Designing Multi-Scale Maps: Lessons Learned from Existing Practices

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Abstract

Mapping applications display multi-scale maps where zooming in and out triggers the display of different maps at different scales. Multi-scale maps strongly augmented the potential uses of maps, compared to the traditional single-scaled paper maps. But the exploration of the multi-scale maps can be cognitively difficult for users because the content of the maps can be very different at different scales. This paper seeks to identify the factors in the design of map content and style that increase or decrease the exploration cognitive load, in order to improve multi-scales map design. We studied sixteen existing examples of multi-scale maps to identify these factors that influence a fluid zooming interaction. Several different analyses were conducted on these sixteen multiscale maps. We first conducted a guided visual exploration of the maps, and a detailed study of the scales of the maps, to identify general trends of good practices (e.g. the WMTS standard that defines zoom levels is widely used) and potential ways of improvement (e.g. a same map is often used at multiple successive zoom levels). Then, we focused on the visual complexity of the multi-scale maps by analyzing how it varies, continuously or not, across scales, using clutter measures, which showed a peak of complexity at zoom level 12 of the WMTS standard. Finally, we studied how buildings and roads are subject to abstraction changes across scales (e.g. at what zoom level individual buildings turn into built-up areas), which can be one of the causes of exploration difficulties. We identified some good practices to reduce the impact of abstraction changes, for instance by mixing different levels of abstraction in the same map.

Keywords cartography · web mapping · zoom · map generalization · level of detail · abstraction · clutter · visual complexity

1 Introduction

Fifteen years ago, before the popularization of Google Maps and geoportals appearing at the same time, maps were used with standalone scales, either on paper or screen. Now, maps are mostly used through geovisualization applications that enable panning and zooming in and out. And these zooming interactions make use of a pyramid of maps at different scales: when a user zooms in, maps at larger scales are displayed and maps at smaller scales are displayed when the user zooms out. They are usually displayed on the web through a slippy map architecture, i.e. an architecture with tiled raster web maps. We call these pyramids of maps *multi-scale maps*, to really capture that the users can zoom in different maps at different scales.

This is a huge improvement in the usability of maps as each scale can convey different and complementary geographic information. But, the picture is not so ideal as users are often troubled by the differences between the maps at different scales, and it takes some time to find your bearings back after each zooming interaction. This cognitive difficulty when map changes is quite common in most multi-scale visualization that enable zooming interactions, and is called the desert fog effect [1]. In most multi-scale environments, particularly in spatial multi-scale environments, novice and expert users all lack exploration cues when they change the level of detail: it is cognitively hard to figure out where the previous visualization is in the current one [1]. It is an analogy with a real exploration task in the desert where desert fog only lets you know where you are, but not where you are coming from and where you are heading to.

Clearly, the desert fog does not exist in multi-scale maps because of poor design, but because it is inherent to such a system with maps at different scales disappearing and appearing when zooming. But the lack of map design theories and methods related to multi-scale maps, contrary to the design of classical topographic maps at a single scale, shows some potential for major improvements. Multi-scale map designers facing this lack of knowledge usually rely on the classical knowledge by designing independent maps at the different scales. But we think we could make much better multi-scale maps by understanding how the users perceive the multi-scale exploration, and what are the factors of map design that are key in this exploration.

In this paper, there is a specific focus on some of the facets of map design: abstraction, scale, map generalization. Our assumption is that we could design better multi-scale maps by adding more scales while preserving the consistency of all maps, and by improving the regularity of content changes from one map to the map at next (resp. previous) scale. For instance, we would like to help someone designing a multi-scale map within the ScaleMaster framework [2] with guidelines to reduce the desert fog effect when zooming in the map. Following this assumption, the aim of the paper is to extract knowledge on the design of multi-scale maps, and to learn from the existing multi-scale maps good practices.

The following section reports similar studies and discusses the problems of multi-scale exploration to introduce the various experiments reported in this paper. Then, Section 3 details the initial visual exploration of the multi-scale maps. Section 4 presents experiments on zoom levels and how they relate to map or display scale. Section 5 then describes our analysis of the visual complexity of the multi-scale maps. Section 6 focuses on abstraction levels and the use of map generalization. The main findings of these experiments are then discussed in Section 7. Finally, Section 8 gives some conclusions and suggestions for further research.

2 Definitions and Experimentations on Multi-Scale exploration

Existing multi-scale maps are very diverse, and we believe that we can learn a lot from what they have in common and from their differences. At the time of this study, many of the existing multi-scale maps were built upon scanned versions of paper maps that were designed for a single scale. Indeed, it was considered as the best compromise between high quality cartography and production cost. Sometimes, the multi-scale maps producers had available vector digital cartographic models [3] and used them. Of course, map producers or designers tried to optimize map content and design to the display scales in a scale pyramid, but their options were limited. This is why we expect that the existing multi-scale maps have positive features regarding multi-scale exploration fluidity, but also features that can be improved.

Comparing existing maps from different countries or producers is not a new idea, and we can also learn from past research how to carry out such a comparison. This section starts with some definitions on zoom and scales, and then discusses the concept of desert fog in multi-scale map exploration. Finally, the experiments are introduced and the common elements of their protocol are described.

2.1 Zoom and Scale

The cartographic scale of a paper map is a key notion in cartography, as it defines the ratio between the size of a feature on the map, and the size of the same feature on the ground, but also guides the content and abstraction choices [4]. On a screen, the same definition of scale applies, and we will call the scale of the map on a screen *display scale* in this paper. But the multi-scale maps are often composed of digitized paper maps, initially produced for a specific cartographic scale. To avoid confusion with the *display scale*, we call the scale of the source paper map *symbolization scale*, as this scale defines the size of the symbols of the map (Figure 1). Visual perception is more limited on screen than on paper, *i.e.* the smallest details we can see on screens are bigger than the smaller details we can see on paper [5, p. 50-53]. So, symbolization scale is usually smaller than display scale.

To better understand how multi-scale maps work, it is essential to clarify how the users of the multi-scale map can interact with it and navigate into scales. In 2016, when this research was conducted, most of the multi-scale maps accessible on the web or on smartphone applications, can be navigated with classical zooming interactions: there are fixed levels in a scale ladder called zoom levels. This a simple case of what is called semantic zooming in human-computer interactions [6]. We call this type of interaction *discrete zooming* (Figure 2). The zoom levels usually follow the WMTS[1] standard prescriptions. At the time of writing this paper, most of the multi-scale maps

[1]Web Map Tile Service

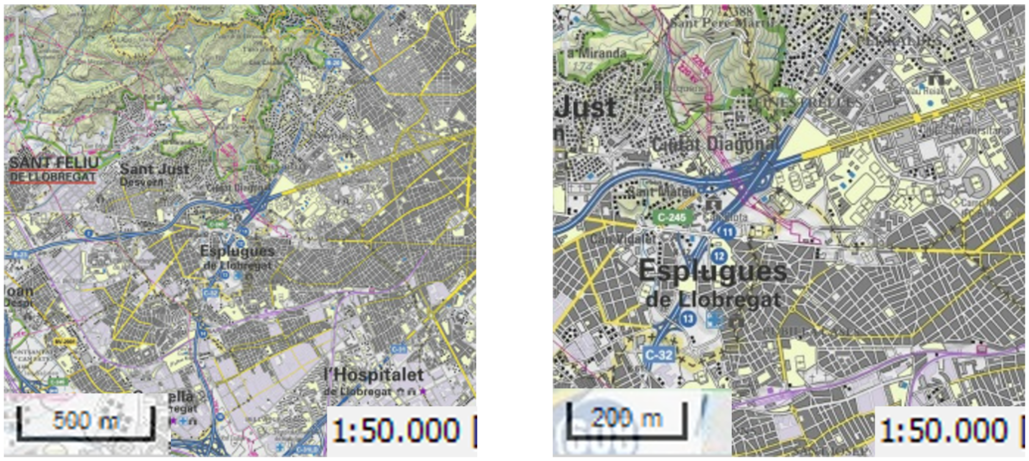

Figure 1: A same map at 1:50k symbolisation scale displayed at two different display scales (source: ICGC Catalonia).

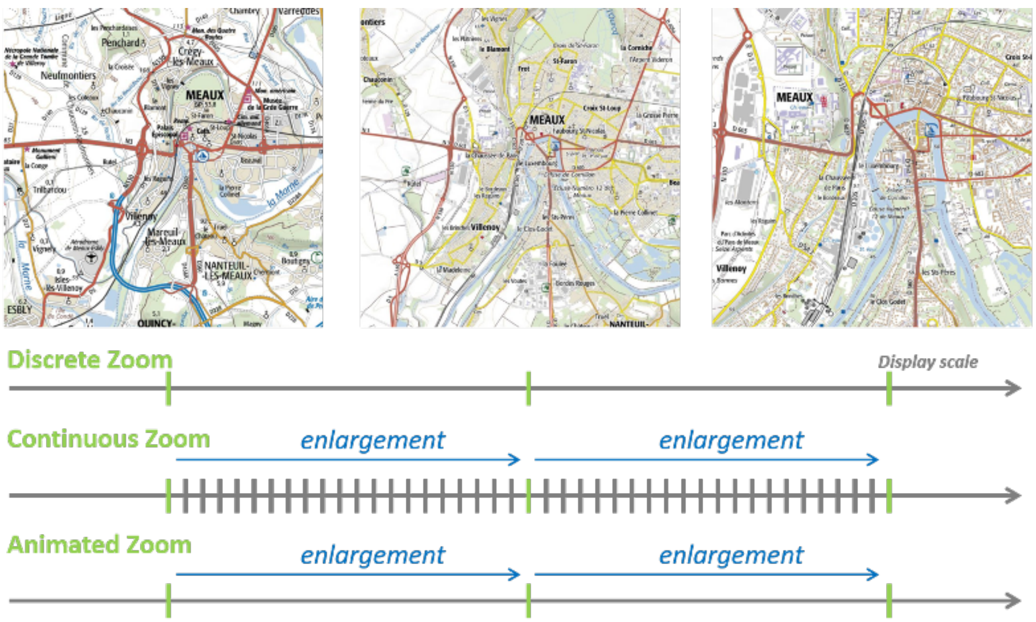

Figure 2: Principles of the three existing zooming interactions (discrete, continuous, animated).

had switched to the new standards of zooming interactions that we call animated and continuous zooming (Figure 2). The transition to animated zooming is based on the evolution of OpenLayers or Leaflet, the libraries behind these web applications. With animated zooming, when the user zooms in to the next zoom level, the zooming interaction enables smooth animated enlargements [6, 7] of the current displayed map, until the next zoom level (green dash). With continuous zooming, available for instance in GoogleMaps when using a touch-based zooming interaction, progressive enlargements of previous map (green dash) are also performed when the user zooms in, but this time, the user can stop at any display scale (gray dash). However, as explained in Figure 2, continuous zooming is really different from continuous generalization as proposed *e.g.* in [8], it just an enlargement of the image of the map from the closest zoom level.

2.2 Multi-Scale exploration and Desert Fog

For most of their usual tasks, the users of multi-scale maps need to navigate in the map by simple interactions such as pan, zoom, or overlay different map layers [9]. In this research, we are only interested in tasks that require to zoom in and out the multi-scale maps, which involves visualizing maps at different scales in the current web mapping applications. This type of interaction is not specific to maps, and so-called multi-scale exploration is a typical problem in human-computer interactions with systems that can be explored at different scales [10].

In order to improve the user experience, the multi-scale map designers would like to allow interactions with the maps at different scales that are as fluid as possible. Fluid interactions with information visualizations promote flow, *i.e.* a mental state of immersion for the user, support direct manipulation of the visualization, and minimize the gaps the computer state and what the user expect it to be (*e.g.* it should not zoom out of four levels when only one is expected by the user) [11].

The desert fog effect introduced by julFurnas is one of the factors that can make the interaction with a multi-scale system, such as a multi-scale map, not fluid. As mentioned in the introduction, the desert fog effect is an analogy with the very dense fogs that can suddenly occur in several desert because of particular humidity conditions. Navigating in such fogs is very complex because you only see where you are, and not where you were coming from and where you are heading to. The desert fog effect is "*inherent and pervasive in multiscale worlds*" [1] In multi-scale systems, such as the famous research environment Pad++ [6] or as a web map, the visualization changes with the scale in a zooming interaction, and there is often no exploration cue in the new visualization to understand where the user, its mouse cursor, or its gaze were in the previous visualization. Past experiments showed that the desert fog effect affected novice and expert users, in very different multi-scale systems [1]. We all experienced this moment when we are a little bit lost after a zooming interaction, and this shared personal experience was also confirmed during sessions with a general public audience asked to zoom in and out to follow a route in a research themed escape game.

But the maps are not totally devoid of exploration cues, as the same features are often represented at multiple scales, which makes the desert fog effect not incapacitating. It just perturbs the user experience, more or less depending on users cartographic and pan-and-zoom literacy. The intensity of the desert fog might also depend on cultural differences: same people might easily see exploration cues in maps from their home country but not in maps with other landscapes and cartographic designs [12].

In addition to the zooming interactions that are used in actual multi-scale maps, researchers tried to propose other zooming paradigm to make a more fluid multi-scale exploration [13, 14, 15]. In a more direct application to multi-scale maps for instance, animations were proposed and tested for panning and zooming interactions [16]. But as noted by Elmqvist2011, improving the interaction method is not the only way to improve exploration fluidity. In this paper, we want to study the influence of the map content on exploration fluidity, and the amount of desert fog effect in this exploration, independently to the type of zooming interaction.

2.3 Experiments with Existing Multi-Scale Maps

A similar cross-country comparison was carried out on the joint use of orthoimages and maps in web mapping applications, on 45 different applications [17]. The study is similar to our problems because it is an interactive map that is compared, with possibilities to pan, zoom, and change the transparency of the layers. The study suggests the use of an observation grid focused on the goal of the survey. An observation grid is a list of quantitative and qualitative elements to note, just like a questionnaire for surveys with users. For instance, hoarau12 note the amount of available base maps in the web applications they surveyed. Among the criteria of the observation grid, trends are important to note. Another survey focused on the analysis of 20 European topographic maps at the 1:50k scale, in order to characterize cartographic style differences [12]. An observation grid is also used in this survey. The authors took care of comparing similar landscapes in each country, because maps from the same producer can be very different in an urban area, or in a rural mountain area. So, to compare the multi-scale maps in our survey, we will also explore similar landscapes in each country, as much as possible (there is no mountain area in Belgium for instance). Another survey focused on the representation of roads in different maps of the same scale [18]. The survey shows that roads can be abstracted in quite different ways at the same scale, particularly for complex junctions. This finding supports our assumption that the level of abstraction can be diverse and can play a critical role in multi-scale navigability. stoterEtAl09 coupled, in another study, the visual comparison of Dutch topographic maps at different scales with a comparison of the specifications of all these maps. Using the specifications really enhanced the visual exploration of the maps to extract some knowledge on how these maps were generalized, but this cannot be applied in our case as specifications are most of the time not public documents. That is why we try to guess some specification elements from a visual exploration when it is possible.

Finally, there are other studies that compare topographic paper maps at different scales, which is closer to our use case, as there is no guarantee that the existing multi-scale maps all use the same scales (and as differences between maps of the same multi-scale map might also be of interest in our study). One focuses on coastal areas [19], another on vegetation and land use [20], and the last one on relief representation [21]. All three studies cover maps from 1:10,000 to 1:1,000,000, and they confirm that a same map feature can be represented in very different ways as scale changes. This variation should be interesting to study in multi-scale maps, and we report a similar survey in Section 6.

Sixteen multi-scale maps available through web applications were selected for our study. They include maps in NMA geoportals, maps designed by private companies (GoogleMaps and BingMaps), and the default multi-scale map from OpenStreetMap:

1. ACT (Administration du Cadastre et de la Topographie) Luxembourg[2]
2. BEV (Bundesamt für Eich- und Vermessungswesen) Austria[3]
3. Bing Maps[4]
4. GDI-DE (Geodateninfrastruktur Deutschland) Germany[5]
5. Google Maps[6]
6. ICGC (Institut Cartogràfic i Geològic de Catalunya) Catalonia[7]
7. IGN (Instituto Geográfico Nacional) Spain[8]
8. IGN (Institut national de l'information géographique et forestière) France - Scan Express, one of the multi-scale maps[9]
9. IGN France - Scan, another multi-scale map[10]
10. Lantmäteriet Sweden[11]
11. NGI (Nationaal Geografisch Instituut) Belgium[12]
12. NLS (National Land Survey) Finland[13]
13. OpenStreetMap[14]
14. OS (Ordnance Survey) Ireland[15]
15. Swisstopo Switzerland[16]
16. USGS (United States Geological Survey) USA[17] (a new version is now available[18])

The aim is not to compare these multi-scale maps, as they are designed for different targets, and their producers have diverse missions. But we need this diversity to extract as much as possible knowledge on good practices to design multi-scale maps. The survey has been carried out in the first months of 2016, and most of these multi-scale maps have changed since then. By the time of this study, very few vector maps were available, so all the selected multi-scale maps are raster slippy maps.

From this past research and our specific goals, we derive an study protocol that can be divided into four smaller surveys with their own specific point of views: a global visual exploration, a survey focused on scales, a survey on visual complexity, and a survey on abstraction and generalization. For each survey, we will describe, in the following sections the specific protocol, the knowledge that we were able to acquire, and more particularly, some good practices for fluid exploration that we were able to identify. Among the criteria of our observation grid, there is a general focus on the number of maps in the multi-scale maps and on the scale ranges in which they are displayed.

[2] http://map.geoportail.lu/
[3] http://www.austrianmap.at/amap
[4] http://www.bing.com/maps
[5] http://www.geoportal.de/EN/Geoportal/Maps/maps.html
[6] http://www.google.fr/maps
[7] http://www.icc.cat/vissir3
[8] http://www2.ign.es/iberpix/visoriberpix/visorign.html
[9] http://www.geoportail.gouv.fr/
[10] http://www.geoportail.gouv.fr/
[11] http://kso2.lantmateriet.se/
[12] http://www.ngi.be/topomapviewer
[13] http://kansalaisen.karttapaikka.fi/kartanhaku/osoitehaku.html
[14] http://www.openstreetmap.org/
[15] http://maps.osi.ie/publicviewer/
[16] http://map.geo.admin.ch/
[17] https://viewer.nationalmap.gov/basic/
[18] https://viewer.nationalmap.gov/advanced-viewer/

Figure 3: Two multi-scale maps (source: IGN France), one with inconsistent styles across scales (on the left), and one with a consistent multi-scale style (on the right).

3 Visual Exploration of the Multi-Scale Maps

3.1 Description of the Survey

We seek to understand the factors of multi-scale map design that aid multi-scale navigability and the ones that penalize it, so the first obvious way to analyze these maps is to navigate into them, to explore them, and to assess the way the desert fog disturbs the exploration. In order to enable a comparison between all the maps that are visually explored, we defined an exploration protocol.

- We set up similar exploration environments: same computer and screen, same way to interact with the map (with a mouse), same web browser, as much as possible same size for the display frame.
- We use systematic zooms in and out, back and forth, with few pan interactions, between consecutive zoom levels, and between distant zoom levels (large scale gaps), and we note qualitative feedback from these interactions: if exploration is generally smooth or difficult, or the zoom levels where exploration is particularly smooth or difficult.
- We explore two types of landscapes per multi-scale map, urban areas and rural areas.
- We record the following information on the exploration experience: style consistency (Figure 3), number of maps, number of zoom levels, visible use of map generalization, amount of information, empirical estimation of the desert fog effect (free text to describe the time to find where we are after each zoom).
- We focus on inconsistencies between maps of the same multi-scale map (content, style, text placement) that can accentuate the desert fog, rather than on possible cartographic problems on a single map (at a single scale).

We performed the visual exploration ourselves for time reasons, but it would be interesting to perform a similar visual exploration task with different users to check for potential differences in the qualitative feedbacks on exploration fluidity. Regarding the recording of a desert fog effect estimation, we also recommend the use of a simple Likert scale (*e.g.* no desert fog/small desert fog effect/significant desert fog effect) to make the analysis of the visual exploration easier.

3.2 Knowledge Acquired on Multi-Scale Maps

The visual exploration supports the conclusions of the survey of road representations in middle scale maps [18]: there is no consensus on the abstraction and generalization levels to use in maps displayed at the same scale. The example of buildings is quite significant: Figure 4 shows the city of Zürich at the same zoom level (and thus a similar display scale, see Section 4) in three multi-scale maps; in GoogleMaps, only the built-up area polygon is represented; in OpenStreetMap, all buildings are displayed; in SwissTopo, the buildings are generalized at the block level [22] for the inner city and typified elsewhere [23, 24]. This variability can be explained by design choices (*e.g.* if the details of individual buildings are not necessary at a given scale for the map purpose, it is a good map design to rather use a built-up area polygon, as for Dutch 1:100k map [25]), but can also be explained sometimes by a lack of effective generalization capabilities for some of the surveyed multi-scale maps, e.g. OSM and Bing.

Figure 4: Three multi-scale maps at the same zoom level (respectively GoogleMaps, OSM, Swisstopo), on the same region: there is no consensus on the content (theme, abstraction, granularity) of a topographic map.

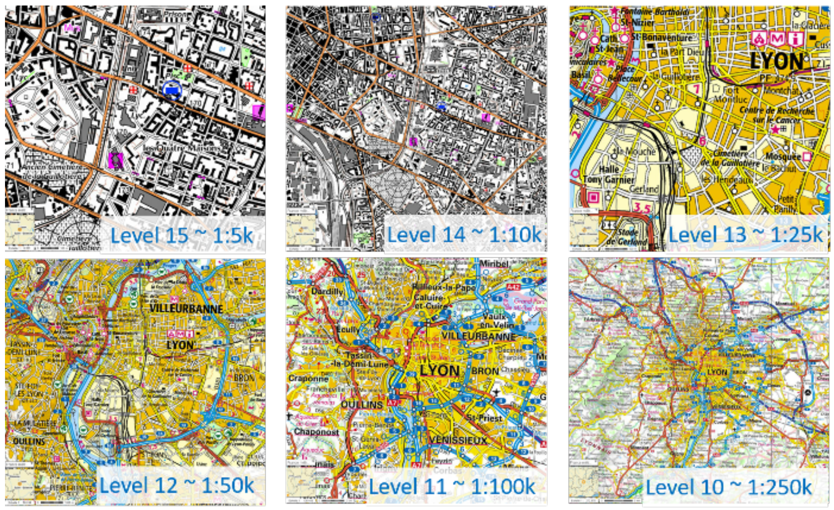

Figure 5: An example of a multi-scale map that contains less maps than WMTS zoom levels (IGN France) : each map is displayed at two consecutive zoom levels (15 and 14, 13 and 12, 11 and 10 respectively).

More generally, the visual exploration clearly highlighted a trade-off between the use of map generalization and the number of maps. The use of map generalization was minimal in multi-scale maps that contain many maps, while the multi-scale maps that were composed of generalized maps had much fewer maps than zoom levels. Some NMAs have already achieved a full automation of the generalization process for some scales, by reducing a little the cartographic quality of the output map [26]. Using such automated processes could be the way to find a balanced position between the number of maps in the multi-scale map and the difficulty of generalization.

The visual exploration also showed that in most of the multi-scale maps of the survey, there were fewer maps than available zoom levels (Figure 5). Some of the maps are displayed at several consecutive zoom levels, and so they are displayed at scales for which they are not optimal. This also makes the exploration jumpy and not smooth at all. That is why this issue of the scale at which maps are displayed is further analyzed in a specific survey presented in the following Section 4.

3.3 Identified Good Practices

The visual exploration highlighted a major factor that penalizes or favors multi-scale navigability: map style consistency across the scales. By style consistency, we mean that all the maps in the multi-scale map have similar style design, features are styled similarly across scales to ease their recognition. But it does not mean that all multi-scale maps should have consistent styles to favor multi-scale navigability, as there is a very large range of good multi-scale map styles that can be used. The multi-scale maps that were designed as multi-scale maps (e.g. GoogleMaps, OpenStreetMap, Lantmäteriet Sweden, OS Ireland, IGN France “Scan Express") have consistent styles: for instance, road symbol width and color do not change when scale changes after a zooming interaction. These multi-scale maps are clearly easier to navigate into. On the contrary, multi-scale maps designed with independent maps put together do not have this style consistency, and the symbol changes really disturb multi-scale exploration. So we consider map style consistency as

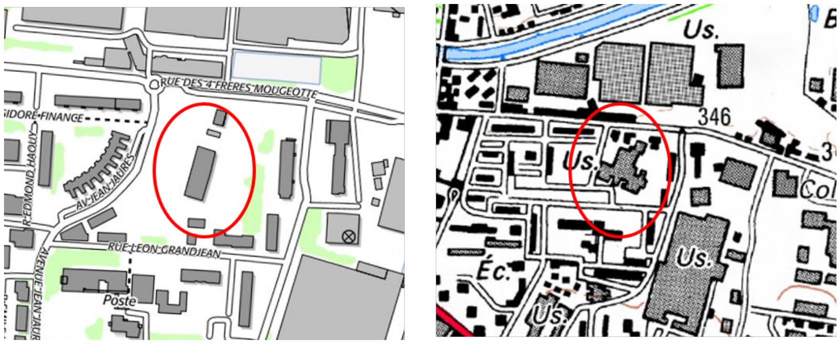

Figure 6: An example of data inconsistency in two successive zoom levels: the encircled building is totally different, maybe due to inconsistent update processes.

a major good practice, and we will consider it out of scope in the remainder of the paper, to focus on the other less obvious factors that enable a good multi-scale exploration.

Text is a very important component of a map, and can greatly help multi-scale exploration by identifying places that can be represented or abstracted differently at different scales. Some of the multi-scale maps propose a more or less effective multi-scale text placement, which means that text stays approximately at the same location in all maps of the multi-scale map. Even when this multi-scale placement is not perfect with some local displacement of the text, the exploration is clearly easier in such multi-scale maps, as shown by the recorded feedbacks of the visual exploration of these maps with multi-scale text placement.

The visual exploration also highlighted the importance of data consistency for fluid multi-scale exploration. Figure 6 shows an example of inconsistent maps with a building at the smaller scale that has very different shape than the building at the larger scale (on the left in the figure). Such data inconsistencies can be due to inconsistent data sources (*i.e.* the cartographic datasets used to make the maps are based on different initial datasets) or inconsistent update processes (*i.e.* maps at different scales are updated independently). Datasets that are used as input in map generalization processes should be as consistent as possible.

4 Scale and Display Issues

4.1 Description of the Survey

In this survey, we record the zooming interaction type, and the number of zoom levels. And then, for each zoom level, we record its display scale, and the symbolization scale of the displayed map if a digitized paper map is used. Regarding symbolization scale, we looked for the information on the Internet, which was not so difficult as these maps are digitized versions of paper map series. Even if it is sometimes displayed in a corner of the screen, most of the time, we had to compute the display scale of each zoom level, by using the small scale ladder indicator, and measuring it on the screen. For each multi-scale map, we checked, on one zoom level only, that the scale ladder was right by comparing a known distance on the ground with the distance on the screen.

4.2 Knowledge Acquired on Multi-Scale Maps

When the survey was carried out, only BEV Austria used an aged zooming interaction with buttons to change the scale of the map. All the other multi-scale maps could be navigated with a discrete zooming interaction (Figure 2). At the time of writing this paper, all these remaining fifteen multi-scale maps, except ICGC Catalonia and OS Ireland, had switched to continuous and animated zooming (Figure 2).

Then we analyzed the display scales that are actually used, how they are distributed, and how they follow the WMTS standard (Figure 7). Generally, the range of scales varies from one multi-scale map to another. It depends on the global extent of the space covered by the map, *e.g.* the size of the country when the map is countrywide. A general trend should be noticed in Figure 7: the range between the display scales 1:10,000 and 1:1,500,000 is covered by all multi-scale maps. It means that we should focus on this range of scales if we want to compare the cartographic content of multi-scale maps, to understand how to improve their navigability.

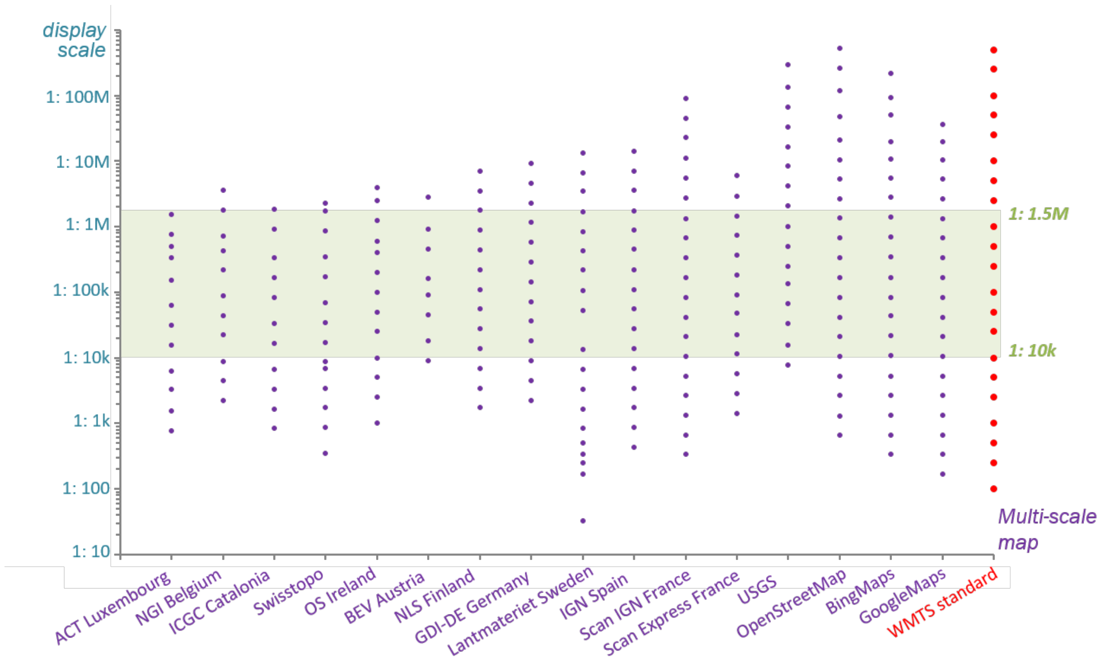

Figure 7: Distribution of the available zoom levels on all tested multi-scale maps, in relation to the display scale. This distribution shows a critical scale range where each multi-scale map contains zoom levels (the colored interval).

Moreover, this figure shows that the zoom levels are regularly spaced, following a logarithmic scale just like prescribed by the WMTS standard (represented in red in Figure 7). However, some multi-scale maps do extend the WMTS standard by adding levels at large scales (*e.g.* Lantmäteriet Sweden). Not surprisingly, a visual exploration of the scale ranges where additional levels are added shows that the exploration is smoother than in the ranges with the standard levels.

Then, Figure 8 shows the distribution of display scales for each zoom level in the surveyed multi-scale maps. For most of the zoom levels, the dispersion around the display scale of the standard WMTS scale is small, except for level 8: in fact, 85% of the multi-scale maps contain an additional level between 1:1,000,000 and 1:2,500,000 scales. The regression line of display scales (in green in Figure 8) and the one of the WMTS standard (in red) are very close to each other. This small shift can be caused by the imprecision of our method to compute the value (measure on screen), and also caused by the map projection used for most of the multi-scale maps (the WMTS standard is defined for geographic coordinates). That is why we consider that the multi-scale maps of the survey all implement the WMTS standard. This common design pattern makes their comparison much easier.

Finally, we compare the display scale to the symbolization scale at each zoom level, for the multi-scale maps that are composed of digitized paper maps (symbolization scale is different from display scale in these maps). It appears that there is no consensus on what map to show at a given display scale: see for instance the vertical green box in Figure 9 where three maps (from different multi-scale maps) with symbolization scales from 1:5k to 1:25k are displayed at the same 1:3k display scale. Conversely, the horizontal green box in Figure 9 shows that maps with a symbolization scale of 1:50k are displayed from 1:10k to 1:60k in different multi-scale maps. So there is no consensus either on the best display scale to use for a given symbolization scale. This lack of consensus supports the lack of knowledge in multi-scale map design.

If we look at the range of display scales for a same symbolization, we can see in Figure 9 that the range increases as scale decreases, *i.e.* small symbolization scale maps seem to be used for more zoom levels than large symbolization scale maps. Conversely, if we look at the symbolization scale range for a same display scale, it seems to be more regular with often two or three different symbolization scales used for a same display scale.

Figure 9 allows the definition of an interval, between the red and blue lines, which contains most of the maps of the surveyed multi-scale maps. There are very few exceptions:

- three maps on the left of the red line, at large display scales, in the IGN Spain multi-scale map; these are maps that are enlarged a lot, which results in a pixelization effect as illustrated in Figure 10;

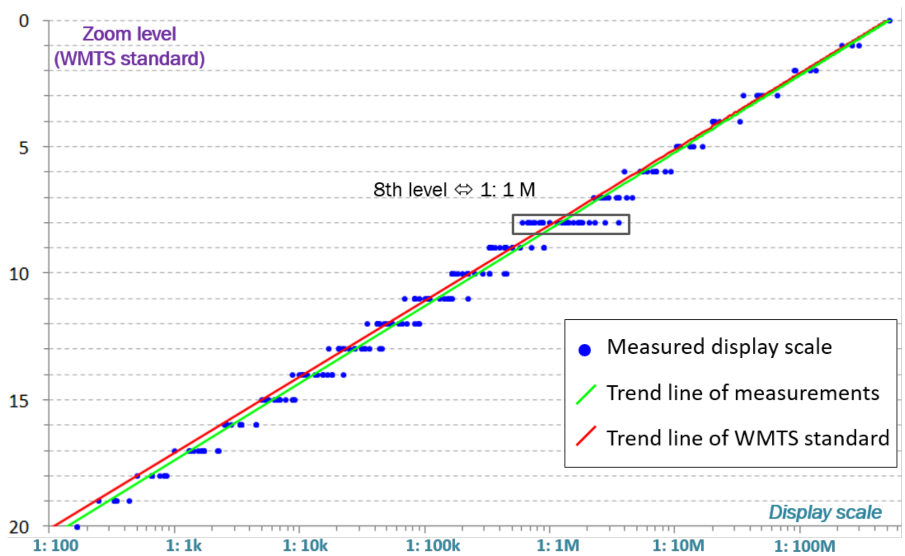

Figure 8: Distribution of the display scales for each zoom level of the WMTS standard.

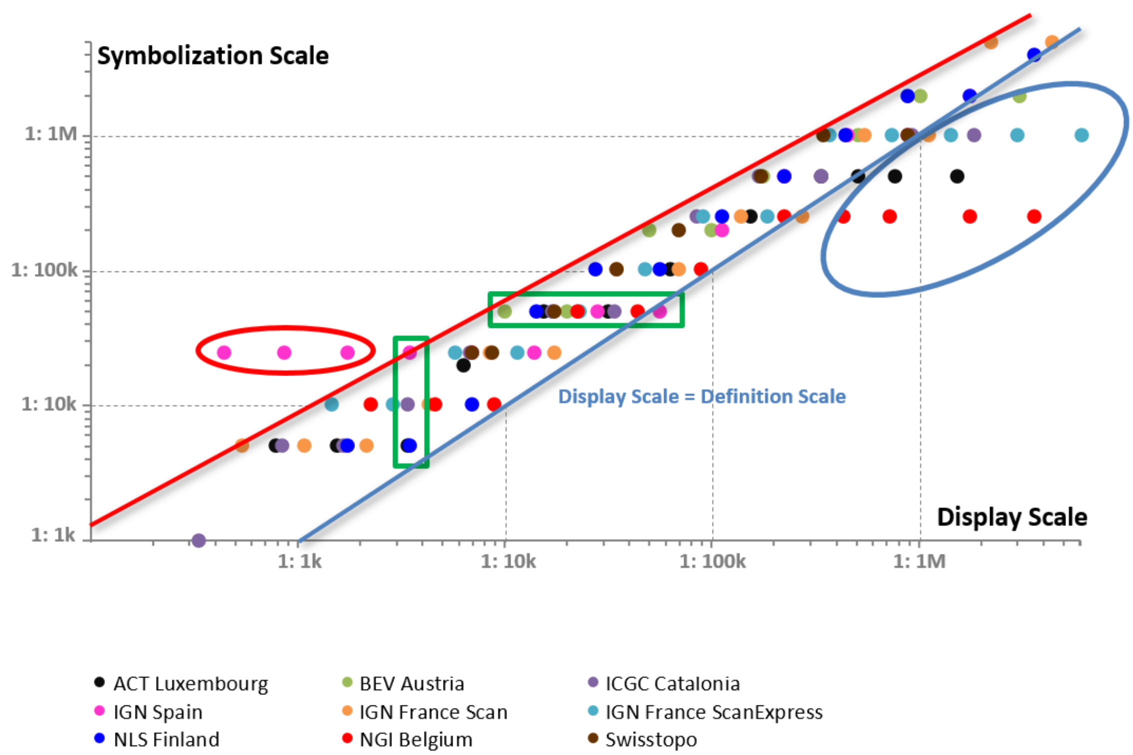

Figure 9: Distribution of the available zoom levels on all tested multi-scale maps, with the display scale (*i.e.* the scale of the map on the screen) in abscissa axis, and the symbolization scale in ordinate axis (*i.e.* the scale of the paper map that was used at this zoom level).

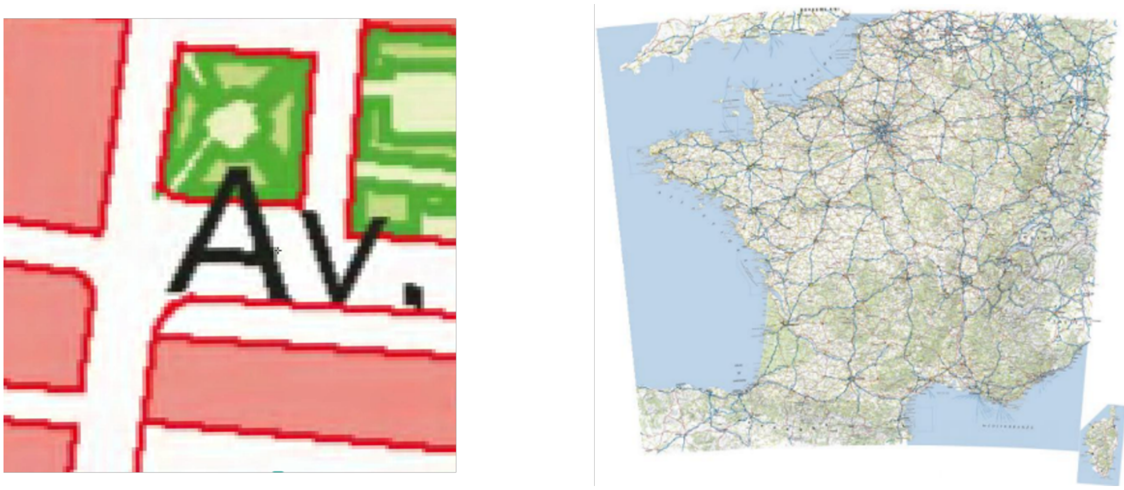

Figure 10: On the left side, an example of a map on the left of the red line on the previous figure, which displays a pixelization effect, and on the right side, a map on the right of the blue line on the previous figure, which is not very legible.

- eleven maps on the right of the blue line at small scales; these scales often go beyond the extent of the country represented in the multi-scale map, and the national mapping agencies that designed these maps often do not possess continent-wide or worldwide maps; they use instead the closest map in terms of symbolization scale, which sometimes results in a lack of generalization and readability issues, as illustrated in Figure 10.

4.3 Identified Good Practices

Continuous zooming seems to be a very good practice as it enables a smoother zooming interaction, and it enables the addition of extra maps compared to the limited number of levels in the WMTS standard.

The analysis of the distributions of display scales highlighted the existence of a critical scale range that was covered by all the surveyed multi-scale maps from 1:10k to 1:1,500k. This scale range seems to contain the scales where most of the map uses are made, and a multi-scale map designer must address all of these scales.

Finally, the comparison of display scales and symbolization scales for a same zoom level highlighted an interval of optimal display for maps with a given symbolization scale. Due to eye perception limits on screens [5], the maps should not be displayed at scales smaller than the symbolization scale, the display scale should not be larger than approximately two times the symbolization scale (as Figure 9 uses a logarithmic scale, this ratio changes according to scale, it is valid for the middle zoom levels).

5 Visual Complexity Analysis

Map complexity is one of the factors that help or hinder a map reader from using and quickly understanding a map [27]. That is why we believe that map complexity also plays a key role in the usefulness and the navigability of multi-scale maps. Map complexity both lies in the visual complexity of the map, but also in the so-called intellectual complexity that refers to the complexity to understand what the map and its symbols mean [28]. Understanding the map symbols plays a key role in intellectual complexity, even if it is not the only factor, and it is difficult to analyze intellectual complexity without focusing on map symbols and style. As a common hypothesis in all the presented studies, we chose not to focus on style, so, here, we only focus on visual complexity. We do not discuss more the notion of visual complexity and related research but such discussion can be found in recent papers [27, 29].

Quantitative indicators have been proposed to measure the complexity of a map [30, 31], but they only concern one map image and not a complete dynamic multi-scale map. Others have proposed to use image clutter as a proxy to map complexity [32, 33, 34, 29]. Clutter is a measure of an image quantity of information and lack of organization. The more clutter increases, the more complex visual search is in the image [35]. As we only have access to the images of the multi-scale maps of the study, and not to the vector cartographic map, we decided to use some of the existing clutter measures [35, 36, 30] to assess the complexity of the maps composing the multi-scale maps. But we are interested in

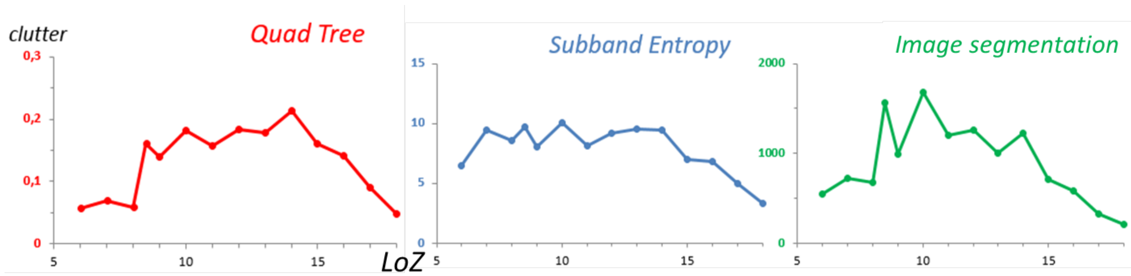

Figure 11: Clutter values evolution across zoom levels for three different measures: *quad tree* [30], *subband entropy* [35], and *image segmentation* [36].

assessing the influence of clutter in multi-scale exploration fluidity. So we are interested in the variations of clutter values for consecutive scales, rather than the clutter values for each scale taken separately.

5.1 Description of the Survey

The first step was to extract an image of each zoom level of each multi-scale map. As past research showed that clutter measures were sensitive to image size and resolution [30], the images were captured with the same size and the same resolution. We also tried to capture similar landscapes as maps in urban areas are often more complex than maps in rural areas. We selected urban areas at large scales, that become mixed with rural and other urban areas as scale decreases.

As noticed in past research where clutter measures were used as a proxy to map complexity [27, 33], there are many existing clutter measures, which do not assess the same components of the visual complexity of an image (for instance, some do not use the colors of the image). A recent literature review [37] gives a good overview of this diversity. From this amount, we selected three measures that have proved useful on generalized maps [32]: *quad tree* [30], *subband entropy* [35], and *image segmentation* [36]. For these measures, it has been proven [35] that a high measured clutter causes difficulties in visual search that is a building block of most map based interactions. We first tried to measure the sensitivity of clutter measures: do they all three capture map complexity dynamics the same way? Figure 11 shows that clutter varies similarly across scales with the three measures, even if some small variations occur at specific scales. In these piecewise linear curves, we were interested in local and global dynamics rather than absolute values for one map at one scale: local variations look at a change of monotony or not at each vertex, while global variations look at the global shape of curve. In Figure 11, the local variations are similar for the three measures for 13 out of the 14 plotted vertices, while the 14th vertex (at level 13) as a similar variation for two of the measures. This pattern was observed for all multi-scale maps, so we decided that comparing the results for all measures was not necessary for further experiments, and only one measure is used in most of the remainder of the section.

We are interested in multi-scale navigability so we are more interested in the complexity of a transition between two scales, but clutter is measured in a single image. That is why we assessed how clutter varies across scales in multi-scale maps, rather than the values of each clutter measurement in a single map.

5.2 Knowledge Acquired on Multi-Scale Maps

Map content is related to scale [4] and map complexity is related to map content. To draw the curves in Figure 12 we compute at each zoom level the mean clutter value for all multi-scale maps. All the three clutter measures show the same bell-shaped pattern: very large scale and very small scale maps are not measured as complex, while maps measured as complex are in the middle zoom levels with a maximum for zoom level 12, which corresponds to a 1:100k display scale.

In order to reduce the complexity of multi-scale navigability, we should focus on those middle zoom levels, where clutter and thus map complexity is important.

5.3 Identified Good Practices

When we initiated this research, we believed that the more maps there are in multi-scale maps, the more effective they are for multi-scale exploration. We tried to find instances of multi-scale maps that support this hypothesis with clutter measures. That is partly why we included two different multi-scale maps from the same NMA (IGN France) that have a different number of maps, particularly in the zoom levels that generally are the most complex (see the

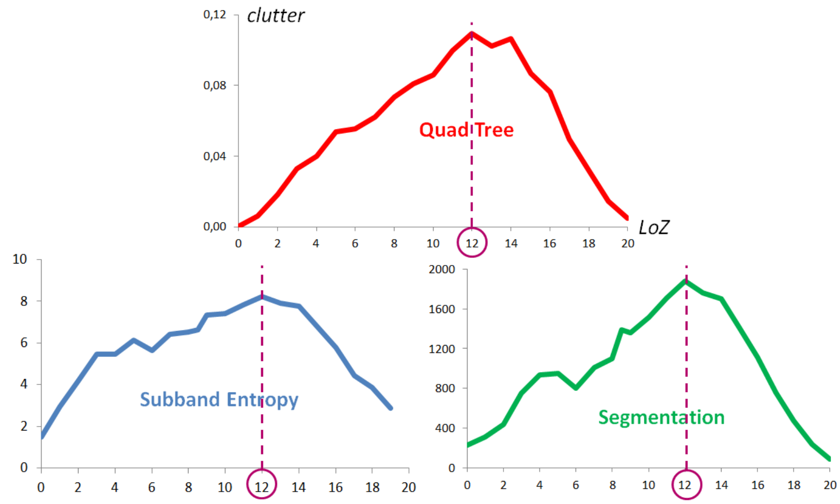

Figure 12: Evolution across scales of the mean of all multi-scale maps clutter values (for each measure, the mean of the 16 clutter values, 1 per multi-scale map, is plotted for each zoom level: it shows a bell shape with a maximum at the zoom level 12.

previous section). We know from the literature in computer vision that when clutter increases, visual search is made more difficult [35, 37], so when a zooming interaction causes up and down variations of clutter, there are multiple instances of clutter increase, and as a consequence more difficulties in visual search and map use. Figure 13 shows three successive maps for the zoom levels 12 to 14, with one multi-scale map (“Scan Express") that presents three different maps, and the other multi-scale map (“Scan IGN") that presents only two maps at zoom levels 12 and 14; zoom level 13 is just an enlargement of the map displayed at zoom level 12. In this one case, our hypothesis is supported by clutter measures, as the “Scan Express" map has stable clutter values at all three levels, while the “Scan IGN" map obviously has a decreased value for the zoom level 13, on then increasing at level 14 causing visual search difficulties while zooming across these levels.

Although this is a single example, this supports the fact adding maps, particularly in the complex middle zoom levels might improve multi-scale navigability through clutter stability.

To better understand if clutter stability is a criterion for a good multi-scale navigability, we tried to measure the variability of clutter in each of the multi-scale maps of the survey, as shown in Figure 14: we measure for each zoom level the difference of the clutter value with the value of the next zoom level.

Then, we can compute the multi-scale map clutter variance, a global indicator of the map multi-scale navigability. The analysis of the variances shows two clear groups of multi-scale maps:

- low variance maps: non-NMA multi-scale maps (*i.e.* BingMaps, GoogleMaps) and multi-scale maps with homogeneous styles (ACT Luxembourg, GDI Germany, USGS United-States).
- high variance maps: multi-scale maps where scanned paper maps are used, which means few maps and heterogeneous styles (*e.g.* IGN Spain, Scan IGN France, Swisstopo).

Given these first indicators, it seems that a low clutter variance is preferred when designing multi-scale maps, so factors that cause clutter variance should be considered carefully: heterogeneous styles, which was already obvious with the visual inspection of the maps, and zoom levels without any specific map, as it causes clutter to consecutively decrease and increase. This influence of clutter variation or stability on multi-scale exploration fluidity is clearly promising and should be investigated in further research.

6 Abstraction Transitions Analysis

6.1 Description of the Survey

When we started this research project, we assumed that abstraction and generalization changes across scales were one of the factors for the desert fog effect, and that a more progressive change would improve multi-scale navigability. That

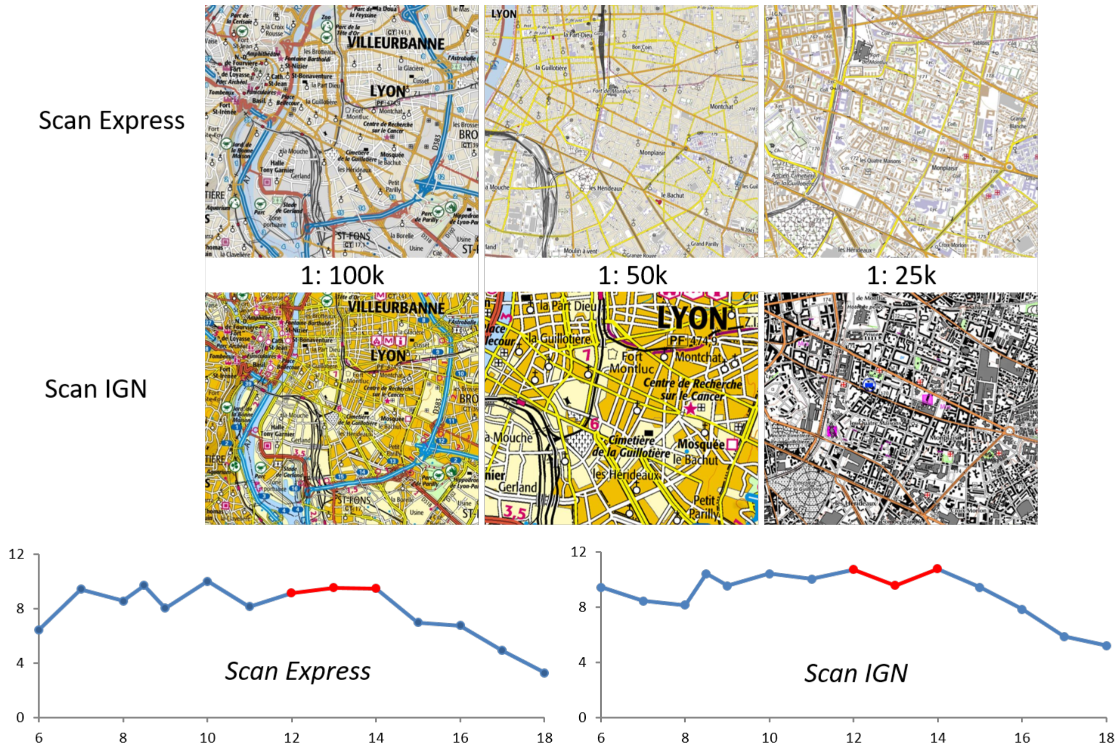

Figure 13: More maps in the multi-scale maps provide a better clutter stability, illustration with two maps of the same area, but one with more maps.

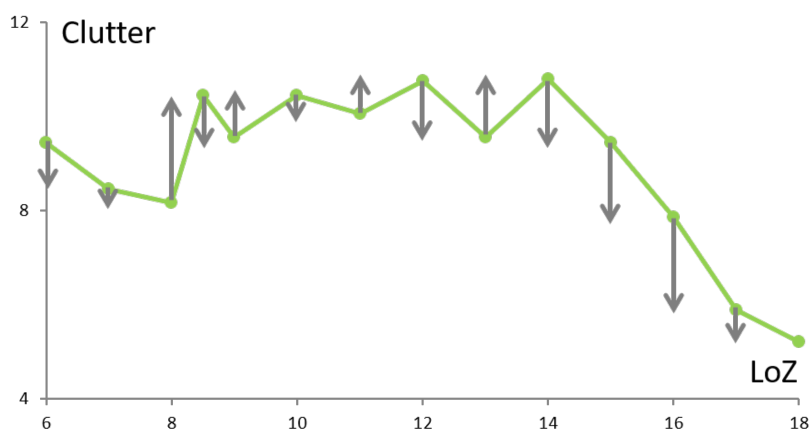

Figure 14: Representation of the clutter variation between a zoom level and the following one: we believe that transitions that are too important are complex for users, even when clutter decreases.

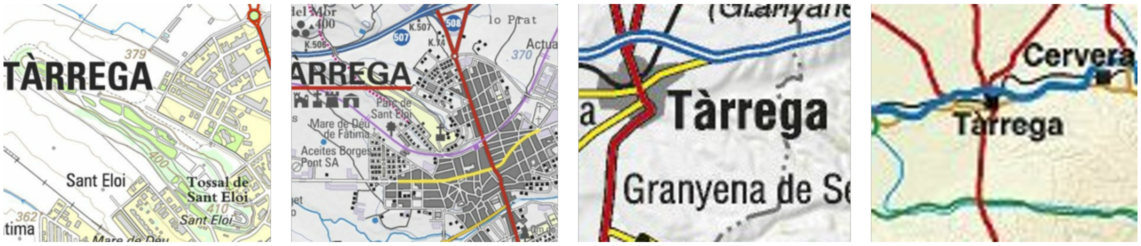

Figure 15: The proposed four abstraction levels of buildings in multi-scale maps: individual building, block, built-up area, and point.

is why we focus in this part of the survey on abstraction and generalization: we analyze how map features change across scales through generalization operations and abstraction changes.

Past research described the level of simplification of map features by using different expressions: scale, granularity, level of detail [38] , or even degree of generalization [39]. In this case, we focus on the level of abstraction (LoA), that refers to the modeling abstraction used to transform the real world geographic feature into a high or low level map feature. For instance, the vegetation theme can be abstracted as points representing trees at one level and as polygons representing forests at another abstraction level. So, in this part of the survey, we recorded for each zoom level, the level of abstraction used. The visual exploration pointed out the existence of multiple abstraction levels at the same zoom level, either on different parts of the territory (one level in urban areas, one level in rural areas), or combined in the same areas (buildings on top of urban areas in OpenStreetMap for instance). So for each zoom level, we record all the abstraction levels, and if there are more than one, we note the type of co-existence.

We also record the generalization operations that were carried out to make the map, either when we are able to guess it by inspecting the map, or when we found additional information on map design. For instance, duchene14 describe the generalization processes used in several mapping agencies, and this knowledge was integrated in the survey.

In order to easily record and analyze LoA, we modeled it with a *scaleline*, *i.e.* like a timeline where scale progression replaces time. This model is inspired from the ScaleMaster [2, 40].

Following the findings of the survey on scales and on clutter, we only focus on the critical scale range between 1:10k and 1:1,500k display scales. As this survey would be too long if we were looking at all the features of the map, we focused on only two types of features, buildings and roads, discussed in the following sections.

6.2 Specific Analysis of Abstractions Transitions of Buildings

We define four progressive abstraction levels that are used in the surveyed multi-scale maps (Figure 15):

1. individual building level: a polygon representing an existing building;
2. building block level: a polygon representing a portion of the urban space mostly covered by buildings, and delimited by roads or city limits;
3. urban or built-up area level: a polygon representing a built-up conurbation;
4. point level: a point symbol, generally coupled with place name, that represents a whole city.

As explained in the previous subsection, we record the generalization processes applied on the buildings at each zoom level. Among the generalization operators that can be applied to buildings [41], we selected the ones we were able to identify, either by visual inspection or by consulting available information on map design:

- selection: keeping or deleting a map feature based on its geometric or semantic characteristics;
- simplification: removal of the small details of the geometry;
- aggregation or amalgamation: merging several features into one;
- typification: reduces the number of features in a group while preserving the spatial distribution of the group;

The recorded information is represented in scalelines in Figure 16. This presentation shows the diversity in the use of buildings LoA. The darker gray represents the first LoA (individual buildings), and the lighter gray represents the last LoA (point level). The red lines show the zoom levels that display a new map. To represent the building abstraction on a continuous range, we make the changes of representation happen (in scalelines) in the middle of the scale range between two consecutive zoom levels.

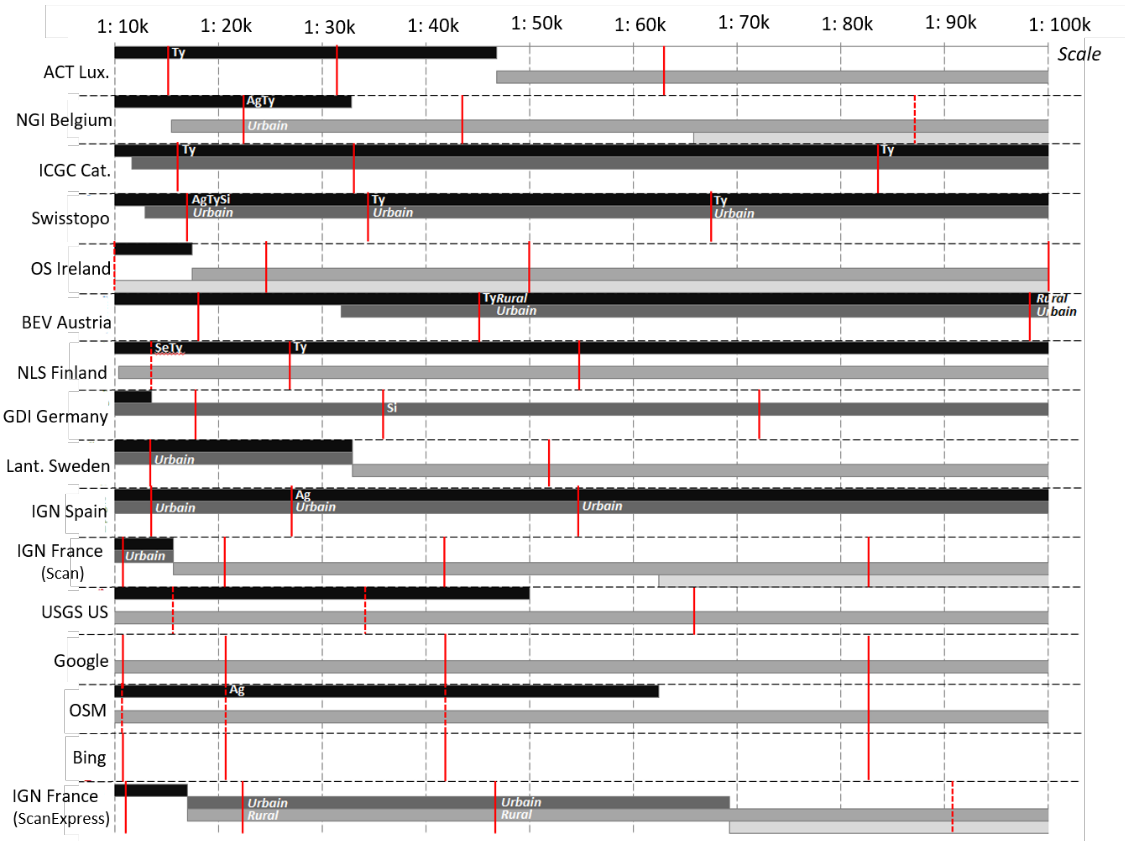

Figure 16: An extract of the produced scaleline for building abstraction transitions (only the scale range between 1:10k and 1:100k is shown). The darker gray is the individual buildings level and the lighter is the point level.

6.3 Specific Analysis of Abstractions Transitions of Roads

The definition of abstraction levels for roads was more complex, as the geometry type, lines, is similar across all the scales. This is why we focus here on the choices made to select or not the roads in the map:

1. area level: all the road sections are represented as areas;
2. full level: all roads and paths are represented;
3. selection level: minor roads and paths are ignored;
4. major level: only major roads are retained.

But it appeared that other LoAs could be defined using a different point of view. Road structures, such as roundabouts, dual carriageways or highway interchanges are key features of road networks, and require specific algorithms [42]. So, in addition to the general abstraction levels for roads, we decided to define abstraction levels for the road structures (Figure 17):

1. area level: all the road sections of the road structure are represented as areas;
2. topographic level: all the road sections of the road structure are represented as lines;
3. topology level: the road sections that are retained are the ones that preserve topology and connections;
4. point level: a point symbol replaces all the roads that compose the road structure.

Although it is used in several countries for very large scale maps, *e.g.* Great Britain [43], or The Netherlands [25], we did not find any level with the area level in the survey, so it will not be discussed in the following paragraphs.

Regarding the generalization operations that were recorded in the survey, they are the same as the ones recorded for buildings, with an additional one:

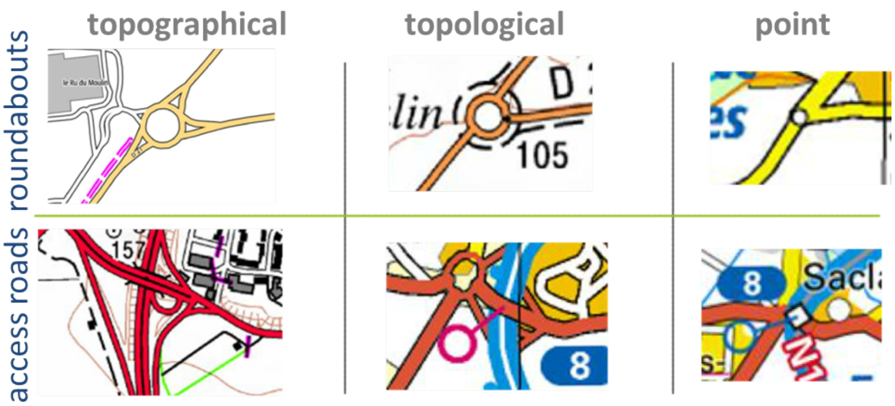

Figure 17: The proposed three abstraction levels of roads in multi-scale maps illustrated with roundabouts and access roads: topographical abstraction, topological abstraction and point abstraction.

- caricature: a simplification that exaggerates some important characteristics to better preserve them (*e.g.* remove a bend to keep space for the other ones in a mountain road);
- selection;
- simplification;
- aggregation or amalgamation;
- typification.

The recorded information is represented in scalelines in Figure 18 for roads abstraction and Figure 19 for road structures abstraction. This presentation shows the diversity in the use of roads LoA. For roads, the darker purple represents the first LoA (full level), and the lighter purple represents the last LoA (major level). For road structures, the darker blue represents the first LoA (topographic level), and the lighter purple represents the last LoA (point level).The red lines still show the zoom levels and we still make the changes of representation happen (in scalelines) in the middle of the scale range between two consecutive zoom levels.

6.4 Knowledge Acquired on Multi-Scale Maps

This part of the survey is another illustration, at least for roads and buildings, that there is no large consensus on which LoA to use at a given scale, and on the scale range in which it is valid to use a LoA. However, some trends are noticeable and are described below.

Figure 20,show an aggregation of the scalelines for buildings, roads and road structures LoA: at each scale, we compute the percentage of multi-scale maps that use one or several LoAs among the four.

First in Figure 20a, the scale range where individual buildings can be used is rather large, but this use really decreases below the 1:10k scale. Th urban block LoA is not used as massively as the individual building and urban area LoAs. The urban area LoA is massively used around the 1:200k scale, but it is the LoA that is used with the larger range.

Then in Figure **??**b, darker scale ranges are more important than for the buildings. The choice of road LoA across scales seems to be more consensual. All roads and paths (full level) are massively represented until the 1:50k scale. The selection level is mainly used between the 1:50k scale and the 1:250k scale. Then, the major level is commonly used between the 1:250k scale and the 1:10M scale.

6.5 Identified Good Practices

The most promising of the identified good practices regarding abstraction transitions is the use of what we called mixed transitions (Figure 21). They seem to smooth the multi-scale exploration when combined with generalization and adapted symbols. We identified two types of mixed transitions of LoA: *aggregation* and *layered transition*. *Aggregation* is composed of at least three consecutive maps in the multi-scale pyramid, with one LoA in the first map, another in the last map, and both LoAs mixed in the middle maps, but not at the same locations of the map. For instance, between a map with individual buildings and a map with building blocks everywhere, there can be a map with building blocks only

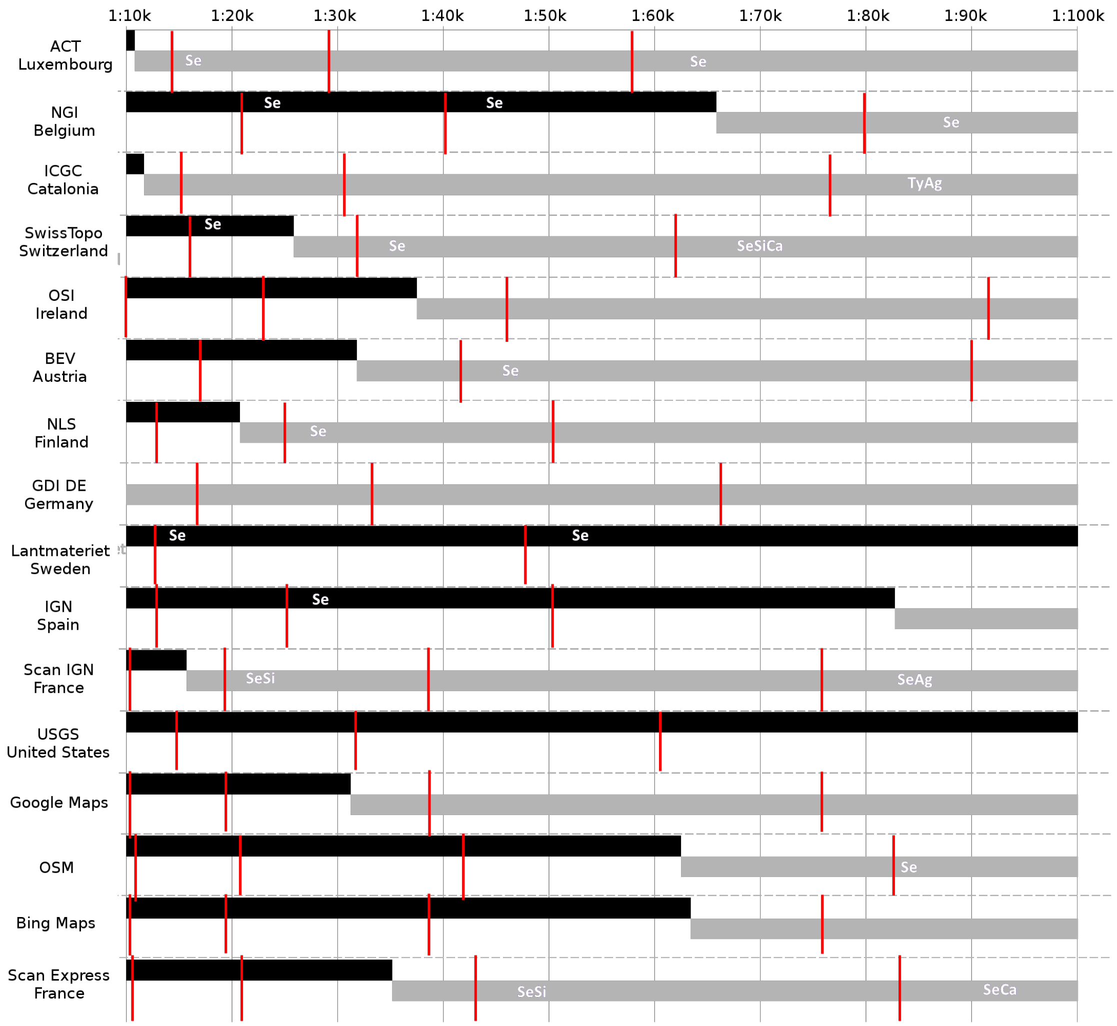

Figure 18: An extract of the produced scaleline for road abstraction transitions (only the scale range between 1:10k and 1:100k is shown). The darker purple is the full level and the lighter is the major level. The abbreviations indicate the identified generalization processes (Se: selection, Si: Simplification, Ca: caricature, Ag: aggregation, Ty: typification). SeSiCa indicates of joint use of selection, simplification and caricature on the roads.

in the more dense regions and individual buildings elsewhere. Several intermediate maps can create a more progressive aggregation transition. *Layered transition* consists in a three-step transition from a LoA to the other, with the middle map displaying both LoAs, one layered on top of the other. For instance, a transition from urban area LoA to point LoA is composed of an intermediate map where the point symbols are displayed on top of the urban areas.

Some of the multi-scale maps use all available LoAs in a progressive way, *i.e.* the more detailed abstraction is used at the larger scales, then the abstraction is replaced (with a mixed transition or not) by the following abstraction in a decreasing complexity order, and so forth. This progressive design clearly helps to avoid abrupt LoA transitions that might appear when a LoA is skipped (ACT Luxembourg or NGI Belgium are good examples of that last point).

The multi-scale map IGN Scan Express proposes an interesting variant of the urban area level at the 1:25k and 1:50k display scales (Figure 22). All the buildings inside the urban area are removed except some important administrative buildings that can be used as landmarks or anchors in multi-scale navigability because they are also salient at the scales where the individual buildings LoA is used (a different color is used for the different types of building).

We also noted that some multi-scale maps (*e.g.* ICGC Catalonia or SwissTopo) use typification generalization operations, at the individual buildings LoA, to preserve spatial patterns such as building alignments. This operation enables a better

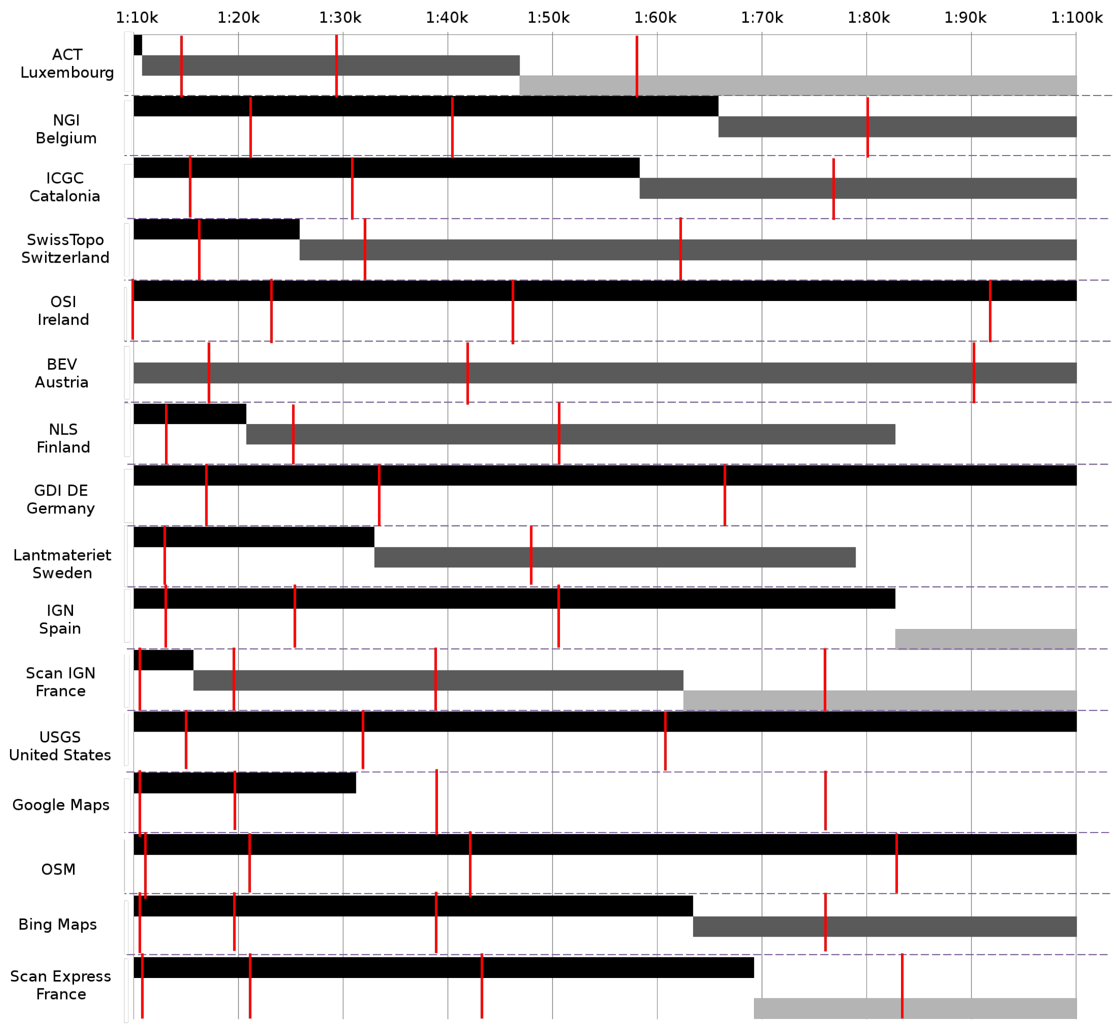

Figure 19: An extract of the produced scaleline for road structures abstraction transitions (only the scale range between 1:10k and 1:100k is shown). The darker blue is the topographic level and the lighter is the point level.

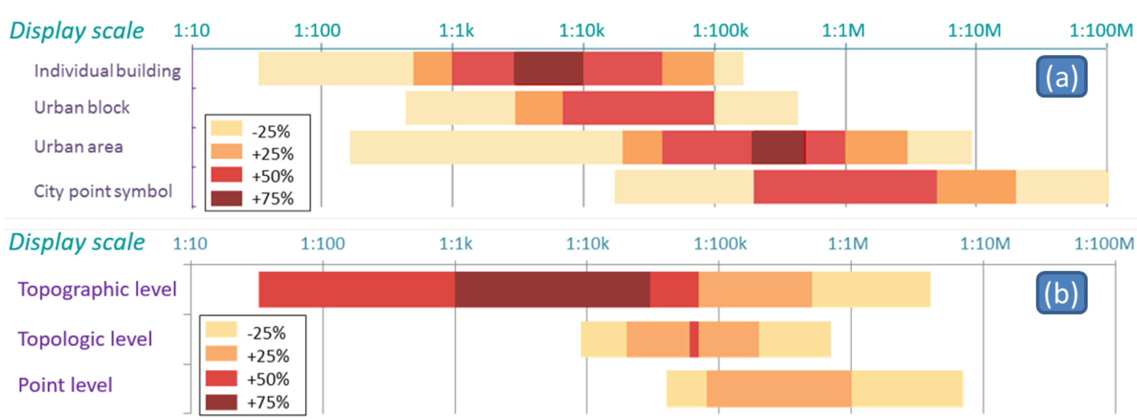

Figure 20: (a) Aggregation of the zoom levels at which building abstraction levels are used in all tested multi-scale maps. (b) Aggregation of the zoom levels at which roads abstraction levels are used in all tested multi-scale maps.

Figure 21: Two approaches to mix abstraction levels in order to ease multi-scale exploration: aggregation (on the left, source: ICGC Catalonia) and layered transition (on the right, source: Lantmäteriet Sweden).

Figure 22: (a) The red center building is preserved as landmark at the urban area LoA (source: IGN Scan Express). (b) the typification of buildings makes building generalization progressive (source: SwissTopo).

progressiveness than aggregation or selection, and this theoretical better progressiveness is supported by the visual exploration of these maps (Figure 22).

7 Discussion

What points should be improved on current multi-scale map products? Some of the surveyed multi-scale maps attract millions of users everyday, and these users see these maps as a great progress, not a regression in cartography, which is completely true, even when no generalization is performed. When we state that the existing maps are not sufficient, the point is not to say that these users are wrong, because they are not. The possibility to zoom in and out and see other maps displayed makes up for the defects of each map taken individually (*e.g.* the lack of generalization). But the desert fog affected us more or less with all surveyed multi-scale maps, and it is important to suppress or at least reduce it. This survey showed that it could be caused by a lack, or an excess of information, by a lack of progressiveness, or by inconsistencies between the different scales, and all this can be solved by improving multi-scale map design.

Added to that, there is still a lot to learn on the perception of maps on screens, and its relation to map scale, level of detail, level of generalization [39], or level of abstraction. What is the best level of abstraction, symbol size, level of generalization for a given display scale/zoom level? What is the impact of screen resolution on the usability of a multi-scale map? The eye perception limits for paper map, *e.g.* “there should be at least 0.1 mm between two maps features to distinguish between two map symbols", were discovered thanks to user surveys. We really need to perform new versions of these user surveys to be able to answer these questions.

Our initial assumption was that adding transitional levels to multi-scale maps, combined with progressive generalization, could reduce the desert fog effect experienced when navigating those maps. If we revisit this assumption in light of the main findings of the survey, it seems true for most of the surveyed maps. The effectiveness of mixed transitions of LoA and the low clutter variance when there are as many maps as zoom levels, both support the idea of adding transitional levels. The observed effectiveness of maps with typification operations (see Section 6.5) supports the idea of progressive generalization. However, our main focus on map generalization and abstraction is not really supported by the survey. Generalization is a key to improve multi-scale maps but might be the least prominent factor compared to map style and text. So multi-scale style and text placement consistency should be tackled in priority to improve multi-scale map design.

Finally, in this study we did not focus so much on the types of interaction offered in the surveyed multi-scale maps (or, more precisely, offered by the web interface in which they are embedded), for two reasons: first, as it was not our first intended focus, we chose to perform the study on a desktop computer equipped with a mouse (no touchpad), so that only classical zooming interactions were available; second, because those classical zooming interactions are very standardized, the offered zooming interactions were similar in all studied multi-scale maps, so that there was nothing to compare across the maps. But, if we are able to improve multi-scale maps by adding consistency and progressiveness, it should be interesting to work on the improvement of multi-scale exploration by novel human-computer interaction techniques, that could be based on lenses, fish-eye views and animations [44, 7].

8 Conclusions and Further Work

To conclude, this paper presented a survey of existing multi-scale maps that aimed at the extraction of new knowledge on multi-scale map design in regard to fluid multi-scale exploration. This survey focused more on map content than on presentation or on interaction facets. The main findings of the survey are the following:

1. consistency seems to be an important target when designing the content (and even the style) of a multi-scale map, as inconsistencies seem to be an important cause of the desert fog effect we experienced in this survey;
2. there should be maps designed for each zoom level of the WMTS standard, and maybe even more between the levels, for more progressiveness in abstraction levels and visual complexity;
3. very small and very large scales are usually not so complex to navigate into because the content of the map does not change too much; the critical scale range, from 1:10k to 1:1000k, is where we should focus to improve multi-scale maps;
4. to avoid abrupt transitions of level of abstraction (LoA) between two maps, using an intermediate map that display both LoAs, can be useful and should be investigated (e.g. building polygons on top of a built-up area for the transition from building polygons to built-up areas);
5. anchors or landmarks, which can be salient map features or structural group of features, can help the user find its way when the map changes with scale.

This survey is just a preliminary study, and there is a lot to do to better understand multi-scale maps and to better design them. We also need a first step would to demonstrate the usefulness of the identified good practices for multi-scale map users: controlled experiments with map users are required to validate our assumptions about adding more levels, using mixed transitions, or the importance of multi-scale landmarks. We also need to update the study now that more and more multi-scale maps are available, and that NMA design multi-scale maps rather than pyramids of scanned paper maps. We should be able to extract additional good practices by reproducing the same protocol now. Regarding the part of the survey related to clutter, we should work on the relation between map complexity for users and clutter values, and on the influence of clutter stability in multi-scale map navigability: to be clear, user surveys are required to go further. Among all the facets of multi-scale map design, we really want to understand the influence of abstraction and map generalization in depth, in regard to the others components of map design. Should there be a paradigm shift in map generalization now that we produce more multi-scale screen maps than single scale paper maps? Finally, as mentioned in Section 7, we believe that a theory of multi-scale map exploration would be very useful. We would like to carry out experiments on multi-scale mental maps that we suppose to work in a similar manner as the theory of anchors from couclelis87.

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