarchy to persist complementary to their scale of appearance. In this sense, we argue that making sense of hierarchies with typographic differentiation (font style, bold/regular, etc.) is still advised for pan-scalar map design. The possibility of transcending scales may be seen as a complementary design variable.

Both OSM and Google Maps use the same topographic technique for establishing hierarchy among hydrographic entities, where river labels of first importance are eventually reduced to the same size as lesser-sized river and tributary labels – at zoom level 11.

Beyond toponymic usage, this pan-scalar design is also used to establish road hierarchy based on each road's size. For example with Google Maps and OSM, a main thoroughfare continually shrinks as one zooms in so that it becomes the same size as less major (though still relevant) roads. Similarly, train station icons gradually shrink from small to large scale, becoming the same size in the visual hierarchy as subway stations and bus stops icons in OSM and Google Maps.

3.4.3 Dealing with Partonomies: From Urban Area to Buildings in Google Maps

The partonomy model helps us analyze pan-scalar maps by tying together map elements with a parent-child hierarchical relationship across zoom levels [27]. For example, urban areas on a map may be represented by a simple polygon at one zoom level but are composed of blocks and roads at another. The blocks and roads are children of the urban area. From there, city blocks may be composed of parcels, buildings, and sidewalks at larger zoom levels.



Figure 5: The disappearance of neighborhoods labels on Google maps through the scales (source: Google map styled(a,b,c), Scan IGN(d)) Attenuation of typographic differences across scales. (Source: Google map stylized(e,f,g), Scan IGN(h))

ScaleMaster allows us to identify and characterize the partonomic relationships and logic used in pan-scalar map design. This method also allows cartographers to explore questions concerning at what moment and how a geographic element has been designed to ascend or descend through its familial hierarchy of symbology. Partonomic representations and design decisions will have an impact of map-user cognition and interpretation, assuming they follow the map user's expectations for "general information characteristics, correct or incorrect of the area in which they are located" [15] and are ontologically consistent [28]. "[I]ntuitive and meaningful interpretation of geographical phenomenon" in maps always benefits from ontologically logical symbol partonomy [27]. In sum, pan-scalar maps benefit from logically conceived partonomic design across scales. They help cognitively structure map user comprehension while panning and zooming across a geographical space in the map, as such hierarchical spatializations are intrinsically relatable "from the actual geographies to the virtual geographies of the information space" (i.e., map) [29].

During our analyses, we will discuss pan-scalar design practices from our ScaleMaster studies that take into account logical partonomy. We will argue that logical partonomic design in pan-scalar maps helps map users navigate by enhancing their memory across scales.

Our ScaleMaster research highlighted that Google Maps embraces two design techniques establishing partonomies when transitioning from urban city centers to buildings. The first technique is a progressive enlightenment of the urban area and the city center from zoom level 15 to zoom level 16, resulting in a de-amalgamation of a single city center polygon into multiple smaller polygons in a pale-orange color representing individual buildings. In a sense, it is at zoom level 16 that Google gives up on the proverbial forest for the trees, with each building intuitively representing a descendent of the urban polygon that has disappeared. This partonomic enlightenment helps the map user logically transition from urban area to buildings.

Beyond user experience, however, the technique may be relevant from an economic perspective, as it may allow Google (or other map producers) to more easily add additional landmarks that are salient and can be placed based on payment (e.g., paid store placements can be more easily added at zoom level 16).

However, this enlightenment practice is also used with other partonomic relationships on Google Maps that seem less than economically incentivized. For example, campus areas disperse into specific school units and buildings from zoom level 17 to 16, national parks to sub-park entities from zoom level 15 to 16, and hillshade adjusts into summits and mountain passes from zoom level 15 to 16. At zoom level 17, the city center building amalgamations again separate into even more defined buildings, again in the same pale orange.

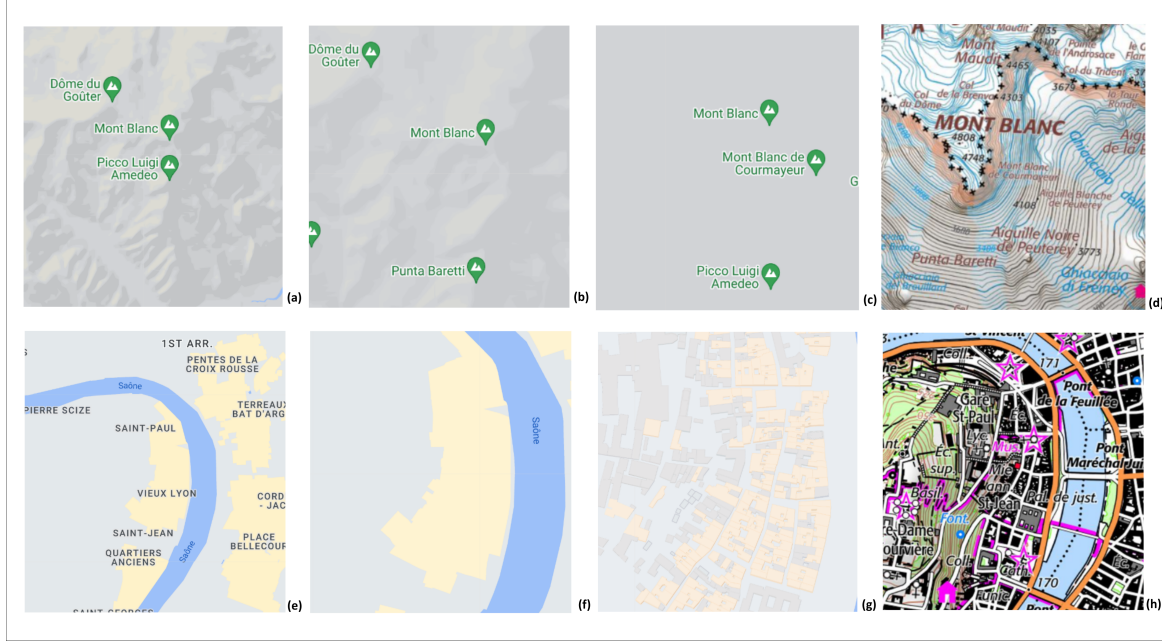


Figure 6: - Partonomic logics for Google maps: Enlightenment of urban areas and city center and de-amalgamation of the city center into economical buildings (source: Google map styled(a,b,c), Scan IGN(d) Enlightenment of the landform and appearance of summits and mountain passes. (Source: Google map stylized(e,f,g), Scan IGN(h))

3.4.4 Gaps Between Realism and Abstraction

In paper map design, changes in abstractions or levels of detail for different maps at different scales are done intuitively and empirically corrected by hand: "this solution looks right" [30] (Figure 7). Frank and Timpf admit that cartographic generalization "require human understanding", "in particular, the recognition of spatial patterns to perform map generalization" [31] and Buttenfield establishes that these processes of cartographic generalization for "visual effectiveness" must be based on the conservation of geographical accuracy and the recognisability of the geographical entity that are scale dependent [30]. Indeed it is admitted that abstraction should be concerned with the psychology of scale and the comprehension of our mental understanding of space [30, 31, 32, 8]. According to Mackaness, scale impacts the psychology of space in the real world [24]. He notes that multi-scalar observation often leads to more insightful perception and analysis. At global scales, we can discern patterns of distribution, association between places, connectivity, and contiguity, whereas at a medium or regional scale we can gain a more contextualized understanding of a particular phenomenon [24]. At the scale of observation, or the "fine scale," he argues that we collect detailed information about the many characteristics comprising the individual phenomena. Abstraction across scales is key to successful interpretation of the real world. Research backs up Mackaness's argument. Several studies have shown that abstract, cartographic representations support a more comprehensive spatial representation of a place than satellite imagery alone [33] [34].

With the ScaleMaster methodology, the main interest with the identification of abstraction gaps (that can be defined as an abrupt change in generalization), may be to identify where a more progressive map generalization process should be used, i.e., the identification of bad pan-scalar design. We found many of these abstraction gaps in all three of our map samples (Figure 8), which can be seen by examining the ScaleMaster. This finding demonstrates that there is definitely room for more efficient pans-scalar map design.

To conclude, we find that Mackaness sums it up nicely by noting that "generalisation is about modelling geographic space - the scale at which we view the world profoundly affecting our ability to understand it. Both the scale of observation and of representation reflects a process of abstraction, an instantaneous momentary "slice" through a complex set of spatio-temporal, interdependent processes" [24]



Figure 7: Two different levels of abstraction for water areas, at successive scales, in the IGN pan-scalar map.

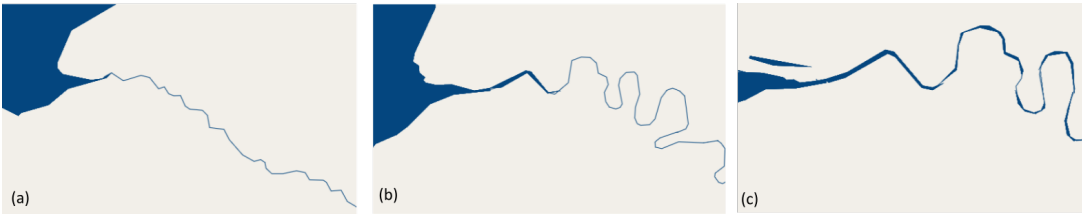


Figure 8: Three successive zoom levels in OSM, with an abstraction gap for rivers between image (a) and image (b).

4 A Review on Multi-Scale Map Design

Although advances in pan-scalar map design are mainly driven by practitioners, researchers also play a key role in analyzing the techniques being used and testing their efficacy in different mapping environments. In this section we review recent research covering general design guidelines, styling, label placement, and map generalization in pan-scalar maps.

4.1 Pan-Scalar Design Guidelines

The first task when designing a pan-scalar map is to organise your source data into a cartographic landscape model [35] that contains as many representations at different levels of detail as possible, for each zoom level of your map [36]. We can see instances of this with in-car navigation pan-scalar maps [37] and in some world population maps [38]. In the Google Maps and OSM maps studied in the previous section, multi-level representation is rather limited. However, it still exists. For example, rivers are sometimes represented with lines, polygons, or a mix of both, depending on the scale. The specification describing how topographic data should be portrayed at different scales is usually contained in stylesheets (see for instance the CartoCSS extract below for the cities layer in OpenStreetMap).

```
#cities{
  [zoom>=4] [population>1000000],
  [zoom>=5] [population>500000],
  [zoom>=6] [population>100000]{
    text-name: [name];
    text-face-name: 'Arial Regular';
  }
}
```

	Local				Region				Country	
	z17	z16	z15	z14	z13	z12	z11	z10	z9	z8
Airport area								x	x	x
Airport buildings						x	x	x	x	x
Airport icons									x	x

Figure 9: A multi-scale legend as defined by [44], applied to Google Maps airport layers.

}
}

The ScaleMaster model provides a more formal way of presenting pan-scalar map specifications [20, 21, 39]. Using an analogy with a timeline where scale replaces time, this model allows the description of scale ranges where a representation of a map layer is valid, and the identification of breakpoints where transformations (generalization or the change of the symbol) are required.

Beyond the specification of the scales corresponding to the zoom levels usually used in pan-scalar maps, adding intermediate scales can be useful to make the scale changes more progressive [40, 41]. Such intermediate levels are particularly important between zoom levels that present conceptual cusps [42], i.e. significant abstraction changes such as a city represented as a polygon becoming a point symbol at a smaller zoom level. The abstraction gaps identified in Section 3 can be seen as cusps in the sense of Müller.

One design solution to mitigate these dramatic representation cusps is to add transitions between significantly different abstractions [41]. Two types of transitions are identified: aggregation and layered transition. Aggregation passes from individual features, such as buildings, or trees, to a more abstracted polygon, such as an urban area or a forest, with partial aggregations of the close individual features at the in-between zoom levels. The layered transition passes from representation a to representation b by showing both a and b at the in-between scales. Finally, when defining the available operators to create the cartographic database, the multi-scale context provides more possibilities than usual map generalisation operators, as shown by a typology [43].

Besides processing the data, it is also important to design a consistent map style across scales, which can be difficult sometimes when there are changes of abstraction [41]. This consistency can be achieved by designing multi-scale styles [44, 45]. Also, the concept of designing a multi-scale legend (Figure 9) might parallel the ScaleMaster we used to synthesize current practices, and helps cartographers make sure the multi-scale style is consistent [44]. It is also possible to compute metrics and automate the assessment of map style consistency across all scales [45].

As noted in Section 3, text placement is another crucial design step, as poorly planned toponym placement at any given zoom level or map scale can negatively impact pan-scalar map design. Though most text placement methods focus on maps at a single scale, the principle of active ranges allows the concurrent optimisation of label positioning across multiple scales [46, 47]. The principle of active ranges, which are multi-scale 3D cones where a label should remain, ensures labels do not get repositioned from scale-to-scale and prevents label overlapping. Another labeling algorithm, one which uses active ranges with leader lines has also been proposed as a viable pan-scalar text-placement solution [48].

4.2 Multi-Scale Map Generalization

Map generalization is one of the main cartographic processes to address when designing a pan-scalar map to visualize data with a good level of detail and level of abstraction for each zoom level. However, most map generalization research focuses on maps at a single scale. Pan-scalar maps, by contrast, require interdependent generalization across myriad scales [40].

Consistency remains a major problem due to the continued use of single-scale map generalization techniques repurposed for pan-scalar map design [49]. Stochastic decisions are often made during single-scale map generalization, meaning that a map symbol moved a certain way at a particular scale, might be moved an opposite way at the following scale if no consistency safeguards are in place. Defining active ranges, as mentioned in the previous subsection for label placement, helps produce a more consistent generalisation of point symbols across scales [50].

The difficulties confronting pan-scalar generalization don't end here, however. Another problem is the need for progressive and logical changes from detail and abstraction and vice-versa. Touya [22] demonstrated that ScaleMaster 2.0 can be used to help develop benchmark locations for certain generalizations across different zoom levels within



Figure 10: The continuous generalization of a mountain road with three intermediate states between the detailed road on the left, and the simplified road on the right. The continuous generalization is obtained with a morphing algorithm [60].

pan-scalar maps. Other research has successfully adapted classical methods of generalization evaluation to help derive progressive outputs across many scales [40]. However, both of these techniques seem like stop-gap measures – workable but not efficient.

The best method is likely yet to be designed – a truly comprehensive, multi-scale, continuous generalization method [51]. Even before the launch of Google Maps, researchers on map generalization imagined continuous transformations to enable smooth zooming interactions [52, 53, 54]. Continuous generalization techniques provide continuous transformations by considering scale range as a real interval, instead of as simple list of discrete scales or ordinal zoom levels.

The most significant proposal about continuous generalization is the Space-Scale Cube data structure, which stores 3D representations of the map with the third dimension corresponding to scale [55, 56]. Others have experimented with storing continuous, multi-scale representations of a river network using a matrix representation [57]. Specialized multi-representation databases [58] can also be used to store continuous data across scale using the concept of ‘degree of generalisation’ [59].

All of the above models can store continuous map representations but none explain what bedevils cartographic designers – *how do we generate these continuous representations?* Two different approaches for pan-scalar generalization generation have been proposed in the literature: *morphing* and *continuous algorithms*.

Morphing is possible when one has two representations already produced for different scales that are not yet continuous. The morphing technique will generate a continuous transformation from one to the other [60, 61, 62, 63, 64].

Continuous generalization algorithms, by contrast, only require one scale as input. The algorithms generate continuous transformations over a predetermined scale range. Continuous generalization algorithms are predominantly used in circumstances where morphing is not particularly efficient, such as with road selection [65, 66], building aggregation [67], and administrative area aggregation [68, 69]

5 A Review on Zooming and Other Multi-Scale Interactions

As highlighted by Roth [4], one of the main differences between zoomable multi-scale maps and paper maps is the interactivity between the reader and the map. To complement our review on pan-scalar map design in the previous section, we offer a review of how people interact with pan-scalar maps. Most of the papers discussed below come from the field of human-computer interactions (HCI).

In human-computer interactions, there are four established types of multi-scale interactions [70]:

- zooming
- overview+detail
- focus+context
- cue-based interactions

We review each of these below, as they relate to pan-scalar map interaction.

5.1 Zooming Techniques

There are three primary zooming techniques found in pan-scalar maps: discrete, animated, and continuous zoom [41]. Among these, almost all contemporary pan-scalar maps now use continuous zoom. Continuous zooming interactions within a map use a space-scale diagram [71] facilitated by a semantic zoom [72]. The technique allows map objects to change over scales with an animation [73] that first zooms (in or out) from the initial view, before displaying a new



Figure 11: Example of an overview+detail interface in a multi-scale map with the small scale inset in the bottom-left corner (<https://www.geoportail.gouv.fr>).

representation. With continuous zoom, the user is not limited to individual zoom levels. If the user stops the zoom between two levels, the map will visualize at the appropriate ratio between the two zooms. Not only is continuous zoom quick, it's intuitive. The zoom animations help users build a mental map of the explored space [74].

Interactive zoom is not only used when a change of scale is necessary but also to make pan interactions across space quicker. The speed-dependant automatic zoom technique has been proposed to automatically zoom out when the user pans, which can help speed up navigation [75]. The scale change depends on the speed of the mouse movement during the pan. This technique has been tested and initial results showed it was more effective for facilitating map-user navigation than standard pan and zoom [76].

Additional zooming techniques are largely inspired from topology-aware navigation in very large graphs [77]. Topology-aware navigation is based on the known topology of a given visualized information space. Basing it on a known topology allows users to take shortcuts during navigation. In the case of multi-scale maps, if the map is a multi-scale cartographic database, and not just a pyramid of image tiles, we could use the data stored at other scale levels to guide the user when zooming in and out.

Using this principle, GravNav uses a gravity-based model to attract a user's zoom actions to predefined points of interest, where users are likely to zoom in on or to [78]. BIGnav uses a Bayesian learning approach to zoom to the good target [79]. For example, on a map showing all of Europe, upon interaction, BIGnav will automatically zoom to one of the largest capitals based on where the interaction took place. If this is not the correct target (i.e., the user immediately decides to zoom back out to go somewhere else), a second likely proposition is chosen and zoomed in on.

Both of these techniques, GravNav and BIGnav, proved more efficient than generic pan-and-zoom techniques when users were tasked with finding a target in the map as quickly as possible. BIGexplore is a recent enhancement of BIGnav applied to map exploration. In BIGexplore, pan-scalar map system can handle a user that changes their target during a zoom or pan exploration [80].

5.2 Overview+Detail Techniques

Overview+detail techniques offer map users a small-scale locator map on top of the primary, detailed larger-scale map. A well-known example of the overview+detail technique from everyday human-computer interaction is PDF reader that shows the outline of the document in a view on the left of the screen and a zoomed-in view of the page you're viewing in the main view. Of course, overview and inset maps have been in use for centuries in print cartography as well. Figure 11 shows a basic application of the overview+detail principle with a small inset showing where the main view is located in the French territory. Such a technique is shown to reduce the amount of pan- and zoom-gestures during search tasks. One study even found that the ideal overview map window size is one sixteenth of the detailed view [81].

In the Géoportail example from Figure 11 and the previous experiment [81], the gap in scale between the overview and detailed views works at a fixed ratio, i.e., there is a zoom in the overview when the user zooms in the detailed view. But

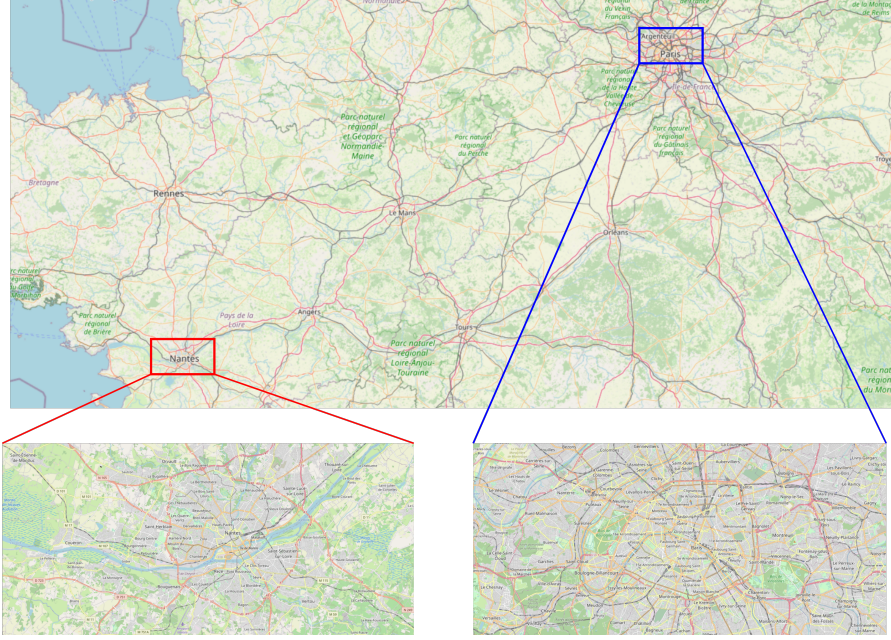


Figure 12: Principles of the PolyZoom interaction, with small insets of past zoomed maps displayed under the main map view.

experiments with gigapixel pathology images show that overview windows don't need to rescale in conjunction with detail windows to remain effective [82].

PolyZoom is a unique overview+detail technique primarily designed for large screen displays [83]. Due to the larger amount of available screen real estate, this technique displays multiple views at different scales, each connected via leader lines (Figure 12). Studies show PolyZoom allows users to solve multi-scale and multi-focus searching tasks more quickly than standard, small-window overview+detail or generic pan-and-zoom techniques.

With WetPaint, the overview window is the larger one, in which a region is scraped (dragged and dropped) by the user to study it in the detailed view [84]. This technique is most useful when the detailed view can be analysed using several distinct layers (e.g. a map layer and a satellite image view).

With the Scalable Insets technique [85], the main view of the map is usually also the small scale map, but every time the user zooms in on the map, a small inset remains linked to its location with a leader line. None of these different overview+detail techniques offer a pure alternative to traditional pan-scalar zooming. However, research shows most of these techniques do offer an upgrade when it comes to managing pan-scalar navigation.

5.3 Focus+Context Techniques

Focus+context techniques are inspired using the principle of a magnifying glass. Each provides a fish-eye, detailed view of a specific area in a complex dataset (or map). In human-computer interaction studies, the first focus+context technique developed was the Magic Lens, found within the ToolGlass widgets tool [86].

In order to work with maps, dedicated fish-eye views were proposed by introducing a glue area around the focus, where the map is distorted to connect the features between the focus and the broader, smaller-scale context [87, 88, 89]. A round focus area is typically not ideal for a unpredictably shaped geographic regions. Thus, map researchers proposed focus+glue+context techniques adapted from the fish-eye. Many maps instead have the fish-eye reshape itself to match the area or object of focus (e.g., an island, city, road, or country) [90, 91].

Other types of focus map techniques were also proposed, including those where the rim of the lens delimiting the magnified area is not visible [92, 93, 94]. Transient overlays are another mixed technique offering a quick preview of a focus area, which can be later decoupled from panning and zooming for separate viewing by the user [95]. Other proposed multi-focus techniques, such as Mélange, connect two focus views with a middle perspective [96].



Figure 13: Example of a focus+context interface in a multi-scale map with the 1:25k map displayed inside the lens, and the 1:100k map displayed outside the moving lens.



Figure 14: A grid of illusory lines used as cue to foster memory processes, inspired from [101].

But all of these techniques have the same limitation – they only present a large-scale view in the focus area, not a more detailed map specifically designed for a larger scale (Figure 13). Several new techniques have been proposed to explore this issue. For example, an attempt has been made to apply generalisation to areas located outside of the focus – in the context – area of the map [97]. When a multi-scale cartographic database is available, the focus and glued areas can load data from more detailed zoom levels and the out-of-focus context can be extracted from less detailed levels [98]. Zhao (2020) even proposes multi-focus areas.

Though focus+context techniques can be very helpful for specific map exploration tasks, they are not always efficient when it comes to HCI. Focus+context methods require panning across maps with the lens and often result in high cognitive loads [99].

5.4 Cue-Based Techniques

Cue-based techniques offer users graphical hints (e.g. symbols, grids, arrows, leader lines) indicating what is located outside the current view and at other scales. Cues can provide direct and seamless feedback to the user during pan-scalar navigation, and thus promote flow, a key factor for designing fluid user interactions [100].

A halo is not specifically a pan-scalar exploration technique, but it does assist user navigation by providing symbol cues along the map border. Halos are cues showing map users what important features and landmarks will be found should they pan in a particular direction [102]. Beyond being beneficial for zooming, the halo method may also make

pan-and-zoom exploration more efficient. Map users can more confidently zoom in and out if it is clear that their intended target is not accessible by panning around the current view.

Illusory lines are another cue-based technique, where grid lines are included on the map but they run under most of the map layers. This not only reduces the additional visual clutter grid lines are bound to create, but the lines can be used to enhance the visual hierarchy of important features at a given scale [101]. The Gestalt laws of perceptual grouping (the closing law here) make our brain close the lines even when hidden by buildings or a lake (Figure 14). Illusory lines may make the memorization of map locations easier according to an unpublished user study testing this technique.

Finally, the semantic depth of field technique is inspired from the depth of field principle used in photography. The depth of field technique artificially blurs the background, or unfocused, data in the visualisation. The area of focus, i.e., foreground layers of a visualization, remain clear and naturally float to the top of the visual hierarchy [103]. When applied to pan-scalar maps, depth of field can guide a user's zooming action toward the optimal scale to allow for the examination of certain types of features, e.g. buildings appear only clear at zoom level 17.

5.5 Discussion

What does this review tell us about all of the interactions currently used in multi-scale maps?

First, we can see that the pan-and-zoom techniques predominantly used in a majority of contemporary pan-scale maps are still the original ones designed in the 1990s for multi-scale environments. Though many additional techniques have been proposed over the past twenty years, very few were ever implemented in the main API and coding libraries used to deliver a majority of pan-scalar maps on the web.

All existing and proposed techniques have the same *raison d'être* – to minimize the desert fog effect [104] and cognitive load of both horizontal and vertical pan-scalar map navigation. Several studies now continue to determine the same thing: contemporary means of navigation are detrimental to map interpretation and navigation [1, 2]. Innovation and, perhaps most importantly, adoption of new pan-scalar map navigation methods are sorely needed to improve user experience and pan-scalar map efficiency.

Though there are far more proposals for overview+detail and focus+context supplemental techniques compared to actual new pan-scalar-specific zooming innovations, supplementation of existing techniques should not be opposed. They can be used jointly with traditional pan-scalar navigation methods to make the navigation experience more efficient.

Perhaps most surprisingly, given the emphasis placed on animation during the rise of multi-scale digital cartography, animation techniques of pan-scalar navigation have largely been neglected by researchers. Preliminary research in this area has shown positive results [74, 70], but the animation technique has yet to gain any traction. This is an area that should be studied further.

Finally, the zooming techniques that use the information space to guide the exploration, such as BIGnav [79] and GravNav [78], are quite promising. Now that vector tiling is ubiquitous, researchers have easier access to the vector data on a client's device, where map interaction is coded. Knowledge about the information space could be used to guide a map user's zoom action toward key anchors or particular landmarks for instance [2].

6 Conclusion and Research Agenda

This research review is both a statement and a call to action.

We argue that cartographers need to start focusing on pan-scalar map design as a major focus of research. Pan-scalar maps – multi-scale and zoomable – are anything but new. However, because they have failed to heretofore been codified into a clear map type, study of their design has been a sporadic and disjointed endeavor.

Moreover, major differences exist between static map design conventions and pan-scalar map design needs. Static (e.g., paper) map design, which is intuitively considered to be more "artistic," compared to pan-scalar design, clearly shows phenomena of accentuation. The cartographic constraint of mapping at a single scale can be seen in the design choices. For example, lakes, ponds or any areal hydrography is more formed, precise, recognizable, more toponymically differentiated on paper maps at the equivalent scales. The relief rendering is remarkably more crafted by the accentuation of the visibility of the contour lines, shading, points of elevation (Figure 15). By this incapacity to transcend the scales by zooming in or out on the final object, these traditional cartographers must hierarchize features, and make them more vertical by accentuating their distinction. One could say that traditional cartographers work at one scale but not inevitably for one scale. Analogically, the art of the comic strip is said to be mainly located in the art of the beautifully named "gutter" which corresponds to the space separating the comic boxes i.e. the art of the images created or implied

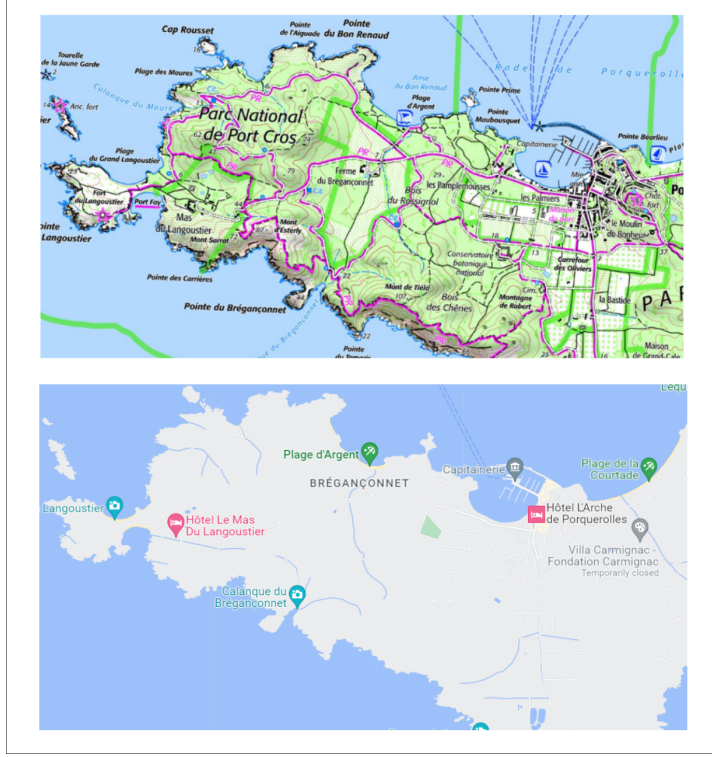


Figure 15: IGN map at the 1:25000 and corresponding Google Map. The relief is more pronounced (contour lines, shading, points of elevation) with IGN map as are urban areas.

between the drawings in a page. Pan-scalar maps aesthetics seem to be about creating or implying images during the dynamic exploration (mountain areas transiting into summits, city center decomposing into buildings...).

As a call for action, we have shown that there is ample preliminary research to derive and plan a new research agenda for pan-scalar map design. First, we further analysis of pan-scalar maps using ScaleMaster is necessary to further extract and expound upon better and worse design choices in pan-scalar map design. In particular here, this research merely skimmed the surface of comparative analysis among different types of maps. We believe that focusing on environmental and physical feature generalization across scales would be particularly fruitful.

To facilitate research in the community broadly, the ScaleMaster analysis of the three maps in this study is online and available for others to analyze or use for further research. One limitation of this study that others may expand upon using this data, is that because many pan-scalar maps are global in scope, they frequently use exactly the same design and generalization rules for every place in the world. Yet, there can be significant landscape differences (e.g., Kansas, United States, versus Katmandu, Nepal) that would benefit from landscape- or environment-aware design rules. Additionally, differently sized urban areas (e.g., Besancon, France, versus Tokyo, Japan) may require different levels of detail to avoid disorientation during spatialization. Future research could focus on specifically associating pan-scalar design to different types of urban environments or physical geographies.

The short review on cognitive mapping demonstrates cartographers still have work to do when it comes to better understanding disorientation (i.e., the desert fog effect) when using pan-scalar maps. We encourage further spatial cognition studies on this phenomenon because understanding disorientation is crucial to bettering pan-scalar map design.

Maps, particularly pan-scalar ones, continue to evolve quickly. The fact that Google maps recently introduced well-known landmarks as anchors visible at multiple scales demonstrates the need for our discipline to more systematically promote using new techniques pan-scalar, including the Google one, which was originally proposed by a research cartographer [1]. Technology companies and data engineers will continue to experiment with different methods of pan-scalar map design, whether the techniques are efficient or not. It's up to cartographic researchers to study the impact of these different design choices on map use and cognitive mapping among map users.

The future of pan-scalar map design research is bright. A systematic and organized approach to studying map styles, text placement, desert fog, and multi-scale generalization will likely prove fruitful fields of study for years to come.

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