Appendix 3b

Summary of Professional Accomplishments

1. **Name:** Tomasz Opach

2. Education

Ph.D. in Earth Sciences with a major in geography

The degree awarded on 23.01.2007, the decision by the Faculty Board of the Faculty of Geography and Regional Studies, University of Warsaw (in Polish – Wydział Geografii i Studiów Regionalnych, WGiSR UW); doctoral thesis: *The Efficiency of Temporal Animated Maps*.

Master's degree in geography with a major in cartography

The degree awarded on 29.05.2002 at WGiSR UW; master's thesis: *The Concept of the Map of the Natural and Cultural Heritage of Poland 1:50 000 and its implementation in the map sheet Koło N-34-134-A* (*Summa Cum Laude*).

3. Professional Experience

01.10-31.12.2014: associate professor, 50% position, Department of Geography, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

From 01.07.2014 **till now**: researcher, 100% position (01.10-31.12.2014: 50% position), Department of Geography NTNU

01.07.2013-28.02.2014: post doc, 75% position, Centre for Climate Science and Policy Research, Linköping University (CSPR LiU), Norrköping, Sweden

01.03.2012-30.06.2014: post doc, 100% position (01.07.2013-28.02.2014: 50% position), Department of Geography NTNU

01.08.2011-31.03.2012, specialist in the area of geography, 50% position, Educational Research Institute, Warsaw

01.04.2007-30.09.2016, assistant professor, 100% position (01.01-31.07.2010 as well as 01.03.2012-30.09.2016: leave of absence granted due to research trainings), the Chair of Cartography, WGiSR UW (since 01.09.2014 – the Department of Geoinformatics, Cartography and Remote Sensing)

01.10.2006-31.03.2007: research assistant, Chair of Cartography, WGiSR UW

01.10.2002-30.09.2006: PhD student, Chair of Cartography, WGiSR UW

4. Scientific Achievement (according to Article 16(2) of the Act of 14 March 2003 about academic degrees and scientific position as well as about the degrees and the position in the area of arts (Journal of Laws from 2016, item 882, as amended in Journal of Laws from 2016, item 1311):

a) Title of the scientific achievement

My scientific achievement is a series of articles. Their overarching title is as follows:

An Application of Complex Interactive Geovisualizations in the Presentation and Analysis of Multivariate Spatial Characteristics on Environmental Vulnerability to Natural Hazards

b) Author/authors, publication title/titles, issue date, publisher, peer reviewers

The scientific achievement that constitutes the basis of my application for admittance to habilitation process has been reported in a series of publications: six articles published in peer-reviewed journals included in Part A of the List of Journals of the Polish Ministry of Science and Higher Education (MNiSW) of 9 December 2016 and in one article published in an international peer-reviewed journal without IF (*impact factor*). The total IF (for the year of issue) of the scientific achievement equals **8.943**. Whereas, for my all scientific publications the overall IF equals **14.915**. The achievement's overall score calculated in accordance with the Ministry of Science and Higher Education of Poland (for the year of issue) equals **155**, whereas for my all scientific publications it equals **408**. The results of the research that constitute my scientific achievement have been reported in the following publications (their order reflects the progress in the research):

[PG-1] **Opach, T.,** & Rød, J. K. (2013) Cartographic visualization of vulnerability to natural hazards. *Cartographica*: *The International Journal for Geographic Information and Geovisualization*, *48*(2), 113-125. doi:10.3138/carto.48.2.1840, 5 points according to the Ministry of Science and Higher Education (in Polish – MNiSW) in Poland.

My contribution to this paper concerned the design of the assumptions and the concept of the geovisualization tool viewExposed. I was responsible for the conceptual research, proof-of-concept implementation, and its empirical evaluation. I am the main author of the manuscript; I have also prepared its all figures. My contribution to the paper is about 80%.

[PG-2] Rød, J. K., **Opach, T**., & Neset, T.-S. (2015) Three core activities toward a relevant integrated vulnerability assessment: validate, visualize, and negotiate. *Journal of Risk Research*, *18*(7), 877-895. doi:10.1080/13669877.2014.923027, **IF (2015): 1.027**, MNiSW: 30 pts (2015; Part A)

My contribution to this research concerned its data processing and computational stage. I was also responsible for conceptual research on the next version of the viewExposed tool as well as for writing its source code. I wrote some parts of the manuscript and participated in the elaboration of its figures. My contribution to the paper is about 35%.

[PG-3] Wiréhn, L., **Opach, T.,** & Neset, T.-S. (2017) Assessing Agricultural Vulnerability to Climate Change in the Nordic Countries – an interactive geovisualization approach. *Journal of Environmental Planning and Management*, *60*(1), 115-134.
doi:10.1080/09640568.2016.1143351, **IF (2016): 1.56**, MNiSW: 25 pts (2016, no index score for 2017; Part A)

My contribution to this paper concerned the design of a concept of a complex geovisualization tool with coordinated and multiple views and its proof-of-concept implementation in the web-application agroEXPLORE. I was also responsible for the tool's empirical evaluation. I participated in drafting the manuscript (I wrote Section 4 and some other parts of the manuscript) and preparing its figures. Finally, I revised the manuscript critically for important intellectual content. My contribution to the paper is about 30%.

[PG-4] Johansson, J., **Opach, T.**, Glaas, E., Neset, T.-S., Navarra, C., Linner, B. O., & Rød, J. K. (2017) VisAdapt: A visualization tool to support climate change adaptation. *IEEE Computer Graphics & Applications*, *37*(2), 54-64.
doi:10.1109/MCG.2016.49, **IF (2016): 1.987**, MNiSW: 25 pts (2016, no index score for 2017; Part A)

My contribution to this research concerned conceptual considerations, the design of the layout of the graphical user interface of the tool VisAdapt. I am coauthor of VisAdapt's source code and also participated in its empirical evaluation. I revised the manuscript critically for important intellectual content and participated in the preparation of its figures. My contribution to the paper is about 20%.

[PG-5] **Opach, T.**, & Rød, J. K. (2014) Do choropleth maps linked with parallel coordinates facilitate an understanding of multivariate spatial characteristics? *Cartography and Geographic Information Science*, *41*(5), 413-429.
doi:10.1080/15230406.2014.953585, **IF (2014): 0.944**, MNiSW: 15 pts (2014; Part A)

I led all stages of the research. My contribution to this paper concerned the empirical research; I designed it and realized. I am also the main author of the manuscript and the only author of its figures. My contribution to the paper is about 90%.

[PG-6] Gołębiowska, I., **Opach, T.**, & Rød, J. K. (2017) For your eyes only? Evaluating a coordinated and multiple views tool with a map, a parallel coordinated plot and a table using an eye-tracking approach. *International Journal of Geographical Information Science*, *31*(2), 237-252.
doi:10.1080/13658816.2016.1191636, **IF (2016): 2.502**, MNiSW: 35 pts (2016, no index score for 2017; Part A)

My contribution to this research concerned conceptual consultancy; I also participated in the preparation of the empirical study and the analysis of collected empirical data. My individual contribution to the research was the concept and the development of the Eye Movement AOI Aggregation Tool (EMAAT) that enables the users to analyze eye movement data. This tool was used—together with other tools—in the analysis of the data that we collected in our *empirical research. Finally, I revised the manuscript critically for important intellectual content and participated in the preparation of its figures. My contribution to this paper is about 30%.*

[PG-7] **Opach, T.**, & Rød, J. K. (2017) Augmenting the usability of parallel coordinate plot: The polyline glyphs. *Information Visualization*, e-publication ahead of print, first published February 1, 2017. doi:10.1177/1473871617693041, **IF (2016): 0.923**, MNiSW: 20 pts (2016, no index score for 2017; Part A)

I am the author of the concept of polyline glyphs. I was responsible for all parts of the research. I designed the study and conducted its empirical part (user testing). I analyzed empirical data and interpreted the results. Finally, I wrote the manuscript and prepared all its figures. My contribution to this paper is about 95%.

c) Overview of the scientific objective of the articles listed above and the achieved results along with a discussion of their potential use

Research goal and an outline of scientific results

The research described in the set of publications that constitute my scientific achievement aimed to identify and empirically verify design solutions from the field of complex and interactive geographic visualizations (*geovisualizations*) that enabled presentation and visual analysis of multivariate spatial characteristics. The characteristics concerned places' vulnerability to natural hazards, whereas their visualization aimed – in a broader sense – to support decision-making processes that are undertaken both by experts in the area of spatial planning, emergency management, by public administration officers, as well as by ordinary users. The research encompassed approaches typically used in geographic information science (GIScience). It consisted of theoretical investigations, conceptual studies, proof-of-concept implementation, as well as empirical evaluation.

The outcome of the theoretical and conceptual investigations are design guidelines as well as concepts of three complex interactive geovisualization tools. They all display data on vulnerability to natural hazards; however, each of them provides different functionality that is tailored to a specific area of use that particular tool is expected to support. Although, all three concepts have a common feature as they all broadly support decision-making processes that employ visual analysis of multivariate spatial characteristics that concern vulnerability to natural hazards, there are essential differences in user tasks those concepts are expected to support, i.e., who can use them and what tasks they can be used for. Proof-of-concept implementations as well as empirical evaluations of proposed design guidelines were integral parts of my research. Therefore, after theoretical and conceptual investigations, the design guidelines and concepts were used to design and develop prototypes of three web applications: *viewExposed*, *agroEXPLORE*, and *VisAdapt*. The applications were next used as study material in user studies. While I am the only author of the source code of the first two applications, the third application was developed together with C. Navarra from CSPR LiU. The design guidelines and the concepts constitute a "knowledge base" whereas their proof-of-concept implementations serve as working examples of how complex interactive geovisualizations can be used to present and visually analyze multivariate spatial characteristics.

The resulting design guidelines, both the entire concepts as well as their parts, can be easily tailored to other application areas in which presentation and visual analysis of multivariate spatial characteristics is of primary importance to decision-making processes. Furthermore, since the three tools have been written with use of open source JavaScript APIs, their source code can be used for other applications. Although, the concepts of the geovisualization tools have been designed in order to implement them in the Nordic countries, and thus, they are well tailored to unique features of these countries, they can be used to prepare geovisualization tools for any area that has necessary data. Finally, the concepts along with the three web tools can serve as inspiration for all those who seek similar solutions; however, for application areas different than Earth sciences, for example, for business intelligence (BI) or logistics.

Research background and context

Data visualization, that is, simply, a set of steps that leads from data towards their visual encoding, as well as the final result of such encoding, is increasingly frequently used in those application areas, in which data analysis is of key importance. There are three factors that influence the growing use of data visualization: (1) growing access to data – often multivariate and spatiotemporal; (2) growing access to communication channels, mostly, to Internet as well as electronic devices in general, and portable devices in particular, in which interactive functions are implementable, and that let users use data visualizations in any situation, for example, as part of a car dashboard or a police officer gear; and (3) technological advances – as a myriad of technologies, both commercial (e.g., Tableau, PI Integrator for ESRI ArcGIS) as well as free, open source solutions such as D3.js, Openlayers.js, or shiny R, that enable mapmakers to quickly and relatively easily elaborate proper tools.

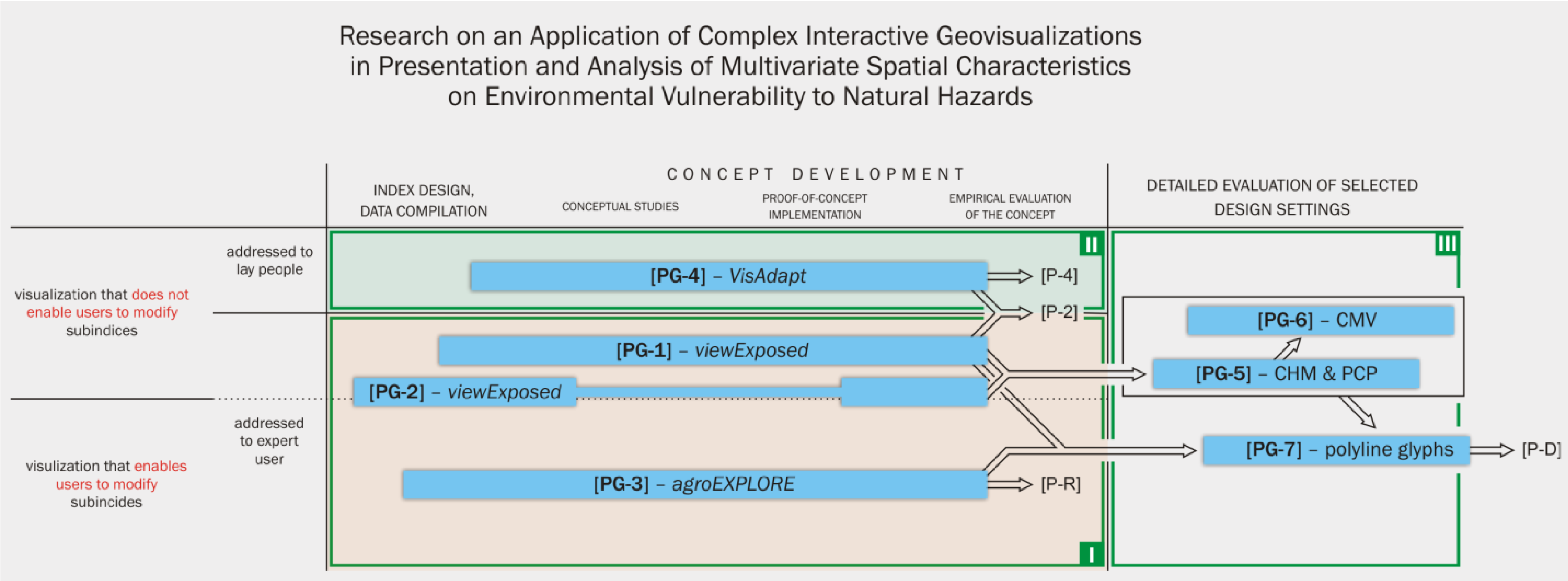
There are many application areas of data visualizations, in particular – those interactive. Such visualizations are addressed to both specific expert users as well as ordinary users. Data analysis, business intelligence, manufacturing process visualization, logistics, decision making processes in spatial planning, as well as daily life needs, such as internet banking or electricity consumption visualization – these are only a few examples from a long list of publications that concern the application areas of information visualization (Bederson & Shneiderman, 2003). On this publication list, specific role is played by studies that concern visualization of geographical data. Such visualization is often called – because of its unique features – cartographic visualization, or oftener, *geographic visualization* – *geovisualization* (Virrantaus & Fairbairn, 2008). Despite various opinions regarding terminology reported in Polish scientific publications, geovisualization is a term commonly used in English publications from the domain of GIScience and geoinformatics. Unlike traditional maps, geovisualization features a broad diversity of design settings, layouts, and visualization techniques, in which map displays are dynamically linked with other information visualization methods and techniques: plots, graphs, diagrams, cross-sections, 3D views, and animations.

Since the 1990s of the past century, when the rapid growth of computer technologies started, such complex geovisualizations—usually equipped with a broad range of interactive functions—has become the subject of growing interest to all those who seek solutions that enable effective presentation and visual analysis of multivariate spatial characteristics. Such systems were then developed as CommonGIS (Andrienko & Andrienko, 1999) and GeoVISTA *Studio* (Gahegan et al., 2002). The primary feature of these systems was the design based on coordinated and multiple views (CMV) (Roberts, 2007) – the approach in which all distinct views are dynamically linked, so that if a user selects/highlights one or more objects in one view, the same data items are simultaneously selected/highlighted in the other views. More recently, the research on complex interactive geographic visualizations, on their design and use, is conducted by both commercial initiatives as well as scientific institutions as part of scientific research. In the latter, the research objectives consist of issues that refer to theoretical foundations, design guidelines and concepts for specific application areas, as well as they refer to more applied studies in which ready-to-use implementations are to be developed. My research refers to all from the mentioned aspects. Its background concerns the need for solutions that support decision-making processes during actions undertaken to prevent or reduce the risk to life, property, social and economic activities, and natural resources that can potentially be caused by natural hazards. Over the last years, in many countries this issue – due to the growing frequency of such hazards (IPCC 2013) – has become one of the strategic areas of geographic research.

My research on the application areas of complex cartographic animations was the inspiration and factor that influenced my interest in the use of complex geovisualizations to support decision-making processes. I conducted this research during the period 2007-2012 in the former Chair of Cartography, Faculty of Geography and Regional Studies, University of Warsaw, as well as during the research trainings in the Group of Geomatics NTNU (2009-2010) and in the Geographic Information Visualization and Analysis (GIVA), University of Zurich (twice, in 2010 and 2011). The result of the research are original concepts of two complex cartographic animations. A proof-of-concept implementation was made for each of the concepts (Opach et al., 2011; Opach et al., 2014). Next, the implementations were empirically tested (Opach & Nossum, 2011; Opach et al., 2014). While the first animation aimed to present the formation of a physical landscape, the second presented a wildland fire along with changing wind and geography of different types of forest. The latter tool, addressed to those users who make decisions based on analysis of multivariate spatial characteristics, has inspired me to continue research on the use (recognize application areas) of not only—this time—complex cartographic animations, but broader – also on complex interactive geovisualizations. Their unique features make them helpful in those application areas in which traditional maps do not fulfil user requirements, that is, in presentation of multivariate data. In such case complex geovisualizations may better facilitate effective communication.

My investigations on the effective use of an interactive geovisualization to present and visually analyze an integrated index of environmental vulnerability to natural hazards in Norway was the starting point of the research whose results constitute the scientific achievement. The interactive geovisualization was addressed to the public sector officers in Norway, since access to such index is of importance to their decision-making processes in spatial planning and emergency management. Therefore, it was necessary to design a tool that could enable them to present and visually analyze the index. I conducted this research as part of the project *Nordic Strategic Adaptation Research* (NORD-STAR), initially, during my postdoctoral training in the Department of Geography NTNU (2012-2014), thereafter, as a researcher in this department. I designed the tool's concept that I next implemented in a prototype of a web application. Apart from the NORD-STAR project, I conducted investigations during my concurrent postdoctoral training at CSPR LiU (2013-2014), in which I participated in the research project *Increasing Nordic Homeowners' Adaptive Capacity to Climate Change* (In Hac Vita). Both projects were thematically interlinked; they were conducted as collaboration between scientific institutes, public authorities, as well as private companies from the insurance sector in the Nordic countries. In the In Hac Vita project my role was to conduct research and develop software, whereas in the NORD-STAR project I was both researcher (in its sub-project *1.3: Integrated vulnerability mapping*), and co-leader of its sub-project *5.1: VisAdapt*. Since July 2015, my research has been part of the project funded by the Research Council of Norway (no 235 490) entitled *Climate change and natural hazards: the geography of community resilience in Norway* (Climres). My role in this project is to conduct research in its work package *3: Visualizing community resilience*. In this research, I focus on solutions that can be used to display indices that are already designed, as well as those resilience indices that enable users to modify their sub-indices. Although, in Climres, I use data that concern the community resilience to natural hazards in Norway, the same as in the previous projects, my research aims to identify design guidelines that let mapmakers prepare such complex interactive geovisualization tools, that are equipped with visualization and human-computer interaction (HCI) techniques and that enable both, effective presentation (adequate for intended content – the semantic aspect of communication efficiency) and visual analysis of multivariate spatial characteristic (adequate for user tasks and their requirements – the pragmatic aspect of communication efficiency). Apart from theoretical and conceptual investigations, an integral part of my research is proof-of-concept implementation, that is, practical verification of the concepts.

My research outcomes have been described in a set of seven thematically interconnected scientific papers. All together, they constitute my scientific achievement. The articles were published over the period 2013-2017 in peer-reviewed journals that represent Earth sciences, GIScience, and information and communication technology. The total IF (*impact factor*) of the articles equals **8.943**, whereas their overall score calculated for the year of issue and in accordance with the Ministry of Science and Higher Education of Poland equals **155**. Figure 1 demonstrates thematic interconnections between the articles.



Key: **[PG-1 – 7]** the main publications that constitute my scientific achievement

[P-2] and **[P-4]** articles included in the inventory of my scientific publications (see Załącznik 4)

[P-D] and **[P-R]** articles in press [P-D] and under review [P-R]

CHM choropleth map

PCP parallel coordinate plot

CMV coordinated and multiple views

I II III the three groups of research issues that I use to frame my research findings

Figure 1. Thematic interconnections between seven publications that constitute my scientific achievement along with their linkages with the three research issues that I use to discuss my research findings.

The scientific achievement consists of results of the research, in which I have addressed the following three groups of scientific issues:

I. Indicate design guidelines that both, (a) enable presentation and visual analysis of integrated indices of environmental vulnerability to natural hazards, and (b) enable vulnerability indices' presentation and visual analysis, and also, modification of their sub-indices. In both cases, expert users are the target audience of geovisualization that aims to support their decision-making processes.
II. Indicate design guidelines that enable presentation and visual analysis of integrated indices of environmental vulnerability to natural hazards if ordinary users are to be the target audience of geovisualization.
III. Empirical evaluation of selected features of proposed design solutions that have not attracted adequate scientific attention yet.

The above three groups of scientific issues constitute the frame that I have used below to discuss the achievements I have gathered in my research. Figure 1 shows how the seven articles that constitute my scientific achievement are embedded into these three groups.

Issue I
Identification of design guidelines for geovisualizations addressed to expert users that enable presentation, visual analysis, and modification of indices of environmental vulnerability to natural hazards

Showing vulnerability indices in the way that enables users to investigate their geography, but also, that enables better understanding of what factors and sub-indices make a particular place vulnerable, is one of the challenges in the application of complex geovisualizations in presentation and visual analysis of indices of environmental vulnerability to natural hazards. The complexity of this challenge results not only from the requirement of a user-friendly presentation of multivariate data that depict geographic space, but also, it results from the variety of ways in which such characteristics are used in practice. The way how a geovisualization tool that displays final indices (already developed by experts, without modification possibility – *top-down approach*) is used in practice, differs from the requirements, if users are allowed to influence the design of such final indices by modifying their sub-indices, or even – this is exactly users' role to select indicators or sub-indices that are to be incorporated into a final index (*bottom-up approach*).

The research reported in papers **[PG-1]** and **[PG-2]** aimed to elaborate the design guidelines and the concept of a complex interactive geovisualization that enables insight into scores of the integrated index of vulnerability to natural hazards calculated for 430 Norwegian municipalities (in 2014). When working on the concept, one of its major assumptions was that <u>the resulting tool would not allow the users to modify the sub-indices of the final integrated vulnerability index</u>. Furthermore, apart from the identification of proper design guidelines, I aimed to develop a prototype of a web application as the proof-of-concept implementation of the concept. Stakeholders responsible for spatial planning, emergency management, and all those users, who deal with climate change adaptation, were the tool's intended users. My research was part of a broader research project that also included other tasks, such as design and development of a vulnerability index for Norwegian municipalities. However, my role in these tasks encompassed only the analysis of exposure to strong winds. The research findings revealed in these tasks are not included as part of my scientific achievement.

In **[PG-1]**, I described the design guidelines of the geovisualization tool, its concept, proof-of-concept implementation, and its empirical evaluation (see Figure 1). Whereas, in **[PG-2]**, apart from the outline of the concept and its proof-of-concept implementation, more detailed information is given on the vulnerability index as well as on how its visualization can facilitate the debate with the target audience. Paper **[PG-1]** was published in the peer-reviewed journal *Cartographica* that, although, is not included in the *Web of Science* database, is a broadly known forum for discussion and debate in GIScience. Whereas paper **[PG-2]** was published in the peer-reviewed *Journal of Risk Research* (IF 2015: 1.027). Apart from **[PG-1]** and **[PG-2]**, my research findings have been also outlined in publications addressed to practitioners in Norway (Rød et al., 2013a; Rød et al., 2013b) and more broadly, in the Nordic countries (Wilk et al., 2013). Moreover, I have frequently demonstrated the *viewExposed* web application during international conferences, and also, in Norway and Sweden, during workshops and seminars with public administration officers. Its prototype can be accessed in the Internet and it is used in public administration.

The investigations on the index as well as the conceptual research on a solution that enabled its presentation and visual analysis were concurrent and multifaceted. The Integrated Vulnerability Index (IntVI) is outlined in **[PG-1]**, whereas it is presented in detail in **[PG-2]**. The concept of the index – designed by J. K. Rød, refers to the vulnerability indices developed either by S. Cutter or under her supervision (Cutter, 1996; Cutter et al. 2000; Cutter et al. 2003; Tate et al., 2010). The concept combines Social Vulnerability Index (SoVI) with the Index of Physical Exposure. The first has been developed for Norway by Holand et al. (2011). It has been done by means of exploratory factor analysis (EFA) based on 33 socio-economic indicators. Whereas the second combines three exposure sub-indices: to strong winds, flooding, and to landslides. The sub-indices are assigned the following weights: 64%, 28%, and 8%, respectively. In order to determine the weights of the individual exposure indices, we used empirical data from the Norwegian Natural Perils Pool on insurance payments due to damage on buildings caused by storms, floods, or landslides over the period 1980-2014.

Four stakeholder workshops were arranged at the Department of Geography NTNU in 2011-2012 in order to recognize user requirements in terms of vulnerability indices (their design) as well as user preferences regarding the way how such indices should be provided to the target audience. A total of 15 representatives from the public administration sector from two counties in central Norway: Sør- and Nord-Trøndelag attended the workshops. An easy-to-understand presentation of the geography of vulnerability indices that also enables users to understand the structure of those indices (weighs of their sub-indices) was the essential requirement reported many times during the workshops **[PG-1]**. Such requirement resulted from the difficulties in understanding of other vulnerability indices, previously developed at the Department of Geography NTNU (Holand et al., 2011; Rød et al., 2012; Holand & Lujala, 2013). Moreover, the attendees suggested using a complex interactive geovisualization that shows multivariate spatial characteristics. Therefore, in my conceptual investigations, from the beginning I focused on the use of—despite criticism reported in the literature—coordinated and multiple views. There are statements reported in the literature that such design is too sophisticated for users (Andrienko & Andrienko, 2007), who might become confused and overwhelmed by the multitude of applied visualization techniques (Baldonado et al., 2000). Investigating data simultaneously in multiple and various visual contexts requires context switching, which occurs when a user switches from one display, based on one particular visualization method, to another display, based on another visualization method. This in turn might require extensive cognitive attention (Baldonado et al., 2000).

I decided to employ only two visualization techniques; I did so in order to fulfill the target audience's requirements, and, on the other hand, to avoid usability obstacles that might result – as already indicated in the literature – from combining multiple visualization techniques. I used a choropleth map that facilitates showing spatial diversity, and a parallel coordinate plot (PCP) (Inselberg, 1985) that allows users to get insight into complex multivariate characteristics as well as visually analyze their geographies. Then, I added to this layout an interactive datagrid that enables users to examine raw data, and finally, I added polyline glyphs. The latter are simply minimized and frozen thumbnails of plots from parallel coordinates. I added such glyphs in order to prevent usability obstacles that might occur when interacting with parallel coordinates (Fotheringham et al., 2000). Such difficulties are typically caused by visual clutter (Heinrich & Weiskopf, 2013) that occurs if many data items are drawn as superimposed graphical entities on a limited screen space. Polyline glyphs were to be used in order to prevent such difficulties by providing easy (separate) access to all multivariate data items (plots).

The novelty of the concept concerned the way how the above visualization techniques were integrated into a single interactive geovisualization of multivariate spatial characteristics. Moreover, novel was also the use of a parallel coordinate plot in order to both, support multivariate data analysis as well as enable users to get a better insight into complex quantitative attributes. Finally, novel was also the concept of polyline glyphs that was an original idea that has been described never before in the literature.

The research's practical outcome was the tool *viewExposed*. Its functionality as well as its empirical evaluation was described in **[PG-1]**. The evaluation aimed to acquire feedback on the efficiency of the tool: its strengths and weaknesses. The World Café method (Brown & Isaac, 2005) was used as the empirical technique; a total of 11 individuals attended the evaluation. The attendees represented various Norwegian authorities. The outcomes of the empirical study were described in **[PG-1]**. Moreover, the gathered empirical data was also analyzed in a broader context – in the study that concerned the use of geovisualization to support decision-making processes in climate change adaptation actions (Bohman et al., 2015).

Apart from a „too scientific" nature of a parallel coordinate plot that requires providing users with necessary instructions how to read such plot **[PG-1]**, the evaluation revealed that the attendees required downscaled vulnerability data, that is, adding index scores also for administrative units smaller than municipalities. Therefore, I experimentally added to *viewExposed* the index scores calculated for wards in Sør- and Nord-Trøndelag. Furthermore, those attendees who represented the municipality of Selbu were skeptical about the index scores that concerned their location. They claimed that the scores are too high than those provided for neighboring municipalities. As a result, attendees from Selbu declared their willingness to comment on: to submit their feedback to the *viewExposed* tool. Therefore, in order to fulfil such requirement, I extended *viewExposed*'s functionality by adding a set of interactive functions that enabled users to submit remarks about IntVI and its sub-indices. This extended functionality also enabled reading comments already submitted by other users **[PG-2]**. After the evaluation, I also added to *viewExposed* an interactive function that enabled users to generate a print-ready report for a selected municipality. I did so since printed documents can facilitate insight into information, especially during collaborative decision-making. Finally, the evaluation revealed that users want and are willing to participate in vulnerability assessments whose outcomes are to be presented in geovisualization tools. It happens since users' local knowledge and more practical experience with local environmental conditions allow them to verify index scores. Such research finding confirms those already reported in the literature (Sieber, 2006), that along with the growing importance of interactive tools to decision-making processes, their users do not want to be only a passive audience. Instead, they rather consider themselves to be active users who can influence conveyed message. Such users want to be able to modify displayed information. This demand is fostered by their local knowledge and the growing access and usefulness of interactive visualization tools (Neset et al., 2016b).

The shift of the user role – from the passive audience to more active users – has been well depicted in MacEachren's map use cube (MacEachren & Kraak, 2001). The cube shows the functions of contemporary maps, in which, among other scenarios, a user of a geovisualization tool uses its extensive interactive functions in order to modify/adjust the tool's data content. Such case was the issue I next addressed in my research on the use of geovisualization to present complex vulnerability indices. I conducted this research in collaboration with L. Wiréhn and T.-S. Neset from CSPR LiU. L. Wiréhn's and T.-S. Neset's role was to design the conceptual framework of a complex vulnerability index and to outline the initial requirements of its visualization. Whereas, my role was to prepare the design guidelines of the visualization as well as to elaborate its concept; it was also my role to make a proof-of-concept implementation and to write the tool's source code. When it comes to the design guidelines, although they were similar to those prepared for *viewExposed*, there were three essential differences. First, allowing users to modify the index's structure was the primary and key difference. The next difference was that the visualization was to be used for a specific kind of vulnerability to natural hazards, i.e., the vulnerability of agriculture in Sweden. Finally, the same as with *viewExposed*, expert users were the target audience of the tool (in this case – agricultural experts). Nevertheless, apart from using the tool by means of individual devices or personal computers, the tool was to be designed as tailored to indoor large displays used in collaborative decision-making processes. The investigations on the design guidelines, on the concept and its experimental implementation in the web application *agroEXPLORE* were reported in the paper **[PG-3]** published in the peer-reviewed *Journal of Environmental Planning and Management* (IF 2016: 1.56). The study was led by L. Wiréhn. This publication included also the results of the empirical evaluation. The latter aimed to test the prototype of the *agroEXPLORE* tool*.* Moreover, a practical benefit of my research is the use of *agroEXPLORE* in *LiU Decision Arena* – a cylindrical room in which all attendees have the same opportunity to simultaneously use the same geovisualization tool. They can show their screens (with multiple types of relevant information) on a cylindrical projection surface facilitating dialogue and transparency across different interpretations and action alternatives. In this context, *agroEXPLORE* serves as a tool that facilitates dialogues on factors that may affect agricultural vulnerability in Sweden to climate change. The empirical data that have been collected during such dialogs are now analyzed in a broader scientific context in which of importance is to gather practical benefits from the collected feedback. The outcomes has been described in the manuscript which is under review (in Figure 1 shown as [P-R]).

The combination of a choropleth map with a parallel coordinate plot, an interactive datagrid, and polyline glyphs is a common feature of *viewExposed* and *agroEXPLORE*. Such combination aims to present multivariate spatial characteristics and to facilitate their visual analysis. However, *agroEXPLORE* provides also an extra functionality that enables users to modify the vulnerability index that is presented in the tool **[PG-3]**. In other words, while *viewExposed* displays an index already developed, *agroEXPLORE* enables its modification in accordance with users' individual preferences. Therefore, in order to provide such functionality, *agroEXPLORE*—apart from displaying the geography of the final agricultural vulnerability index—features extra choropleth maps that display three sub-indices of exposure, sensitivity, and adaptive capacity. In addition, each of the sub-indices has been provided with a list of included indicators (9, 11, and 5, respectively). The tool is designed so (see the description in **[PG-3]**) that its users are able to move the indicators across the sub-indices (by dragging and dropping selected indicators in dedicated panels). They can also adjust the indicators' weights (from 0 to 5; the default weight is 1). Besides, the users can revise the shares of the sub-indices in the final vulnerability assessment. Once the adjustments are applied and the data recalculated, new geographies are displayed on the maps and the resulting index structure is presented in *agroEXPLORE* too. Since such procedure can be repeated, each time if a user disagrees with the assessment, the tool required a solution that would enable users to get a quick insight into the most recent index design. Therefore, I extended the tool's concept by adding a Sankey diagram that shows the shares of the indicators in the sub-indices as well as reveals the shares of the sub-indices in the final index of agricultural vulnerability.

Visualization techniques applied in *agroEXPLORE*—the same as those used in v*iewExposed*—have been already described in the literature. Except the concept of polyline glyphs, they do not serve as the added value of my research. However, the way how they are all integrated into an interactive graphical user interface displaying a complex vulnerability index, it constitutes the added value of my research. These techniques as well as their interactive functions **[PG-3]**, they all enable the visual interface to present and to support visual analysis and modification of the vulnerability index. Thus, the role of the user evolves – from the passive user to the active one, in this particular case, to the co-author of the complex index of agricultural vulnerability to climate change. The user is also able to save new settings (modifications) and restore them in the future. Individuals can also restore settings saved by other users. By doing so, they can confront their point of view with the perspectives of other users. Finally, modifications that have been already saved in a database can be used to verify the default settings of the vulnerability index as the latter can be confronted with the most frequent scores among those saved by users. Then, such confrontation can lead to the modification of the index's default settings: of the initial structure of the sub-indices as well as their initial shares in the vulnerability assessment. However, such functionality requires proper filtering mechanism for saved modification in order to ensure that only meaningful modifications are taken into account, i.e., those executed by competent users.

Although the depicted above design guidelines concern the use of geovisualization in the presentation, visual analysis, and modification of a complex index of agricultural vulnerability, the concept that has been used to design and develop the *agroEXPLORE* tool, can be used broader then only to support decision-making processes in the agricultural adaptation to climate change in Sweden. For example, the design guidelines prepared for *agroEXPLORE* I have later used for other purposes: to prepare the concept of a tool that enables users to plan the costs of flood mitigation actions, and also, in the concept of a tool that enables visualization and assessment of community resilience to natural hazards.

Issue II
Identification of design guidelines for geovisualizations addressed to ordinary users that enable presentation and visual analysis of indices of environmental vulnerability to natural hazards

While I was conducting the research described in **[PG-1]** and **[PG-2]** that aimed to design a concept of a geovisualization tool that conveys the scores on the Index of Integrated Vulnerability to natural hazards (IntVI) to expert users, I was also invited to the collaboration with scientists from CSPR LiU. The collaboration aimed to prepare the design guidelines and the concept of a geovisualization tool that was intended to present such vulnerability index to ordinary users. Of importance to us was also that – apart from displaying IntVI – the tool was to present and facilitate visual analysis of other multivariate spatial characteristics that primarily concerned the climate change effects in the Nordic countries. Finally, the tool was also to provide practical tips for adaptation measures to climate change/to more frequent climate impacts as such tips might be of value to regular house owners. All these tasks directed my scientific interest towards new challenges and broadened my research to a new research issue.

At the beginning, our collaboration was conducted under the umbrella of the multifaceted research project NORD-STAR; both the Department of Geography NTNU and CSPR LiU belonged to its consortium. Then, my research generally concerned the use of IntVI to support decision-making processes undertaken by homeowners in order to adapt to climate change. Subsequently, formally, during my postdoctoral training at CSPR LiU, I focused on the design guidelines and the concept of a geovisualization tool that displays IntVI along with extra spatial characteristics; I focused on the design of the tool's graphical user interface, selection of adequate visualization techniques, and finally, on its interaction design. Moreover, together with C. Navarra from CSPR LiU, we were responsible for the proof-of-concept implementation in the web application *VisAdapt*. All these tasks constitute parts of the In Hac Vita project, which was realized by universities, research institutes, and insurance industry from the Nordic countries. The initial research findings were presented at the IEEE VAST 2014 conference (Johansson et al., 2014), whereas the final outcomes were reported in the paper **[PG-4]** published in the peer-reviewed journal *IEEE Computer Graphics & Applications* (IF 2016: 1.987). The research outcomes described in this paper constitute part of my scientific achievement.

An essential challenge of the visualization of multivariate spatial characteristics that is addressed to ordinary users is the assumption that they are unexperienced in visualization tools and they have no knowledge that facilitates data interpretation. This assumption determines conceptual investigations, since the way how complex spatial characters are read by those who have knowledge on presented topic and experience in reading such characteristics, differs from the requirements and abilities of ordinary users. The latter require, first of all, easy-to-read and easy-to-understand visualization that leads towards a proper mental image of those characteristics. Although such users may desire to make use of presented complex information in their decision-making processes, they may have neither skill nor experience enough to properly interpret encoded message. Therefore, an expert user as well as an ordinary user might have the same goal: presentation of multivariate spatial characteristics intended to support decision-making processes. However, their circumstances and their contexts may differ and require different approaches to the concept of a visualization tool that is to present and enable visual analysis of such characteristics. In the case of ordinary users, it will be a straightforward and suggestive presentation (MacEachren & Kraak, 2001). Therefore, in order to properly determine the design guidelines necessary for the concept of a visualization tool, and also necessary for the proof-of-concept implementation, one needs to apply user-centered design (Norman, 1986) that requires designers to analyze and envision user needs, requirements, and limitations at each stage of the visualization design process.

When working on the design guidelines for a visualization tool, and later, on its concept and proof-of-concept implementation in the web tool V*isAdapt*, in our initial efforts we aimed to determine user tasks that solving was to be supported by the *VisAdapt* tool. This research has been reported in the article **[PG-4]**. The tool's default user scenario was determined during three workshops arranged with representatives of insurance industry and climatologists. The scenario consisted of the following steps: 1) locate your house; 2) provide the system with the house's features (such as type of roof); 3) visually investigate your location's multivariate spatial characteristics; and finally 4) explore the adaptation measures for your location and act. Such a multistep user scenario required proper design guidelines for the graphical user interface and proper interaction design. Therefore, in the tool's first concept, we used coordinated and multiple views, already tested in the tool *viewExposed* **[PG-1].** This approach enabled us to integrate the above four steps of the default user scenario into a single graphical user interface. Furthermore, the first concept of the user interface included five windows: two choropleth map displays showing data on vulnerability, risk, and flood prone areas (the first display) as well as climate data (the second); a window that enabled the users to locate their houses, a window that enabled providing the system with the house's features, and a window with an interactive plot displaying climate data. Finally, as ordinary users were to be the tool's target audience, its concept was to be designed with the use of only well-known visualization techniques and commonly used interactive functions.

The concept of the tool was used to develop the prototype of the *VisAdapt* web application, which was next tested empirically with a multi-step evaluation procedure **[PG-4]**. The evaluation consisted of interviews with potential end users, workshops with specialists from Nordic insurance companies, seminars with climate change experts, and consultancy with information visualization experts. The interviews with potential end users turned out to be the most fruitful. Although end users did not report information overload, they did not fully understand the goal of showing various information simultaneously. They did not know where to start using the tool, and how to combine into one comprehensive message the information provided in various visualization components. In other words, the evaluation revealed that those users who have neither proper skills nor suitable instructions, they may be unable to intuitively understand the goal of dynamically linking various interactive visualization components. Thus, such users may get lost in the complexity that is typical for such geovisualization tools with multiple views.

The results of the evaluation triggered my further investigations on the concept of the *VisAdapt* tool. Positive thoughts expressed by insurance companies' representatives, climate change experts, as well as information visualization specialists **[PG-4]** constituted the argument for applying the coordinated and multiple views approach. However, on the other hand, the potential end users expressed skepticism, as they claimed that the proper explanation is necessary on how to start using a complex graphical user interface. I attempted to solve this issue by arranging the parts of a visual interface in a sequence of predefined and logical steps (panels) that direct user attention: (1) determine your address and depict your house; (2) analyze multivariate characteristics for your geographic location; and (3) get acquainted with suggested adaptation measures. It was my original concept and individual contribution to the research. Although it was a simple solution, there were no studies about this idea reported in the literature on the design of complex geovisualizations with coordinated and multiple views (CMV). Regarding the latter, researchers have rather concurrent opinions, as they commonly claim that only those individuals should use CMV tools, who are able to make use of the freedom which is given, if an interactive geovisualization is composed of multiple views which can be used freely, with no particular viewing order. In the case of V*isAdapt* – a tool addressed to ordinary users, such freedom may be treated not as advantage but as inconvenience. Therefore, I suggested setting some constraints in terms of the order that was to be followed by the users when interacting with V*isAdapt*'s visual components. I used similar approach in my previous concept of the complex cartographic animation showing the formation of Kampinos Forest's physical landscape (Opach et al., 2011). Its users can choose—depending on their tasks—one of the five available graphical user interfaces in which the layout directs user attention. Although *VisAdapt*'s layout is based on a similar assumption, the tool has different context, goal, and also different is its rationale. Moreover, *VisAdapt* provides the users with only one graphical user interface, in which the recommended viewing order is strongly visually emphasized.

The modification of the concept was next used to develop the second prototype of the *VisAdapt* tool. Its multi-step empirical evaluation, partially with 35 potential end users from Denmark (Aarhus), Sweden (Norrköping), and Norway (Trondheim), proved the value of the modifications. The interviewees had no problems with getting acquainted with the new version of the tool. The adjusted visual interface of the tool turned out to be legible and easy to use. However, in the received feedback, it was suggested to equip the tool with a tutorial. We did so in the next step of the research. The conceptual investigations as well as the multi-step empirical evaluation were reported in the article **[PG-4]**. Additionally, the findings revealed in the last steps of the evaluation have been more extensively presented in two papers (Glaas et al., 2015; Neset et al., 2016a), in which the emphasis has been laid on the practical aspects of the application of *VisAdapt* in the climate change adaptation.

The research that led (as practical contribution to the application area) to the development of the *VisAdapt* tool consisted of a data acquisition stage, conceptual considerations, a programming stage, as well as a multi-step empirical evaluation. Although all these tasks were teamwork, my individual contribution to the research, and thus, part of my scientific achievement, are the design guidelines and the concept of the graphical user interface that directs user attention through the manner how the interface's elements are arranged. Although this solution has been to be used in interactive visualization of multivariate spatial characteristics that supports climate change adaptation, it can be also used for other data and other application areas. Directing user attention on complex interactive geovisualization tools through a proper design of the tools' visual components and functionality can facilitate their use, particularly if they—the same as *VisAdapt*—use coordinated and multiple views and are addressed to ordinary people.

Issue III
Empirical evaluation of the solutions that are of importance to the presentation and visual analysis of complex vulnerability indices

Although the concepts of *viewExposed*, *agroEXPLORE*, and *VisAdapt* were—in the empirical evaluation—confronted with user requirements, it was of importance to me to gather a better insight into those functionalities, which were not adequately commented on in the literature. The three concepts differ essentially in terms of their functionality; however, they feature a few commonalities: a) combine choropleth maps with a parallel coordinate plot (in *viewExposed* and *agroEXPLORE*); b) use coordinated and multiple views (all three concepts); and finally c) employ polyline glyphs (in *viewExposed* and *agroEXPLORE*). Since these three functionalities played important roles in the presentation and visual analysis of multivariate spatial characteristics on indices of vulnerability to natural hazards, they were better investigated by means of various empirical techniques. The research findings have been reported in three peer-reviewed articles: **[PG-5]** published in *Cartography and Geographic Information Science* (IF 2014: 0.944), **[PG-6]** published in the *International Journal of Geographical Information Science* (IF 2016: 2.502), and finally **[PG-7]** published in *Information Visualization* (IF 2016: 0.923).

Although the main research issue addressed in the empirical study described in paper **[PG-5]** was the efficiency of the solution that combines a choropleth map with a parallel coordinate plot, the study also aimed to investigate the effectiveness of the remaining two functionalities, i.e., polyline glyphs (in **[PG-5]**, I used E. Tufte's term sparklines (2006)) as well as a graphical user interface that consists of coordinated and multiple views. Due to such multifaceted nature, the research reported in **[PG-5]** constituted the foundation of my further investigations and attempts that aimed to get a better insight into the effectiveness of coordinated and multiple views **[PG-6]** as well as to better study the concept of polyline glyphs. The latter was to be used as solution facilitating the use of parallel coordinate plot **[PG-7]**.

The research reported in paper **[PG-5]** was conducted simultaneously to the studies described in **[PG-1]** and **[PG-2]**, which resulted in the preparation of the concept of the *viewExposed* tool. Apart from an interactive datagrid and polyline glyphs, in *viewExposed*—the same as, later, in *agroEXPLORE*—of importance to the presentation of a complex index of vulnerability was the combination of a choropleth map with a parallel coordinate plot. This solution commonly used in coordinated and multiple views (Edsall, 2003a) aimed to facilitate the analysis of multivariate quantitative data referring to administrative units. However, as claimed by some authors (Edsall, 2003b; Roberts, 2005; Robinson et al., 2005; Heinrich & Weiskopf, 2013), such solution may be inconvenient for users. Therefore, I decided to empirically verify this issue. I used *viewExposed* as empirical material; 53 individuals participated in the study in which they were requested to use *viewExposed* to solve 16 tasks arranged into 6 groups. The tasks were designed so, to verify whether participants were able to use any of the tool's views, and also, whether they are able to effectively use interactive functions that dynamically link those views. Among the tasks, there were both, relatively simple inquiries about index scores in certain municipalities, as well as more complex tasks, in which individuals were requested, first, to select on the map display specific municipalities that score on a sub-index above certain value, and next, to comment on the similarities between the municipalities in terms of their multivariate signatures.

After a short introduction, the participants could easily get understanding how to interact with *viewExposed*. The tool's graphical user interface turned out to be intuitive; its choropleth map dynamically linked with the parallel coordinate plot turned out to be helpful if the users were trying to read multivariate spatial characteristics necessary to solve those tasks that required them to provide precise index scores for specific municipalities. One important finding of the research was that it did not confirm the skepticism expressed by other authors that users were not willing to use parallel coordinate plot. This visualization technique turned out to be helpful if a user was to get better understanding of multivariate characteristics. The attendees also managed to interact with the interactive datagrid as well as the polyline glyphs. The latter however was not used as a solution that facilitated reading index scores from the parallel coordinate plot, but as a separate data visualization technique. Nevertheless, the research revealed that, if more sophisticated tasks were to be solved, for example, tasks that required both an efficient interaction with *viewExposed* to read its multivariate spatial data as well as more complex inference and cognitive efforts, then the results of the participants were worse. This observation has confirmed opinions of other authors (e.g., Fabrikant et al., 2010) that an effective use of complex geovisualization tool requires both a high level of proficiency with the tool in general, and with its visualization and interaction techniques in particular, as well as proper skills regarding the interpretation of information provided in the tool along with adequate inference-making abilities.

The research findings reported in **[PG-5]** reveal that a tool that consists of a choropleth map dynamically linked with a parallel coordinate plot, an interactive datagrid, and with polyline glyphs, can be used by experts and also—after a short instruction—by less proficient users. Such tools enable users to present and visually analyze multivariate spatial characteristics. However, their efficiency depends not only on users' proficiency with certain functionality, but also, on users' individual skills regarding causal reasoning, data interpretation, and inference-making abilities. Therefore, if a complex geovisualization tool primarily aims to present multivariate spatial characteristics, it is likely that it will be used by a broad group of users. However, if it is also to enable analysis of such characteristics, facilitate hypothesis formulation, then, its effective use requires not only the proficiency with its functionality, but also, the proficiency with the interpretation of provided data and with the inference based on such information.

The investigations described in **[PG-5]** were continued in the research that aimed to get a better understanding of how people use coordinated and multiple views. Although the research findings described in **[PG-5]** suggested that such geovisualizations can be used—after a brief instruction—also by less proficient users, it was of importance to investigate more deeply user behavior (users' choices) if the same data are simultaneously provided in various visual components. Then, a question arises whether users tend to use various visualization techniques, or whether there are specific preferences in their choices regarding visualization techniques, and thus, providing the same data in various visual components makes no sense. Again, *viewExposed* served as empirical material, nevertheless, this research differed from the previous as eye-tracking was use as the primary technique for collecting empirical data. The research was realized as the individual research project of I. Gołębiowska from WGiSR UW who did her research training at the Department of Geography NTNU. She led the study, whereas my contribution to this research concerned conceptual consultancy; I also participated in the study design, the analysis of collected empirical data and their interpretation. I also critically revised manuscript **[PG-6]** which reports on the research as well as on its outcomes.

The factor that inspired us to continue the research initially reported in **[PG-5]**, was the opinion that although coordinated and multiple views can provide users with more information than geovisualization with a single visual component (Edsall, 2003a), their complexity may discourage potential users (Baldonado et al., 2000). It is in turn caused by the diversity of simultaneously used visualization methods (Griffin & Fabrikant, 2012) that require context switching. Therefore, the research aimed to verify the effectiveness of coordinated and multiple views if their various visual components display the same data. It was of importance to me to better understand this issue, as I was applying coordinated and multiples views in all design guidelines and concepts that I worked on. Moreover, the research also aimed to verify whether there were specific preferences in terms of users' choices regarding visualization techniques used for certain user tasks. Finally, it was of importance to us to figure out whether users are eager to use parallel coordinates if the data their display are also provided in other visual components of a complex geovisualization tool.

In the empirical research, 29 participants were requested to use *viewExposed* to solve five user tasks that were designed according to the taxonomy of Amar et al. (2005), which refers to low level operations. Thus, amongst the tasks, there were rather simple inquiries such as a question on an index score in a specific municipality, as well as a question about the similarities between certain municipalities regarding their multivariate signatures. During task accomplishment, the participants were free in terms of visualization techniques they could make use of. We were recording their eye movements, answers, and comments. In the data analysis stage we performed areas of interest (AOI) analysis (total fixation length), sequence alignment analysis, task execution analysis, viewing purpose analysis, and finally, we also verified answer correctness. My individual contribution to the data analysis stage was the design and development of the Eye Movement AOI Aggregation Tool (EMAAT) that was used in the task execution analysis **[PG-6]**. The EMAAT was developed as a single page web application based on JavaScript (D3.js, jQuery) and HTML5; it filters eye-movement data based on tasks and the participants' IDs. The tool depicts aggregated AOI locations of fixations over standardized task execution times and enables comparison between participants' task execution.

The research revealed that, during task execution, various participants were using various visualization techniques, also, the parallel coordinate plot. As a result, the research did not confirm the skepticism reported in the literature, regarding the effectiveness of such plot. The research also revealed that, there are no preferred visualization techniques with regard to particular user tasks. Therefore, an interactive geovisualization tool that integrates various visualization techniques in the form of coordinated and multiple views in order to provide users with multivariate spatial characteristics can be beneficial for potential users. They have choice, and thus, they can make use of those visualization techniques that fulfil their requirements.

Polyline glyphs were the next solution that I focused on in my research. Although their concept, potential application areas, as well as their empirical evaluation were to some extent described in my previous works **[PG-1]** and **[PG-5]**, they were not fully examined. Therefore, I conducted a separate study in order to summarize the state of the art in polyline glyphs, and to better investigate their advantages.

The primary objective of the research described in **[PG-7]** was to investigate the performance of polyline glyphs if they are to be used together with a parallel coordinate plot. As I have already mentioned, the use of such plot, in which (often) overlapping lines may lead to its visual clutter (Ellis & Dix, 2007), can be troublesome. Polyline glyphs may be a remedy, as they can facilitate getting a proper insight into the shapes of the polylines originally included in the plot. Two research questions were formulated in the research: (1) do polyline glyphs dynamically linked to a PCP augment insights into multivariate geographical data drawn from geovisualization provided through a PCP alone? And (2) what user tasks, if any, can be solved if task-solving activities are supported by the dynamic linking of a PCP to polyline glyphs?

Article **[PG-7]** consists of a theoretical part and of an empirical one. The first includes conceptual considerations, in which I have described the polyline glyphs in the context of similar visualization techniques. Polyline glyphs are to some extent similar to E. Tufte's sparklines (2006). Therefore, I initially used such term when working on the concept of polyline glyphs (Opach et al., 2013) **[PG-1]**, **[PG-2]**. Next, along with the research progress, I used the term polyline glyphs. Although the term "glyphs" has not been traditionally used in cartography; however, it refers to the visualization technique that is broadly used both in maps (i.e., *multivariate symbol map*) (Slocum et al., 2010) and in interactive information visualization (Takatsuka & Gahegan, 2002; Ho et al., 2012). Glyphs are simply minimized plots or diagrams without any axes and labels (Gribov et al., 2006; Ward, 2008). They can be geographically (on maps) or topologically distributed (Dorling, 1995), and also, as in *viewExposed* and in *agroEXPLORE*, they can be shown as arranged in a grid plot. In the tools that I have designed, the combination of regularly arranged polyline glyphs with a parallel coordinate plot was to enable users to get a good insight into particular graphical entities as they (the glyphs) were displayed as juxtaposed. However, on the other hand, such combination was also to enable users to compare particular multivariate data items if the corresponding polylines are displayed as superimposed in a parallel coordinate plot.

Apart from the conceptual considerations on polyline glyphs, in the theoretical part of article **[PG-7]**, I have also described my findings from their proof-of-concept implementations in *viewExposed* and *agroEXLORE*. In both tools, the glyphs turned out to be a valuable supplement of remaining visualization techniques; nevertheless, there was no scientific evidence that they could facilitate certain user tasks, particularly in combination with a parallel coordinate plot. Regarding *agroEXPLORE*, the high suitability of polyline glyphs for visual data analysis seemed to be caused by their reordering in a display with respect to the similarity to a selected glyph. This reordering was executed through the use of *n*-dimensional distance-based similarity measures: the Euclidean distance in *n*-dimensional space, the city-block metrics (Manhattan), and a modified version of the latter metrics.

The empirical study was to augment the conceptual considerations and to acquire evidence of the polyline glyphs' potential benefits initially recognized in their proof-of-concept implementations in *viewExposed* and *agroEXPLORE*. The study was described in the second part of article **[PG-7]**. The empirical study aimed to practically verify the conclusions of the theoretical part. A total of 36 individuals participated. As study material, I designed and developed a single-page web application in which a parallel coordinate plot was dynamically linked to a table with polyline glyphs. All 428 municipalities (at the time of writing) in Norway were used as multidimensional data items; each was characterized by 10 socioeconomic indicators. Apart from a common functionality, a similarity-check mechanism was implemented because we considered it substantial for polyline glyphs. The participants were requested to use the application freely to solve four tasks. The tasks were elaborated so to verify user behavior if a summary of multivariate signatures was to be done for all data items, part of them, and also, if the visual analysis to be conducted was to investigate the similarity of data items' multivariate signatures.

The participants were using polyline glyphs linked to a parallel coordinate plot if their visual analysis aimed to compare multivariate signatures of all presented municipalities with respect to their similarity to selected one. The glyphs were then particularly useful since visual clutter impeded the use of the parallel coordinate plot. Whereas the participants were using mostly the latter plot in the user tasks that aimed to visually analyze reduced number of data entities. The research revealed that in such case polyline glyphs were skipped. Finally, the empirical investigations revealed that some of participants instead of using polyline glyphs together with a PCP used polyline glyphs as an independent visualization technique.

Summary

The outcomes of my research reveal that:

1. Complex interactive geovisualizations that employ coordinated and multiple views can work as effective solution that enables presentation and visual analysis of multivariate spatial characteristics that support decision-making processes. Two applications developed as proof-of-concept implementations were to be used for the presentation of complex indices of environmental vulnerability to natural hazards in Norway (*viewExposed* – **[PG-1]**, **[PG-2]**) and agricultural vulnerability in Sweden (*agroEXPLORE* – **[PG-3]**). They turned out to be effective tools supporting decision-making processes when both the user is not able to modify presented characteristics (*viewExposed*), as well as such modifications are feasible and a tool is used, e.g., in collaborative decision-making processes (*agroEXPLORE*).
2. Interactive geovisualizations that use coordinated and multiple views and display data on environmental vulnerability to natural hazards can be also of value to ordinary users. However, for such users, user attention—when interacting with a tool—should be directed to suggest intended map use scenario. This solution has proved to be effective in *VisAdapt* **[PG-4]**. For users' convenience, the number of employed visualization techniques has been reduced and also only necessary interactive functions have been implemented.
3. Parallel coordinate plot is a solution that enables users to visually analyze multivariate spatial characteristics provided by means of choropleth mapping. A choropleth map dynamically linked with a parallel coordinate plot can be used also—after an adequate instruction—by less competent users. Nevertheless, effective use of such combination requires proper skills regarding inference-

making abilities. The latter in turn requires a comprehensive ability to use a tool's interactive functions, but also, an ability to construct judgments on the basis of the multivariate characteristics read from both visual components.

4. Polyline glyphs dynamically linked with a coordinate polyline plot facilitate the visual analysis and comparison of the multivariate characteristics of data items if visual clutter hinders the use of such plot. If parallel coordinates are legible, then one may question employing polyline glyphs.

Conclusions and Suggestions for the Application of Research Findings

The primary scientific achievement reported in this application for admittance to habilitation process are the design guidelines and the concepts of three complex interactive geovisualizations that enable the presentation and visual analysis of multivariate spatial characteristics that concern environmental vulnerability to natural hazards. All three concepts use coordinated and multiple views; however, they differ in terms of their application areas as well as their functionality. I used the design guidelines and the concepts to develop three web applications: *viewExposed*, *agroEXPLORE*, and *VisAdapt* (the latter was written together with C. Navarra from CSPR LiU) that constitute the practical contribution of my research that is applied to support decision making processes during climate change adaptation in Norway and Sweden. Although the applications are deliverables of two separate research projects: NORD-STAR and In Hac Vita, their developments were conducted simultaneously, and they are parts of the same scientific achievement. Moreover, I used the research findings to prepare, together with M. Hounjet from Deltares in the Netherlands, work package *WP3: Interactive Applications and Databases*, which constitutes part of the research project *Citizen Sensing – Urban Climate Resilience through Participatory Risk Management Systems* that has been granted financing in the program *European Research Area for Climate Services* (ERA4CS).

The concepts that constitute my scientific achievement can be used as a whole as well in parts (only their selected solutions) in order to design and develop tools supporting decision-making processes in any area for which necessary data exist. They can be used not only for displaying spatial characteristics that concern environmental vulnerability to natural hazards, but also more broadly, by all those who aim to present and visually analyze multivariate spatial characteristics in general. Three web applications: *viewExposed*, *agroEXPLORE*, and *VisAdapt* serve as examples of how such tools can look and work, both, if users are able to modify provided spatial characteristics as well as if they only aim to get insight into predefined complex information.

5. Overview of other scientific achievements

I graduated from WGiSR UW in 2002 with a Master's degree in geography. I wrote my thesis under the supervision of Professor J. Pasławski. The thesis concerned the concept of the map of the natural and cultural heritage of Poland in scale 1:50 000; I also made its proof-of-concept implementation. After master studies, I started, at the same faculty, PhD studies (2002-2006). In this period, apart from my interest in mapping of cultural heritage, I also began my research on animated mapping. I described its results in my PhD dissertation that I prepared under the supervision of Professor J. Pasławski. The thesis concerned the efficiency of temporal animated maps. After my PhD studies, I was employed at WGiSR UW, initially as research assistant, afterwards, after the defense in January 2007, as assistant professor (*adiunkt* in Polish). I was employed in this faculty (with leave of absence) till September 2016. Over this period, my scientific interest evolved from the effectiveness of animated maps, through the use of interactives maps, towards broadly understood interactive visualization of geographical data. Undoubtedly, of primary importance to my scientific career have been investigations that I have conducted at NTNU in Trondheim: In the years 2009-2010 I did at NTNU a research training (in the Department of Geomatics), in the years 2012-2014 I did a post-doctoral training at its Department of Geography, whereas since July 2014 I have been employed at NTNU as researcher. Meanwhile, I did also another post-doctoral training at the CSPR LiU (2013-2014). In the research that I have been conducting at NTNU I have focused on the use of complex interactive geovisualization in the presentation and analysis of multivariate spatial characteristics.

At the moment, there are 66 scientific publications in my scientific track record:

- 25 peer-reviewed journal articles, in which 21 have been published after my PhD defense, 18 have been written in co-authorship, and 10 have been included in Part A of the List of Journals of the Polish Ministry of Science and Higher Education;
- 18 peer-reviewed book chapters, in which 11 have been published after my PhD defense and 7 have been written in co-authorship;
- 5 peer-reviewed poster presentation published as extended abstracts in conference proceedings; one of these publications has been included in the *Web of Science* indexing service;
- 2 books with multiple contributors;
- 7 reviews published in the peer-reviewed journal *Polish Cartographical Review*;
- 9 short reports published in the news section of the *Polish Cartographical Review*.

According to the *Web of Science* indexing service (access on the 1. of July 2017) my *h*-index equals 3, whereas my total number of citations (without self-citations) equals 10. I participated in 9 research projects, in which one was financed by the Polish Ministry of Science and Higher Education and four were arranged as international collaboration. Apart from the articles that constitute my scientific achievement (main articles, in Polish – *publikacje główne*, PG), my remaining scientific papers can be grouped into the following five thematic categories:

A. Animated mapping
B. Web cartography

C. Cartographic symbolization techniques
D. The use of the eye-tracking technique in empirical studies on maps and geovisualizations
E. The use of maps in the presentation and research on cultural landscape

A. Animated mapping

I conducted research on animated mapping in the period 2002-2012. Initially, when working on my PhD thesis over the years 2002-2006, I investigated the effectiveness of temporal animated maps. This research aimed to recognize areas of effective application of animated maps (Opach, 2005a, 2005c) and also, to recognize those factors that influence their effectiveness. In order to reach this research goal I used the theory of the efficiency of cartographic communication (Ostrowski, 1974). Its two key concepts: semantic and pragmatic aspect of the communication efficiency, constituted the theoretical frame that enabled me to analyze those communication steps that can be considered to be critical for animated maps (Opach, 2005b, 2006b). Next, I carried out an empirical research in order to verify the theoretical considerations. I included its outcomes in my doctoral thesis and I described them in two papers (Opach, 2007a, 2007b) published after the public defense.

After the defense, I initially continued the work that I had initiated during my PhD studies. I published a paper (Opach, 2007d), in which I described the use of the theory of cartographic communication in studies on the efficiency of animated maps. In the following investigations, I focused on more applied issues. In 2008 I began collaboration with the Museum of King Jan III's Palace in Wilanów that aimed to design a concept of an animated map presenting the evolution of Poland's borders and that was to be included in the museum's e-learning web portal. This conceptual research was next described in a paper (Opach, 2008a), in which I also discussed the features of the "little" web cartography (this term refers to the phrase that was used for the very first time by J. Goleń in 1997).

My research further evolved towards complex cartographic animations that integrate animated maps with other visual representations. I then conducted my research as two individual research projects, in collaboration with scientists from foreign universities. In both projects, I accomplished part of their tasks/milestones during my research trainings at foreign universities. The first, financed by the Research Council of Norway (project no 195 755), aimed to prepare the concept of the complex cartographic animation showing the formation of the physical landscape of Kampinos Forest. I was realizing this project over the period 2009-2011; part of its research I conducted in collaboration with T. Midtbø and A. Nossum, during my research training at the Department of Geomatics NTNU (2009-2010). I continued my research on complex cartographic animations in the second project, which was partially financed by the scholarship program "The Modern University" for young researchers and teaching staff of the University of Warsaw. I realized this research in the period 2010-2012 in collaboration with S. I. Fabrikant and I. Gołębiowska, partially during two study visits at the University of Zürich (in 2010 and 2011). This research aimed to find out whether the users of complex cartographic animations are able to split their visual attention when viewing them.

The research I conducted in both projects was based on the same three-step study design I developed: conceptual investigations, proof-of-concept implementation, and finally, empirical evaluation. I have used this design in my empirical studies up to now. Moreover, in both projects, the practical benefit of the research was an original concept of a complex geovisualization (cartographic animation), its proof-of-concept implementation (prototype), as well as empirical evaluation by means of the *eye-tracking* technique (Opach & Nossum, 2011; Opach et al., 2014). The two studies I then conducted differed in respect of the aim of animation. In the first study, animation aimed to show the formation of a specific physical landscape (Opach et al. 2011), whereas in the second, it was intended to support decision making processes during a wildfire (Opach et al. 2014). Furthermore, in the first case, the most challenging research issue was to design a complex animation so, that it could provide as much comprehensive image of factors affecting landscape formation as possible (the semantic aspect of cartographic communication). Whereas, in the second study the most challenging was proper empirical evaluation of the original concept of a complex animation consisting of two animated maps and a static map (pragmatic aspect). The latter study was particularly inspiring for me, as it was the first time when I focused on the use of complex interactive geovisualizations with coordinated and multiple views to support decision making processes in mitigation and adaptation to natural hazards. As I have already mentioned, this research has inspired me to carry out the research, whose outcomes constitute my scientific achievement.

B. Web cartography

My interest in web cartography have been initially triggered by my investigations on animated maps. For the latter, the Internet is as essential as paper for traditional static maps. Apart from technological issues, the primary factor that distinguishes web cartography from traditional one is a common access to maps with interactive functions (Nowacki & Opach, 2006). Due to the commonness of portable electronic devices interactive web maps became ubiquitous (Werner & Opach, 2013). Web cartography encompasses both complex and sophisticated online map services as well as straightforward, relatively simple web maps – the "little" web cartography (Opach, 2008a). Such "little" web cartography includes both digitized versions of traditional paper maps as well as those maps that have been by default designed as interactive map displays, often accompanied with animations, movies, textual descriptions, images, and sounds. The map use cube (MacEachren & Kraak, 2001) places the "little" web cartography in the corner in which the relationships within the data are known, users are unknown, and interactive functions are basic.

In the period 2007-2008 I investigated the quality of web maps. At that time, I analyzed the quality of geographical data used in online map services (Opach, 2007c) as well as web maps available at the websites of Polish national parks (Opach, 2008b). In June 2005 Google launched the free service Google Maps API. It was the revolution in web cartography as this JavaScript API completely changed the way how web maps can be designed, developed, and used. The Google Maps JavaScript API allowed unskilled people (with neither cartographic nor ITC background) to make interactive maps. Google Maps API used with PHP and MySQL enabled developers to prepare relatively quickly also more sophisticated mapping services that displayed information from databases (Nowacki & Opach, 2009). As a result, a myriad of new web maps appeared quickly in the Internet. Nevertheless, the quality of their data content was not so high as the multiplicity and diversity of such web maps. Low quality of the data for densely populated areas was a good example of this issue (Opach, 2007c). Adobe Flash was another common technology in those days; it was based on ActionScript. I used this technology in several tasks, e.g., in the proof-of-concept implementation of the animated map about the formation of the physical landscape of Kampinos Forest (Opach et al., 2011).

More recently, my interest in web cartography is reflected in the research on map-based tools that support climate change adaptation. In 2014 T.-S. Neset from CSPR LiU invited me to a common research that aimed to structure existing knowledge on map-based climate services. In this research, first, we investigated 20 such services, and then, we grouped them into four categories, by data type and provided functionality. The four categories elaborated in the study, it was my original contribution to the research. Apart from the classification, we also described climate services. To do so we used the three dimensions included in the map use cube (MacEachren & Kraak, 2001), that is: users, data content (provided information), and interactive functions. The research findings of this study have been reported in a paper published in *The Professional Geographer* (Neset et al., 2016b); I am the second author of this paper.

In turn, the investigations I have conducted since 2015 are part of the research project that aims to use participatory techniques in order to design an integrated index of community resilience to natural hazards. To do so, I have prepared the design guidelines as well as concepts of two web tools (Opach & Rød, 2016) that enable users to identify factors that affect community resilience, and also, that allow them to report on individual perspectives on natural hazards they have experienced in their life. While the first tool enables insight into explicit knowledge, the second might get a deeper insight into tacit knowledge (Polanyi & Sen, 2009).

C. Cartographic symbolization techniques

Regarding cartographic symbolization techniques, my research have concerned three issues: their formalization, their use when designing public transportation maps, and the similarities between cartographic design and graphic design.

The first from the above issues was of importance to my research that I realized in the period 2010-2012. Then, my investigations contributed to the research project N N526 073838 *Formalization* *of quantitative cartographic methods of presentation and its implementation in the Web Atlas of Cartographic Methods of Presentation*, financed by the Polish Ministry of Science and Higher Education, and led by Professor J. Pasławski. The research along with its findings have been reported in a set of publications (Pasławski et al., 2011a; Korycka-Skorupa et al., 2012; Pasławski et al., 2012) as well as they have been presented at two thematic conferences (Korycka-Skorupa et al., 2010; Pasławski et al., 2011b). The research aimed to formalize the map design processes in which a mapmaker is to design either a choropleth map, symbol map, isarithmic map, dot map, or a quantitative points map. According to Korycka-Skorupa (2002), formalization requires splitting the thematic mapping process into two essential phases: representation and symbolization. The first term – representation, is the act of representing data on map, process, whereas symbolization is the result of this act, that is – signs on map. The result of our theoretical and conceptual investigations was the description of the design steps that lead from geographical data to map, whereas the deliverable was the *Web Atlas of Cartographic Methods of Presentation*. The Atlas enables users to view and seek recommendations for mapping techniques that can be used for various datasets included in the *Atlas*. Such functionality lets its users better understand the logics behind various cartographic symbolization techniques.

Regarding the second issue, public transportation maps are one of the most common ways of graphically conveying spatial information to the general public. Despite the fact they have been designed, at least, from the 1930', they have no comprehensive design guidelines. In the research that I conducted together with my bachelor's student A. Mućko, we focused on those challenges that influence the efficiency of such maps; we have described our findings in a common article (Mućko & Opach, 2009). We have in our research focused particularly on simplification, geometrization and style selection. We have also discussed the key issues of the design of public transportation maps such as: stops, stop coincidences, as well as overlapping lines. We have also investigated selected public transportation maps of Polish cities.

The research on public transportation maps has afterwards inspired me to seek the similarities between cartographic symbolization techniques and the design principles used in graphic design in general (Opach, 2010). The importance of the map design in the efficiency of the cartographic communication process has been already recognized by cartographers. Therefore, terms well known from the graphic design such as informativeness, layout, usability, visual hierarchy, or aesthetic values, they are all commonly used in cartographic design. Their application is of importance to the design process of a map of any kind as doing so may increase the efficiency of cartographic communication.

D. The use of the eye-tracking technique in empirical studies on maps and geovisualizations

My interest in the use of the eye-tracking technique to collect user data in empirical studies on maps and geovisualization was triggered during my research training at the Department of Geomatics NTNU that I did in the period 2009-2010. Then, in the research that I conducted together with A. Nossum, we applied eye-tracking in an empirical evaluation of two animated maps. We conducted the research in accordance with our own study design, whereas we described the research findings in a common paper (Opach & Nossum, 2011), which, according to Google Scholar (on the 1st of July 2017), is my most cited publication, cited 21 times without self-citations (7 citations in journals with IF).

The novelty of our research concerned the use of eye-tracking in an empirical research that aimed to test cartographic animations. Such approach, enabled us—at the data analysis stage—to identify areas where participants were looking at, as well as to investigate the changes of users' visual behavior caused by looking at an animated image. The results inspired us (Nossum & Opach, 2011) to use, in the data analysis part, the space-time cube introduced in the mid-1960s by the Swedish geographer T. Hägerstrand (1967). I continued with this idea in my subsequent research, in which I used ArcGIS ArcScene to visualize eye movement data in a space-time cube (Opach, 2011). I used this software to make a 3D visualization, in which the vertical height of the space-time-path – the trajectory of eye movements consisting of eye fixations at particular locations connected by saccades (movements of eye), indicates the duration of the user's eye movement recording.

In user studies in GIScience and cartography, the eye-tracking technique can be combined with other empirical techniques such as thinking aloud or interviews. The basic advantage of such combination is a more comprehensive insight into users' visual behavior. Eye-tracking enables researchers to empirically verify those aspects, which they could before only speculate about: users' visual behavior during map use (Opach, 2011). Eye-tracking supplements the set of empirical techniques applied in user studies and thus allows researchers to better understand the way how users interact with maps, both static and animated. Eye movement analysis provides us with information on visual behavior, which reflects mental attention (Webb & Renshaw, 2008). My research has confirmed this opinion; I used *eye-tracking*, as already mentioned (see section 5A), in the research on visual behavior of those who use a complex animated map display consisting of two animated maps and a static map (Opach et al., 2014), as well as in the research that aimed to reveal visual behavior of users of visual tools with coordinated and multiple views. The latter research constitutes part of my scientific achievement **[PG-5]**. I also use eye-tracking in my current research that aims to better investigate the usability of polyline glyphs. The outcomes of the research, in which we have compared polyline glyphs with star glyphs, have been reported in the manuscript that has been accepted for publication in the journal *Cartography and Geographic Information Science* (in Figure 1 shown as [P-D]).

E. The use of maps in the presentation and research on cultural landscape

Issues that concern the use of maps in the presentation and research on cultural landscape were the subject on my investigations in the years 2001-2012. I have in my scientific career always been interested in the cartographic representation of those objects known from geographical landscape that constitute its tangible and intangible cultural heritage. This interest affected my decision to prepare, as my Master's thesis, the concept of the map of the natural and cultural heritage of Poland 1:50 000 (along with its proof-of-concept implementation). This research has resulted in three scientific publications: one in Polish (Opach & Pasławski, 2003) and two in English (Opach, 2003a; Opach, 2006a). The research subject that I initiated in the former Chair of Cartography, was next continued by the Chair's master students. They have verified my concept of the heritage map of Poland by preparing proof-of-concept implementations for another test areas: the municipality of Tarnowskie Góry (J. Paździor, 2006), the city and the municipality of Puławy (A. Chodoła, 2009), as well as the Augustów region (K. Miszkurka, 2010). The latter two were prepared under my supervision. I have been next interested in cultural heritage with regard to distinguishing its particular elements as well as elaborating on their adequate cartographic representation. In contrast to the cartographic representation of both natural and man-made features, e.g., on topographic maps, the difficulty of the cartographic representation of cultural landscape concerns the ambiguous nature of the latter. Unclear definitions of cultural landscape imply differences in objects which such landscape may encompass. Furthermore, of importance to the graphical representation of cultural landscape are such issues as: proper map scale (adequate for showing all necessary objects), proper map symbols for boundaries, especially those fuzzy, and finally, properly designed map symbols for thematic content (Opach, 2004a).

Topographic maps play important role in the research on cultural landscape as their diverse and rich content can constitute a good starting point in the research of various cultural landscape's objects (Opach, 2003b; Opach, 2004b). One example can be a study that aims to indicate those objects which do not exist anymore such as former railway tracks or folwarks (no English term); however, whose remaining are still visible in the landscape. Historical and recent topographic maps constitute also valuable source of information in the research of landscape evolution over time, for example, in research on shift from rural to urban areas. Such information, about urbanization processes or other landscape changes over time, can constitute valuable content of maps of cultural heritage (Opach, 2012).

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